Performance Analysis of Multi-services Call Admission Control in Cellular Network Using Probabilistic Model Checking

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Abstract. This paper deals with formal verification to evaluate performances of Call Admission Control (CAC) schemes in cellular mobile network. Call Admission Control is a mechanism regulating cellular network access to ensure QoS provisioning. From the fact that cellular networks have many classes of services and each class has different QoS requirements, we study CAC schemes supporting two classes of services, real time (RT) and non-real time (NRT), and for each class we distinguish two types of calls, handoff calls (HCs) and new calls (NCs). The studied CAC schemes give priority to RT calls over NRT calls and to HCs over NCs. Traditionally, performance analysis of CAC schemes is performed using analytic and/or simulation models by computing the main steady-state performance measures: new call blocking probability, handoff call dropping probability and mean channels occupation rate. In this work we propose to employ Continuous-time Stochastic Logic (CSL) to specify QoS requirements using transient and steady-state formulas supported by this formalism. Indeed, CSL is a specification language that can be used for Continuous Time Markov Chains (CTMCs) and offers the flexibility to express both transient and steady-state measures including probabilistic path and steady-state formulas. We model the studied CAC schemes with labelled CTMCs then we formalize QoS requirements of each traffic class with CSL. We perform the verification of the considered formulas with PRISM model checker. A performance comparison of the studied CAC schemes is provided based on verification results.

Keywords: Probabilistic model checking · CTMC · CSL · CAC schemes · PRISM

1 Introduction

Probabilistic model checking is a formal verification technique for modelling and analysis systems which exhibit stochastic behavior. It has been employed in different application domains such as wireless communication protocols, security, power management [9,10]. Probabilistic model checking, using Continuous Time Markov Chains, is widely employed to perform quantitative measurements of

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properties such as performance and reliability. In this context we use this formalism to evaluate performances of Call Admission Control (CAC) schemes in cellular network.

In cellular network, base station (BS) is a radio access point covering certain geographic area (cell). Each cell is equipped with a limited number of channels to serve different user's connections. If there is no available channel the connection request will be rejected. Call admission control is the mechanism handling the acceptance or rejection of arriving calls. Several CAC schemes are proposed and can be classified based on different criteria [1]. One criterion is the number of services/classes. Indeed, traffic arriving to BS can be classified to RT such as voice, streaming applications or NRT such as web services or file transfers. For each class two types of calls can be differentiated, NCs originating from the underlying cell and HCs coming from neighboring cells. Each traffic class has different Quality of Service (QoS) requirements. Indeed, RT traffic has stringent QoS requirements because it can contains interactive applications compared to NRT traffic which contains non-interactive applications. Moreover, HCs are prioritized over NCs because dropping a HC in progress is more annoying than blocking a NC request.

Several CAC schemes have been discussed in the literature [5,6,8,17] to provide priority to HC without significantly forgoing NC requests. These schemes can be categorized into two basic methods: The first is by reserving, statistically or dynamically, a number of channels exclusively for handoff calls called guard channels [6]. The second by queuing handoff request [8] if all channels are not available, waiting that channel be free.

Recently much research work has been done on call admission control for multi-service mobile networks by favoring RT calls over NRT calls. In [16], the authors propose a multi-service CAC schemes improving bandwidth utilization in case of bandwidth asymetry (between uplink and downlink) environment. In [5], the authors propose a CAC schema based on the classification of channels to bad and good. This classification is done by estimating the quality of channel according to received signal strength. Calls with high priority are favored by taking good channels. In [17], an adaptive CAC schema based on degradation procedure is presented. The authors propose to reduce the width of channels allocated to calls having lower priority in order to maximize the number of calls having higher priority. We refer reader to these surveys [1,11] that explain and classify different CAC schemes.

The main QoS requirements that a CAC schema should satisfy are: HC dropping probability and NC blocking probability should be below certain predefined value and the channels occupation rate should be greater than some threshold to obtain a good bandwidth utilization. Different works have studied performance evaluation of CAC schemes. To the best of our knowledge, all studies are performed using simulation technique [5,8,17] and/or analytic approaches [6,15,16]. In this paper, we propose to use probabilistic model checking to check and compare performances of different CAC schemes. This work contains two contributions: Firstly we propose two multi-service CAC schemes prioritizing RT calls over NRT calls, secondly we compare their performances with two classic ones using probabilistic model checking. We model CAC schemes with labelled CTMCs then we formalize QoS requirements of each traffic class with CSL. The verification of the considered formulas is performed with PRISM model checker which has been used in wide range of case studies [9,10]. A performance comparison of the studied CAC schemes is provided based on verification results.

This paper is organized as follows. In Sect. 2 we briefly give an overview of labelled CTMC and CSL. Section 3 provides a modeling of studied CAC schemes. In Sect. 4, we formalize QoS requirements with CSL. We give in Sect. 5 numerical results of verification. Finally, Sect. 6 concludes the paper.

2 Probabilistic Model Checking

In this section we present briefly formalisms (labelled Continuous-Time Markov Chain (CTMC) and CSL [3]) that we use to evaluate performance measures for the studied CAC schemes. We refer to the book [13] for more details on Markov chains. Recall that in this paper, we model CAC schemes by labelled CTMCs and we formalize QoS constraints with CSL.

2.1 Labelled CTMC

A labelled CTMC $\mathcal{M}$ is a tuple $(S, \mathbf{R}, L)$ where S is a finite set of *states*, $\mathbf{R} : S \times S \rightarrow \mathcal{R}^+$ is the *rate matrix* and $L : S \rightarrow 2^{AP}$ is the *labelling* function which assigns to each state $s \in S$, the set $L(s)$ of atomic propositions $a \in AP$ that are valid in s, AP denotes the finite set of atomic propositions. Remark that the infinitesimal generator $\mathbf{Q}$ can be easily deduced as $\mathbf{Q}(s, s') = \mathbf{R}(s, s')$ if $s \neq s'$ and $\mathbf{Q}(s, s) = -\sum_{s' \in S} \mathbf{R}(s, s')$. A path through a CTMC is an alternating sequence $\sigma = s_0 t_0 s_1 t_1 \cdots$ with $\mathbf{R}(s_i, s_{i+1}) > 0$ and $t_i \in \mathcal{R}^+$ for all $i \geq 0$. t_i represents the amount of time spent in state s_i. Let us denote by $path_s$ the set of paths through $\mathcal{M}$ starting from the state s. For a CTMC, there are two types of state probabilities: transient probabilities where the system is considered at time t and steady-state probabilities when the system reaches an equilibrium if it exists. In the sequel, we denote by $\mathbf{\Pi}_s^{\mathcal{M}}(t)$ the transient distribution at time t of Markov chain $\mathcal{M}$ starting at $t = 0$ from the initial state s. The probability to be in state s' at time t starting initially from s will be denoted by $\mathbf{\Pi}_s^{\mathcal{M}}(s', t)$. $\mathbf{\Pi}_s^{\mathcal{M}}(s') = \lim_{t \rightarrow \infty} \mathbf{\Pi}_s^{\mathcal{M}}(s', t)$ is the steady-state probability to be in state s'. If $\mathcal{M}$ is ergodic, $\mathbf{\Pi}_s^{\mathcal{M}}(s')$ exists and it is independent of the initial distribution that we will denote by $\mathbf{\Pi}^{\mathcal{M}}(s')$. We denote also by $\mathbf{\Pi}^{\mathcal{M}}$ the steady-state probability vector. For $S' \subseteq S$, we denote by $\mathbf{\Pi}_s^{\mathcal{M}}(S', t)$ (resp. $\mathbf{\Pi}^{\mathcal{M}}(S')$) the transient probability to be in states of S', $\mathbf{\Pi}_s^{\mathcal{M}}(S', t) = \sum_{s' \in S'} \mathbf{\Pi}_s^{\mathcal{M}}(s', t)$ (the steady-state probability to be in states of S', $\mathbf{\Pi}^{\mathcal{M}}(S') = \sum_{s' \in S'} \mathbf{\Pi}^{\mathcal{M}}(s')$).

2.2 Temporal Logic CSL

Continuous Stochastic Logic is an extension of CTL (Computational Tree Logic) [7] with two probabilistic operators that refer to steady-state and transient behaviors of the underlying system.

Let p be a probability threshold, $\lhd$ be a comparison operator such that $\lhd \in \{\leq, \geq, <, >\}$ and I be an interval of real numbers. In the sequel, we denote by S_ϕ or ϕ-states the set of states that satisfy ϕ property and by $\models$ the satisfaction relation. The syntax of CSL is defined by:

$$\phi ::= true \mid a \mid \phi \wedge \phi \mid \neg\phi \mid \mathcal{P}_{\lhd p}(\phi\, \mathcal{U}^I \phi) \mid \mathcal{S}_{\lhd p}(\phi)$$

In this paper, we will use probabilistic operators $\mathcal{P}_{\lhd p}(\phi_1\, \mathcal{U}^I \phi_2)$ and $\mathcal{S}_{\lhd p}(\phi)$ to define and quantify performance measures of studied systems. In fact these operators are refering to transient and steady state behavior of the considered system.

$\mathcal{P}_{\lhd p}(\phi_1\, \mathcal{U}^I \phi_2)$ asserts that the probability measure of paths satisfying $\phi_1\, \mathcal{U}^I \phi_2$ meets the bound given by $\lhd p$. Whereas, the path formula $\phi_1\, \mathcal{U}^I \phi_2$ asserts that ϕ_2 will be satisfied at some time $t \in I$ and that at all preceding time ϕ_1 holds. $\mathcal{S}_{\lhd p}(\phi)$ asserts that the steady-state probability for ϕ-states meets the bound $\lhd p$.

Let us present briefly the semantics of these formulae [4]:

$s \models true$	for all $s \in S$
$s \models a$	iff $a \in L(s)$
$s \models \neg\phi$	iff $s \not\models \phi$
$s \models \mathcal{P}_{\lhd p}(\phi_1\, \mathcal{U}^I \phi_2)$	iff $Prob^{\mathcal{M}}(s, \phi_1 \mathcal{U}^I \phi_2) \lhd p$
$s \models \mathcal{S}_{\lhd p}(\phi)$	iff $\mathbf{\Pi}_s^{\mathcal{M}}(S_\phi) \lhd p$

Where $Prob^{\mathcal{M}}(s, \phi_1 \mathcal{U}^I \phi_2)$ denotes the probability measure of all paths σ starting from s ($\sigma \in paths_s$) satisfying $\phi_1\, \mathcal{U}^I \phi_2$ i.e. $Prob^{\mathcal{M}}(s, \phi_1 \mathcal{U}^I \phi_2) = Prob\{\sigma \in paths_s \mid \sigma \models \phi_1\, \mathcal{U}^I \phi_2\}$.

In this paper we will use also two reward operators belonging to CSRL logic. Continuous Stochastic Reward Logic (CSRL) [12] is an extension of Continuous Stochastic Logic (CSL) by adding constraints over rewards. The steady-state operator $\mathcal{E}_J(\phi)$ asserts that the expected (long run) reward rate for ϕ-states lies in J (J is an interval of real numbers). The transient operator $\mathcal{E}_J^t(\phi)$ asserts that the expected instantaneous reward rate at time t for ϕ-states lies in J. $\rho : S \rightarrow \mathcal{R}^+$ is a *reward structure* that assigns to each state $s \in S$ a reward $\rho(s)$. The verification of these reward formulas $\mathcal{E}_J(\phi)$ (resp. $\mathcal{E}_J^t(\phi)$) requires the computation of the steady-state (resp. transient at t) distribution of the considered CTMC $\mathcal{M}$.

$$\begin{array}{l} s \models \mathcal{E}_J^t(\phi) \text{ iff} \sum_{s' \in S_\phi} \mathbf{\Pi}_s^{\mathcal{M}}(s', t) \cdot \rho(s') \in J \\ s \models \mathcal{E}_J(\phi) \text{ iff} \sum_{s' \in S_\phi} \mathbf{\Pi}^{\mathcal{M}}(s') \cdot \rho(s') \in J \end{array} \quad (1)$$

3 Formal Modelling of CAC Schemes

In this section we describe and model with labelled CTMC four CAC schemes. We compare next their performances in Sect. 5 using probabilistic model checking. Let us first describe the system under consideration.

We consider a single cell and the arrival traffic to the base station (BS) is categorized in two classes of services: RT class and NRT class. The RT class is prioritized over the NRT class. This latter is assumed best effort traffic. For each class of service, we distinguish two types of calls: NCs originating from the underlying cell and HCs coming from neighboring cells. BS channels are divided into two parts: NRT channels and RT channels. RT channels serve only RT calls whereas NRT channels can serve both NRT and RT calls depending on the CAC schema. In this paper we study performances of four CAC schemes. The first two schemes named B-CAC (Basic CAC) and Q-CAC (Queuing CAC) are classics and their performances are studied in many works [2,8]. The two other schemes RTP-CAC (Real Time Priority CAC) and RTPQ-CAC (Real Time Priority Queuing) schemes are proposed in this paper in order to enhance QoS of RT calls by carrying out mechanisms that give priority to this class of calls.

All the investigated CAC schemes use guard channels in order to prioritize HC over NC since dropping handoff calls is less tolerable than blocking new calls. In fact, from user's point of view, a call being forced to terminate during a service (HC) is more annoying than a call being blocked at its start (NC). B-CAC is a static admission control schema. It does not consider the priority between classes of calls and only prioritize HCs over NCs for each class by reserving exclusively guard channels used only by HCs. Similarly, the second schema Q-CAC uses guard channels and further adds, for each class of traffic, a queue used by HC if all channels are occupied. In RTP-CAC, we give RT priority by permitting RT calls to use NRT channels if there is no idle RT channels. For the last CAC schema RTPQ-CAC, we combine mechanisms of RTP-CAC and Q-CAC in order to improve QoS of Calls with high priority (RT calls and HCs).

Let C_1 (resp. C_2) be the total number of NRT (resp. RT) channels. Let g be the number of guard channels reserved exclusively for HCs. We assume that the arrival processes for different traffic are independent and follow Poisson distribution with the following rates: λ_{Nh} for NRT HCs, λ_{Nn} for NRT NCs, λ_{Rh} for RT HCs and λ_{Rn} for RT NCs. We denote by $\lambda_N = \lambda_{Nh} + \lambda_{Nn}$ (resp. $\lambda_R = \lambda_{Rh} + \lambda_{Rn}$) arrival rate of NRT (resp. RT). We suppose that the holding time of channels is exponentially distributed with mean $1/\mu$.

In order to check CSL formulas that specify QoS requirements in terms of NC blocking probability and HC dropping probability for both NRT and RT classes, we need to label CTMC states with atomic propositions that characterize the state. Let us consider the following set of atomic propositions AP.

$$AP = \{\mathrm{RT\_Drop}, \mathrm{RT\_Block}, \mathrm{NRT\_Drop}, \mathrm{NRT\_Block}\} \tag{2}$$

RT_Drop (resp. NRT_Drop) is assigned to states in which RT (resp. NRT) HC is dropped. RT_Block (resp. NRT_Block) is assigned to states in which RT (resp. NRT) NC is blocked.

Let us detail the corresponding labelled CTMC of studied CAC schemes. We start by classical and existing schemes (B-CAC and Q-CAC) and then we detail proposed schemes in this work (RTP-CAC and RTPQ-CAC).

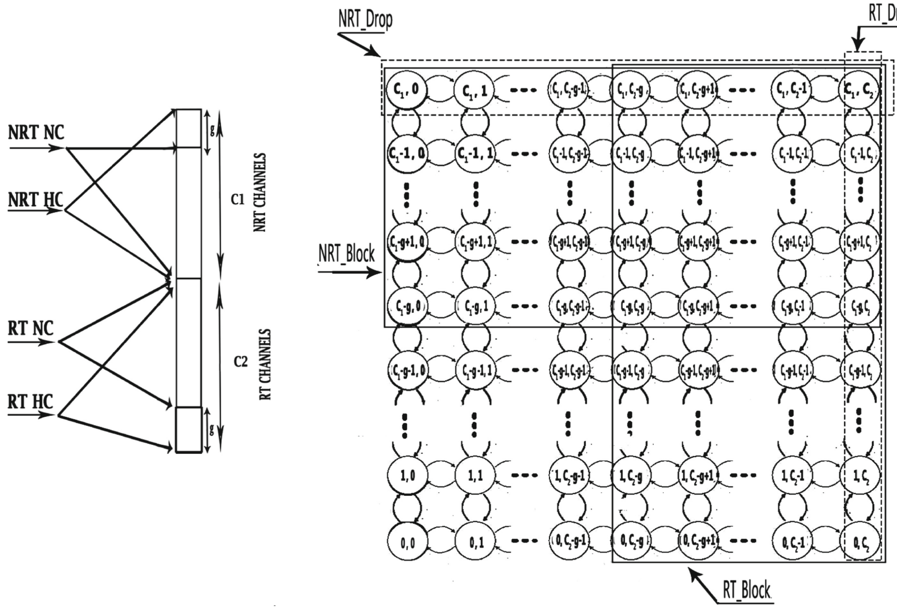
3.1 Basic CAC (B-CAC) Schema

B-CAC is a static admission schema that does not take into account the priority between classes of traffic. For both classes NRT and RT, the priority is given only to HCs over NCs by assigning g channels used exclusively by HCs. HCs and NCs for NRT (resp. RT) class are sharing $C_1 - g$ (resp. $C_2 - g$ channels). The channel allocation in B-CAC is presented in Fig. 1(a). A NRT (resp. RT) NC is blocked if the number of available channels in NRT (resp. RT) channel part is less or equal to $(C_1 - g)$ (resp. $C_2 - g$). Whereas, A NRT (resp. RT) HC is dropped if the number of occupied channels in NRT (resp. RT) channel part is equal to C_1 (resp. C_2).

Based on assumptions for arrival and service rates described previously, we obtain a two dimensional homogeneous CTMC (see Fig. 1(b)). The state space is given by:

$$S_{B-CAC} = \{(c_1, c_2)|0 \leq c_1 \leq C_1; 0 \leq c_2 \leq C_2\} \tag{3}$$

In state (c_1, c_2), c_1 (resp. c_2) represents the number of busy NRT (resp. RT) channels. The transition rate $\mathbf{R}_{B-CAC}(c_1, c_2; \bar{c_1}, \bar{c_2})$ from state (c_1, c_2) to state



(a) Channels allocation (b) Labelled CTMC

Fig. 1. B-CAC schema

$(\bar{c_1}, \bar{c_2})$ in B-CAC schema is defined as follows:

$$\mathbf{R}_{B-CAC}(c_1, c_2; c_1+1, c_2) = \begin{cases} \lambda_N & \text{if } (0 \le c_1 < C_1 - g; 0 \le c_2 \le C_2) \\ \lambda_{Nh} & \text{if } (C_1 - g \le c_1 < C_1; 0 \le c_2 \le C_2) \end{cases}$$
$$\mathbf{R}_{B-CAC}(c_1, c_2; c_1, c_2+1) = \begin{cases} \lambda_R & \text{if } (0 \le c_1 \le C_1; 0 \le c_2 < C_2 - g) \\ \lambda_{Rh} & \text{if } (0 \le c_1 \le C_1; C_2 - g \le c_2 < C_2) \end{cases}$$
$$\mathbf{R}_{B-CAC}(c_1, c_2; c_1-1, c_2) = \mu c_1 \qquad \text{if } (0 < c_1 \le C_1; 0 \le c_2 \le C_2)$$
$$\mathbf{R}_{B-CAC}(c_1, c_2; c_1, c_2-1) = \mu c_2 \qquad \text{if } (0 \le c_1 \le C_1; 0 < c_2 \le C_2)$$

We label states by atomic propositions of AP set defined in Eq. 2. The obtained satisfaction sets are marked in Fig. 1(b) and defined formally by:
$S_{NRT\_Drop} = \{(c_1, c_2) \mid c_1 = C_1 \text{ and } 0 \le c_2 \le C_2\}$
$S_{NRT\_Block} = \{(c_1, c_2) \mid C_1 \ge c_1 \ge C_1 - g \text{ and } 0 \le c_2 \le C_2\}$
$S_{RT\_Drop} = \{(c_1, c_2) \mid c_2 = C_2 \text{ and } 0 \le c_1 \le C_1\}$
$S_{RT\_Block} = \{(c_1, c_2) \mid C_2 \ge c_2 \ge C_2 - g \text{ and } 0 \le c_1 \le C_1\}$

3.2 Queuing CAC (Q-CAC) Schema

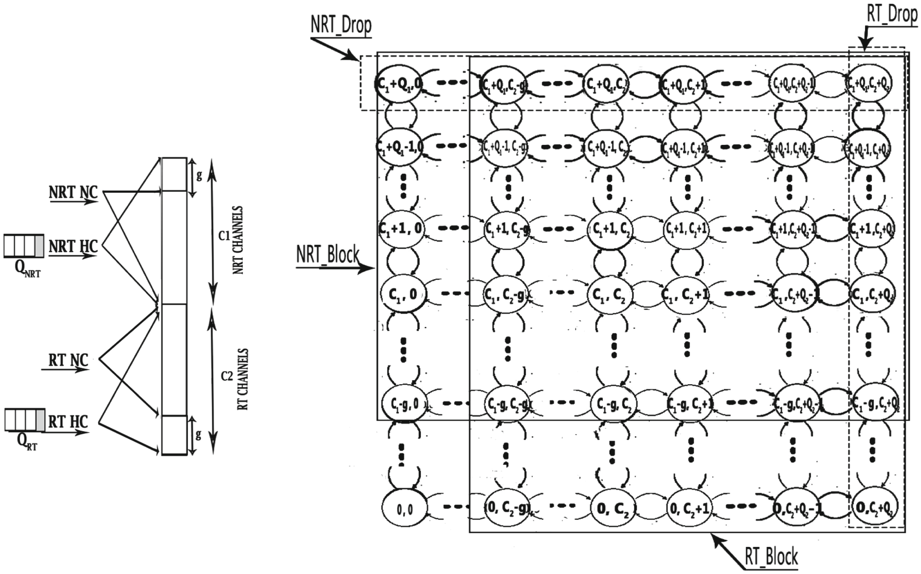
In order to improve the QoS of HCs, two queues Q_{NRT} (resp. Q_{RT}) can be added to put HC for NRT (resp. RT) traffic. If a HC arrives and there is no idle channels, it is pushed in the corresponding queue. A HC is deleted from the queue when it moves out handoff area before getting channel (it is forced to terminate) or if the conversation is completed before living handoff area. The HC is dispatched from the queue to as soon as any channel is released. It is clear that this schema offers the same QoS for NCs as B-CAC but improve the QoS of HCs. The description of the channels allocation of this schema is given in Fig. 2(a).

We suppose that queues Q_{NRT} (resp. Q_{RT}) is finite with capacity Q_1 (resp. Q_2). We assume that the overtime in each queue is exponentially distributed with mean $1/\mu_{to}$. Based on these assumptions, the underlying model is a homogeneous two dimensional CTMC and the state space is defined by Eq. 4 where i is the sum of number of NRT busy channels and number of NRT HC requests in the queue Q_{NRT}, j is the sum of number of RT busy channels and number of RT HC requests in the queue Q_{RT}. The obtained CTMC is presented in Fig. 2(b).

$$S_{Q-CAC} = \{(i,j) | 0 \le i \le C_1 + Q_1; 0 \le j \le C_2 + Q_2\} \tag{4}$$

The transition rate from state (i,j) to state $(\bar{i}, \bar{j})$ is defined by:

$$\mathbf{R}_{Q-CAC}(i,j; i+1, j) = \begin{cases} \lambda_N & \text{if } (0 \le i < C_1 - g; 0 \le j \le C_2 + Q_2) \\ \lambda_{Nh} & \text{if } (C_1 - g \le i < C_1 + Q_1; 0 \le j \le C_2 + Q_2) \end{cases}$$
$$\mathbf{R}_{Q-CAC}(i,j; i, j+1) = \begin{cases} \lambda_R & \text{if } (0 \le i \le C_1 + Q_1; 0 \le j < C_2 - g) \\ \lambda_{Rh} & \text{if } (0 \le i \le C_1 + Q_1; C_2 - g \le j < C_2 + Q_2) \end{cases}$$
$$\mathbf{R}_{Q-CAC}(i,j; i-1, j) = \begin{cases} \mu\ i & \text{if}(0 < i \le C_1; 0 \le j \le C_2 + Q_2) \\ \mu C_1 + \mu_{to}(i - C_1) & \text{if}(C_1 < i \le C_1 + Q_1; 0 \le j \le C_2 + Q_2) \end{cases}$$
$$\mathbf{R}_{Q-CAC}(i,j; i, j-1) = \begin{cases} \mu\ j & \text{if}(0 \le i \le C1 + Q_1; 0 < j \le C_2) \\ \mu C_2 + \mu_{to}(j - C_2) & \text{if}(0 \le i \le C_1 + Q_1; C_2 < j \le C_2 + Q_2) \end{cases}$$



(a) Channels allocation (b) Labelled CTMC

Fig. 2. Q-CAC schema

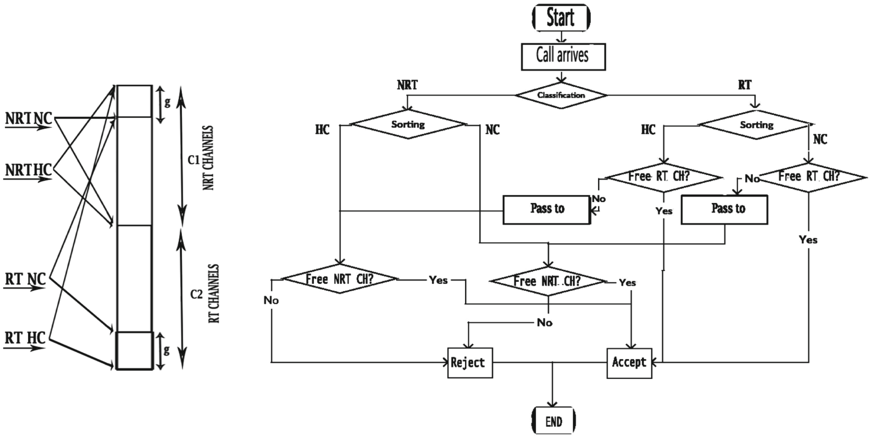
By the same mean, we label states of obtained CTMC corresponding to Q-CAC by atomic propositions of set AP (Eq. 2). The obtained satisfaction sets are marked in Fig. 2(b) and formally defined by:

$$\begin{aligned}
S_{NRT_Drop} &= \{(i,j) \mid i = C_1 + Q_1 \text{ and } 0 \leq j \leq C_2 + Q_2\} \\
S_{NRT_Block} &= \{(i,j) \mid C_1 - g \leq i \leq C_1 + Q_1 \text{ and } 0 \leq j \leq C_2 + Q_2\} \\
S_{RT_Drop} &= \{(i,j) \mid 0 \leq i \leq C_1 + Q_1 \text{ and } j = C_2 + Q_2\} \\
S_{RT_Block} &= \{(i,j) \mid 0 \leq i \leq C_1 + Q_1 \text{ and } C_2 - g \leq j \leq C_2 + Q_2\}
\end{aligned}$$

We have described and modelled two classics CAC schemes B-CAC and Q-CAC that give priority to HC over NC without priortising RT calls over NRT calls. Next, we propose two CAC schemes in which we take into account the prioritization of RT calls over NRT calls and preserve priority given to HCs. We show in Sect. 5 that these proposed schemes improve QoS of RT calls and satisfy requirements expressed with CSL formulas.

3.3 Real Time Priority CAC (RTP-CAC) Schema

In this schema, to decrease the blocking/dropping of RT calls, we permit RT calls to use channels of NRT part. Hence, NRT calls are served only by NRT channels whereas RT calls can use NRT channels if there is no RT available channels. If $C_2 - g$ channels are occupied and a RT NC arrives to BS, it is not blocked and can



(a) Channels allocation

(b) RTP-CAC Flowchart

Fig. 3. RTP-CAC schema

take a NRT channel. In case of occupation of $C_1 - g$ channels (number authorized for NRT NC) then the RT NC will be blocked. A RT HC can take NRT channel if all C_2 channels are occupied. But if the number of busy NRT channels is equal to C_1 then it will be dropped. The channels allocation is presented in Fig. 3(a) and a flowchart that details mechanism of acceptation/rejection of calls is provided in Fig. 3(b).

Obviously, the CTMC state space of RTP-CAC and B-CAC is the same. And transition rates of these two CACs are the same except the arrival rate to NRT channels $\mathbf{R}_{RTP-CAC}(c_1, c_2; c_1 + 1, c_2)$ defined by:

$$\mathbf{R}_{RTP-CAC}(c_1, c_2; c_1+1, c_2) = \begin{cases} \lambda_N & \text{if}(0 \le c_1 < C_1 - g; 0 \le c_2 < C_2 - g) \\ \lambda_N + \lambda_{Rn} & \text{if}(0 \le c_1 < C_1 - g; C_2 - g \le c_2 < C_2) \\ \lambda_N + \lambda_R & \text{if}(0 \le c_1 < C_1 - g; c_2 = C_2) \\ \lambda_{Nh} & \text{if}(C_1 - g \le c_1 < C_1; 0 \le c_2 < C_2) \\ \lambda_{Nh} + \lambda_{Rh} & \text{if}(C_1 - g \le c_1 < C_1; c_2 = C_2) \end{cases}$$

We give now the satisfaction sets of AP atomic propositions. It is clear that S_{NRT_Drop} and S_{NRT_Block} sets are equals for RTP-CAC and B-CAC because NRT HC dropping and NRT NC blocking conditions are the same. Based on the dropping and blocking conditions for RT calls proposed in this CAC schema, S_{RT_Drop} and S_{RT_Block} are defined by:

$$S_{RT\_Drop} = \{(c_1, c_2) \mid c_1 = C_1 \text{ and } c_2 = C_2\}$$
$$S_{RT\_Block} = \{(c_1, c_2) \mid C_1 - g \le c_1 \le C_1 \text{ and } C_2 - g \le c_2 \le C_2\}$$

Clearly, the improvement in terms of RT class QoS that we expect with this RTP-CAC schema is fulfilled through the reduction of NRT class QoS.

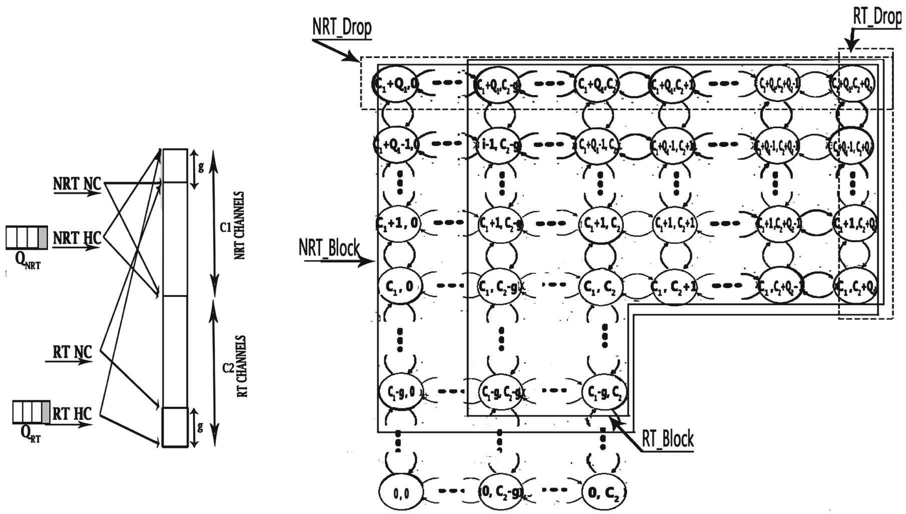
3.4 Real Time Priority and Queuing (RTPQ-CAC) Schema

In this schema, we propose to combine RTP-CAC and Q-CAC in order to improve simultaneously performances of RT calls and HCs for (RT and NRT) classes. Indeed, acceptance and rejection conditions of NRT calls are the same of Q-CAC schema. The acceptance and blocking conditions of RT NC are identical to RTP-CAC schema. For RT HC (the type of call that has the higher priority), the dropping condition is defined differently. In fact, when a RT HC arrives and all RT channels are occupied, it passes to NRT part to take channel. If all NRT channels are occupied, it is put into Q_{RT} queue waiting the release of one RT channel. The channels allocation is presented in Fig. 4(a) and the flowchart of RTPQ-CAC is described in Fig. 5. The CTMC of this proposed schema is given in Fig. 4(b) and the state space is defined by the following set (see Eq. 4 for S_{Q-CAC}):

$$S_{RTPQ-CAC} = S_{Q-CAC} \backslash \{(i,j) | 0 \leq i < C_1; C_2 < j \leq C_2 + Q_2\} \qquad (5)$$

As we can see in Fig. 4(b) that the CTMC of this schema contains two parts. Transition rates of the lower part are equal to transition rates of CTMC in RTP-CAC and the transition rates of higher part are equal to transition rates of CTMC in Q-CAC schema. Hence, we have:

$$\begin{array}{ll} \mathbf{R}_{RTPQ-CAC} = \mathbf{R}_{RTP-CAC} & \text{if } (0 \leq i < C_1; 0 \leq j \leq C_2) \\ \mathbf{R}_{RTPQ-CAC} = \mathbf{R}_{Q-CAC} & \text{if } (C_1 \leq i \leq C_1 + Q_1; 0 \leq j \leq C_2 + Q2) \end{array}$$



(a) Channels allocation (b) Labelled CTMC

Fig. 4. RTPQ-CAC schema

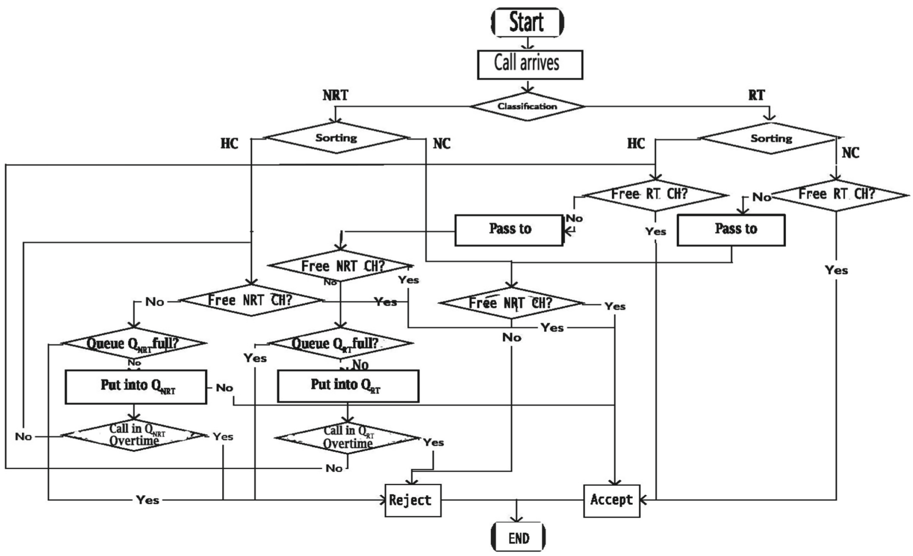


Fig. 5. RTPQ-CAC flowchart

Satisfaction sets of AP atomic propositions are marked in Fig. 4(b) and formalized by:

$$
\begin{array}{ll}
S_{NRT\_Drop} & = \{(i,j) \mid i = C_1 + Q_1 \text{ and } 0 \le j \le C_2 + Q_2\} \\
S_{NRT\_Block} & = \{(i,j) \mid C_1 - g \le i < C_1 \text{ and } 0 \le j \le C_2\} \\
 & \cup\ \{(i,j) \mid C_1 \le i \le C_1 + Q_1 \text{ and } 0 \le j \le C_2 + Q_2\} \\
S_{RT\_Drop} & = \{(i,j) \mid C_1 \le i \le C_1 + Q_1 \text{ and } j = C_2 + Q_2\} \\
S_{RT\_Block} & = \{(i,j) \mid C_1 - g \le i < C_1 \text{ and } C_2 - g \le j < C_2\} \\
 & \cup\ \{(i,j) \mid C_1 \le i \le C_1 + Q_1 \text{ and } C_2 - g \le j \le C_2 + Q_2\}
\end{array}
$$

4 Formal Specification of Performance Properties by CSL Formulas

In this section, we formalize QoS requirements of each type of call with CSL in order to check if these requirements are satisfied by different CAC schemes. We express requirements using steady-state formulas, transient path formulas and reward formulas.

4.1 Checking Steady-State Formulas

The verification of steady-state formulas needs the computation of steady-state distribution $\mathbf{\Pi}^{\mathcal{M}}$ of the considered CTMC $\mathcal{M}$. It is clear that obtained CTMCs of different CAC schemes presented in Sect. 3 are ergodic (finite and irreductible) so the steady-state probability vector $\mathbf{\Pi}^{\mathcal{M}}$ of each CTMC $\mathcal{M}$ exists and is unique.

$\boldsymbol{\mathcal{S}_{\leq 0.2}}$**(NRT_Block).** We check this formula to evaluate the expected steady-state blocking probability for NRT NC in all obtained CTMCs. For a model $\mathcal{M}$, this formula is satisfied if steady-state blocking probability for NRT NC is less or equal to the probability threshold 0.2 (i.e. $\mathbf{\Pi}(S_{NRT\_Block}) \leq 0.2$).

$\boldsymbol{\mathcal{S}_{\leq 10^{-2}}}$**(NRT_Drop).** This formula is checked to estimate steady-state dropping probability for NRT HC. Because HC requires strict QoS, this dropping probability must be less or equal to 10^{-2}. This formula is then satisfied if $\mathbf{\Pi}^{\mathcal{M}}(S_{NRT\_Drop}) \leq 10^{-2}$.

$\boldsymbol{\mathcal{S}_{\leq 10^{-1}}}$**(RT_Block).** By checking this formulas, we evaluate the RT steady-state blocking probability for NC. This formula is satisfied if $\mathbf{\Pi}(S_{RT\_Block}) \leq 10^{-1}$.

$\boldsymbol{\mathcal{S}_{\leq 10^{-3}}}$**(RT_Drop).** We check this formula to estimate the RT steady-state dropping probability for HC. This formula is satisfied if $\mathbf{\Pi}(S_{RT\_Drop}) \leq 10^{-3}$.

4.2 Checking Transient Formulas

The verification of transient formulas requires the computation of the transient distribution $\mathbf{\Pi}_s^{\mathcal{M}}(t)$ which depends on the initial distribution. We choose to evaluate transient formulas at time 2 because after making some tests we observe that studied CTMCs reach equilibrium state at around $t = 4$. We suggest to check transient QoS requirements at the middle of time before reaching the steady-state of considered CTMCs. We suppose that at $t = 0$ all channels are empty (i.e. $s = (0, 0)$).

$\boldsymbol{\mathcal{P}_{\leq 10^{-1}}}$(**true** $\boldsymbol{\mathcal{U}^{[2,2]}}$ **NRT_Block**). We check this formula to evaluate the NRT transient blocking probability of NC at time 2 in the considered model $\mathcal{M}$. This formula is satisfied if (i.e. $\mathbf{\Pi}_s^{\mathcal{M}}(S_{NRT\_Block}, t) \leq 10^{-1}$)

$\boldsymbol{\mathcal{P}_{\leq 10^{-3}}}$(**true** $\boldsymbol{\mathcal{U}^{[2,2]}}$ **NRT_Drop**). This formula is checked to evaluate the transient dropping probability at time 2 for NRT HC. If this probability is less or equal to 10^{-3} then it is satisfied. We have to check if $\mathbf{\Pi}_s^{\mathcal{M}}(S_{NRT\_Drop}, 2) \leq 10^{-3}$.

$\boldsymbol{\mathcal{P}_{\leq 10^{-2}}}$(**true** $\boldsymbol{\mathcal{U}^{[2,2]}}$ **NRT_Block**). By checking this formulas, we evaluate the RT transient blocking probability of NC. This formula is satisfied if $\mathbf{\Pi}_s^{\mathcal{M}}(S_{RT\_Block}, 2) \leq 10^{-2}$ in the underlying model $\mathcal{M}$.

$\boldsymbol{\mathcal{P}_{\leq 10^{-4}}}$(**true** $\boldsymbol{\mathcal{U}^{[2,2]}}$ **NRT_Drop**). We check this formula to estimate the RT transient dropping probability at time 2 for HC. This formula is satisfied if $\mathbf{\Pi}_s^{\mathcal{M}}(S_{RT\_Drop}, 2) \leq 10^{-4}$.

Let us note that RT HCs have the most strict QoS requirements that's why the dropping probability threshold in the transient (resp. steady-state) formula must be the lowest, 10^{-4} (resp. 10^{-3}).

4.3 Checking Reward Formulas

We use CSRL [12] logic to express requirements related to the occupation rate of channels. Hence, we define three reward function ρ_1, ρ_2 and ρ to evaluate respectively the occupation rate of NRT channels, RT channels and the whole BS channels. ρ_1 (resp. ρ_2) associates to each state of the CTMC a reward value equal to percentage of occupied NRT (resp. RT) channels. ρ associates to each state of the CTMC a reward value equal to percentage of occupied BS station. Therefore, for each state $s = (c_1, c_2)$ of CMTCs in B-CAC and RTP-CAC schemes, the reward value associated to s is:

$$\rho_1(s) = 100c_1/C_1 \quad \rho_2(s) = 100c_2/C_2 \quad \rho(s) = 100(c_1 + c_2)/(C_1 + C_2)$$

For each state $s = (i, j)$ of CMTCs in Q-CAC and RTPQ-CAC,the reward value assigned to s is:

$$\rho_1(s) = 100\text{min}(i, C_1)/C_1 \qquad \rho_2(s) = 100\text{min}(C_2, 100)/C_2$$
$$\rho(s) = 100(\text{min}(i, C_1) + \text{min}(j, C_2))/(C_1 + C_2)$$

Now, for each reward function (ρ_1, ρ_2 and ρ), we check the two following reward formulas related to the transient and the steady-state behavior in each obtained CTMC.

$\boldsymbol{\mathcal{E}^2_J}(\mathbf{true})$. We check this formula for each reward function ρ_1, ρ_2 and ρ to evaluate respectively the mean occupation rate of NRT, RT and BS channels. For a given reward function, this formula is satisfied if the mean occupation rate at time 2 lies in J. To check this formula we compute transient distributions at time 2 and then we sum over the probabilities of all CTMC states (because all CTMC states are $true$) multiplied with the corresponding rewards and finally we check if the obtained reward lies in J or not (see Eq. 1).

$\boldsymbol{\mathcal{E}_J}(\mathbf{true})$. This formula is checked to evaluate the expected steady-state occupation rate of NRT, RT and BS channels by considering respectively the reward function ρ_1, ρ_2 and ρ. These reward measures are derived from steady-state distributions of studied CTMCs and reward functions (see Eq. 1).

5 Model Checking Results of CSL Formulas

The aim of this study is to compare performances of proposed CAC schemes (RTP-CAC and RTPQ-CAC) with classical schemes (B-CAC and Q-CAC). In this section, we give numerical results obtained based on the following parameters: we suppose that the number of RT channels ($C_2 = 50$) is greater than the number of NRT channels ($C_1 = 30$) and traffic intensity of RT class ($\lambda_{Rn} = \lambda_{Rh} = 25$) is higher than the traffic intensity of NRT class ($\lambda_{Nn} = \lambda_{Nh} = 10$). The time unit is 1 minute, we suppose that the channel holding time $\mu = 1$, $Q_{NRT} = Q_{RT} = 5$ and $\mu_{to} = 0.75$. In this scenario, the

Table 1. Model checking results of CSL transient formulas

Transient formulas	B-CAC		Q-CAC		RTP-CAC		RTPQ-CAC	
	Prob.	Sat?	Prob.	Sat?	Prob.	Sat?	Prob.	Sat?
$\mathcal{P}_{\leq 10^{-1}}(true\ \mathcal{U}^{[2,2]}$ NRT_Block)	$4,4\ 10^{-3}$	Yes	$4,4\ 10^{-3}$	Yes	$2,0\ 10^{-2}$	Yes	$2,0\ 10^{-2}$	Yes
$\mathcal{P}_{\leq 10^{-3}}(true\ \mathcal{U}^{[2,2]}$ NRT_Drop)	$2,9\ 10^{-4}$	Yes	$6,7\ 10^{-7}$	Yes	$1,0\ 10^{-3}$	Yes	$3,1\ 10^{-6}$	Yes
$\mathcal{P}_{\leq 10^{-2}}(true\ \mathcal{U}^{[2,2]}$ RT_Block)	$1,1\ 10^{-1}$	No	$1,1\ 10^{-1}$	No	$6,0\ 10^{-3}$	Yes	$6,1\ 10^{-3}$	Yes
$\mathcal{P}_{\leq 10^{-4}}(true\ \mathcal{U}^{[2,2]}$ RT_Drop)	$3,8\ 10^{-3}$	No	$6,3\ 10^{-5}$	Yes	$8,7\ 10^{-5}$	Yes	$2,6\ 10^{-7}$	Yes

Table 2. Model checking results of steady-state CSL formulas

Steady-state formulas	B-CAC		Q-CAC		RTP-CAC		RTPQ-CAC	
	Prob.	Sat?	Prob.	Sat?	Prob.	Sat?	Prob.	Sat?
$\mathcal{S}_{\leq 0.2}$(NRT_Block)	$1,3\ 10^{-2}$	Yes	$1,3\ 10^{-2}$	Yes	$7,1\ 10^{-2}$	Yes	$7,1\ 10^{-2}$	Yes
$\mathcal{S}_{\leq 10^{-2}}$(NRT_Drop)	$1,0\ 10^{-3}$	Yes	$3,7\ 10^{-6}$	Yes	$6,1\ 10^{-3}$	Yes	$2,1\ 10^{-5}$	Yes
$\mathcal{S}_{\leq 10^{-1}}$(RT_Block)	$1,5\ 10^{-1}$	No	$1,5\ 10^{-1}$	No	$1,9\ 10^{-2}$	Yes	$1,9\ 10^{-2}$	Yes
$\mathcal{S}_{\leq 10^{-3}}$(RT_Drop)	$5,5\ 10^{-3}$	No	$1,8\ 10^{-4}$	Yes	$2,6\ 10^{-4}$	Yes	$1,1\ 10^{-6}$	Yes

traffic load of RT class (25 requests per minute) is higher than the traffic load to NRT class (10 requests per minute). This choice is justifiable because the number of user's requests with high exigence in terms of QoS (RT calls) is continually increasing.

We use the probabilistic model checker PRISM [14] to construct and solve considered CTMCs. This tool is a high-level modeling language and formulas are checked automatically. Recall that the main relevant QoS requirements are NC blocking probabilities, HC dropping probabilities and the channels occupation rate. The best CAC schema is which provides: the lowest values of call dropping probabilities, the lowest values of call blocking probabilities and the highest value of channels occupation rate.

In Table 1 (resp. Table 2) we present model checking results of transient at time $t = 2$ min (resp. steady-state) formulas described in Sect. 4. For each CAC schema we give the probability value and the satisfaction results of considered formulas. As observed, RTP-CAC and RTPQ-CAC satisfy all underlying formulas and therefore requirements in terms of HC dropping probabilities and NC blocking probabilities for both NRT and RT classes are fulfilled. Whereas, these probability measures in B-CAC and Q-CAC are greater than the probability thresholds measures given in formulas related to RT traffic. This implies that QoS requirements for RT traffic (which must has the best QoS) are not satisfied with these classical CACs.

We note that the size of obtained CTMCs is 1581 for B-CAC and RTP-CAC, 2016 for Q-CAC and 1866 for RTPQ-CAC. The checking time of each formula presented in the following tables is less than 2 s.

Table 3 provides model checking results of transient (at $t = 2$ min) and steady-state reward formulas. These formulas are checked by considering reward functions defined previously: ρ_1 for NRT channels occupation rate, ρ_2 for RT

Table 3. Model checking results of Reward CSRL formulas

Reward formulas	B-CAC		Q-CAC		RTP-CAC		RTPQ-CAC	
	Mean occupation rate of NRT channels							
	Mean ρ_1	Sat?	Mean ρ_1	Sat?	Mean ρ_1	Sat?	Mean ρ_1	Sat?
$\mathcal{E}^2_{[60,100]}(true)$	57,51%	No	57,48%	No	63,98%	Yes	63,99%	Yes
$\mathcal{E}_{[75,100]}(true)$	65,28%	No	65,15%	No	77,35%	Yes	77,36%	Yes
	Mean occupation rate of RT channels							
	Mean ρ_2	Sat?	Mean ρ_2	Sat?	Mean ρ_2	Sat?	Mean ρ_2	Sat?
$\mathcal{E}^2_{[80,100]}(true)$	81,95%	Yes	81,98%	Yes	81,95%	Yes	81,95%	Yes
$\mathcal{E}_{[84,100]}(true)$	84, 56%	Yes	84,60%	Yes	84,56%	Yes	84,50%	Yes
	Mean occupation rate of BS channels							
	Mean ρ	Sat?	Mean ρ	Sat?	Mean ρ	Sat?	Mean ρ	Sat?
$\mathcal{E}^2_{[75,100]}(true)$	72,79%	No	72,79%	No	75,22%	Yes	75,21%	Yes
$\mathcal{E}_{[80,100]}(true)$	77,33%	No	77,30%	No	81,86%	Yes	81,82%	Yes

channels occupation rate and ρ for BS channels occupation rate. As observed, proposed CACs (RTP-CAC and RTPQ-CAC) provides the highest transient and steady-state values of NRT and BS occupation rates which implies that proposed schemes provide a good utilization ratio of BS bandwidth. We can observe also that the occupation rate of RT channels is the same in all CAC schemes which are predictable because RT channels allocation mechanism is the same in all studied CAC schemes.

6 Conclusion

In this paper, we have presented a formal modeling and verification of different CAC multi-service schemes. We have proposed two CAC schemes that consider the prioritization of RT traffic over NRT traffic and HC over NC. We model CAC schemes with labeled CTMC. In order to compare their performances, we use CSL logic to specify QoS requirements of each class of call. We perform numerical results using the PRISM model checker. Results show that the proposed CAC schemes (RTP-CAC and RTPQ-CAC) satisfy QoS requirements of different classes of traffic compared to classical schemes (B-CAC and Q-CAC). This work can be extended by checking other CSL formulas providing further performance measures like queue occupation rate and queue waiting time. We can verify also the satisfaction of other QoS requirements over the execution paths of the considered model using the until path formula $\mathcal{P}$. Moreover, we envisage to consider vertical handoffs by taking into account traffic coming from networks having different access technologies as WLAN.

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