A Call Admission Control Mechanism based both on Queueing and the Probabilistic Bandwidth Reservation Policy in Mobile Hotspots

Marinos Vlasakis
School of Science & Technology
Hellenic Open University
Patras, Greece
std138028@ac.eap.gr

Irene Keramidi
Dept. Informatics & Telecommunications
University of Peloponnese
Tripolis, Greece
ekeramidi@uop.gr

Ioannis Moscholios
Dept. Informatics & Telecommunications
University of Peloponnese
Tripolis, Greece
idm@uop.gr

Panagiotis Sarigiannidis
Dept. Electrical & Computer Engineering
University of W. Macedonia
Kozani, Greece
psarigiannidis@uowm.gr

Michael Logothetis
Dept. Electrical & Computer Engineering
University of Patras
Patras, Greece
mlogo@upatras.gr

***Abstract*—In this paper we study a mobility-aware call admission control mechanism applied in a mobile hotspot. We consider a vehicle, which can alternate between stop and moving phases and has an access point of a fixed capacity. In the stop phase, the vehicle accommodates both new and handover calls. To prioritize handover calls a probabilistic bandwidth reservation (BR) policy is applied where some of the system's resources are reserved for handover calls. Based on this policy, new calls may enter the reservation space with a predefined probability. In addition, handover calls can wait in a queue of finite size if there are no available resources at the time of their arrival. In the moving phase, the vehicle services only new calls under the probabilistic BR policy. In both phases, arriving calls follow a Poisson process, require a single bandwidth unit from the system and have an exponentially distributed service time. To analytically determine the most significant performance measures such as call blocking probabilities an efficient iterative algorithm is presented.**

Keywords: mobility, hotspot, loss, queueing, admission, handover, probabilistic reservation

I. Introduction

A call admission control (CAC) mechanism is a significant quality of service (QoS) mechanism in a mobile hotspot since it provides access to the resources required by calls, either new or handover. To reduce call blocking probabilities (CBP) of handover calls the most common call CAC mechanism is based on the bandwidth reservation (BR) or guard channel policy (e.g., [1]-[7]). According to the BR policy, some resources are reserved to favor handover calls. Other policies that may also prioritize handover calls are the multiple fractional channel reservation policy and the threshold call admission policy (e.g., [8]-[10]).

Herein, we focus on a BR CAC mechanism applied on a mobile hotspot which was initially proposed in [11]. More specifically, in [11] a vehicle has an access point (AP) installed on it with a wireless local area network (WLAN) of fixed capacity. The vehicle can be in the stop or in the moving phase. During the stop phase, a vehicle can accommodate new and handover users. The former initiate a call in the vehicle while the latter already have an ongoing call and therefore perform a handover from a NodeB (NB) to the AP of the vehicle. To favor handover users, a part of the fixed capacity is reserved for them. In addition, handover users may wait to be served in a finite queue (if there are no available resource at the time of their arrival), an option that is not available for new users. During the vehicle's moving phase, only new calls can be generated. In both phases, incoming calls arrive according to a Poisson process, require a single bandwidth unit (b.u.) and have an exponentially distributed service time.

In this paper, we extend [11] by proposing a probabilistic BR policy that can be applied to new calls in both phases with a predefined probability. The advantage of such a policy, compared to the BR policy, is that it provides a way to alter CBP of both new and handover calls by modifying the BR policy probabilities. Note that the probabilistic BR policy has also been considered in [12], [13]. Contrary to [12] where pure loss models have been considered, in this paper we further assume that handover users have the option to wait to be served. Based on the above, the contribution of our paper is summarized as follows: i) we propose the probabilistic BR loss/queueing model where the probabilistic BR policy is applied only to new calls during both phases while handover calls have the option to enter a queue of finite size (the case of the probabilistic BR policy for new calls in the stop phase only has been studied in [13]), and ii) we present an iterative algorithm as in [12] for the determination of CBP, system's utilization and mean waiting time in the queue.

This paper is organized as follows: Section II, includes the presentation of the proposed probabilistic BR loss/queueing analytical model, the review of the iterative algorithm presented in [12] used for the calculation of the steady state probabilities, and finally the formulas used for the performance metrics calculation. Section III, includes some basic analytical results for the performance measures. Section IV, concludes this paper.

979-8-3503-9958-5/22/$31.00 ©2022 IEEE

II. The Proposed Probabilistic BR Loss/Queueing Model

A. *The Analytical Model*

We assume that a vehicle exists which has: (i) an AP of C WLAN capacity and (ii) a finite first-in-first-out (FIFO) queue of length K (both C and K are measured in bandwidth units - b.u.). As in [11] and [12], the above-mentioned system has two CAC phases: a stop and a moving. Calls arrive at random (via a Poisson process) to the system and are divided into new and handover, with arrival rates λ_{new} and λ_h, accordingly. Each call needs one b.u. to be admitted in the system, so at each time the number of occupied b.u. equals the number of calls/users served/waiting in the queue. The call service time is exponentially distributed with mean values of μ_s^{-1} and μ_m^{-1} (respectively in the stop and moving phase).

The queue accommodates exclusively handover calls, so if an arrived handover call's requested b.u. is not available, the call waits in the queue (if it's not full) to be serviced. Also, the probabilistic BR policy is applied, whereby t_{new} b.u. (out of the C b.u.) are probabilistically reserved to favor handover calls, so if one b.u. is available in the BR space: an arrived handover call is always serviced while an arrived new call is accepted only with a predefined probability ($p_{s,new}$ or $p_{m,new}$ if the vehicle/system is in the stop or moving phase, accordingly).

In the stop phase, the vehicle is located at predefined places such as a bus stop and remains still for a time duration which is exponentially distributed with mean θ_s^{-1}. In this phase both handover and new calls arrive at the system as in [11], [12]. A handover call is being serviced by a NB until the time its user rides on the vehicle, and therefore it needs to be transferred to the vehicle's AP. A new call can arrive at any time initiated by a user after he/she rides on the vehicle. The probabilistic BR policy is applied in the stop phase and specifically t_{new} b.u. are probabilistically reserved to favor handover calls, meaning that an arrived new call is accepted in the BR space with a predefined probability $p_{s,new}$.

In the moving phase, whose duration is also exponentially distributed with mean θ_m^{-1}, exclusively new calls arrive as in [11], [12]. The probabilistic BR policy is also applied in the moving phase and specifically t_{new} b.u. are probabilistically reserved, meaning that an arrived new call is accepted in the BR space with a predefined probability $p_{m,new}$.

Based on the above, call blocking of new calls happens in the following cases: (i) in both phases when the occupied b.u. (n) is $C \leq n \leq C+K$ and (ii) in the stop phase with probability $1\text{-}p_{s,new}$ and in the moving phase with probability $1\text{-}p_{m,new}$, when the occupied b.u. is $n = C\text{-}t_{new},\ldots,C\text{-}1$ (BR space). Also, call blocking of handover calls occurs only in the stop phase if both the capacity and the queue are full at the time of their arrival, i.e., if the occupied b.u. is $n = C + K$.

Worth mentioning is the fact that when $t_{new} = 0$ or $p_{s,new} = p_{m,new} = 1$, new calls have full access to the capacity (all C b.u.). The described CAC mechanism is represented through the flowchart of Fig. 1.

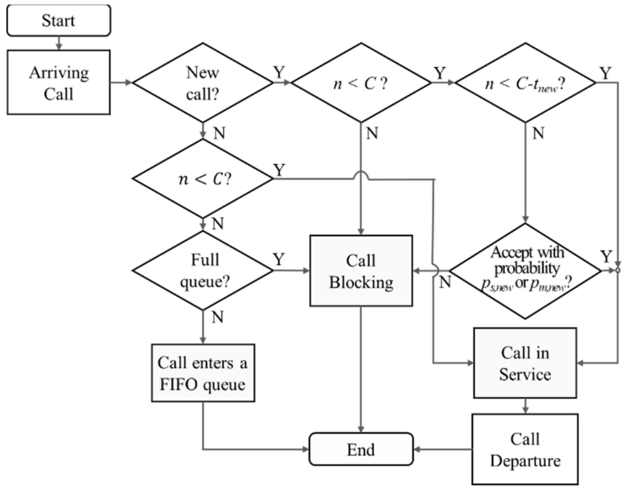

Fig. 1. Flowchart of the proposed model.

The proposed model can be described by the Markov chain of Fig. 2. Each state is represented by the ordered pair (i, n) where i is the phase (0 for the stop phase and 1 for the moving phase) and n is the number of calls in the system ($0 \leq n \leq C+K$).

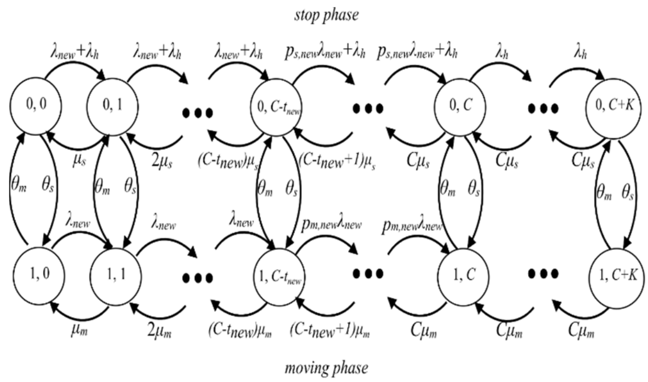

Fig. 2. The 2-D Markov chain in the proposed model.

B. *Global Balance Equations*

If $P(i,n)$ is the steady-state probability of state (i,n) where i=0,1, $0 \leq n \leq C+K$ and assuming that:

$$\lambda_i(0) = \begin{cases} \lambda_{new} + \lambda_h, & i = 0 \\ \lambda_{new}, & i = 1 \end{cases}, \quad \theta_i = \begin{cases} \theta_s, & i = 0 \\ \theta_m, & i = 1 \end{cases} \text{ and}$$

$$\mu_i(0) = \begin{cases} \mu_s, & i = 0 \\ \mu_m, & i = 1 \end{cases}, \quad j = 1 - i,$$

then, based on the above assumptions, the global balance equation for states (0,0) and (1,0) is the following:

$$(\lambda_i(0) + \theta_i)P(i,0) - \mu_i(0)P(i,1) - \theta_j P(j,0) = 0 \tag{1}$$

For states (i,n) where i=0,1 and $0 < n < C+K$, assuming that:

$$\lambda_i(n) = \begin{cases} \lambda_{new} + \lambda_h, & i=0,\ \ 0<n\le C\text{-}t_{new}\text{-}1 \\ p_{s,new}\lambda_{new}+\lambda_h, & i=0,\ \ C\text{-}t_{new}\le n<C \\ \lambda_h, & i=0,\ \ C\le n<C+K \\ \lambda_{new}, & i=1,\ \ 0<n\le C\text{-}t_{new}\text{-}1 \\ p_{m,new}\lambda_{new}, & i=1,\ \ C\text{-}t_{new}\le n<C \end{cases},\ j=1\text{-}i$$

and

$$\mu_i(n) = \begin{cases} n\mu_s\ , & i=0,\ 0<n\le C \\ C\mu_s\ , & i=0,\ C+1\le n<C+K \\ n\mu_m\ , & i=1,\ 0<n\le C \\ C\mu_m\ , & i=1,\ C+1\le n<C+K \end{cases},$$

we get the following global balance equation:

$$\begin{aligned}&(\lambda_i(n)+\mu_i(n)+\theta_i)P(i,n)\text{-}\lambda_i(n\text{-}1)P(i,n\text{-}1)\\&\text{-}\theta_j P(j,n)\text{-}\mu_i(n+1)P(i,n+1)=0\end{aligned} \quad (2)$$

Finally, for the boundary states (i, C+K) where i=0,1 , the global balance equation is as follows:

$$\begin{aligned}&(C\mu_i+\theta_i)P(i,C+K)\text{-}\lambda_i(C+K\text{-}1)P(i,C+K\text{-}1)\\&\text{-}\theta_j P(j,C+K)=0\end{aligned} \quad (3)$$

C. Steady-State Probabilities

The steady-state probabilities $P(i,n)$ can be calculated using the iterative algorithm of [12]. Initially:

$$P(i,n)=S^0_{i,n}\,P(0,0)+S^1_{i,n}\,P(1,0) \quad (4)$$

Using (4) and (2), $S^0_{i,n}$ and $S^1_{i,n}$ can be calculated iteratively:

$$\begin{aligned}&S^0_{i,n+1}P(0,0)+S^1_{i,n+1}P(1,0)=\\&\frac{\lambda_i(n)+\mu_i(n)+\theta_i}{\mu_i(n+1)}\left(S^0_{i,n}P(0,0)+S^1_{i,n}P(1,0)\right)\\&-\frac{\lambda_i(n\text{-}1)}{\mu_i(n+1)}\left(S^0_{i,n\text{-}1}P(0,0)+S^1_{i,n\text{-}1}P(1,0)\right)\\&-\frac{\theta_j}{\mu_i(n+1)}\left(S^0_{j,n}P(0,0)+S^1_{j,n}P(1,0)\right)\end{aligned} \quad (5)$$

Based on (5) and assuming that $P(1,0) = 0$, $P(0,0) = 1$, $S^0_{0,0}=1$, $S^0_{1,0}=0$ and $S^0_{0,y}=0$ for $y < 0$, the values of $S^0_{i,n}$ can be calculated as follows:

$$S^0_{i,n+1}=\frac{\lambda_i(n)+\mu_i(n)+\theta_i}{\mu_i(n+1)}S^0_{i,n}-\frac{\lambda_i(n\text{-}1)}{\mu_i(n+1)}S^0_{i,n\text{-}1}-\frac{\theta_j}{\mu_i(n+1)}S^0_{j,n} \quad (6)$$

Similarly, the values of $S^1_{i,n}$, based on (5) and by assuming that $P(1,0) = 1$, $P(0,0) = 0$, $S^1_{0,0}=0$, $S^1_{1,0}=1$ and $S^1_{0,y}=0$ for $y < 0$, can be calculated via:

$$S^1_{i,n+1}=\frac{\lambda_i(n)+\mu_i(n)+\theta_i}{\mu_i(n+1)}S^1_{i,n}-\frac{\lambda_i(n\text{-}1)}{\mu_i(n+1)}S^1_{i,n\text{-}1}-\frac{\theta_j}{\mu_i(n+1)}S^1_{j,n} \quad (7)$$

Having found the values of $S^0_{i,n}$ and $S^1_{i,n}$, it is possible to calculate $P(0,0)$ and $P(1,0)$ through (3), for $i = 0$:

$$\begin{aligned}&(C\mu_s+\theta_s)P(0,C+K)\text{-}\lambda_h P(0,C+K\text{-}1)\\&\text{-}\theta_m P(1,C+K)=0\end{aligned} \quad (8)$$

Based on (4), (8) takes the following form:

$$\begin{aligned}&P(0,0)\left(S^0_{0,C+K}(C\mu_s+\theta_s)-S^0_{0,C+K\text{-}1}\lambda_h-S^0_{1,C+K}\theta_m\right)+\\&P(1,0)\left(S^1_{0,C+K}(C\mu_s+\theta_s)-S^1_{0,C+K\text{-}1}\lambda_h-S^1_{1,C+K}\theta_m\right)=0\end{aligned} \quad (9)$$

Given that $\sum_{i=0}^{1}\sum_{n=0}^{C+K}P(i,n)=1$, (4) becomes:

$$P(0,0)\sum_{i=0}^{1}\sum_{n=0}^{C+K}S^0_{i,n}+P(1,0)\sum_{i=0}^{1}\sum_{n=0}^{C+K}S^1_{i,n}=1 \quad (10)$$

Using the system of equations (9) and (10), both $P(0,0)$, $P(1,0)$ can be calculated. That makes possible the calculation of all the steady-state probabilities $P(i, n)$ via (4).

D. Performance Metrics

Since the steady-state probabilities $P(i, n)$ are known, several performance metrics can be calculated.

The CBP of new calls in the stop phase $B_{s,new}$, is given by:

$$B_{s,new}=(1\text{-}p_{s,new})\sum_{n=C\text{-}t_{new}}^{C\text{-}1}P(0,n)+\sum_{n=C}^{C+K}P(0,n) \quad (11)$$

Similarly, the corresponding CBP values of new calls in the moving phase, $B_{m,new}$:

$$B_{m,new}=(1\text{-}p_{m,new})\sum_{n=C\text{-}t_{new}}^{C\text{-}1}P(1,n)+\sum_{n=C}^{C+K}P(1,n) \quad (12)$$

The total CBP of new calls, B_{new} is the sum of both $B_{s,new}$ and $B_{m,new}$:

$$B_{new}=B_{s,new}+B_{m,new} \quad (13)$$

Arriving handover calls in the stop phase are blocked only in state (0, C+K), so their CBP ($B_{s,h}$), is determined via:

$$B_{s,h} = P(0, C+K) \tag{14}$$

Via (14) we can also compute the CBP of handover calls given that the vehicle is in the stop phase, $B^*_{s,h}$:

$$B^*_{s,h} = \frac{B_{s,h}}{\sum_{n=0}^{C+K} P(0,n)} \tag{15}$$

The link utilization, U, can be determined via:

$$U = \sum_{i=0}^{1}\sum_{n=0}^{C} nP(i,n) + C\sum_{i=0}^{1}\sum_{n=C+1}^{C+K} P(i,n) \tag{16}$$

Finally, the average queue length L can be determined as the average number of handover calls waiting to be served:

$$L = \sum_{i=0}^{1}\sum_{n=C+1}^{C+K} (n-C)P(i,n) \tag{17}$$

Using Little's law ($L = \lambda W$) [14], the mean waiting time W of handover calls in the stop phase is:

$$W = \frac{L}{\lambda} \tag{18}$$

where λ refers to the effective arrival rate:

$$\lambda = \sum_{i=0}^{1}\sum_{n=0}^{C-t_{new}-1} (\lambda_{new} + j\lambda_h)P(i,n) + \left(p_{s,new}\lambda_{new} + \lambda_h\right)\sum_{n=C-t_{new}}^{C-1} P(0,n)$$
$$+ p_{m,new}\lambda_{new}\sum_{n=C-t_{new}}^{C-1} P(1,n) + \lambda_h \sum_{n=C}^{C+K-1} P(0,n)$$

for j=1-i.

III. Numerical Results

A vehicle with a WLAN AP installed on it, of variable capacity C, remains in the stop and in the moving phase, for exponentially distributed times with means θ_s^{-1} =1.0 min and θ_m^{-1} =5.0 min accordingly. Handover and new calls arrive to the system with rates λ_h = λ_{new}= 24, and those who are admitted get serviced for exponentially distributed times with mean values $\mu_s^{-1} = \mu_m^{-1}$ = 5.0 min in the stop and moving phase accordingly. To favor handover calls, the probabilistic BR policy is applied in both phases. Additionally, a finite FIFO queue of length K=3 is considered. More specifically, t_{new} = 8 b.u.s are reserved mainly for handover calls, but also new calls have access to the reserved space with various predefined probabilities, $p_{s,new}$ and $p_{m,new}$ in the stop and moving phase accordingly.

The total CBP of new calls (B_{new}) and the CBP of handover calls ($B^*_{s,h}$) are depicted in Fig. 3 and Fig. 4 accordingly, as a function of variable values of C (C = 30, 31, … ,80) and for 9 combinations of $p_{s,new}$ and $p_{m,new}$ (each getting its values from the set {0, 0.5, 1}). When ($p_{s,new}$, $p_{m,new}$) = (0.0, 1.0), the system is the mobility-aware CAC with handoff queue (MA-CAC HQ) scheme studied in [11].

According to Fig. 3: (i) an increase of C decreases the value of B_{new}, since more b.u. become available to accommodate new calls, (ii) higher values primarily of $p_{m,new}$ and secondary $p_{s,new}$ lead to lower values of B_{new}, something that is logical, since as these probabilities get closer to 1.0, new calls get accepted more frequently in the reserved space, conversely lower values of primarily $p_{m,new}$ and secondary of $p_{s,new}$ lead to higher values of B_{new}, (iii) the lowest values of B_{new} are obtained via the systems that have practically no reserved b.u. for handover calls, that is when $p_{s,new}$=$p_{m,new}$=1.0, (iv) the highest values of B_{new} are obtained by the system that have fully reserved space in favor of handover calls in both phases, that is when $p_{s,new}$=$p_{m,new}$=0.0. (v) the systems' B_{new} "behaviour" can be clustered/grouped in sets based on their value of $p_{m,new}$. (vi) B_{new} increases with the increase of the queue's length.

According to Fig. 4: (i) an increase in C lowers the CBP of handover calls ($B^*_{s,h}$) something expected since more bandwidth becomes available for servicing handover calls, and is worth noted that the rate of decrease seems to be higher in the case where $p_{s,new}$=0 and $p_{m,new}$=0.5 (ii) the lowest values of $B^*_{s,h}$ are obtained via the systems that have fully reserved b.u. for handover calls, that is when $p_{s,new}$=$p_{m,new}$=0.0, (iii) the highest values of $B^*_{s,h}$ are obtained by the systems that have practically no reserved b.u. in favor of handover calls in both phases, that is when $p_{s,new}$=$p_{m,new}$=1.0. (iv) generally, but not always, higher values primarily of $p_{m,new}$ and secondary of $p_{s,new}$ tend to lead to higher values of $B^*_{s,h}$, because as mentioned for Fig.3, as these probabilities get closer to 1.0, new calls get accepted more frequently in the reserved space causing an increased competition with arriving handover calls for the seizure of the available bandwidth, (v) contrary to Fig.3, the systems' $B^*_{s,h}$ "behavior" cannot be clearly clustered/grouped in sets based on their value of $p_{m,new}$. For example, according to Fig. 4, at least the system cases with $p_{s,new}$=0 break the clustering. (vi) $B^*_{s,h}$ decreases with the increase of the size/length of the queue.

Based on the previous, for each value of C and K the two systems with full ($p_{s,new}$=$p_{m,new}$=0.0) and with no bandwidth reservation ($p_{s,new}$=$p_{m,new}$=1.0) demarcate the limits of B_{new} and $B_{s,h}$ between which the remaining cases take their values (see Fig. 3 and Fig. 4). This means that by adjusting the ($p_{s,new}$, $p_{m,new}$) values, the CBP of calls and therefore the QoS can be regulated as shown in [12], [13]. Also, the addition of a queue to the system seems to surpass the effect of BR policy as is depicted in Fig. 5 for B_{new} and Fig. 6 for $B^*_{s,h}$. That is, the effect of BR policy becomes weaker, since the increase of queue length, on the one hand, shifts the graphs of B_{new} and $B^*_{s,h}$ even more (up and down accordingly) for every system case i.e., for each pair ($p_{s,new}$, $p_{m,new}$) and on the other hand, it brings the graphs closer together. Also, it seems that the introduction of a queue leads to the clustered behavior of B_{new} (see Fig. 5), as described above for Fig.3.

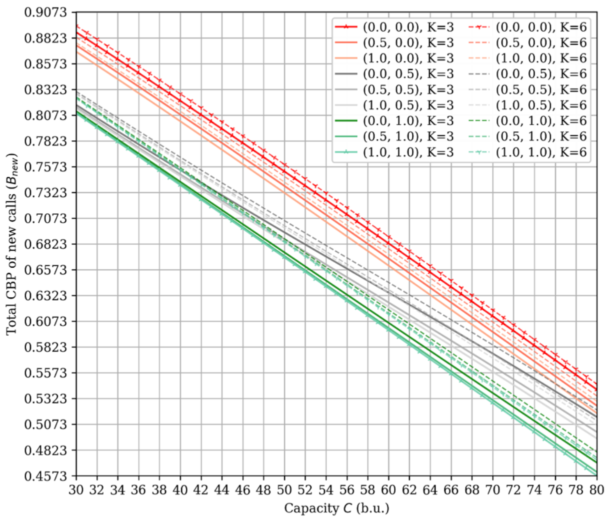

Fig. 3. Total CBP of new calls (B_{new}) for variable *C*, various combinations $(p_{s,new}, p_{m,new})$ and *K*=3, 6.

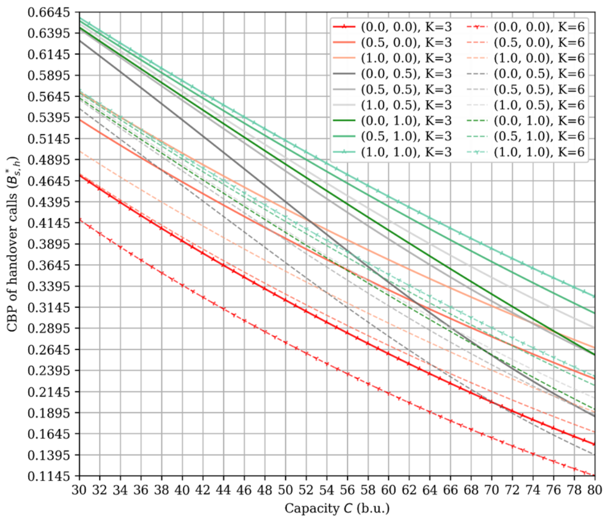

Fig. 4. CBP of handover calls ($B^*_{s,h}$) for variable *C*, various combinations $(p_{s,new}, p_{m,new})$ and *K*=3, 6.

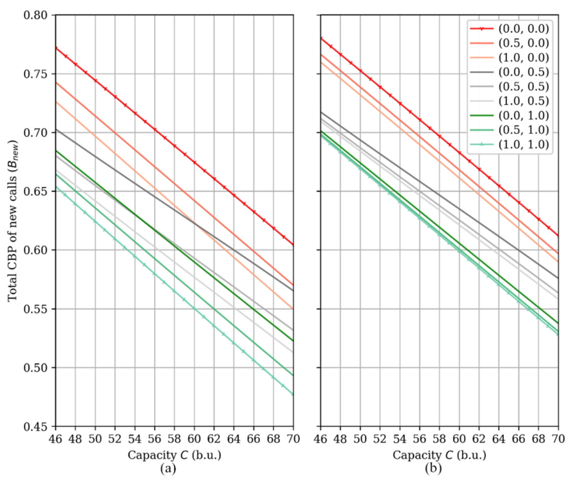

Fig. 5. Total CBP of new calls (B_{new}) for variable *C*, various combinations $(p_{s,new}, p_{m,new})$ and (a) *K*=0 & (b) *K*=3.

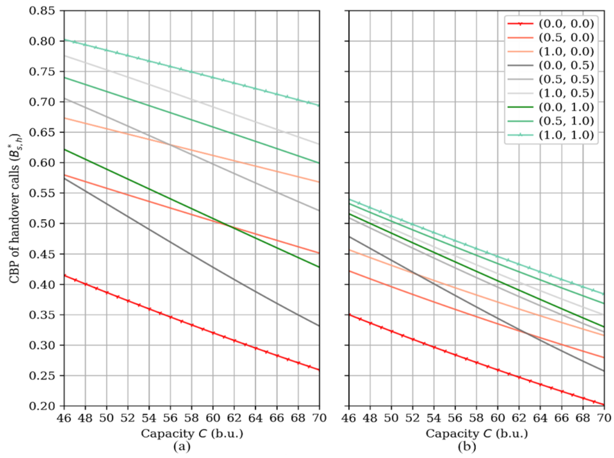

Fig. 6. CBP of handover calls ($B^*_{s,h}$) for variable *C*, various combinations $(p_{s,new}, p_{m,new})$ and (a) *K*=0 & (b) *K*=3.

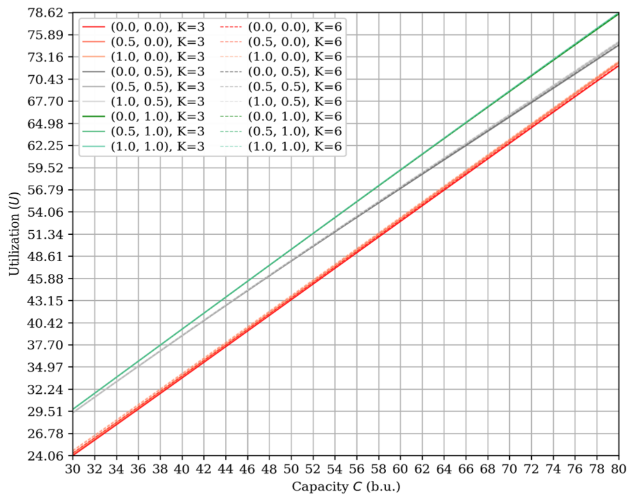

Fig. 7. System's utilization for variable *C* various combinations $(p_{s,new}, p_{m,new})$ and *K*=3, 6.

In Fig. 7, the link's utilization is depicted, as a function of variable values of *C* (*C*=30, 31, … ,80) and for 9 combinations of $p_{s,new}$ & $p_{m,new}$ (each probability is getting its values from the set {0, 0.5, 1}). According to Fig.7, the system's utilization increases (as is normal) with the increase of *C*, differences exist only between the cases where $p_{m,new}$ differs, and specifically higher utilization is achieved for higher values of $p_{m,new}$. The latter means that when a probabilistic bandwidth reservation policy in favor of handover calls is applied in the moving phase, with $p_{m,new} < 1$, part of the capacity is not utilized properly. Also, a change in the queue length seems to have a small effect (positively correlated) on capacity utilization, which is more intense for $p_{m,new}$ values near zero. In Fig. 8, the mean waiting time in the queue (*W*) of handover calls is depicted, for variable *C* (*C* = 30, 31, … ,80) for 2 values of *K* (*K*=3,6) and for 9 combinations of ($p_{s,new}$, $p_{m,new}$) with each probability getting its values from the set {0, 0.5, 1}. According to it, *W* is decreased with: (i) the increase of *C*, (ii) the decrease of $p_{s,new}$ or $p_{m,new}$, meaning that shorter mean waiting times correspond to fully reserved space, as was expected and (iii) the decrease of the queue's length.

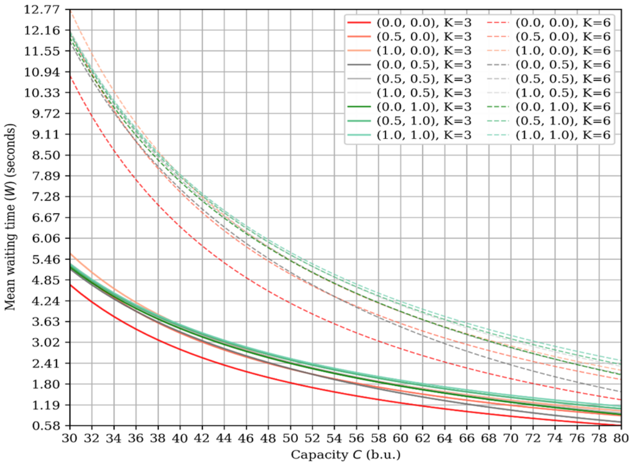

Fig. 8. Mean waiting time (W) of handover calls in the queue for variable C, various combinations ($p_{s,new}$, $p_{m,new}$) and K=3, 6.

IV. Conclusion

A loss/queueing model for a mobile hotspot was presented, in which a probabilistic BR policy in both phases and a queue of finite size is utilized in favor of handover calls. To analytically calculate the various performance metrics, an efficient iterative algorithm initially presented in [12] is adopted. The proposed probabilistic BR loss/queueing model makes possible the CBP regulation through the adjustment of the values of the BR policy probabilities $p_{s,new}$ and $p_{m,new}$. That can mitigate, to some extent, the negative impact that the BR policy has on the QoS of new calls. Although, the existence of a finite queue brings about an additional negative impact on the CBP for new calls, the CBP regulation still holds, although to a lesser extent compared to the case of a pure loss system presented in [12]. A potential future work, would be the study of a mobile hotspot that accommodates calls of various service-classes, that is, calls that need more than one b.u. to be serviced by the system [15]-[23] something not studied yet for mobile hotspots.

References

[1] M. Stasiak, M. Glabowski, A.Wisniewski, and P. Zwierzykowski, Modeling and Dimensioning of Mobile Networks, John Wiley, 2011.

[2] M. Stasiak, M. Glabowski, "A simple approximation of the link model with reservation by a one-dimensional Markov chain", Performance Evaluation, 41, issues 2-3, pp. 195-208, July 2000.

[3] I. Moscholios, J. Vardakas, M. Logothetis and A. Boucouvalas, "A Batched Poisson Multirate Loss Model Supporting Elastic Traffic under the Bandwidth Reservation Policy", Proc. IEEE ICC, Kyoto, Japan, June 2011.

[4] V. Vassilakis, I. Moscholios and M. Logothetis, "The Extended Connection-Dependent Threshold Model for Call-level Performance Analysis of Multi-rate Loss Systems under the Bandwidth Reservation Policy", Int. Journal Commun. Syst., vol. 25, issue 7, pp. 849-873, July 2012.

[5] C. Kim, V. Klimenok and A. Dudin, "Analysis and optimization of guard channel policy in cellular mobile networks with account of retrials", Computers & Oper. Research, vol. 43, pp. 181-190, 2014.

[6] I. Moscholios, V. Vassilakis, M. Logothetis and A. Boucouvalas, "State-dependent Bandwidth Sharing Policies for Wireless Multirate Loss Networks," IEEE Trans. Wireless Commun., vol. 16, issue 8, pp. 5481-5497, Aug. 2017.

[7] S. Sagkriotis, S. Pantelis, I. Moscholios and V. Vassilakis, "Call blocking probabilities in a two-link multi rate loss system for Poisson traffic", IET Networks, vol. 7, issue 4, pp. 233-241, July 2018.

[8] E. Bernal-Mor, D. Garcia-Roger, J. Martinez-Bauset and V. Pla, "Optimal design of multiple fractional guard channel policy in multiservice cellular networks", Proc. UBICOMM, Valencia, Spain, Oct. 2008.

[9] I. Moscholios, "Congestion Probabilities in Erlang-Engset Multirate Loss Models under the Multiple Fractional Channel Reservation Policy", Image Proc. & Commun., vol. 21, no. 1, pp. 35-46, 2016.

[10] I. Moscholios, V. Vassilakis, G. Bouloukakis, P. Panagoulias and M. Logothetis, "A convolution algorithm for a multirate loss system with Poisson arrivals and a threshold call admission policy", Proc. IEEE/IET CSNDSP, Budapest, Hungary, July 2018.

[11] Y. Kim, H. Ko, S. Pack, W. Lee and X. Shen, "Mobility-Aware Call Admission Control Algorithm With Handoff Queue in Mobile Hotspots", *IEEE Trans. Veh. Tech.*, vol. 62, no. 8, pp. 3903-3912, Oct. 2013.

[12] I. Keramidi, I.Moscholios and P. Sarigiannidis, "Call Blocking Probabilities under a Probabilistic Bandwidth Reservation Policy in Mobile Hotspots", *Telecom*, 2(4), pp. 554-573, 2021.

[13] M. Vlasakis, I. Keramidi, I. Moscholios, P. Sarigiannidis and M. Logothetis, "Call admission control under a probabilistic bandwidth reservation policy and handover queueing in mobile hotspots", Proc. CSNDSP, Porto, Portugal, July 2022.

[14] I. Moscholios and M. Logothetis, Efficient Multirate Teletraffic Loss Models Beyond Erlang, John Wiley & IEEE Press, 2019.

[15] J. Kaufman, "Blocking in a shared resource environment", IEEE Trans. Commun., vol. 29, no. 10, pp. 1474-1481, Oct. 1981.

[16] J. Roberts, "A service system with heterogeneous user requirements", Performance of Data Communications systems and their applications, North Holland, Amsterdam, pp.423-431, 1981.

[17] M. Glabowski and M. Stasiak, "Point-to-point blocking probability in switching networks with reservation", Annals of Telecommun., vol. 57, issues 7-8), pp. 798-831, July-August 2002.

[18] I. Moscholios, M. Logothetis and P. Nikolaropoulos, "Engset multi-rate state-dependent loss models," Performance Evaluation, vol. 59, issues 2-3, pp. 247-277, Feb. 2005.

[19] I. Moscholios, M. Logothetis and M. Koukias, "An ON-OFF multirate loss model of finite sources", IEICE Trans. Commun., vol. E90-B, no.7, pp. 1608-1619, July 2007.

[20] J. Vardakas, I. Moscholios, M. Logothetis and V. Stylianakis, "On code reservation in multi-rate OCDMA passive optical networks", Proc. IEEE/IET CSNDSP, Poznan, Poland, July 2012.

[21] D. Parniewicz, M. Stasiak and P. Zwierzykowski, "Traffic engineering for multicast connections in multiservice cellular networks", IEEE Trans. Industrial Informatics, vol. 9, issue 1, pp. 262-270, Feb. 2013.

[22] I. Moscholios, G. Kallos, V. Vassilakis and M. Logothetis, "Congestion Probabilities in CDMA-based networks supporting batched Poisson input traffic", Wireless Personal Commun., vol. 79, issue 2, pp. 1163-1186, November 2014.

[23] A. Avramova and V. Iversen, "Radio access sharing strategies for multiple operators in cellular networks", IEEE ICC Workshop on 5G & Beyond, London, U.K., June 2015.