Additional Information

Optimal Radio Access Technology Selection on Heterogeneous Networks

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Abstract

The joint management of radio resources in heterogeneous networks is considered to raise the resource occupation efficiency. We propose joint schemes for admission control and access technology selection with vertical handoff. We determine optimal policies for a radio systems that support two multiple access techniques, TDMA and WCDMA, covering the same geographical area. In addition, the system under study also supports both streaming and elastic traffic. First, we explore different optimization criteria expressed in terms of blocking probabilities and throughput. We accomplish an exhaustive numerical analysis that allows us to characterize the optimal admission policies according to the arrival type and system load. Based on this characterization, we design heuristic policies and compare their performance to ones obtained by previously proposed schemes. This analysis is also done when constraints are added to provide QoS. Second, we also study an extension of the previous system that includes vertical handoffs, in order to evaluate their impact on the system performance. For the four types of vertical handoffs considered, we determine and characterize optimal policies according to the arrival type, system load and vertical handoff action. Since it is not feasible to calculate the optimal policies online, new heuristic policies with vertical handoff are constructed and evaluated. Finally, in order to take into into account the cost of performing vertical handoffs, a new optimization problem is formulated that relates voice and data blocking with vertical handoff costs.

Keywords: joint call admission control, vertical handoff, resource allocation, Markov decision process

1. Introduction

The new generation wireless systems allow the subscribers to exploit the availability of multiple radio access technologies (RATs) in the same geographical area to achieve a permanent connection with the best possible performance [1]. This coexistence of various RATs has promoted the interest in joint management of their radio resources. Common radio resource management (CRRM) has been proposed as a model to control several RATs in a coordinated way, exploiting the fact that this coordination allows an improvement in the use of the limited resources [2]. Among the CRRM functions, there is a special interest in the joint call admission control (JCAC), which in this new scenario not only defines if a call should be accepted but also in what technology, depending on user's or operator's criteria [3].

Proposals for JCAC in heterogeneous networks, such as those found in [4] and [5], show the improvement in network's stability based on a load balancing scheme.

Even though, some other advantages can be exploited from a common admission control scheme. In this article, we are interested in finding an optimal scheme for a heterogeneous network with two technologies, and where both streaming and elastic traffic are supported. Several JCAC policies have been studied in [5] for a scenario similar to ours, in terms of throughput and blocking probability. Nevertheless, it has to be considered that the best possible policy may not follow a simple scheme, since its behavior may be affected by different parameters that depend on the technologies involved or the traffic characteristics. Therefore, in this paper there is an analytical study to obtain the optimal policy and its main characteristics in relation to the parameters named before. Similar works have been done in order to define a scheme that enhance network's performance.

In [6] a Markov model is used for an heterogeneous network (WLAN and CDMA), and a linear programming method is used to solve the optimization problem. This study explicitly acknowledges the inherent

complexity of the problem which could make it computationally intractable for large systems, and proposes reinforcement learning as a possible solution method. Although we still have that limitation, the objective of this work is to obtain the main characteristics of the optimal solutions to propose heuristic schemes that can be extrapolated to bigger systems. In [7] a genetic algorithm is used to find a common access control scheme based on a Markov model and a cost function which depends on several factors. However, the initial conditions play a crucial role in the results obtained by genetic algorithms, therefore affecting the objective of obtaining heuristic solutions that apprehend the main characteristics of the optimal solutions under different conditions.

Finally, fuzzy-based solutions are used in [8] and [9]. This solutions take different parameters from the user and the system, weights them, and make a decision into a complex online solution. On the other hand, our focus is to synthesize the characteristics of the optimal solutions for two explicit optimization functions: throughput and blocking probabilities. As other works mentioned before, a Markovian model is used, but the Markov decision process is solved based on policy iteration, a method that does not depend on the initial conditions used and always allows to find the optimal solution in a finite and usually low number of steps. Once the main characteristics of the optimal solutions are described in relation to the system and traffic characteristics, a new access control scheme is proposed and analyzed.

Acknowledging the importance that vertical handoffs have as part of the joint radio resource management functions, and based on the analysis previously done on the system, different types of vertical handoffs are introduced according to the type of the arriving service and some specific conditions of the system. Since there is an inherent complexity in vertical handoff as it is pointed out in [3], it is required that the proposed schemes do not boost it. On the other hand, most vertical handoff schemes like those in [14],[15], privilege user preferences, and we consider that the operator's point of view is also important. The last part of the article focuses on the cost of vertical handoffs. In previous studies like [16], it is defined a monetary cost for this function so users can use it as a parameter to decide which technology is more suitable. On our work, we relate this cost to those associated to the blocking of voice and data sessions in order to understand when it is useful.

The rest of the paper is structured as follows. In Section 2 we describe the Markov model according to the characteristics of the system. The solution method is described in Section 3. In Section 4 the results of the optimization are shown, and analyzed for a static scenario. The optimal solutions for various traffic values are studied in Section 5. In Section 6, we add QoS restrictions into optimization and analyze its results. Section 7 introduces vertical handoff in the action set, and new optimal policies are found in order to obtain the main characteristics of the optimal solutions. New heuristic solutions are described and evaluated in different scenarios and simulations are performed in order to validate analytic results. In Section 8 we study the cost of performing a single vertical handoff to understand its impact in relation to performing data and voice blocking. Finally, Section 9 concludes the work.

2. System description and Markov model

The system of our interest uses two multiple access techniques, TDMA and WCDMA. Their characteristics allow us to model technologies such as GSM and UMTS. However,the proposed model and analysis can be expanded to cover other multiple access techniques like OFDMA, which has been defined to support technologies like WiMAX and LTE. Additionally, both access techniques provide voice and data services in the same area as it was proposed in [10]. As a call arrives to the system, a decision has to be made about if it is served in one or another technology. Initially, we consider that a decision is made once a session starts and will be held until is served, i.e. there are no vertical handoffs.

In order to obtain an analytically tractable model, we assume that voice (data) call (session) arrivals follow a Poisson process with rate $\lambda_v(\lambda_d)$. We also assume that the service time for voice calls is exponentially distributed with mean $1/\mu_v$. On the other hand, as data sessions generate elastic traffic, their sojourn time will depend on the available resources. The size of the flows generated by the data sessions is exponentially distributed with mean σ (in bits). If BR_d is the data bit rate experienced for a given user, then the service time will be exponentially distributed with mean $1/\mu_d = \sigma/BR_d$. Clearly, BR_d might depend on the system state as discussed later.

2.1. State space

The system is modeled as a 4 dimensional continuous time Markov chain (CTMC), with state represented by the state vector $s = (s_1, s_2, s_3, s_4)$ where s_1 represents the number of ongoing voice sessions on TDMA, s_2 the data sessions on TDMA, s_3 the voice sessions on WCDMA and s_4 the data sessions on WCDMA.

We define C as the fixed number of channels per slot in TDMA. A voice session will always use a whole channel, so there can only be C simultaneous voice sessions on this technology. On the other hand, data sessions can share a channel when TDMA is at full capacity, in such a way that n_c data sessions can be served per channel. This means that we can have a maximum of $C \cdot n_c$ simultaneous data sessions in TDMA. According to this, the first condition that a state must fulfill to be feasible is given by

$$s_1 \cdot n_c + s_2 \leq n_c \cdot C. \qquad (1)$$

The capacity on WCDMA is defined by

$$s_3 \left(\frac{W/BR_{w,v}}{(E_b/N_0)_v} + 1 \right)^{-1} + s_4 \left(\frac{W/BR_{w,d}}{(E_b/N_0)_d} + 1 \right)^{-1} \leq \eta_{ul}, \quad (2)$$

where W is the chip rate, $BR_{w,x}$ is the bit rate used for transmitting service x in WCDMA, $(E_b/N_0)_x$ is the bit energy to noise density required for service x, and η_{ul} is the uplink cell load factor. This is the same expression used in [11].

Considering that each technology has independent resources, the feasible combination of data and voice users can be determined for each technology separately. We define S as the set of feasible states, that is all the state vectors s that fulfill the conditions defined in (1) and (2).

2.2. System metrics

After the CTMC is constructed, that is we have defined the state space and the transition rates, we obtain different system metrics using the steady state probabilities. In particular, we are interested in the voice blocking probability, the data blocking probability, and the total throughput. The total blocking probability refers to the probability that the system is in a state where all calls are blocked, independent of the service it requires. In the same way the voice (data) blocking probability refers to the probability of being in those states where voice (data) calls are blocked. To calculate the throughput we have to consider that the bit rate is independent for each service and technology and that data sessions in TDMA can share a channel, which is reflected in the $\min(C - s_1, s_2)$ factor of the following equation:

$$Th = \sum_{s \in S} P(s)(s_1 BR_{t,v} + s_3 BR_{w,v}$$
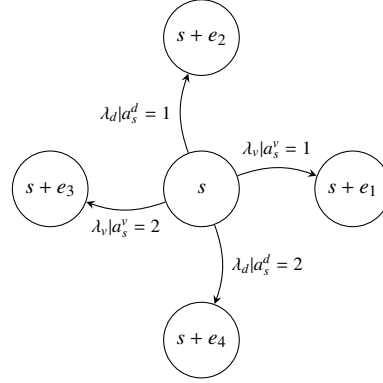$$+ \min(C - s_1, s_2) BR_{t,d} + s_4 BR_{w,d}), \qquad (3)$$

Figure 1: Transitions for voice and data arrivals.

Table 1: Set of possible actions A

value	action
0	Block call
1	Send call to TDMA
2	Send call to WCDMA

where $P(s)$ is the steady state probability of being in state s and $BR_{x,y}$ is the bit rate used for transmitting service y (voice or data) in technology x (TDMA or WCDMA).

3. Optimization problem

For each possible state defined in the last section, a decision must be made whether an arriving call should be admitted and given the case, the appropriate technology according to the service, i.e. voice or data. In a Markov decision process (MDP), a policy π defines which actions $a=(a_s^v, a_s^d)$ should be taken at each state s for voice a_s^v and data a_s^d arrivals. It should be clear that decision epochs occur only at arrivals. The main objective is to find among the possible policies the one that optimizes a chosen function.

In this system, the set of actions A defines the possible values for a_s^v and a_s^d, and it is defined in Table 1. Figure 1 shows the transitions from state s for arrivals conditioned by a_s^v and a_s^d, where e_i is a 4 dimensional vector of zeros with a 1 on the i–th position. The transitions from state s for departures are shown in Figure 2.

We define now three different admission schemes and set the values taken by a_s^x accordingly, where x could be voice or data. Let AC_{TDMA} and AC_{WCDMA} be the available free capacity in TDMA and WCDMA,
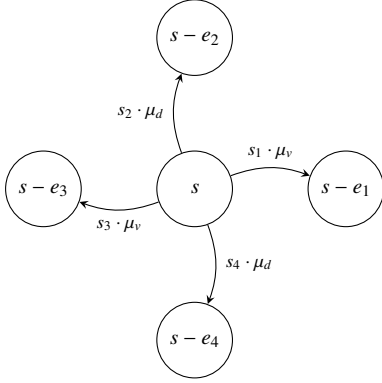
Figure 2: Transitions for voice and data departures.

respectively.

Scheme i : Calls are sent to TDMA (if possible)

$$a_s^x = \begin{cases} 1 & \text{if } AC_{TDMA} > 0 \\ 2 & \text{if } AC_{TDMA} = 0 \text{ and } AC_{WCDMA} > 0 \\ 0 & \text{if } AC_{TDMA} = AC_{WCDMA} = 0 \end{cases}$$

Scheme ii: Calls are sent to WCDMA (if possible)

$$a_s^x = \begin{cases} 2 & \text{if } AC_{WCDMA} > 0 \\ 1 & \text{if } AC_{WCDMA} = 0 \text{ and } AC_{TDMA} > 0 \\ 0 & \text{if } AC_{TDMA} = AC_{WCDMA} = 0 \end{cases}$$

Scheme iii: Calls are sent to the technology with lower occupation

$$a_s^x = \begin{cases} 1 & \text{if } AC_{TDMA} > AC_{WCDMA} \\ 2 & \text{if } AC_{WCDMA} > AC_{TDMA} \\ \text{random} & \text{if } AC_{WCDMA} = AC_{TDMA} > 0 \\ 0 & \text{if } AC_{WCDMA} = AC_{TDMA} = 0 \end{cases}$$

Using these schemes we define three policies:

Policy	Scheme for voice	Scheme for data
1	i	ii
2	ii	i
3	iii	iii

It should be noted that Policies #1 and #2 exploit the hypothesis that each technology is more appropriate for a specific service, which is not the case of Policy #3 that focuses on improving radio resource utilization.

3.1. Cost function

Considering that the state space of the MDP is defined by (1) and (2), and the possible set of actions and the transition rates associated to them are defined in Table 1 and Figures 1 and 2, it is necessary to define the optimization functions and the cost/reward associated to them.

Since our interest relies on data and voice blocking probabilities, as well as the total throughput, we have defined two different objective functions. The first one, is the weighted sum of the voice and data blocking probabilites (BP_v and BP_d),

$$F_{BP} = BP_v \cdot \alpha + BP_d \cdot (1 - \alpha). \qquad (4)$$

The parameter α, $0 \le \alpha \le 1$, is the one responsible for giving more or less weight to each blocking probability. When α is closer to 0, minimizing the objective function will have a bigger impact on data blocking probability than on voice blocking probability, and the opposite will happen when α is closer to 1. Thus, α relates the way in which the blocking probabilities will be minimized. The cost function associated to the objective function for each feasible state s is

$$\text{cost}(s) = 1 - (\alpha \cdot F_v(a_s) + (1 - \alpha) \cdot F_d(a_s)), \quad (5)$$

where $F_x(a_s)=1$ if a_s is 1 or 2, and 0 otherwise, being x the service.

The second objective function is the aggregated throughput, so in that case we try to maximize the value defined by (3). The reward for each state s is

$$\begin{aligned} \text{cost}(s) = & \, s_1 BR_{t,v} + s_3 BR_{w,v} \\ & + \min(C - s_1, s_2) BR_{t,d} + s_4 BR_{w,d}. \end{aligned} \qquad (6)$$

Therefore, the reward associated to each state when maximizing the throughput does not depend on the actions taken on that state. It must be noted that we use the term *cost* for notational purposes, even when a reward is expected from throughput.

3.2. Solution method

The method used to find the optimal policy π_{opt} is policy iteration [12]. This method can search among the finite group of possible policies for the MDP and find the optimal in a finite number of steps. The relative values V allow to relate the cost obtained in the actual state with costs expected from future actions, and are found using the next equation:

$$\mathbf{c}^\pi - c_\pi \cdot e + V_\pi R_\pi^T = 0. \qquad (7)$$

Table 2: Policy iteration algorithm.	
Step 1.	Choose an arbitrary policy π_i
Step 2.	Calculate relative values V_{π_i} and the mean cost (revenue) c_{π_i} for the initial policy π_i using expression 7
Step 3.	Find action a for each state s that minimize (maximize) the expression in 8. The resulting policy is called π_f.
Step 4.	If the resulting policy π_f differs from the initial policy π_i, go back to step 2, using π_f as the initial policy. If not, π_f is the optimal policy.

Table 3: Initial Scenario for Policy Iteration.

WCDMA	TDMA
W=3.84 Mcps	$C = 4$
$(E_b/N_0)_v$=14 dB	n_c= 2
$(E_b/N_0)_d$=14 dB	$BR_{t,v}$=12.2 kbps
$BR_{w,v}$=12.2 kbps	$BR_{t,d}$=44.8 kbps
$BR_{w,d}$=44.8 kbps	
η_{ul}= 1	

Clients
λ_v= 0.025
λ_d= 0.134
μ_v= 0.0083
σ= 1 Mb

The $\mathbf{c}^\pi$ in the previous expression is the vector of costs associated to being in each state, R_π is the transition matrix, and c_π is the value of the objective function for policy π.

Once V and c_π are found using (7), it is possible to find the action on each state that will minimize the objective function using the next expression:

$$\min_a \{c_s^a - c_\pi + \sum_{s \neq u} r_{s,u}^a (v_\pi^u - v_\pi^s)\}, \qquad (8)$$

where v_π^u and v_π^s are the relative values for states u and s respectively when the policy π is used, c_s^a is the cost associated to state s when action a is taken, $r_{s,u}^a$ is the transition rate from state s to state u, when the action for state s is a. The set of actions will define a new policy and the process is repeated until the optimal policy is found. In Table 2 the policy iteration algorithm is shown. It is important to recall that the optimal policy will be found no matter what initial policy is used. However, the number of iterations could change.

4. Optimal Policy Analysis: Static Scenario

The parameters of the system are defined in Table 3. As it can be seen, bit rates are independent of the technology used, and are higher for data than for voice. Also, the (E_b/N_0) required for both services in WCDMA are the same, and along with the parameters C and n_c from TDMA, their values are chosen in order to mantain a similar capacity on both technologies while at the same time keeping the optimization problem computationally tractable. The maximum voice and data capacities are of 4 and 8 users in TDMA and of 13 and 4 users in WCDMA. The objective of this section is to explore the optimal policy when the two optimization functions are used: blocking probability and throughput.

4.1. Blocking function optimization

Unless otherwise stated, throughout the document we use a value of $\alpha = 0.5$. That is, the objective function will be defined by $F_{BP}(\pi)$=0.5 · BP_v+ 0.5 · BP_d. Fig. 3 shows the value of the objective function for every iteration until the optimal policy is achieved and results are compared with those obtained with the fixed policies described in Section 3. We can summarize the main characteristics of the optimal policy as follows:

Service	Action
Voice	scheme ii
Data	• if there is no channel sharing on TDMA: scheme i • if there is channel sharing on TDMA: $\cong$ scheme iii

The initial policy, Policy #2, has the closest performance to the optimal policy because they both send voice calls to WCDMA (scheme ii). The decisions for data calls depend on channel sharing since this reduces the transmission rate, which raises the residence time and thus the blocking probability. Therefore, channel sharing produces a policy very similar to scheme iii where resources are used according to occupation.

Only 22.3% of a_s^d from Policy #2 differ from the optimal, and there is only a 6.1% probability for these actions to occur. However, results differ considerably. The cost for the optimal policy is 34.78% of the one obtained with Policy #2, and of course similar results are found
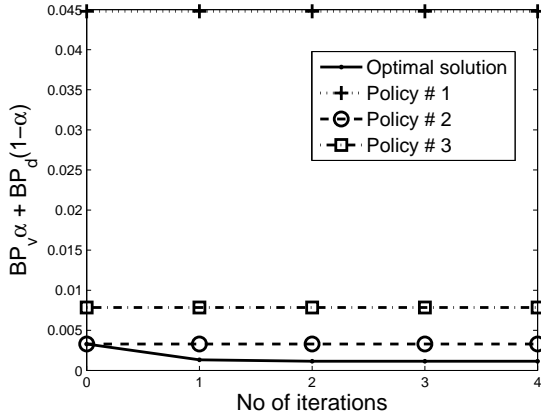
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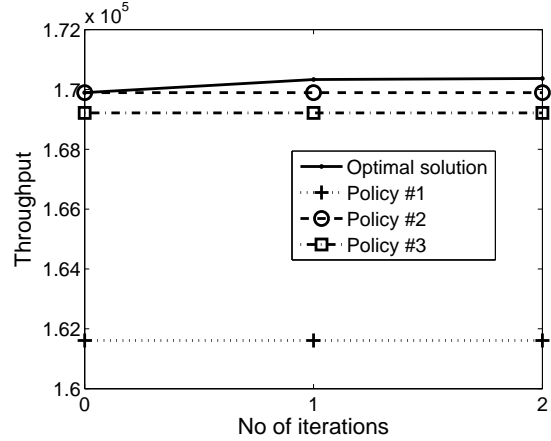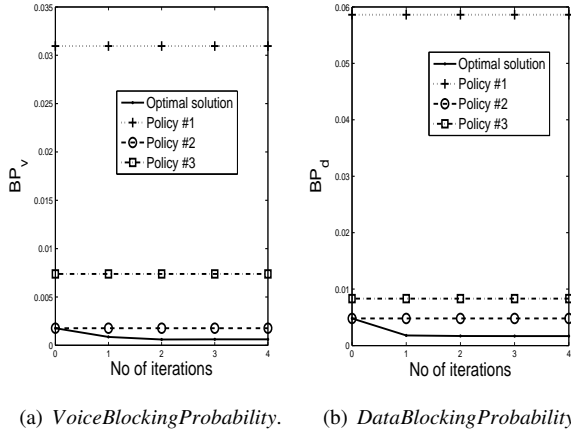Figure 3: Blocking probability function optimization.

Figure 5: Throughput optimization.

(a) *Voice Blocking Probability*.

(b) *Data Blocking Probability*.

Figure 4: Blocking Probabilities.

on BP_v and BP_d, as it is shown in Figs. 4(a) and 4(b). This improvement also added 462 *bps* to the throughput obtained with Policy #2.

4.2. Throughput optimization

The characteristics of the optimal policy for throughput optimization, can be summarized as:

Service	Action
Voice	scheme *ii* with blocking
Data	• if there is no channel sharing on TDMA: scheme *i* • if there is channel sharing on TDMA: $\cong$ scheme *iii*

Although voice calls are sent to WCDMA (scheme *ii*), there may be blocking when there is available capacity on TDMA. This happens in order to save capacity for data calls, which contribute more to the total throughput. In the optimal policy, nearly 25 % of the states where no more capacity is available on WCDMA, even if there is capacity in TDMA, voice calls are blocked. Also, since channel sharing on TDMA directly reduces the total throughput, a policy similar to scheme *iii* is used for data calls.

Figure 5 shows the throughput until the optimal policy is reached. After two iterations, the throughput raises to 170.366 *kbps*, a gain of 474 *bps* over Policy #2. The policy obtained with the first iteration is very similar to the optimal, since the second iteration only improves the total throughput in 35.8 *bps*, about 8% of the 438.9 *bps* gained before. Therefore, it is possible to use this sub-optimal solution in order to solve larger systems, in a similar approach as it was used in [13]. An interesting fact of throughput optimization, is that it also improves BP_v and BP_d. Since these parameters have very low values in the initial policy the improvement is small, going from 0.17 % to 0.079 % for BP_v and from 0.48 % to 0.15 % for BP_d, but it shows their correlation with the total throughput. Actually, the BP_d is lower than the one obtained optimizing the blocking function (0.167 %), indicating the importance of accepting data calls for the improvement of the total throughput.

5. Optimal Policy Analysis: Parameter Variation

In this section we study the impact of traffic values over the optimal policy and based on the analysis of dynamic behaviour we define a heuristic policy.

5.1. Voice users arrival rate variation

Although they are not identical, the main characteristics of optimal policies for both optimization functions as λ_v grows can be summarized as:

Service	Lower λ_v	Higher λ_v
Voice	scheme *ii*	scheme *ii* with blocking
Data	If there is no channel sharing on TDMA: scheme *i*	If there is no channel sharing on TDMA: scheme *i*
	if there is channel sharing on TDMA: $\cong$ scheme *iii*	if there is channel sharing on TDMA: $\cong$ scheme *iii*, preferably TDMA

Figure 6 shows the results obtained with the optimal policy for the blocking optimization function, and the values obtained with the fixed policies. When λ_v reaches 0.047, the offered load for voice is 5.64 *Erl*, almost two times the offered load for data (3 *Erl*). Given the great impact on data calls, the optimal policy blocks voice calls, and this is more intense for higher values of λ_v. For λ_v=0.047 only 3 of 80 states where voice calls were sent to TDMA according to scheme *ii*, decide to block in the optimal policy. At this point, BP_v=0.2 % and BP_d=1 %. When λ_v grows to 0.065, 26 of those 80 states block voice calls, that is eight times more states than before. As expected, BP_d only grows to 2.5 %, but the impact on BP_v is bigger, since it grows almost ten times, to 2.056 %.

Dependance on channel sharing for a_s^d is mantained for all λ_v, but once sharing is mandatory, some changes occur. As λ_v grows, the number of states that decide to send data calls to TDMA under this circumstances, grows from 180 of 400 when λ_v=0.005 to 225 of 400 when λ_v=0.065. This is done in order to reduce BP_v, since WCDMA capacity is saved for voice calls. It is also worth noting that when TDMA is almost at full capacity (>95%), data calls are blocked. This effect can be seen for the full range of λ_v values that appear on Fig. 6.

Figure 7 shows the throughput when it is used as the optimization function for the optimal policy and the three fixed policies as λ_v grows. As λ_v grows, it becomes mandatory to save resources for data calls since they have a higher throughput. For this reason, voice calls may be blocked even when there is room on TDMA. For λ_v=0.005, 14 of 80 states where occupancy
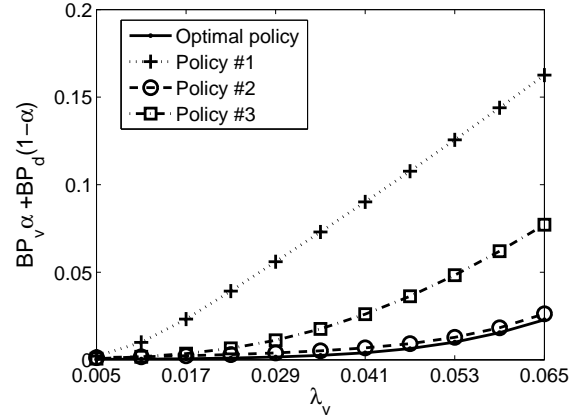

Figure 6: Blocking function for various λ_v.

on WCDMA is full but there is still room on TDMA, block voice calls. When λ_v grows to 0.065, 36 of the same 80 states block voice calls. This affects BP_v, and when λ_v>0.041, the optimal policy has a higher BP_v than Policy #2.

Dependance on channel sharing for a_s^d is mantained for all λ_v, but when sharing is mandatory, optimal policies vary. As λ_v grows, the occupation of WCDMA does too, so more data calls must be sent to TDMA in order to increase the total throughput. When λ_v=0.005, 144 of the 400 states that use TDMA channel sharing send data calls to TDMA. For λ_v=0.065, 212 of the same 400 states send calls to TDMA.

Therefore, for both optimization criteria, voice calls are sent to WCDMA, with more blocking states as λ_v grows, and data calls are sent to TDMA while no sharing is needed. When sharing is mandatory, data calls may be sent to WCDMA or TDMA with more states using TDMA as λ_v grows.

5.2. Data users arrival rate variation.

Although not identical, the main characteristics of the optimal policies for both optimization function as λ_d grows can be summarized as:
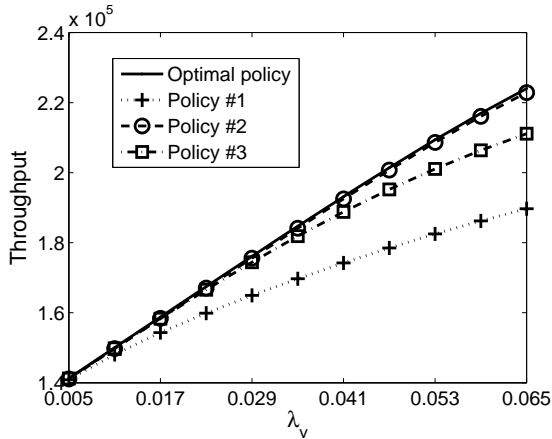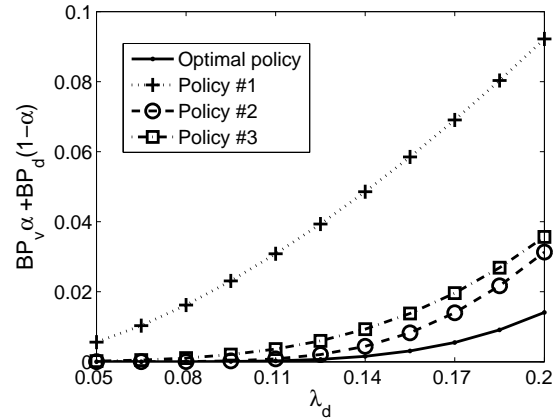
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Figure 7: Throughput for various λ_v.

Figure 8: Blocking function for various λ_d.

Service	Lower λ_d	Higher λ_d
Voice	scheme *ii*	scheme *ii*
Data	If there is no channel sharing on TDMA: scheme *i*	If there is no channel sharing on TDMA: scheme *i*
	if there is channel sharing on TDMA: $\cong$ scheme *iii*	if there is channel sharing on TDMA: $\cong$ scheme *iii*, preferably WCDMA

Figure 8 compares the blocking function values for the optimal policy with different values of λ_d with those obtained with the three fixed policies. In this scenario, voice calls follow scheme *ii* for every λ_d, showing that the load of data calls has no impact on a_s^v. On the other hand, the big influence of TDMA occupancy over a_s^d, suggest the opposite. In fact, when λ_d=0.2, data calls arrive with a higher rate than voice calls, so in order to mantain a low objective function value, it is necessary to send more data calls to WCDMA so TDMA's capacity is not exhausted too fast. This is the opposite case of the one we saw in the last section where as λ_v grew, more data calls were sent to TDMA. The second effect is that as λ_d grows, it is necessary to block calls in order to minimize the optimizing function. For the values of Fig. 8, the system has 1000 states. Only 70 of the total do not allow data calls, thus these are data blocking states. For the optimal policy, while $\lambda_d \leq 0.095$, data calls are only blocked on those 70 states. Once this value is surpased, the optimal policy may block data calls even when there is capacity left. When λ_d=0.11, 4 of the 930 states with capacity left decide to block data

calls, and this number grows to 30 of those 930 states when λ_d=0.2, more than seven times the initial number of blocking states.

Figure 9 shows the throughput when it is used as the optimization function for various λ_d. Since data calls have a higher throughput, the optimal policy may penalize some voice calls to maximize the objective function. When λ_d=0.2, BP_v is higher in the optimal policy than in Policy #2, reaching 2%. In fact, if we let λ_d=0.275, BP_v for the optimal policy would be higher than any of the fixed policies. In order to maximize the throughput, the opposite happens for BP_d, which is always the lowest in the optimal policy. As usual, voice calls are treated according to scheme *ii*, but as λ_d grows higher than 0.05, instead of sending calls to TDMA when WCDMA is full, they may be blocked. The number of states doing this grows slowly, but when λ_d=0.3 no voice calls are ever sent to TDMA, saving the space for data calls.

TDMA occupancy influence on a_s^d is increased by λ_d. When sharing becomes mandatory, as λ_d grows there seems to be a preference for sending calls to WCDMA using the capacity saved by voice calls. As a consequence of the importance of data calls for throughput, for the values of λ_d in Fig.9, the optimal policy never blocks data calls unless there is no other chance. That is, as λ_d grows voice calls are always sent to WCDMA, but some blocking may appear when we optimize the throughput. On the other hand λ_d does not affect decisions for voice calls when the blocking function is optimized. Data calls are sent to TDMA while no sharing is needed, but when sharing is mandatory, calls may be sent to TDMA or WCDMA, but as λ_d grows, a clear tendency towards WCDMA is seen for both optimiza-
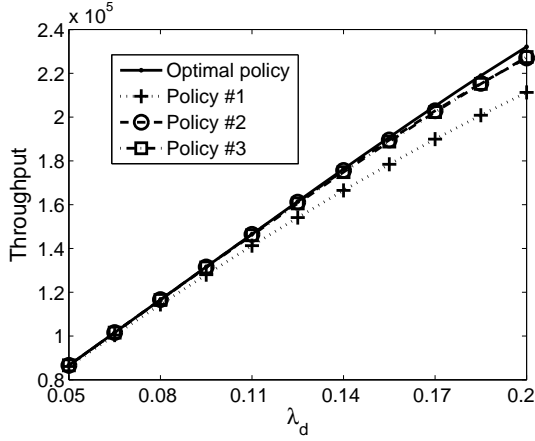
Figure 9: Throughput for various λ_d.

(a) *Blocking Optimization.*   (b) *Throughput Optimization.*
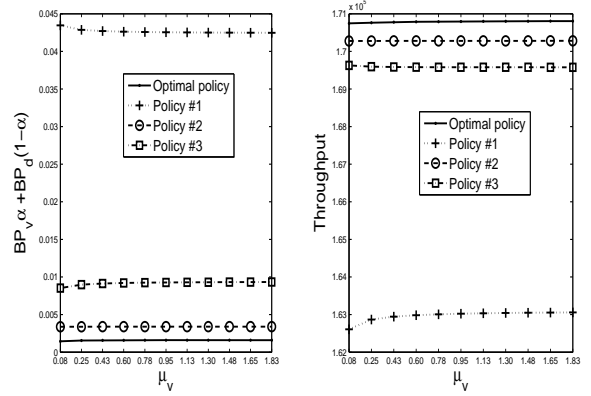
Figure 10: Optimization for various μ_v.

tion criteria.

5.3. Voice users service rate variation

Figure 10(a) shows the blocking function value while mantaining a constant offered traffic of 3 *Erl* for both services (as the static scenario), and changing μ_v from 0.0833 to 1.833. It is easy to realize how changes on μ_v have little or no impact in the blocking function for different policies. This behaviour is a result of what happens with the blocking probabilities and the throughput, where the results are almost constant for the full range of μ_v. The optimal policies can be summarized as:

Service	Lower μ_v	Higher μ_v
Voice	scheme *ii*	scheme *ii* with blocking
Data	If there is no channel sharing on TDMA: scheme *i*	If there is no channel sharing on TDMA: scheme *i*
	if there is channel sharing on TDMA: $\cong$ scheme *iii*	if there is channel sharing on TDMA: $\cong$ scheme *iii.*

As μ_v grows, some voice calls are blocked. However, it only differs on 0.2% of the states when μ_v changes from 0.258 to 1.833. Also, μ_v has little influence over a_s^d. As μ_v grows, a small percentage of states (<5%) where calls used to be sent to WCDMA are sent to TDMA. In Fig.10(b) it is shown the throughput as the optimizing function for a constant load of 3 *Erl* in both

services, while μ_v changes. When throughput is optimized, BP_v can be higher in the optimal policy than in other policies. The main characteristics of the optimal policies can be summarized in the same way as in the blocking function optimization shown before in this section.

5.4. Data service rate variation

Fig.11(a) shows the blocking function value for a constant load of 3 *Erl* on both services while μ_d changes. To change this parameter, we kept $BR_{x,d}$ in 44.8 kbps, and changed the mean data length σ. The main characteristics of the optimal policies can be summarized as:

Service	Lower μ_d	Higher μ_d
Voice	scheme *ii*	scheme *ii* with blocking
Data	If there is no channel sharing on TDMA: scheme *i*	If there is no channel sharing on TDMA: scheme *i*
	if there is channel sharing on TDMA: $\cong$ scheme *iii*	if there is channel sharing on TDMA: $\cong$ scheme *iii.*

In Fig.11(b) appears the throughput (used as the optimization function) for the optimal and the fixed policies when μ_d changes and the load for each service is kept constant (3 *Erl*). The optimal policies are very similar to those obtained with the blocking function. For the

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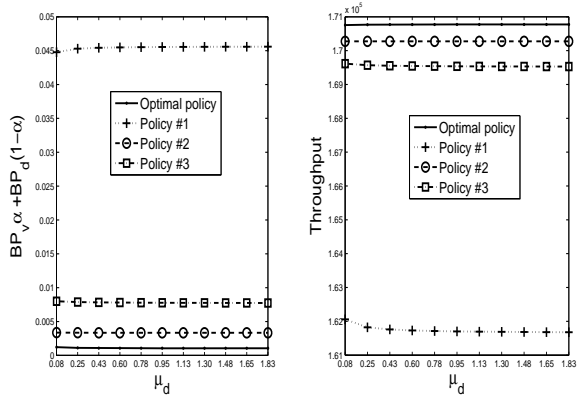
(a) *Blocking Optimization.* (b) *Throughput Optimization.*

Figure 11: Optimization for various μ_d.

Figure 12: Blocking function for various λ_v.

lowest values of μ_d in Fig.11(b) most of the states where the capacity of WCDMA is full, decide to block calls even when there is space left on TDMA. As μ_d grows, these states decide to send voice calls to TDMA. This blocking is done in order to protect data calls, whose contribution to throughput is higher.

5.5. Heuristic policy

According to the analysis realized in previous sections, it is possible to define a heuristic policy based on those characteristics that were common for all the scenarios.

Therefore, the heuristic policy is summarized as:

Service	action
Voice	scheme *ii*
Data	• if no channel sharing on TDMA: scheme *i* • if channel sharing on TDMA: scheme *iii*

The heuristic policy sends voice calls to WCDMA which is a very simple solution that is consistent with optimal solutions of Section 5.2 and for the lower values of λ_v in Section 5.1. On the other hand, the optimal solution for data calls is more complex and composed by two stages as previous analysis showed. On the first stage, data calls are sent to TDMA (scheme 1) until the arrival of a new call would force channel sharing. On the second stage decisions depend on voice and data loads, as can be seen from Sections 5.1 and 5.2. When
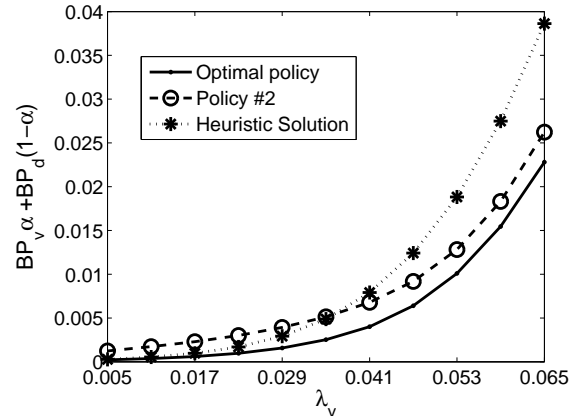
λ_v grows, data calls are sent to TDMA, making the optimal policy for data calls as scheme 1. On the other hand, when λ_d is the one that grows, more data calls are sent to WCDMA. Therefore the heuristic policy uses scheme 1 for the first stage, and scheme 3 for the second stage, that is, compares the occupancy on each technology and sends calls to the one with the lowest value.

Figure 12 compares the blocking function of the heuristic policy and Policy #2 for the same values of Fig.5. It is evident that for the lowest values of λ_v, the heuristic policy is better than Policy #2, but this changes when $\lambda_v > 0.035$. This occurs because Policy #2 always sends calls to TDMA, and this behaviour is similar to what is done by the optimal solution as λ_v grows (Section 5.1). The same could be said for Fig.13, where the throughput is the optimization function. In this case the improvement of the heuristic solution over Policy #2 is very small, but it is mantained while $\lambda_v < 0.041$. When this value is reached, Policy #2 is better than the heuristic solution because of its similarity to the optimal solution.

Figure 14 compares the heuristic solution with Policy #2 and the optimal solution, when the blocking function is optimized and λ_d changes. In this case, for the lowest values of λ_d Policy #2 is better than the heuristic, but once $\lambda_d>0.08$, the heuristic is better. This can be explained by the fact that the optimal solution sends more data calls to WCDMA as λ_d grows, and while Policy #2 always sends data calls to TDMA, the heuristic policy may send some calls to WCDMA according to occupation on each technology.This behaviour has the same effect over the throughput as can be seen on Fig.15, where it is compared the throughput for the heuristic solution and Policy #2. For the lowest values
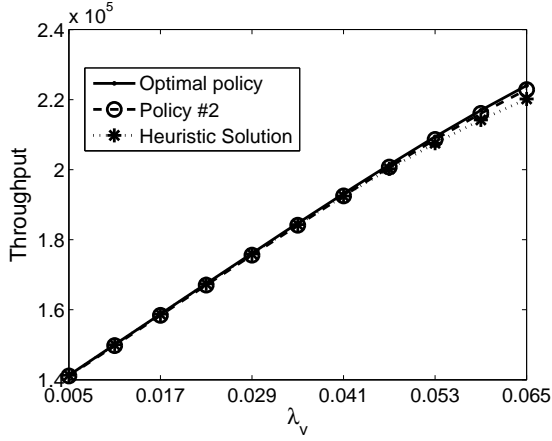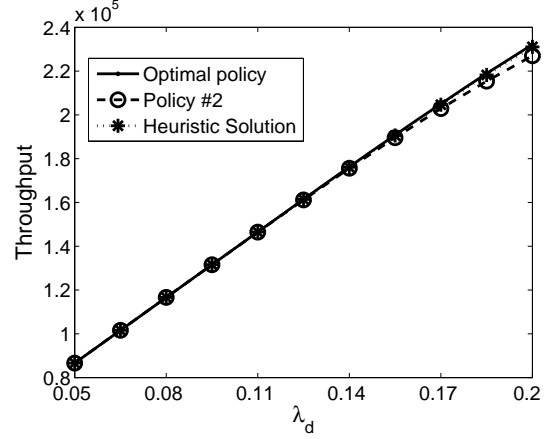
10

Figure 13: Throughput for various λ_v.

Figure 14: Blocking function for various λ_d.

Figure 15: Throughput for various λ_d.

of λ_d, Policy #2 is better than the heuristic, but when $\lambda_d > 0.65$ the heuristic solution has a higher throughput. Therefore the heuristic policy represents some advantages over the best fixed policy when data load is high, but its behaviour is not as good as that of Policy #2 when voice load is high.

6. Throughput optimization with QoS constraints

In this section we compare the policies in terms of the maximum arrival they can support subject to QoS constraints. Until now, we considered throughput optimization independent of other factors, but to provide QoS, it is necessary to limit both PB_v and PB_d. To do this, we defined the parameter β, which is the fraction of λ_v over the total arrival rate λ_T, that is, $\lambda_v = \lambda_T \cdot \beta$ and $\lambda_d = \lambda_T \cdot (1 - \beta)$. In Fig.16 it is shown the throughput as a function of β for three policies: The optimal policy
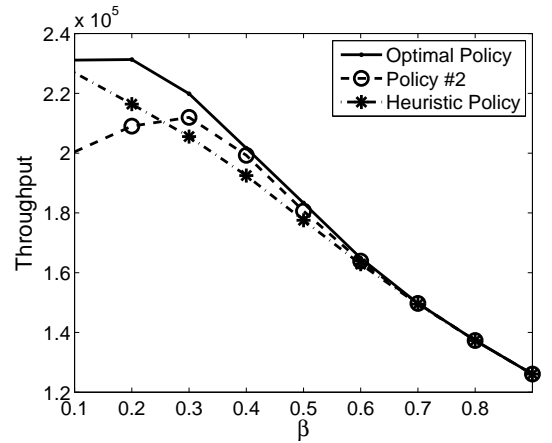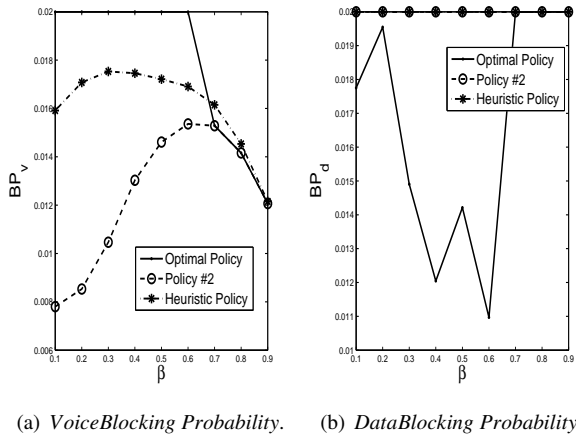

Figure 16: Throughput as a function of β.

(a) *VoiceBlocking Probability.* (b) *DataBlocking Probability.*

Figure 17: Blocking probabilities for various β.

Figure 18: Transitions for voice and data arrivals using VH.

when we optimize the throughput, Policy #2, and the heuristic policy defined in the last section. It has to be considered that even when they share the same value of β, the arrival rates differ for each policy according to the restrictions imposed by the blocking probabilites (max 2 %). For example, when β=0.2, the total arrival rate λ_T that the optimal policy can handle is 0.2158, while it is of 0.2018 for the heuristic policy and 0.1945 for Policy #2. Therefore, the optimal policy is able to receive a higher arrival rate for voice and data calls while mantaining PB_v and PB_d below 2 %. Figures 17(a) and 17(b) show the voice and data blocking probabilities for different values of β. It can be seen that the optimal policy is the only one able to change its active constraint between PB_v and PB_d, taking advantage of the contribution of data calls on the throughput. This cannot be done by the other two policies, which penalize PB_d=0.2 for every β. As for the heuristic policy, it shows a higher maximum throughput for low values of β than Policy #2, and this behaviour is reversed as β grows when voice calls are more important in order to maximize throughput, a behaviour consistent with the results of the previous section.

7. Optimization with vertical handoff

So far, we have analyzed a system where no vertical handoff is used (now referred to as NVH), i.e. a call is served in the same technology where it was accepted. However, vertical handoff is considered an important feature in common radio resource management that improves the use of resources. In Table 4 we introduce four types of vertical handoff based on the analysis done in
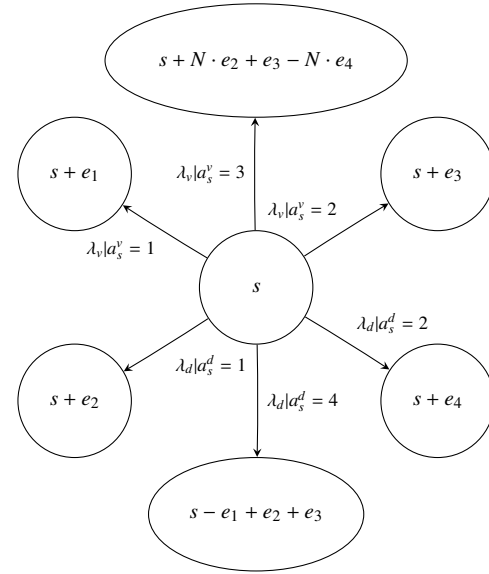
previous sections, where N is the necessary number of data calls such that one voice call can access WCDMA. All types of vertical handoff are based on the results obtained in Sections 4 and 5, but the first two types are triggered by the arrival of a call, while the other two occur when a call is served. This distinction is important, since it affects the construction of the new Markov decission processes. The addition of types I and II of vertical handoff to NVH defines VH-A. The Markov model for this system has the same state space S of NVH, since restrictions (1) and (2) are not affected by vertical handoff. The same applies for the Markov model of system VH-B, which uses all types of vertical handoff (I-IV). However, the set of actions A and the transitions associated to them do change. For VH-A, a decision is made each time a call arrives as can be seen in Table 5 and in Figure 18, where actions 0,1 and 2 do not include vertical handoff, while actions 3 and 4 correspond to vertical handoff types I and II respectively. For action 3, the value N is the number of data calls that need to be moved so that a new voice call can access WCDMA according to (2). The same applies for system VH-B, which includes vertical handoff types III and IV. The reason why handoff types III and IV do not affect the set A is that decisions are made only when a call arrives. In our model, handoffs triggered by service completion are done every time their specific conditions are fulfilled, so there are no decisions involved.

With this in mind, and using the same cost functions of

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Type	Triggering Event	Conditions	Number / Class of calls	From $\Rightarrow$ To	NVH	VH-A	VH-B
I	voice **arrival**	Full occupation on WCDMA	N **data** calls	WCDMA$\Rightarrow$TDMA	–	✓	✓
II	data **arrival**	Channel sharing on TDMA	One **voice** call	TDMA$\Rightarrow$WCDMA	–	✓	✓
III	voice or data **departure** from WCDMA	Channel sharing on TDMA	One **voice** call	TDMA$\Rightarrow$WCDMA	–	–	✓
IV	voice or data **departure** from TDMA	VH does not produce channel sharing on TDMA	One **data** call	WCDMA$\Rightarrow$TDMA	–	–	✓

Table 4: Vertical Handoff Types

(4) and (5), two new MDPs are constructed. These new MDPs will show the improvement when vertical handoff is included, where the MDP based on VH-A uses handoff when calls arrive and the MDP based on VH-B uses handoff for both arrivals and departures.

7.1. Optimal policy using vertical handoff

In the last section were introduced two new systems that included vertical handoff: VH-A and VH-B. The difference between them is that VH-B includes vertical handoff for users departures. In this section we use two new MDPs that are based on VH-A (MDP VH-A) and VH-B (MDP VH-B), and compare results with those obtained with the MDP for the NVH system (MDP NVH). It is our interest to study the impact that vertical handoff has over the optimal solutions and performance. Using the scenario specified in Table 3 for MDP VH-A and MDP VH-B, it is possible to extract the main characteristics of the optimal solutions as different parameters vary. Results for optimization of the blocking function defined in (4) while λ_v varies from 0.005 to 0.095 are summarized in Table 6. In general, the behaviour for voice and data calls are very similar in both MDPs. Nevertheless, some minor differences change the structure of the optimal solutions, and that has an important impact on the results obtained. Optimal solutions for MDP VH-A show a lower percentage of unused states than those solutions obtained using MDP VH-B. This is because Vertical Handoff types III and IV organize calls in such a way that a larger number of states from set S are left unused. When λ_v=0.005 the percentage of unused states is three times higher for the solution obtained with MDP VH-B

Table 5: set of actions A for MDPs with vertical handoff

value	action
0	Block call
1	Send call to TDMA
2	Send call to WCDMA
3	VH for N data calls from WCDMA to TDMA and the voice call is sent to WCDMA.
4	VH for 1 voice call from TDMA to WCDMA and the data call is sent to TDMA.

than for the one obtained with MDP VH-A, and while this difference shortens when λ_v= 0.095, the percentage of unused states grows. This growth shows that an organized use of resources is necessary in order to obtain the optimal solution in both MDPs. Also, it may occur some voice blocking when there are resources available, but this behaviour is expected only for the highest values of λ_v, when its influence is higher on the optimization function.

Similar results are obtained for optimization of the blocking function defined in (4) when λ_d varies from 0.05 to 0.225. Voice and data calls use Vertical Handoff types I and II respectively, but the percentage of unused states follows a different pattern. As λ_d grows, the percentage of unused states for the optimal solutions obtained with MDP VH-A remains constant, and it decreases for the solutions of MDP VH-B. This decrease

shows that Vertical Handoff types III and IV allow more flexibility on how resources are managed, because a higher data arrival rate demands that more data calls share channels in order to reduce the blocking probability, something that cannot be done as successfully by only using Vertical Handoff types I and II. Also, for the highest values of λ_d, some states decide to block data calls even when there is capacity left, in order to save space for voice calls. However, the percentage of states doing this is below 3% for both MDPs. A summary of these results is shown in Table 7.

Using the scenario specified in Table 3 and the throughput optimization function defined in (5) while λ_v varies from 0.005 to 0.095, the optimal policies for MDP VH-A and MDP VH-B are summarized in Table 8. Again, voice and data calls use vertical handoff types I and II respectively in both MDPs. For the lowest values of λ_v, both MDPs decide to block voice calls (<1%) in order to enhance throughput, since data calls contribute more to the total throughput. However, this situation changes as λ_v grows when voice calls are accepted as long as it is possible. On the other hand, the percentage of unused states differs for each MDP. For MDP VH-A, the percentage of unused states grows with λ_v from 16% to 41.7%. On the other hand, for MDP VH-B, the percentage of unused states diminishes from 61.2% to 49.5% as λ_v grows.

The optimal policies for MDP VH-A and MDP VH-B as λ_d varies from 0.05 to 0.225 are summarized in Table 9. Voice and data calls use vertical handoff types I and II respectively in both MDPs. For the highest values of λ_d MDPs decide to block some voice calls, even though in a very small percentage (<1%). This is done in order to accept more data calls since they contribute more to the total throughput. For both MDPs the percentage of unused states grows with λ_d, and it is always higher for MDP VH-B.

7.2. Result analysis for vertical handoff MDPs

Considering the optimal policies obtained in the previous section for MDP VH-A and MDP VH-B, we propose two new heuristic policies that make use of their main characteristics. Heuristic VH-A makes use of vertical handoff types I and II, as it was seen for the optimal policies found using MDP VH-A. On the other hand, Heuristic VH-B also includes vertical handoff types III and IV, as it was done by the optimal policies obtained

Table 11: New study Scenario.

WCDMA	TDMA
W=3.84 Mcps	$C = 8$
$(E_b/N_0)_v$=6.5 dB	n_c= 3
$(E_b/N_0)_d$=5 dB	$BR_{t,v}$=12.2 kbps
$BR_{w,v}$=12.2 kbps	$BR_{t,d}$=44.8 kbps
$BR_{w,d}$=44.8 kbps	
η_{ul}= 1	
Clients	
μ_v= 0.0083	
σ= 1 Mb	

using MDP VH-B. In this section we compare the results obtained by the two new heuristic policies with the optimal solutions of the MDPs and the three fixed policies that were explained earlier for the system described in Table 11. For this system, the maximum capacity for voice and data calls in WCDMA are 71 and 28 respectively, so the capacity has grown over 6 times over the system described in Table 3 . However, the computational cost does not grow linearly. Using a 2 Quad CPU @2.4GHz, 3.24 GB RAM, it took around 1 minute to find the optimal solution of a single load point for the smaller system, while it took around 6 hours in this system. Therefore, the calculation time of the optimal solutions makes them unfeasible for on-line use. It should be noted that this is not an issue for the heuristic schemes that can be used as a JCAC algorithm.

In Fig. 19 it is shown the blocking function for the three MDPs, the two heuristics and the three fixed policies when λ_v varies from 0.09996 to 0.4998 and λ_d=0.448. The blocking function value when λ_v=0.4998 is reduced to less of the half of the value of Policy #2 when the heuristic policies are used, and this improvement is more visible when comparing to the other fixed policies. Also, it should be noted that the heuristic policies may even improve over the optimal solution of MDP NVH as λ_v grows. The improvement of the blocking function has an effect in the aggregated throughput, which raises to 1.156 Mbps for Heuristic VH-A while it only reaches 1.116 Mbps for Policy #2 when λ_v=0.4998. Therefore under these conditions, using an heuristic policy represents an improvement of 40 kbps, close to one data channel, or 3 voice channels, with blocking probabilities of 2.2 % and 1.8 % for data and voice, while Policy #2 raises them to 6.5% and 4.6%, respectively.

		MDP VH-A	MDP VH-B
Voice calls	Lowest λ_v	• Sent to WCDMA or VH type I is used. • 10.4% of states are not used.	• Sent to WCDMA or VH type I is used. • 32.1% of states are not used.
	Highest λ_v	• Sent to WCDMA or VH type I is used. • 41.7% of states are not used. • Blocked in 1.00% of usable states.	• Sent to WCDMA or VH type I is used. • 50.4% of states are not used. • Blocked in 1.2% of usable states.
Data calls	Lowest λ_v	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 10.4% of states are not used.	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 32.1% of states are not used.
	Highest λ_v	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 41.7% of states are not used.	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 50.4% of states are not used.

Table 6: Main characteristics of the optimal solutions for the blocking function for various λ_v.

		MDP VH-A	MDP VH-B
Voice calls	Lowest λ_d	• Sent to WCDMA or VH type I is used. • 41.6% of states are not used.	• Sent to WCDMA or VH type I is used. • 49.4% of states are not used.
	Highest λ_d	• Sent to WCDMA or VH type I is used. • 41.6% of states are not used.	• Sent to WCDMA or VH type I is used. • 39.6% of states are not used.
Data calls	Lowest λ_d	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 41.6% of states are not used.	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 49.4% of states are not used.
	Highest λ_d	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 41.6% of states are not used. • Blocked in 2.56% of usable states.	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 39.6% of states are not used. • Blocked in 2.98% of usable states.

Table 7: Main characteristics of the optimal solutions for the blocking function for various λ_d.

In Fig. 20 is shown the blocking function for the MDPs, the heuristics and the fixed policies when λ_d varies from 0.3584 to 1.792 and λ_v is 0.0833. The blocking function values are lower for the heuristic functions when compared to the fixed policies, but they are higher than those obtained by MDP NVH

		MDP VH-A	MDP VH-B
Voice calls	Lowest λ_v	• Sent to WCDMA or VH type I is used. • 16% of states are not used. • Blocked in 0.71% of usable states.	• Sent to WCDMA or VH type I is used. • 61.2% of states are not used. • Blocked in 0.25% of usable states.
	Highest λ_v	• Sent to WCDMA or VH type I is used. • 41.7% of states are not used.	• Sent to WCDMA or VH type I is used. • 49.5% of states are not used.
Data calls	Lowest λ_v	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 16% of states are not used.	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 61.2% of states are not used.
	Highest λ_v	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 41.7% of states are not used.	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 49.5% of states are not used.

Table 8: Main characteristics of the optimal solutions for throughput for various λ_v.

		MDP VH-A	MDP VH-B
Voice calls	Lowest λ_d	• Sent to WCDMA or VH type I is used. • 41.6% of states are not used.	• Sent to WCDMA or VH type I is used. • 45.4% of states are not used.
	Highest λ_d	• Sent to WCDMA or VH type I is used. • 43% of states are not used. • Blocked in 0.7% of usable states.	• Sent to WCDMA or VH type I is used. • 47.2% of states are not used. • Blocked in 0.56% of usable states.
Data calls	Lowest λ_d	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 41.6% of states are not used.	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 45.4% of states are not used.
	Highest λ_d	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 43% of states are not used.	• Sent to TDMA while no sharing is needed. If so, VH type II is used or sent to WCDMA. • 47.2% of states are not used.

Table 9: Main characteristics of the optimal solutions for throughput for various λ_d.

when $\lambda_d > 1.0752$. However, when $\lambda_d = 1.792$, the total throughput for heuristic VH-A is of 1.4896 Mbps and of 1.466 Mbps for MDP NVH. That is, the heuristic solutions cannot diminish the value of the blocking function for the higher values of λ_d as much as MDP NVH does, but they still raise the throughput, even though this is not

Heuristic	Event	Action
Heuristic VH-A	Voice arrival	• Send to WCDMA. • If it is not possible, use VH type I. • If it is not possible, send to TDMA.
	Data arrival	• Send to TDMA if no channel sharing is needed. • If there is channel sharing, use VH type II. • If it is not possible, send to WCDMA. • If it is not possible, send to TDMA.
Heuristic VH-B	Voice arrival	• Send to WCDMA. • If it is not possible, use VH type I. • If it is not possible, send to TDMA.
	Data arrival	• Send to TDMA if no channel sharing is needed. • If there is channel sharing, use VH type II. • If it is not possible, send to WCDMA. • If it is not possible, send to TDMA.
	Voice departure	• Use VH type III if departs from WCDMA • Use VH type IV if departs from TDMA
	Data departure	• Use VH type III if departs from WCDMA • Use VH type IV if departs from TDMA

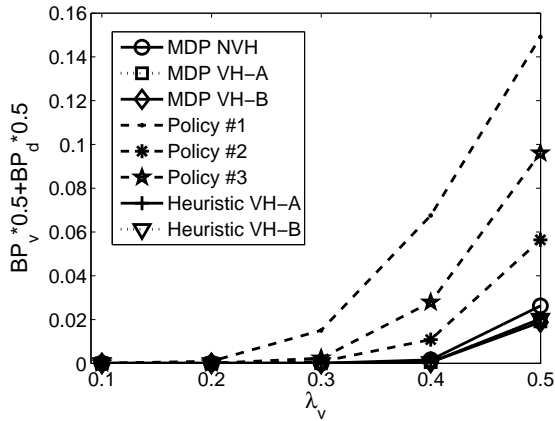Table 10: Definition for Heuristic policies with vertical handoff.
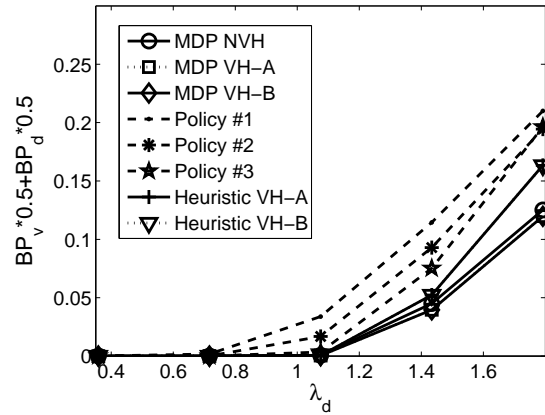

Figure 19: Blocking function for various λ_v.

Figure 20: Blocking function for various λ_d.

the objective function. As in the case when λ_v varies, the differences for both heuristics are not very significant.

The optimal throughput for the MDPs, as well as the throughput obtained by the heuristic solutions and the fixed policies as λ_v grows from 0.09996 to 0.4998 keeping λ_d=0.448 is shown in Fig. 21. There is an improvement of throughput of the heuristic solutions not only over the fixed policies, but also over the optimal solutions of MDP NVH. Although the improve-
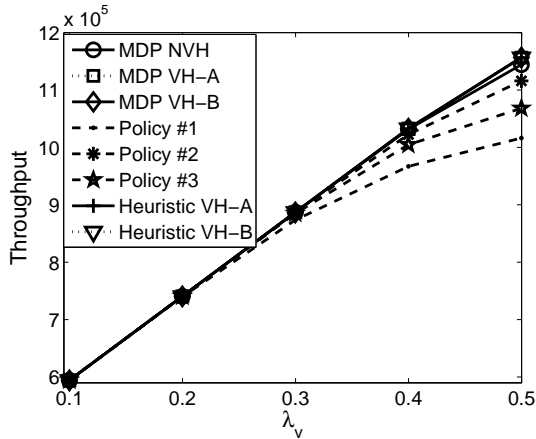
Figure 21: Throughput for various λ_v.
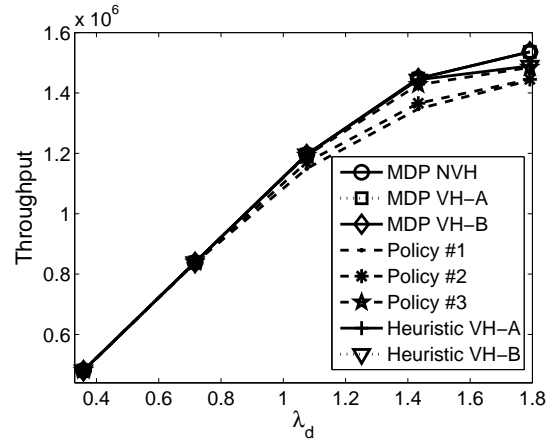

Figure 22: Throughput for various λ_d.

ment in throughput is small when λ_v=0.4998, 12 kbps over MDP NVH and more when compared to the fixed policies, it is significant when we consider that the voice and data blocking probabilities of Heuristic VH-A are of 2.2% and 1.8% respectively, while these probabilities are of 1.5% and 3.8% for MDP NVH, and raise to a range of 6.5–19.5% and 4.6–10.5% for the fixed policies. That is, the heuristic solutions are able to improve throughput while mantaining low blocking probabilites (around 2%), and the other policies are not.

In Fig. 22 is shown the throughput for the MDPs, the heuristics and the fixed policies when λ_d varies from 0.3584 to 1.792 and λ_v is 0.0833. It is shown that there is not to much room for improvement of the throughput when λ_d varies, since most solutions obtain similar values. The only real difference is seen when λ_d=1.792, when the MDPs raise around 6 kbps over the other solutions, but since this is done blocking all the voice calls, this solutions cannot be considered useful. It is interesting to see that that the heuristics still achieve a higher throughput than all the fixed policies, while keeping lower voice and data blocking probabilities. However, when λ_d=1.4336, the voice and data blocking probabilities of the heuristic solutions are of 5% and 2.9% for data and voice, thus the load limit lies around these values. A closer look at the performance of the heuristic solutions shows that any degradation when compared to the optimal solutions behaviour is negligible, and this performance is consistent for both optimization criteria and several system's parameters.

7.3. Model Validation

In order to validate the solutions found by the Markov model, we have evaluated the system by discrete event
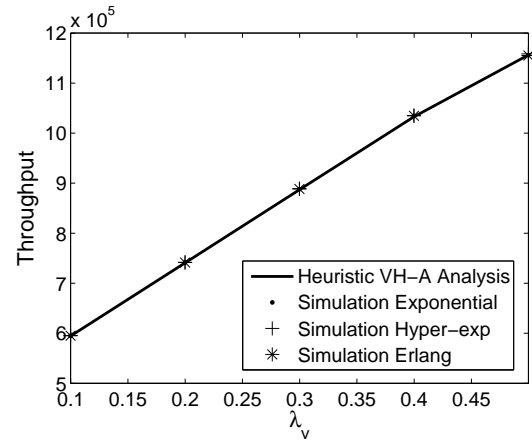

Figure 23: Simulation vs Analysis results of throughput as λ_v varies.

simulation using three different distributions for the service time of voice calls T_v and data size (σ), namely, exponential, hyper-exponential and erlang, with variation coefficients of 1, 2 and 0.5 respectively. Our purpose here is not only to establish the correctness of our mathematical analysis, but also to asses the impact of the assumption of exponentially distributed data size and voice service time. The results of the simulations for different distributions of data size using heuristic VH-A appear on Fig. 23 and Fig. 24. As it is shown, there is an excellent agreement between the analytical model and the simulations. The same applies for the simulations of Heuristic VH-B shown in Fig. 25 and Fig. 26. It is worth noting that all results proved that, under the proposed heuristic policies, the system is insensitive with respect to the distribution of both voice service time and data size beyond their means.
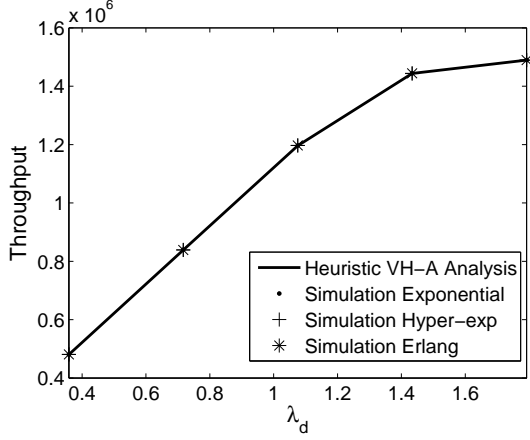
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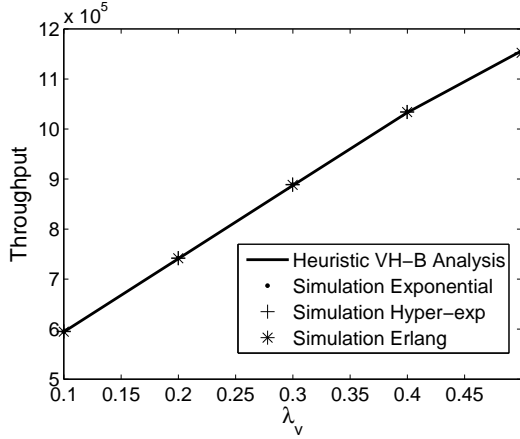Figure 24: Simulation vs Analysis results of throughput as λ_d varies.

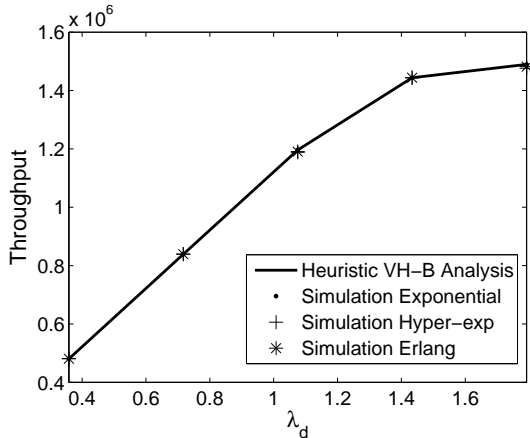Figure 25: Simulation vs Analysis results of throughput as λ_v varies.

Figure 26: Simulation vs Analysis results of throughput as λ_d varies.

8. Cost of the Vertical Handoff

So far, we have introduced four types of vertical handoff derived from the knowledge we have obtained from the system. These types were used to find new optimal solutions and then two new heuristics were constructed, improving performance over the optimal solutions from the MDP without vertical handoff. The main issue in this section is to explore the impact of adding a cost to vertical handoff.

In order to do this, it is defined a new objective function based on the blocking rates and the vertical handoff rate. The new objective function is defined by

$$F_{VH} = \theta \cdot \zeta_{VB} + (1 - \theta) \cdot \zeta_{DB} + C_{VH} \cdot \zeta_{VH}, \quad (9)$$

where θ, $0 \leq \theta \leq 1$, is the factor that defines the cost for blocking a single voice or data call, and ζ_{VB} and ζ_{DB} are the mean voice and data blocking rates. In the same way, C_{VH} is the cost of performing a single vertical handoff, and ζ_{VH} is the mean rate of vertical handoffs performed. Hence, by assigning values to θ and C_{VH}, a new optimal policy that minimizes F_{VH} can be found using a markov decision process.

8.1. Markov decision process for VH cost

In this section we define three new MDPs based on (9). The first one does not use vertical handoff (MDP BR), the second one uses vertical handoff types I and II (MDP C-1), and the last one uses all four types of vertical handoff (MDP C-2). These MDPs are different from those exposed in Section 7.1 because of their objective functions. The state space for all of them S is defined by (1) and (2) and the set of actions a is that of Table 1 for MDP BR and that of Table 5 for MDP C-1 and MDP C-2. The cost function associated to the objective function for each feasible state s for MDP BR is

$$\text{cost}(s) = \lambda_v \cdot G(a_s^v) \cdot \theta + \lambda_d \cdot G(a_s^d) \cdot (1 - \theta), \quad (10)$$

for MDP C1 is

$$\begin{aligned} \text{cost}(s) = {} & \lambda_v \cdot G(a_s^v) \cdot \theta + \lambda_d \cdot G(a_s^d) \cdot (1 - \theta) \\ & + C_{VH} \cdot (\lambda_v \cdot R(a_s^v) + \lambda_d \cdot R(a_s^d)), \quad (11) \end{aligned}$$

and for MDP C2 is

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$$\text{cost}(\boldsymbol{s}) = \lambda_v \cdot G(a_s^v) \cdot \theta + \lambda_d \cdot G(a_s^d) \cdot (1 - \theta)$$
$$+ C_{VH} \cdot \left(\lambda_v \cdot R(a_s^v) + \lambda_d \cdot R(a_s^d) \right)$$
$$+ C_{VH} \cdot \left(T(s_{TDMA}^v) + T(s_{TDMA}^d) \right.$$
$$\left. + T(s_{WCDMA}^v) + T(s_{WCDMA}^d) \right), \qquad (12)$$

where the coefficients are explained in Table 12.

8.2. Result analysis

In this section, policy iteration is used to solve the MDPs. The reference scenario is defined in Table 3 with $\theta = 0.5$, which means that the cost of blocking voice and data calls is the same.

In Fig. 27 we can see the optimal values for each of the MDPs introduced in the last section for different values of C_{VH}. MDP C2 has the lowest optimal value when $C_{VH}=0$ and is followed closely by MDP C1. However, as C_{VH} grows, the value of MDP-R2 rapidly grows surpasing MDP C1 and MDP BR because of the large amount of vertical handoff of types III and IV performed. In fact, for values of C_{VH} as low as 0.01, the optimal value of MDP C2 is higher than that of MDP BR. This means that when C_{VH} is higher than this, it is not justified to use the policy this MDP uses. Keeping in mind that the cost of blocking voice and data calls is of 0.5, we could say that it is necesary that the cost of blocking voice and data calls to be about 50 times higher than that of vertical handoff for this policy to be useful.

On the other hand, results found using MDP C1 vary slowly and are limited by those of MDP BR. This occurs because if it is the vertical handoff which causes the objective function to grow, MDP C1 can always choose not to use it, and then its optimal policy will be identical to that of MDP BR. The interesting point here is to find that value of C_{VH} that makes both MDPs to reach the same optimal policiy and therefore the same results. For Fig. 27, when $C_{VH}=0.9$, both policies are the same. This means that when the cost of vertical handoff is about 1.8 times higher than that of blocking voice or data calls, vertical handoff is not useful anymore.

It is interesting to notice that when $C_{VH}=0$, the optimal policies of MDP C1 and MDP C2 are very similar to those of MDP VH-A and MDP VH-B, even though the objective functions are different. Therefore, the values of parameters such as throughput and blocking probabilities (BP_v and BP_d) are similar as well. As C_{VH} grows, the performance of these parameters degrade, and this happens at a faster rate for MDP C2 than for
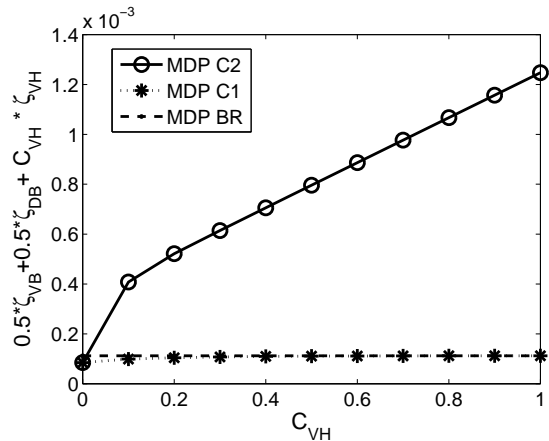

Figure 27: Optimization values for various C_{VH}.

MDP C1. Hence, while the ratio of voice/data blocking cost to C_{VH} is high, one could expect that the heuristic policies VH-A and VH-B will fairly represent the optimal policies. This last remark is true even for a higher rank of ratios in the case of MDP C1 and the heuristic VH-A, for the reasons explained earlier.

9. Conclusions

We have studied the optimal radio access technology selection policy in a system with heterogeneous technologies (WCDMA and TDMA) and services (voice and data) for two different criteria: a function of the blocking probability of each service and the total throughput. The solution method used is policy iteration based on a MDP, which proved to be computationally tractable and robust, since the number of iterations needed is not restrictive, and a solution can be found no matter what initial policy is used. Also, it has been found that one iteration is enough to find a quasi-optimal policy, and this can be useful for large systems.

Optimal policies have been found for various traffic scenarios using both optimization functions, and results were compared with those of three fixed policies. Analysis of optimal policies for different scenarios allowed to find the relation in their construction with technologies's inherent characteristics, and also with traffic values and services provided. Based on these characteristics, a heuristic solution has been proposed, and results have shown that it is better than the three fixed policies while data arrival rate is larger than voice arrival rate. Also we have extended the optimization of throughput considering QoS restrictions, and results showed that

SYMBOL	DEFINITION	VALUE
$G(a_s^x)$	Indicates if s is a blocking state for service x	• If action a_s^x is blocking, $G(a_s^x)$=1. • Otherwise $G(a_s^x)$=0.
$R(a_s^x)$	Indicates the number of calls that suffer vertical handoff when a call of service x arrives while the system is on state s.	• If a_s^x=3, and all the conditions for vertical handoff type I are fulfilled, $R(a_s^v) = N$. • If a_s^x=4, and all the conditions for vertical handoff type II are fulfilled, $R(a_s^d) = 1$. • Otherwise, $R(a_s^x) = 0$.
$T(s_{TDMA}^v)$	Indicates the rate of calls that suffer vertical handoff when a voice call is served on TDMA while the system is on state s.	• If the conditions for vertical handoff type IV are fulfilled once a voice call is served on TDMA, $T(s_{TDMA}^v) = s_1 \cdot \mu_v$. • Otherwise $T(s_{TDMA}^v) = 0$.
$T(s_{TDMA}^d)$	Indicates the rate of calls that suffer vertical handoff when a data call is served on TDMA while the system is on state s.	• If the conditions for vertical handoff type IV are fulfilled once a data call is served on TDMA, $T(s_{TDMA}^d) = \min(C\text{-}s_1, s_2) \cdot BR_{t,d}/\sigma$. • Otherwise $T(s_{TDMA}^d) = 0$.
$T(s_{WCDMA}^v)$	Indicates the rate of calls that suffer vertical handoff when a voice call is served on WCDMA while the system is on state s.	• If the conditions for vertical handoff type III are fulfilled once a voice call is served on WCDMA, $T(s_{WCDMA}^v) = s_3 \cdot \mu_v$. • Otherwise $T(s_{WCDMA}^v) = 0$.
$T(s_{WCDMA}^d)$	Indicates the rate of calls that suffer vertical handoff when a data call is served on WCDMA while the system is on state s.	• If the conditions for vertical handoff type III are fulfilled once a data call is served on WCDMA, $T(s_{WCDMA}^d) = s_4 \cdot BR_{w,d}/\sigma$. • Otherwise $T(s_{WCDMA}^d) = 0$.

Table 12: Coefficients for vertical handoff cost optimization functions.

adding these do not affect the advantages of the heuristic policy over the others.

We introduced different types of vertical handoff based on the knowledge gained about the behaviour of the system. New optimal solutions were found for a system with more capacity, but their calculation time makes them unfeasible for on-line use. Considering this, new easily programmable heuristics that perform in excellent agreement with the optimal solutions were described and evaluated in different scenarios. Additionally, computer simulations were performed in order to validate the mathematical analysis. Moreover, different probability distributions were checked and, under the proposed policies, the system proved to be insensitive with respect to the the distribution of voice service time and data size beyond their means.

Finally, the cost of vertical handoff was studied in relation to those of voice and data blocking, and some interesting remarks were done in order to understand the impact that vertical handoff has.

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