A New Markovian Approach for Dynamic Bandwidth Allocation in Wireless Networks

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Abstract— **In wireless networking, users mobility has a heavy impact on QoS parameters and the existing architectures for real-time services with motionless hosts become inadequate for QoS management. In particular Doppler shift and multipath fading introduce some degradations in wireless transmissions. For these reasons, the management of real-time flows and hand-over events (in terms of bandwidth guarantee and service continuity) when the system is dealing with Mobility Independent Predictive (MIP) services is mandatory, if QoS constraints need to be satisfied. In order to offer a soft QoS increasing the total system utilization, a bandwidth reallocation algorithm has been considered for dynamic resource adaptation, based on wireless channel modeling, in order to take into account the degradations related to the channel state conditions. The main idea of this proposal is the utilization of a pre-reservation phase in the admission control through a Markovian approach, in order to predict the amount of bandwidth needed by a mobile host during its movements among active and passive cells. The performance evaluation of the proposed idea has been made in terms of total admitted/dropped MIP flows, assigned bandwidth and system utilization.**

Keywords-WLAN; Bandwidth allocation; Markov model; ISPN; Predictive service; Mobility Independent Predictive.

I. INTRODUCTION

In recent years, wireless networks are proving to be the next major evolution of technology for businesses. But, in comparison with wired networks, the fluctuation in resource availability is much more severe: they introduce the concept of complete mobility provided by air travel and communication is no longer limited to the infrastructure of wires. Although their flexibility and scalability, wireless networks pose special problems, such as limited bandwidth and high error rate, that do not exist in wired networks. The dynamics of physical channels cause variations in received signals and, for these reasons, deterministic service guarantees and bandwidth allocation, commonly used in wired networks, become inadequate for dealing with wireless communications. It has been proven that the adaptive multimedia networking paradigm can play an important role to mitigate the highly-varying resource availability in wireless/mobile networks, introducing the dynamic bandwidth allocation mechanism. We considered two main features for link quality variations or degradations: fading and mobility [1],[2]. The first is highly-varying with time and space and it has been considered through the channel modeling, accounting the slow fading effects. The second (mobility) has been considered through the host movements, that results in many hand-in (when a new flow enters in a cell for hand-off or for a new call request) and hand-out (when a flow leaves a cell) events among the visited cells into the system. User mobility has an important impact on Quality of Service (QoS) parameters of real-time applications and the existing protocols need to be extended in order to manage host's mobility. This can be handled by using, for example, the MRSVP protocol, which is based on active and passive reservations and capable to pre-reserve an amount of bandwidth, before a mobile host enters a cell.

Our previous works [3],[4] and many other works in the literature [5],[6] treat the problem of future cells estimation in a 1D or 2D scenario, by the employment of a prediction algorithm. In this work, instead, the attention is focused on a new prediction algorithm aimed to the evaluation of the amount of bandwidth that a user needs when it enters a new cell, where some passive bandwidth has been reserved. The most general and fast approach to solve the problem is the reservation of the maximum available bandwidth level, but this kind of policy leads to a bandwidth wastage, either because there is a pre-reserved and unused bandwidth, or because the incoming mobile user may not need the maximum amount of bandwidth. The proposed Markovian model, that does not depend on the adopted call admission control or bandwidth reallocation scheme, is used to evaluate the minimum amount of bandwidth necessary to cover passive reservations in future visited cells, minimizing the resource wastage into the system. The paper is organized as follows: section II illustrates the considered reference scenario, in terms of architectures, protocols and modeling; section III describes the proposed idea, while in section IV performance evaluation has been carried out; conclusions are summarized in Section V.

II. REFERENCE SCENARIO

A. *Resource Reservations*

While dealing with mobile hosts and channel degradations, an architecture capable to reserve dynamic resources and to offer guaranteed services is needed when the system has to offer an adaptive QoS, due to the inherent time varying environmental conditions evident in radio communications. There have been different research groups that tried to define some service model, in order to deal with applications variety in packet networks. Integrated Services networks are the results of such kind of [10]. In a real network, resources reservations can be made by protocols, in order to satisfy QoS requirements and to offer to mobile hosts a service "better than best-effort", accounting the inherent time varying environmental conditions evident in radio communications (e.g. fading). In IS networks, each flow can receive different QoS, which must be negotiated at the beginning of sessions, between flows and network, by the Mobile-RSVP [3], [16], in mobile scenarios: it is used for exchanging state information of wireless networks and it can offer soft QoS (adaptive QoS) for a class of services called Mobility Independent Predictive (MIP).

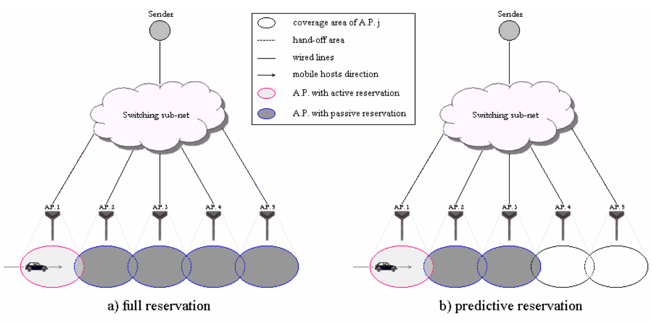

Figure 1. A MIP host can make a: a) Full reservation over all cells of the system; b) Partial reservation over predicted cells.

Figure 1 shows how a MIP user can reserve passive reservations over all the cells in the system (a) or on a reduced set (b), if a prediction algorithm is used.

Users belonging to MIP class request service guarantees, regarding delay in packet delivery and drop probability during hand-off events. They are not subject to mobility effects and the packet delay must be always respected; tolerant and real-time applications with a limited delay-bound belongs to this class. Many studies in literature [7],[8] have shown that a good system utilization can be obtained if the bandwidth level is adjusted dynamically, on the basis of system requirements. Let us now hypothesize that a transmission source can dynamically adjust its transmission rate during an active session. Considering this feature, when wireless network is in congestion temporarily, some services' bandwidth can be adjusted (we call it as rate adaptation), to avoid disconnecting some connections, resulting in an improved QoS for all the users. Suppose there are n total Mobile Nodes (MN) in a cell. So the set of active connections is F = $\{f_0, f_1, ..., f_{n-1}\}$. Then the k-th connection ($0 \leqslant k \leqslant n-1$) can operate at any of the j bandwidth levels $l_0, l_1, ..., l_{j-1}$, where $l_0 > l_1 > ... > l_{j-1}$. It is also assumed that both sides of the connection have negotiated the bandwidth level. We call l_0 and l_{j-1} as the maximal bandwidth requirement and minimal bandwidth requirement respectively. We assume that the *k-th* connection currently operates at l_i, with ($0 \leqslant i \leqslant j-1$). Let C be the total capacity of the cell. When:

$$\sum_{f \in S} l^{k}{}_{(j-1)} < C < \sum_{f \in S} l^{k}{}_{0} \qquad (1)$$

the cell is in congestion, where l^k_i is the current bandwidth level for the *k-th* connection . All the connections operate at a level between the maximal and minimal bandwidth requirements. There are two kinds of rate adaptation: rate degrade and rate upgrade, which mean to change MN's bandwidth from high level to low level or from low level to high level respectively. For example, the rate degrade can be described as: "when $C < \sum_{f_k \in S} l^k{}_i$ find a subset $F' \subseteq F$ and change the bandwidth of each connection in F' to $l^k_{i'}$, so that $\sum_{f_k \in S} l^k{}_i - l^k{}_{i'} \geq \sum_{f_k \in S} l^k{}_i - C$ ". The rate upgrade can be described in a similar way. In order to handle users mobility and to offer guaranteed services (mobility independent) different service classes have been defined and the ReSerVation Protocol has been extended, with the MRSVP [3],[10], [16].

In MRSVP sessions, after the proxy addresses are discovered, users send active_RESV messages to their local access points and passive_RESV messages to their remote access points, so the system must effect an admission control, in order to accept or refuse users' requests. MIP flows can reserve a bandwidth level that can change during call holding time. These behaviors can guarantee a more flexible resource management increasing system utilization. When a user moves from a coverage area to another one, the hand-off event is managed by a reservation switch (from passive to active).

The reserved resources in the old access point are released in both cases and, if the user belongs to MIP class, the passive resources can be assigned by switching to an active reservation. For more details about MRSVP to see [3],[10]. Most rate adaptation algorithms tend to maximize the throughput, so the system may allocate resource in a fair way (i.e. following an intra-class fairness criterion), disregarding the degradations introduced by channel conditions.

B. *Channel modeling*

If the system attempts to provide fair treatment to all users, users with worse channel conditions tend to be allocated more resource so as to compensate for their channel conditions. For these reasons two important concepts have to be considered: channel modeling and users satisfaction level. The first contribution can be taken into account by introducing a channel modeling as in [11], employing a Markovian stochastic process modeling. Let $S=\{s_0, s_1, s_2, ..., s_{K-1}\}$ denote a finite set of states and $\{S_q\}$, $q=0,1,2,...$ be a constant Markov process. Since the constant Markov process has the property of stationary transitions, the transition probability is independent of the time index n and can be written:

$$t_{j,k} = \Pr(S_{q+1} = s_k \mid S_q = s_j), \qquad (2)$$

for all $q=0,1,2,...$ and $j,k \in \{0,1,2,...,K-1\}$. The model is so characterized by T (the transition probabilities matrix) composed by the $t_{j,k}$ elements, p (the vector of steady states probabilities) for which:

$$p^t T = p^t, \quad (3)$$

where p^t is the transpose of p and e (the cross-over probabilities vector), strictly related to physical parameters (such as modulation scheme, carrier frequency and instantaneous user speed). The considered model is based on the Signal to Noise Ratio (SNR) interval partitioning and on the association of each range to a state of the chain [11].

C. *Utility functions*

The utility concept in telecommunications generally refers to a function which describes the degree of user satisfaction with a certain amount of allocated resource. The exact expression of a utility function may depend on the traffic type and can be obtained by studying the behavior and feeling of users (this kind of study is made by psychologists and economists) [12]. Some examples of utility functions applications are [13] and [14]. Each MN in a cell may have a different degree of satisfaction with a given resource, guided by the respective utility function of the traffic. Users with the same kind of traffic may not have the same utility function in a wireless network, because the wireless channel quality of each user may not be identical. Let q_k denote the channel quality of user k (associated to flow $f_k \in F$), with $0 \leqslant q_k \leqslant 1$ and $k = 0, 1, \ldots, n-1$. A smaller value of q_k indicates a worse channel quality. Given an amount of resource l^k_i and channel quality q_k, the amount of resource actually beneficial to user k is equal to $\theta_k = l^k_i \bullet q_k$ (pedex i is related to the specific level of bandwidth).

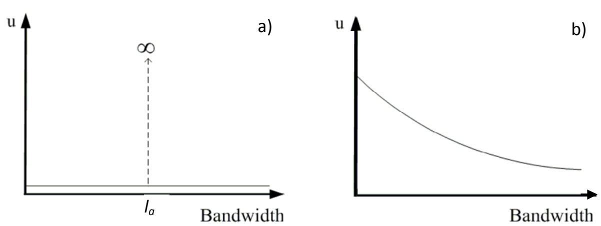

Figure 2. Different courses of marginal utility functions for a) Hard QoS and b) Best Effort traffic.

Therefore, the utility function of user k can be expressed as $U_k(l_k) = U(\theta_k)$, where $U(.)$ is the utility function of the considered traffic. The marginal utility function of $U(.)$ is:

$$u(l) = \frac{\partial U(l^k{}_i \cdot q_k)}{\partial l^k{}_i} \quad (4)$$

Figure 2 shows two examples of marginal utility functions for QoS and Best-Effort traffics. The main goal of a utility-based objective is to maximize:

$$\sum_{k=0}^{n-1} U_k(l^k{}_i), \ \ subject \ \ to \ \ \sum_{k=0}^{n-1} l^k{}_i < C \ \ and \ \ l^k{}_i > 0 \ \forall k, \ \ k \in \{0,1\ldots,n-1\} \quad (5)$$

D. *Contributions*

In our previous works [3],[4] we considered a utility-oriented bandwidth reallocation and Call Admission Control (CAC) schemes, taking into account channel conditions, utility functions and making some predictions on the number of cells that mobile users will visit during their connections (for partial reservations, as illustrated in figure 1). However, no estimations on the required bandwidth levels during hand-off events have been made. In particular, the new idea aims to predict the needed rate level for any mobile host after a hand-off event, leading the system to gain resources in terms of passive reservation. The main contributions of the paper are:

- Introduction of a Markovian approach for bandwidth evolution modeling in wireless environments;
- Optimization of wireless system utilization, in terms of resource gain during the pre-reservation phase;
- Prediction of the needed amount of bandwidth after a hand-off event.

III. MARKOVIAN RATE-ADAPTATION PREDICTOR (M-RAP)

In this section the proposed idea is illustrated. Let us suppose that d is the Call Holding Time (CHT) of a generic flow $f_k \in F$ (exponentially distributed with mean μ); indicating the average user speed with v_{avg} and hypothesizing that the connection starts at time $t_0 = 0$, then in the interval $[0,d]$ the hand-off times t_i, with $i = 1,..,h$, can be determined as in [4]. A Markovian approach to "a-priori" estimate the wireless link status at times t_i is now described, making possible to reserve the adequate level of passive bandwidth (instead of the maximum one) when a mobile host enters into the system. Recall that, as described in section II, the wireless link can be described with a Finite State Markov Chain (FSMC), completely characterized by the triplet $<T,p,e>$. In particular, p and e do not vary during the connection because they are independent from transmission rate and host speed [11]. Matrix T, instead, has dynamic elements, because they depends on v_{avg}, λ (the wavelength of the carrier signal, generally constant during a transmission), and transmission rate Rt. Recall that for the k-th flow f_k, there is a bijective relation between l^k_i and Rt^k_i (it depends on physical parameters and it is not an object of our proposal).

Without loss of generality, let us hypothesize that for each coverage cell there are H available transmission rates $Rt_1, \ldots, Rt_H$ (the same for all flows in the system, so independent from k) and the channel model has K states: so, during bandwidth reallocations, the FSMC can have H associated transition matrices $T_1, \ldots, T_H$. For all matrices the following relations are valid ($t^h_{i,j}$ indicates the element (i,j) of matrix T_h, with $h = 1,\ldots,H$):

$$t^h{}_{p,p+1} \cong \frac{N_{p+1}}{Rt_h{}^{(k)}} \qquad p = 0,1,2,\ldots,K-2, \ \ t^h{}_{p,p-1} \cong \frac{N_p}{Rt_h{}^{(p)}} \quad p = 1,2,3,\ldots,K-1. \quad (6)$$

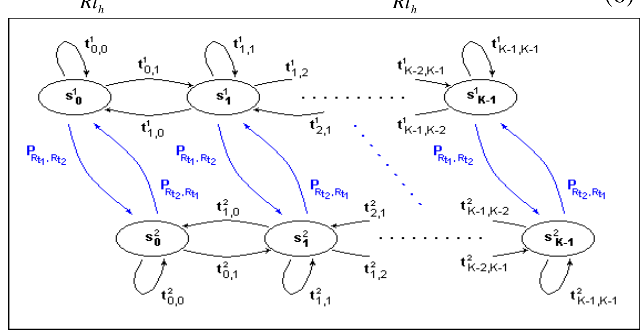

Figure 3. An example of channel modelling with H=2.

Figure 3 shows how, for H=2, the Markov model changes its states from the set S_1 (associated to rate Rt_1) to S_2 (associated to rate Rt_2) and vice-versa. In order to completely describe the model above, the probabilities of a rate change $P_{Rti,Rtj}$ (for H=2, they are indicated as $P_{Rt1,Rt2}$ and $P_{Rt2,Rt1}$), with $i,j=1,\ldots,H$ and $i\neq j$ and state sojourn times have to be determined. It must be underlined that when there is a switching event among S_i and S_j, no state transition occurs, but only a variation of the transition matrix from T_i to T_j. The proposed idea does not depend on the employed bandwidth reallocation algorithm and it is of general application. For the state sojourn times and rate change probabilities evaluation, many simulations have been carried out: we experienced an exponential distribution for the former (verified with the Chi-Square goodness-of-fit test and not shown for space constraints), while table I shows some values for $P_{Rti,Rtj}$.

TABLE I. RATE CHANGE PROBABILITIES FOR H=4 AND K=4.

	R_{t1}	R_{t2}	R_{t3}	R_{t4}
R_{t1}	-	0.37	0.21	0.42
R_{t2}	0.31	-	0.11	0.58
R_{t3}	0.18	0.16	-	0.66
R_{t4}	0.39	0.25	0.36	-

Choosing H and K is out of the scope of this paper, but more details can be found in [3]. Hypothesizing that t_1, t_2, …, t_h are the predicted hand-off times in the interval $[0,d]$, our scope is the evaluation of channel states at times t_i and the following assumptions can be made:

- if the rate is fixed at level l_i for the average time t_{mi}, then the FSMC model will follow matrix T_i for its evolution;
- when the transmission rate changes from l_i to l_j, the FSMC channel model will remain in the current state for the remaining permanence time, then it will follow the new matrix T_j;
- the initial transmission rate is chosen by the proper CAC scheme (the proposed model is independent from it).

Figure 4 illustrates the evolution of the proposed model with the FSMC. Let L be the set of the states associated to the H discrete bandwidth levels (i.e. transmission rates) and N the set of the K states associated to the wireless channel. For a given bandwidth level, the transition probabilities of the associated Markov model have to be determined; in this way, it is possible to know the evolution of the channel model for a fixed transmission rate.

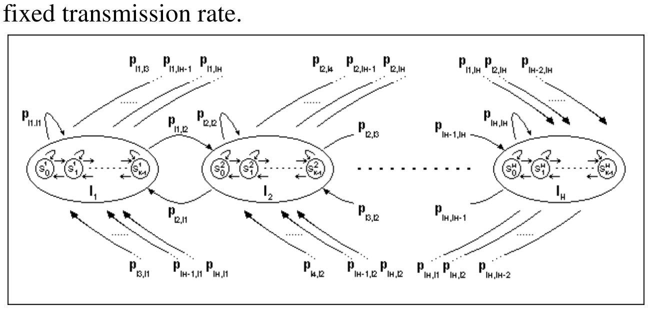

Figure 4. An illustration of the proposed model.

Let Ts_i be the average sojourn time associated to the state $i\in L$ and $Ts_{i,j}$ the average sojourn time associated to the channel state $j\in N$ inside the bandwidth state $i\in L$ (as illustrated in figure 4, the system can be considered as two embedded chains). Let $p_{i,j}$ be the transition probability associated to the states $i\in L$ and $m_{i,j}$ the transition probabilities associated to the states $j\in N$. The model is completely characterized by the couple of matrices P and M. Clearly, $m_{i,j} = f(l_i)$, where l_i represents the i-th bandwidth level currently assigned to the user. So $\forall i \in S$, $\exists M$ that gives the opportunity to evaluate π_{m_i} (stationary probability associated to the i-th state of the channel) and the n-step transition probabilities as follows:

$$\begin{cases} \pi_m = \pi_m M \\ \sum_{1}^{|M|} \pi_{mi} = 1 \end{cases} \quad \begin{cases} \pi_m^{(n)} = \pi_m^{(0)} M^n \\ n = \dfrac{Ts_i}{Ts_{i,j}} \end{cases} \tag{7}$$

Similarly, for bandwidth transitions:

$$\begin{cases} \pi_p = \pi_p P \\ \sum_{1}^{|P|} \pi_{p_i} = 1 \end{cases} \quad \begin{cases} \pi_p^{(n)} = \pi_p^{(0)} P^n \\ n = \dfrac{T}{Ts_i} \end{cases} \tag{8}$$

In eq. 8, T represents the predicted hand-off time. Indicating with n_m and n_p the number of steps associated to the channel and bandwidth chains respectively and knowing the initial states of the system, then:

$$\pi_m^{(0)} = \left[D_{m,1}, D_{m,2}, \ldots, D_{m,n}\right] \qquad \pi_p^{(0)} = \left[l_1, l_2, \ldots, l_n\right] \tag{9}$$

represent, respectively, the channel state in the admission control phase and the bandwidth levels associated with the CAC phase, dependent from the channel state. In order to evaluate n_p and n_m it is possible to estimate the mean of the sojourn time in the states and set this value to $Ts_{i,j}$ in eq.7 and to Ts_i in eq.8. Once these parameters are determined, the embedded model is completely defined.

IV. PERFORMANCE EVALUATION

In order to appreciate the effectiveness of the proposed idea, some campaigns of simulations have been led out. The bandwidth reallocation scheme and CAC are the same of [3], as well as the channel modeling scheme. The employed simulator, written in C++, has been integrated with the implementation of the analytical treatment introduced in previous section. We are not interested to the observation of a two-dimensional system, so the network illustrated in figure 1 has been considered (the prediction of future visited cells are beyond the scope of this paper, since it has been already proposed in previous works): there are 5 wireless cells, each one covered by an AP; a MRSVP sender is connected to the APs through an "infinite-bandwidth" wired switching-subnet. The total bandwidth of each link is 11Mbps. Each mobile host starts its flow (after the CAC) in a certain current cell (e.g. mobile host 1, MH1, in cell C1), then it moves straight in a circular way (e.g. if it starts in the cell C4, it will visit C4, C5 then C1, C2, etc.), until it has visited all the cells or the connection has finished. Some important simulation parameters are: mean of requests arrival rate (Poisson process) λ_α: 3 flows/s, exponentially distributed call duration with mean μ = 180s, token bucket size: 896000 bit, token bucket rate: 512000 bit, packet size: 512 byte. The considered bandwidth levels are {512, 640, 768, 896 kbit/sec.}. A radio coverage of 250 meters has been assumed and users moves according to the Random Way Point Mobility Model (RWPMM) [15], adapted to a one dimensional space with a speed selected uniformly in the range [v_{avg}-α, v_{avg}+α], where α=10%*v_{avg} and the simulated average speeds (v_{avg}) are {10, 20, 30, 40, 50, 60, 70, 80 Km/h}. MIP users are assumed to receive QoS traffic, with the same associated utility function of [3] (the discrete values of 1,2,3 and 4 associated to the considered bandwidth level). The proposed algorithm (*M-RAP*) has been compared with three schemes: *Static Min*, *Static Max* (there is no reallocation and each flow receives always the minimum or maximum level of bandwidth) and *Dynamic* (the rate adaptation scheme proposed in [3]).

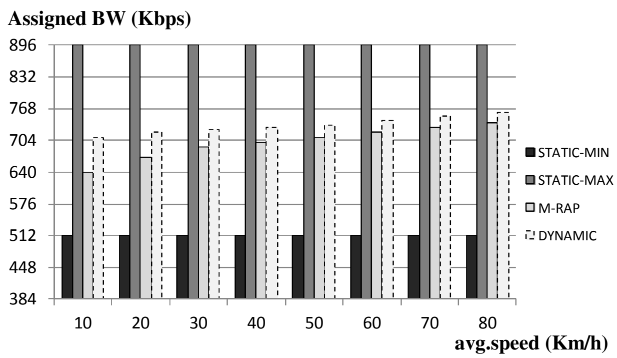

Figure 5. Average assigned bandwidth to MIP users.

Figure 5 shows the average assigned bandwidth to MIP users that are admitted into the system for different average speeds: for the *Static* cases, neglecting the effects of the wireless link and packet errors, the average assigned bandwidth is the same of the chosen input level (maximum or minimum) and no other considerations are needed (no reallocations are made, so each AP always gives to the admitted user the requested bandwidth). For the Dynamic and *M-RAP* cases, mobility effects are evident, due to the slight increasing trend for higher speeds: the time spent in a cell for each user goes decreasing and a higher bandwidth availability is offered. If link behavior is taken into account, there is an enhancement in the received bandwidth, because the system reacts to link quality variations. The classical *Dynamic* scheme outperforms *M-RAP* because it reserves always the maximum level of bandwidth for passive reservations and a higher gap is observable for low average speeds (about 60Kbps).

Figure 6 depicts the average number of admitted MIP flows for different average speeds values; as it can be expected, it increases for higher average speeds because of the higher bandwidth availability: increasing the average speed the cell sojourn time decreases, so more users can enter into the system. The difference between *Static Min* and *Static Max* is due to the difference of the assigned bandwidth level: when the highest bandwidth level is assigned there are less available resources for admitting new flows (a similar treatment can be made when the lowest bandwidth level is assigned). For the *Dynamic* and *M-RAP* cases, the number of admitted flows is higher than the *Static Max* case because a lower amount of resources are assigned to the users on the average; lower performance are obtained in comparison with the ideal *Static Min* case, because no lower resources than the *Static Min* case can be assigned to users; concluding, *M-RAP* offers some performance that are comparable with those of the ideal *Static Min* scheme, in terms of admitted flows.

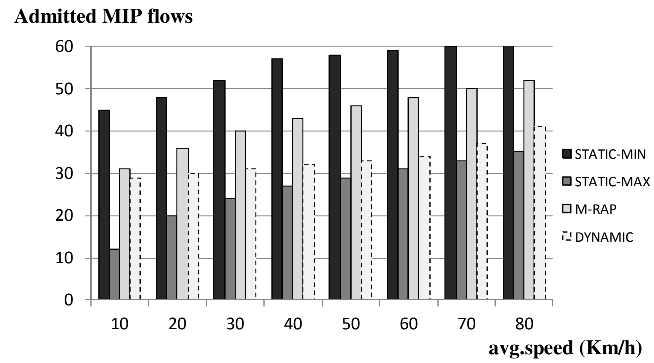

Figure 6. Average number of admitted MIP users.

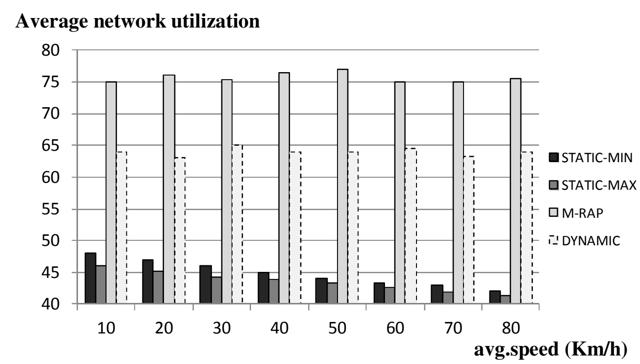

Figure 7. Average wireless system utilization.

The main differences among static and dynamic schemes are evident when considering the average system utilization: figure 7 shows the enhancements introduced by the *M-RAP* scheme. In the Dynamic and M-RAP cases the number of admitted flows increases, respect to *Static* schemes, because the system is able to adapt itself to traffic conditions, dynamically reallocating the assigned bandwidth; in this way, respecting the chosen outage threshold [3], the system can admit a higher number of users by degrading the bandwidth of existing users to lower permitted levels; in addition, the bandwidth is upgraded when a user leaves the current cell (call termination or handover). For the *Static Case*, in addition to the lower obtained values, there is a decreasing trend for increasing speeds: this is due to the higher overhead introduced by the increased number of hand-over events. In the Dynamic and *M-RAP* cases, this phenomenon is not so evident: system utilization cannot reach the maximum value of 100% because of the intrinsic protocol overhead and passive reservations, but there is not the decreasing trend for higher average speeds because, when a user leaves/enters a cell, the AP is able to react immediately to the new system conditions.

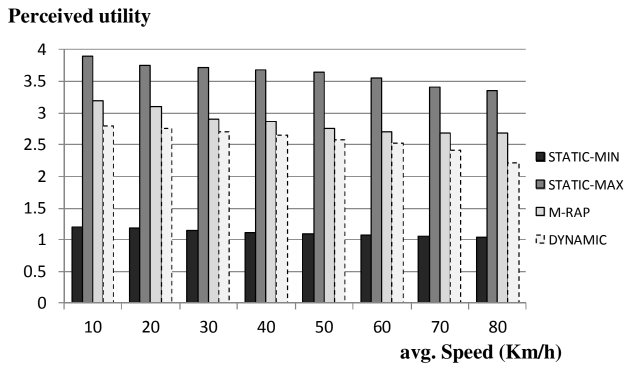

Figure 8. Average perceived utility by MIP flows.

Figure 8 shows how the satisfaction level of mobile users varies on the basis of the adopted rate adaptation policy: it is clear that for the *Static Max* and *Static Min*, the values of perceived utility are near the maximum and the minimum admissible. The *M-RAP* scheme outperforms the *Static Min* and the *Dynamic* algorithms, leading the utility values to reach higher levels.

V. CONCLUSIONS

This work proposed a new algorithm for rate adaptation prediction in wireless environments, based on Markovian theory and models. The proposed model aims to estimate the adequate level of bandwidth through the evolution of two Markov chains, related to wireless channel states and bandwidth levels. The attention has not been focused neither on the specific reallocation algorithm nor on the prediction of future cells: the proposed model predicts the bandwidth levels needed by users in the new cells after an hand-off event, remedying to the problem of assigning the maximum level of bandwidth to mitigate channel and mobility effects. Simulation results have shown that system utilization can be considerably enhanced, as well as the number of admitted flows and perceived utility, introducing a negligible worsening in the average assigned bandwidth.

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