OPTIMAL CALL ADMISSION CONTROL AND BANDWIDTH ADAPTATION IN MULTIMEDIA CELLULAR MOBILE NETWORKS

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KEYWORDS

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ABSTRACT

Third and future generations of cellular mobile networks are designed to provide adaptive multimedia services with QoS guarantees. In this scenario call admission control and bandwidth adaptation work together in order to improve the system's performance by reducing blocking probability of multimedia calls. However, this improvement is done at cost of the QoS degradation of ongoing multimedia calls, which may be unacceptable to the users of real time services as videoconference, videophone, so on. Another problem concerns with the bandwidth adaptation is that it may consume a lot of wireless and wireline resources due to extra signalling overhead as well as battery power in the mobile station. In addition, frequent bandwidth switching among different bandwidth levels may be worse than a large degradation ratio. Thus, an important aspect to be considered in the design of Radio Resource Management is how to optimize the system's performance by minimizing blocking probability, controlling bandwidth adaptation, and maximizing user's satisfaction. In this paper we address this subject by proposing a Semi-Markov Decision Model that seeks an optimal stationary policy that match this goal. Results show that the optimal policy outperforms the performance of a non-optimal adaptive resource allocation scheme that seeks only to improve blocking probability.

INTRODUCTION

QoS provisioning in wireless network has been beneficed by the development of adaptive multimedia applications such as MPEG-2 and MPEG-4, etc (Huang et al. 2004; Yu et al. 2004). When acting together with Call Admission Control (CAC), bandwidth adaptation improves the system's performance by adapting (promoting or reducing) the bandwidth of the ongoing calls accordingly network condition. In order to achieve highest bandwidth utilization in a multimedia environment it is mandatory that the Service Providers make fully use of this feature. Thus, resource allocation in third (3G) and future generation (4G) of cellular mobile networks must be designed to support CAC and bandwidth adaptation. When the bandwidth adaptation is performed, the bandwidth of ongoing multimedia calls are degraded in order to release radio resources to accept an incoming call thereby reducing blocking probability. In spite of improving the system's performance, this degradation may cause dissatisfaction in some users of real time bandwidth-intensive application such as videoconference, videophone, etc. Another drawback of bandwidth adaptation is that frequent bandwidth adaptation may consume a lot of wireless and wireline resources due to extra signalling overhead as well as battery power in the mobile station (Yu et al. 2004). In addition, frequent bandwidth switching among different bandwidth levels may be worse than a large degradation ratio (Chou and Shin 2004). Thus, a key point in the design of Radio Resource Management (RRM) is to find a balance among the blocking probability, the adaptation frequency, and the user's satisfaction. In this paper we propose a Semi Markov Decision Model (SMDM) for call admission control and bandwidth adaptation in multimedia cellular mobile networks that seeks to optimize the goals listed above.

RELATED WORKS AND CONTRIBUTION

Adaptive resource allocation schemes combing CAC and resource reservation is studied in Huang et al. 2004). In (Yu et al. 2004) the authors use a SMDM to optimize frequency adaptation in adaptive resource allocation scheme. The SMDM is solved by means of the recent reinforcement learning approach. In (Ahn

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and Kim 2003) the authors propose an optimal bandwidth adaptation that maximizes user's satisfaction. They formulate the problem as a binary linear integer. None of the papers discussed above investigated explicitly an adaptive resource allocation that effectively seeks performance tradeoffs among the radio resource utilization, adaptation frequency and user's satisfaction. This problem is studied in the current paper by modelling the RRM as a Semi Markov Decision Model, which give us an optimum solution. We look into the behavior of the optimal policy and compare its results with a non-optimal scheme that seeks only to improve blocking probability. We show that optimal policy outperforms the non-optimal scheme.

SYSTEM MODEL AND ASSUMPTIONS

Traffic

As usual, the arrivals of new real time multimedia calls and their hand off follow two Poisson processes mutually independents with parameters $\lambda_{n,c}$ and $\lambda_{h,c}$. Thus, the offered real time traffic is also a Poisson process with arrival rate $\lambda_c = \lambda_{n,c} + \lambda_{h,c}$. The dwell time and the call duration time of real time call are random variables exponentially distributed with parameters $1/\mu_{h,c}$ and $1/\mu_{d,c}$, respectively. The channel holding time is thus a random variable with negative exponential distributions with mean $1/\mu_c = 1/(\mu_{h,c} + \mu_{d,c})$. Non real time traffic is modelled according to (Meo and Marsan 2004), where an incoming packet session (web browsing session) is represented by a sequence of packet calls and reading times. One or more IP packets form a packet call. According to (Meo and Marsan 2004), we also assume the packet sessions remain active for an indefinite amount of time, which implies that the number of concurrently active packet sessions is fixed. The reading time between packet calls is an exponentially distributed random variable with mean $D_{pc}=1/\beta$ =41.2s. The number of IP packets within a packet call is geometrically distributed with mean $N_d=25$, while the interarrival time between these packets is exponentially distributed with mean $D_d=(1/\lambda_{IP})=0.5s$. The average packet call duration is given by $1/\alpha = D_d N_d$. We also assume the IP service time as exponentially distributed random variable with mean $1/\mu_s$, which is defined as the time in which a packet of 480 bytes of size is carried out by a radio channel with data rate of 100 kbit/s.

Optimal policy

Our optimal call admission control and bandwidth adaptation is modelled as a Semi Markov Decision Model, whose the state is given by:

$$E = \{(c,b,ev,k,m)/ 0 \le c \le \Theta, b \in \{0,1\}, ev \in \{0,1,2\}, 0 \le k \le B_s, 0 \le m \le S; \quad if\, b=0,\ then\ \Theta = \left\lceil \frac{N}{bw_{\max}} \right\rceil \quad if\, b=1,\ then\ \Theta = \left\lceil \frac{N}{bw_{\min}} \right\rceil \} \tag{1}$$

where c is the number of ongoing real time multimedia calls using the bandwidth given by b, i.e., if $b=0$, then all c calls are with maximum bandwidth; otherwise, $b=1$, minimum bandwidth. ev is the last event occurred; it may be an arrival ($ev=1$) or a departure ($ev=0$) of real time multimedia call or other events ($ev=2$) as generation or transmission of IP packet; starting or finishing of a packet call. The information about the last event is introduced in the state space in order to define the set of possible actions in each state. The number of IP packet in the buffer and the number of active packet call are, respectively, k and m. B_S is the buffer capacity while S is the maximum amount of active data session. We assume that each state means the system's configuration just after an event occurrence and just before a decision making.

The decision epochs are departure and arrival of real time multimedia call, i.e., $ev=0,1$. An interesting feature of optimal CAC and bandwidth adaptation is that when the resource allocation takes into account only CAC, the service completion epochs are fictitious, but when bandwidth is taking into account in the design of resource allocation, these decision epochs are real ones. For $ev=2$ no decision is taken. In arrival epochs the decision maker may make the decision (actions) of rejecting and does not adapt the bandwidth of ongoing calls (NN); rejecting and adapting the bandwidth of ongoing calls (NA); accepting and does not adapt the bandwidth of ongoing calls (AN) or accepting and adapting the bandwidth of ongoing calls (AA). In service completion epochs the decision maker may make the decisions not to adapt the bandwidth of ongoing calls (NN) or to adapt the bandwidth of ongoing calls (NA). Note that in this case there is not decision about rejecting or admitting incoming calls. Thus, for all $i \in E$ the set of possible action is given by Equation (2)

For the sake of simplicity we denote each action by a number $\in$ {0,1,2,3} in such a way that the action NN is 0; NA is 1; and so on. It permits us to simplify the decision making by separating the decision about rejection and adaptation. Hence, whenever the quotient of $A(i)/2 =1$ an incoming call is accepted; otherwise, $A(i)/2 =0$, it is rejected. At the same way, whenever the remainder of $A(i)/2 =1$ the bandwidth of the ongoing calls are adapted; otherwise, $A(i)/2 =0$, they are not. The term $ac=1$ is used whenever an incoming multimedia call is accepted and $ac=0$, otherwise. The term $ad=1$ is used whenever bandwidth of the ongoing calls are adapted and $ac=0$, otherwise.

$$A(i)=\begin{cases} 0- \quad NN, & \forall ev\in\{0,1,2\} \\ 1- \quad NA, & \begin{cases} ev=0\wedge b=0; \\ \vee ev=0\wedge b=1\wedge\left(c\le\lceil N/bw_{\max}\rceil\right); \\ \vee ev=1\wedge\left(c\le\lceil N/bw_{\max}\rceil\right) \end{cases} \\ 2 \quad AN, & \begin{cases} ev=1\wedge b=0\wedge\left(c<\lceil N/bw_{\max}\rceil\right); \\ \vee ev=1\wedge b=1\wedge\left(c<\lceil N/bw_{\min}\rceil\right); \end{cases} \\ 3 \quad AA & \begin{cases} ev=1\wedge b=0; \\ \vee ev=1\wedge b=1\wedge\left(c<\lceil N/bw_{\max}\rceil\right); \end{cases} \end{cases} \quad (2)$$

For this process, given that in a decision epoch the system is in the state $i \in E$ and the action $a \in A(i)$ is chosen, we define: $\tau_i(a)$ as the expected time until the next decision epoch; $p_{ij}(a)$ as the probability that in the next decision epoch the state will be j; $C_i(a)$ as the expected cost incurred until the next decision epoch. From the transition rates $\Lambda_{ij}(a)$ we obtain the total output rate from each state given by $\Lambda_i(a) = \sum_{j\neq i} \Lambda_{ij}(a)$. Thus, the transition probabilities and the mean time between transitions are given, respectively, by $p_{ij}(a) = \Lambda_{ij}(a)/\Lambda_i(a)$ and $\tau_i(a) = 1/\Lambda_i(a)$. Figure 1 presents the pseudo-code used to generate the transition among the states of the SMDM. For convenience for each state $i=(c,b,ev,k,m) \in E$ we named $i.c$ as its number of ongoing multimedia call, and so on. The same nomenclature is used to the state r and $t \in E$

```
Begin
For all i ∈ E and a ∈ A(i) do:
r←i;
if(ac=1) then {r.c←r.c+1};
if(ad=1) then {r.b←1-r.b};
// By default do r.ev←2;
// Arrival of real time multimedia call
t←r;
t.ev←1;
Do the transition i→t with probability λc(a)/Λi(a) ;
// Departure of real time multimedia call
if (r.c>0) do {
    t←r;
    t.c←t.c-1;
    t.ev←0;
Do the transition i→t with probability r.cμc(a)/Λi(a)} ;
// Packet call starts
if (r.m<S) do {
    t←r;
    t.m←t.m+1;
Do the transition i→t with probability (S-r.m)β/Λi(a)} ;
// Packet call finishes
if (r.m>0) do {
    t←r;
    t.m←t.m-1;
Do the transition i→t with probability r.mα/Λi(a)} ;
// Generation of IP packet
if (r.k<Bs & r.m>0) do {
    t←r;
    t.k←t.k+1;
Do the transition i→t with probability r.mλIP/Λi(a)} ;
// Transmission of IP packet
if (r.b=0) do {band←bwmax}
if (r.b=1) do {band←bwmin}
trans←min(N-r.c band,r.k;)
if ( trans>0) do {
    t←r;
    t.k←t.k-1;
Do the transition i→t with probability transμs/Λi(a)} ;
End
```

Figures 1: The pseudo-code of transition among the states of the SMDP

In order to optimize the CAC and bandwidth adaptation that seeks the best tradeoff among blocking probability, adaptation frequency, and user's satisfaction, we use the following cost structure:

$$C_i(a) = C_B(i,a) + C_{AD}(i,a) + C_H(i,a) \quad (3)$$

where $C_B(i,a)$, $C_{AD}(i,a)$, and $C_H(i,a)$ are, respectively, the blocking cost, the adaptation cost, and the holding cost. Let $i \in E$ be the state of the system, $a \in A(i)$ be the action, n_{ad} be the number of ongoing multimedia calls just before a decision making, the expressions of these costs are:

$$C_B(i,a) = c_b, if\ ev = 1 \wedge a = ac = 0 \quad (4)$$

$$C_{AD}(i,a) = c_{ad} n_{ad}, if\ ev \in \{0,1\} \wedge a = ad = 1$$

$$C_H(i,a) = \begin{cases} C_{\max} = c_{\max} n \tau_i(a), if\ b = 0 \\ C_{\min} = c_{\min} n \tau_i(a), if\ b = 1 \end{cases}$$

With $\tau_i(a)$, $p_{ij}(a)$ and $C_i(a)$, we may use the value iteration algorithm and the uniformization method (Tijms 1994), to obtain the optimum stationary policy for the system. A stationary policy R, defined by the decision rule $f:E\rightarrow A$, prescribes the action $f(i) \in A(i)$ each time the system is observed in the state $i \in E$.

The carried multimedia traffic when the system is in the state $i \in E$ and $ev=1$ and the action $a=ac=1 \in A(i)$ is chosen is given by Equation (5). π_i is the steady state probability. Thus the real time multimedia call blocking probability is given by Equation (6).

$$T_C = \sum_{\forall i \in E, ev=1, a=ac=1 \in A(i)} \Lambda_i(a)\pi_i \quad (5)$$

$$P_{BC} = 1 - \frac{T_C}{\lambda_c} \quad (6)$$

Likewise in the pseudo-code, we assume the *band*=bw_{max} if (b=0) and *band*=$bw_{\min}$ if (b=1); and *trans=min(N-cband,k)*; thus the utilization of radio resources is given by :

$$U_{OP} = bw_{\max} \frac{\sum_{\forall i \in E, a \in A(i); c>0, b=0} c\pi_i}{N} + bw_{\min} \frac{\sum_{\forall i \in E, a \in A(i); c>0, b=0} c\pi_i}{N} + \frac{\sum_{\forall i \in E, a \in A(i)} trans\, \pi_i}{N} \quad (7)$$

The offered data traffic is given by Equation (8) (Meo and Marsan 2004). The IP packet blocking probability is given by Equation (9). Thus, the throughput and mean delay are, respectively given by Equation (10) and Equation (11).

$$O = \lambda_{IP} \frac{\beta}{\beta + \lambda} S \quad (8)$$

$$P_{BIP} = \sum_{\forall i \in E, a \in A(i), k = B_s} \pi_i \quad (9)$$

$$X = O(1 - P_{BIP}) \quad (10)$$

$$W = \frac{\sum_{\forall i \in E, a \in A(i)} k\pi_i}{X} \quad (11)$$

RESULTS

Table 1 summarizes the underlying parameters used in our experiments. In the following results the optimal CAC and bandwidth adaptation will be referred as OP, while the non-optimal will referred as NOP.

Table 1 – Parameters used.

Parameters		Value
Number of radio channnels	N	*20*
Number of data sessions	S	*5*
Buffer size	B_s	*20*
Mean call duration (s)	$1/\mu_{d,c}$	*120*
Mean dwell time (s)	$1/\mu_{h,c}$	*60*
Percentage of hand off calls		*10* %
Blocking cost	c_b	*100*
Adaptation cost	c_{ad}	*5*
Maximum bandwidth cost	c_{max}	*1*
Minimum bandwidth cost	c_{min}	*2*

Table 2 shows the behaviour of the optimal policy when the last event is the arrival or the departure of multimedia real time call and the ongoing calls are with bw_{max}. As the optimal policy seeks to maximize the user's satisfaction, it never adapts from bw_{max} to bw_{min}. Besides, it is greedy, i.e., if possible it always accepts an arrival of multimedia call with bw_{max}. Table 3 presents the behavior of optimal policy when the last event is an arrival of multimedia call and the ongoing call are with bw_{min}. For low traffic load (0.011 to 0.088 calls/s) the optimal policy is also greedy; thus, it accepts the incoming call and adapts the ongoing calls if possible. Otherwise, it accepts the incoming call and does not adapt the ongoing calls. For medium traffic load (0.11 to 0.176 calls/s) the behavior of the optimal policy may be divided into two cases: when it is possible to accept the incoming call and to adapt the ongoing calls to bw_{max}, and when it is not possible to accept the incoming call and to adapt the ongoing calls to bw_{max}. In the first case, the optimal policy assumes a fixed behavior whenever the number of ongoing calls is c< $\lceil N/bw_{max} \rceil$. At the limit c= $\lceil N/bw_{max} \rceil$, it does not accept the incoming call and adapts the ongoing calls from minimum bandwidth to maximum bandwidth. In the second case, when it is not possible to adapt ongoing calls to maximum bandwidth (c> $\lceil N/bw_{max} \rceil$), we can note that, as the traffic increases, the optimal policy starts to reject the incoming calls when it would be possible to accept them in order to minimize the long run average cost per unit time. At the limit, that is, for high traffic, the optimal policy rejects all incoming calls when c≥ $\lceil N/bw_{max} \rceil$. We can conclude that for low, medium, and high traffic load the behavior of the optimal policy is fixed, so that simple to be deployed in a real system when c< $\lceil N/bw_{max} \rceil$. However, when the traffic increases, its behavior is not so simple to be deployed when c≥ $\lceil N/bw_{max} \rceil$. This fact has motivated us to derive simple sub-optimal policies. They will be reported in forthcoming works. Table 4 presents the behavior of the optimal policy when the last event is the departure of multimedia call and the ongoing calls are with minimum bandwidth. Again, in order to improve user's satisfaction, the optimal policy always adapts the ongoing calls to maximum bandwidth.

Table 2 – Optimal policy: arrival and departure when ongoing calls are with bw_{max}.

State	Action
(c≤9 ,b=0,ev=1,k,m)	*AN*
(c=10 ,b=0,ev=1,k,m)	*NN*
(0≤c≤9 ,b=0,ev=0,k,m)	*NN*

In the following figures we present a performance comparison study between the optimal and the non-optimal policies. This last one is the policy that only minimizes blocking probability, but does not guarantee the user's satisfaction and does not control frequency adaptation. The adaptive resource allocation scheme that minimizes blocking probability is that one in which the bandwidth of all ongoing calls is demoted if there is not available radio resource to admit an incoming call. Besides, if the network is overloaded and there is not radio resource to accept the call with minimum bandwidth, it is blocked. When a multimedia call leaves the system, the bandwidth of ongoing calls are promoted if possible. This scheme is fair because the bandwidth of all real time calls are fairly demoted in order to benefit an incoming call, and at the same way, they will be fairly promoted when there are enough radio resources. Note that this scheme is simple enough and may be deployed in a real system. Figure (2.a) shows the total costs of optimal and non-optimal policies. We highlight that this difference reaches 22.59% showing that the optimal policy has better performance than non-optimal. Figure (2.b) shows the mean adaptation cost for both policies. This parameters shows that the optimal policy keeps the frequency adaptation much lower than the non-optimal policy especially for medium and high traffic load. Figure (2.c) shows the real time multimedia call blocking probability for both policies. We can see that the non-optimal policy accepts more calls because it cannot guarantee user's satisfaction, i.e., as the traffic increases it reduces the bandwidth of all ongoing calls from maximum to minimum in order to accept more calls. On the other hand, the optimal policy tries at the same time to balance blocking probability, frequency adaptation, and user's satisfaction. This last criterion penalizes so much the system's performance by forcing the decision maker to keep as possible as it can the bandwidth of all ongoing calls with maximum bandwidth. Therefore, we can see in Figure (2.d) that the bandwidth utilization of optimal policy is greater than the non-optimal, particularly for high traffic load where the network congestion occurs. Finally, Figure (2.e) shows how both policies handle the non real time traffic. Since the optimal policy spends more time serving ongoing calls with maximum bandwidth there are few radio resources to be exploited by non real time traffic. As a consequence, the mean delay is longest. In opposite, the non-optimal policy has more radio channels to carry this traffic out. However, we can note that the mean delay of optimal policy is not abusive even for high traffic load.

CONCLUSION

In this paper we address the problem of optimal call admission control and bandwidth adaptation in multimedia cellular mobile networks. We model the RRM as Semi Markov Decision Model and find an optimal policy that seeks to optimize blocking probability, frequency adaptation, and user's satisfaction. We see that in spite of the optimal policy may not guarantee a low blocking probability when compare with a policy that seeks only to improve this parameter, it obtains the highest radio resource utilization as well as the minimum long run average cost per unit time. Additionally, the optimal policy maximizes the user's satisfaction even during network congestion, i.e., high traffic load. Finally, it optimizes the frequency adaptation. As a consequence of serving the users with maximum bandwidth as possible as it can, the optimal policy has longest mean delay. However, the value of this metric is not abusive.

Upon investigating the behavior of the optimal policy we can conclude that it is not simple enough to be deployed in a real system. Thus, it is necessary to derive simple sup-optimal policy. Such a study is currently under development and will be reported in forthcoming paper.

Table 3 – Optimal policy: arrival when ongoing calls are with bw_{min}.

Traffic	State	Action
Low	**Fixed behavior**	
	(c≤9 ,b=1,ev=1,k,m)	*AA*
0.011 to 0.088	*(10≤c≤19 ,b=1,ev=1,k,m)*	*AN*
	(c=20 ,b=1,ev=1,k,m)	*NN*
Medium	**Fixed behavior**	
	(c≤9 ,b=1,ev=1,k,m)	*AA*
0.11 to 0.176	*(c=10,b=1,ev=1,k,m)*	*NA*
	(c=20,b=1,ev=1,k,m)	*NN*
Medium	**Dynamic behavior**	
0.11	*(c=11 ,b=1,ev=1,k,m)*	***NN***
	(12≤c≤19,b=1,ev=1,k,m)	*AN*
0.121	*(11≤c≤12,b=1,ev=1,k,m)*	***NN***
	(13≤c≤19,b=1,ev=1,k,m)	*AN*
0.132	*(11≤c≤13,b=1,ev=1,k,m)*	***NN***
	(14≤c≤19,b=1,ev=1,k,m)	*AN*
0.143	*(11≤c≤15,b=1,ev=1,k,m)*	***NN***
	(16≤c≤19,b=1,ev=1,k,m)	*AN*
0.154	*(11≤c≤16,b=1,ev=1,k,m)*	***NN***
	(17≤c≤19,b=1,ev=1,k,m)	*AN*
0.165	*(11≤c≤17,b=1,ev=1,k,m)*	***NN***
	(18≤c≤19,b=1,ev=1,k,m)	*AN*
0.176	*(11≤c≤18,b=1,ev=1,k,m)*	***NN***
	(c=19,b=1,ev=1,k,m)	*AN*
High	**Fixed behavior**	
	(c≤9 ,b=1,ev=1,k,m)	*AA*
0.22 to 0.55	*(c=10 ,b=1,ev=1,k,m)*	*NA*
	(11≤c≤20 ,b=1,ev=1,k,m)	***NN***

Table 4 – Optimal policy: departure when ongoing calls are with bw_{min}.

State	Action
(1≤c≤10 ,b=1,ev=0,k,m)	*NA*
(c=0 and 11≤c≤19 ,b=1,ev=0,k,m)	*NN*

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REFERENCES

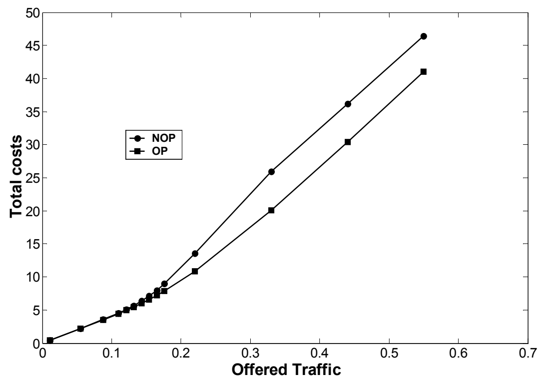
Ahn, K.-M., and Kim, S. 2003. "Optimal bandwidth Allocation for bandwidth adaptation in Wireless Multimedia Network". *Computers and Operational Research*, No. 30, 1917-1929.

Huang, L., Kumar, S., and Kuo, C.C.J. 2004. "Adaptive Resource Allocation for Multimedia QoS Management in Wireless Networks". *IEEE Transactions On Vehicular Technology*, vol. 53, No 2, 547-558.

Meo, M., and Marsan, M. A. 2004. "Resource management policies in GPRS systems". *Performance Evaluation*, vol. 56, No. 1-4, 73-92.

Yu, F., Wong, V. W.S., and Leung, V. C.M. 2004. "A new QoS provisioning method for adaptive multimedia in cellula wireless networks". *Proceedings of IEEE INFOCOM*.

Tijms, H. C. 1994. "Stochastic models: an algorithmic approach", *John Wiley & Sons*.



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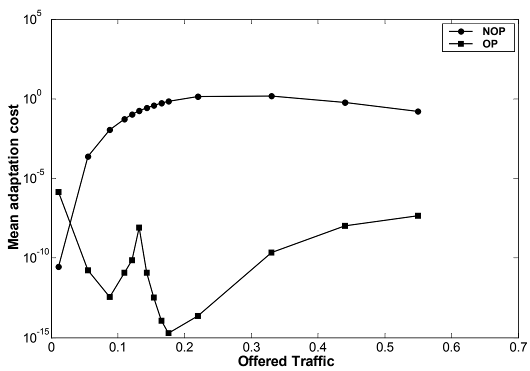

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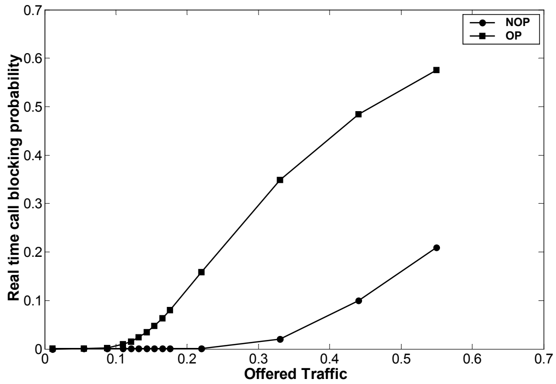

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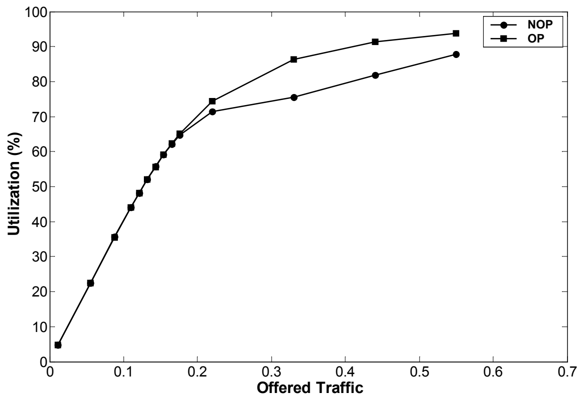

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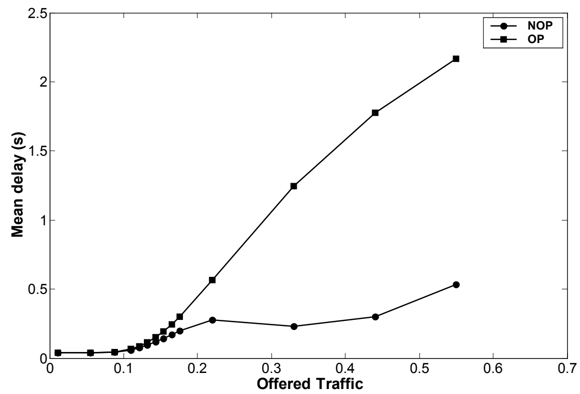

(e)

Figures 2: Performance study: (a) Total cost; (b) Mean adaptation cost; (c) Blocking probability; (d) Utilization; (e) Mean delay.