Executive summary

With the ever-increasing need for a wireless communication that comprises multiple air interfaces coexisting in the same operating area, advanced Radio Resource Management (RRM) is vital to take advantage of the available system resources. The Joint Radio Resource Management (JRRM) - which is the object of this deliverable - is part of this advanced RRM. JRRM could be seen as a spectrum management procedure operating at the session or packet level. This is the reason why our work on JRRM has been done within the URC (Urbanisme des Radio Communications) project [1] that is investigating novel methods for flexible spectrum management in the Île-de-France Region.

In this chapter, we consider a heterogeneous network where cells include two co-localized Radio Access Technologies (RAT): WiMAX [2] and UMTS [3]. The study focuses on the downlink channel for both RATs in the presence of multi-class streaming traffic and elastic traffic. We propose a JRRM algorithm responsible for routing every arriving user to one of the two RATs, while taking into account the radio mode, the joint spatial distribution of already accepted users, the current load of each RAT, the power control, the location of the newly accepted user and its influence on global performance. The routing decision is formulated as a Semi Markov Decision Process (SMDP) [4]. This theoretical framework is suitable for network-centric JRRM, and generates for a given scenario, an optimal access policy that maximizes a predefined reward function, which accounts for both the operator and users satisfaction.

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# 1. Introduction

## 1. Toward 4G Era

Digital wireless communication, that replaced its old analog ancestor, has experienced striking advances. Nowadays, wireless networks are gaining in diversity and heterogeneity where a number of Radio Access Technologies (RATs) with different characteristics, compete for offering a great variety of services.

After the world-wide deployment of the Second Generation (2G) systems, such as GSM (Global System for Mobile Communications) [6] [10] and its data extension GPRS (General Packet Radio Service), intensive efforts were made to elaborate Universal Mobile Telecommunications Systems (UMTS) third Generation (3G) system. Meanwhile, other standards have been developed for broadband wireless access. The 802.11 standard [8] has gained a widespread usage as a wireless equivalent of Ethernet, while the emerging WiMAX technology [2] aims at providing WMAN services and Wireless DSL access.

Far from being a hindering factor, this proliferation of air interfaces can be turned into an advantage from the Beyond 3G (B3G) perspective: all RATs will act as possible access networks to a common IP-based core network. This leads inevitably to situations in which heterogeneous networks can coexist and offer cooperatively communications services.

This services convergence will be promoted by the fast developing SDR (Software Defined Radio) [9] technology that enables wireless terminals to easily access and adapt to different RATs. SDR should evolve toward *cognitive radio* where a wireless terminal is capable of detecting its radio condition and choosing the best configuration (reconfigurability).

Such heterogeneous context with converged services and intelligent terminals raises a number of issues that can be summarized by the following two questions:

* How to optimize user QoS in the presence of more than one access network?
* How to optimize the spectrum utilization?

The first question invokes the notion of being always best connected (ABC) [11] and the answer to this question is not so straightforward. On one hand, users are expecting services that are getting increasingly diversified and implicating more than one traffic type. On the other hand, users are not restricted by a single RAT. The choice of the RAT that fits better the terminal capabilities requires advanced RRM mechanisms that transcend individual networks and offer the means for RATs to cooperate and communicate with the terminal, in order to take the best decision. This decision will take into account both user and network information.

The second question is tightly related to the general problem of *spectrum management*. Being a rare resource, the shortage of spectrum becomes more concrete with the ever increasing demand. The Federal Communications Commission in USA (FCC) has shown in the report [12] that “spectrum is available, but its use is compartmented by traditional policies based on traditional technologies”, concluding that the real cause of crowded spectrum is often a spectrum access problem. The coexistence and cooperation of several RATs in a given geographical area will surely help in improving the spectrum utilization by adding more flexibility.

## 2. Joint Radio Resource Management - WiMAX-UMTS case

The Joint Radio Resource Management (JRRM) can be defined as the set of “controlling mechanisms that support intelligent admission of calls and sessions for a set of networks or cell layers. They control the distribution of traffic, power and the variances of them, thereby aiming at an optimized usage of radio resources and maximized system capacity. JRRM mechanisms work over multiple radio networks or cell layers with the necessary support of reconfigurable/multi-mode terminals” [13].

The JRRM in WiMAX-UMTS hybrid networks is gaining more attention after a large interest in WLAN and UMTS cooperation. UMTS and WLAN were considered as complementary because, while the former provides wide-area coverage coupled with high mobility and medium rates, the latter provides local coverage and low mobility with high data rates.

However, the UMTS-WLAN JRRM methods do not apply to the interworking between 3G (especially HSDPA) and WiMAX. In fact, both RATs are cellular networks with full coverage offering data-oriented services with high data rates and mobility support.

We can distinguish three JRRM functions as defined in [14]: *RAT and cell selection*, *bit rate allocation*, *and admission control*. Our proposal tackles the issue of RAT selection and admission control in a cell serviced by WiMAX and UMTS RATs. It builds upon the work proposed in [15] where the globally optimal association of the two RATs is formulated as an SMDP (Semi Markov Decision Process) routing decision problem. Optimality is defined through a utility function that consists of a financial gain component, an aggregate throughput component and a blocking cost; hence accounting for both the operator and user satisfaction. However, we choose to work with different RATs and consider multi-class users with different QoS requirements. As in [16], spatial distribution of users is taken into account through the division of the cell into zones. These zones may be concentric rings or portions of concentric rings. Yet, the division is done astutely in order to make the analysis tractable. Moreover, contrary to [15] and [16] that consider simplifying assumptions, the key feature of our approach lies in accounting for the effect of interference, for the physical layer and channel characteristics. Also, our model takes into consideration scheduling aspects and proposes a power control scheme for UMTS that accounts for fading while freed from the saturation assumption as in [15].

The chapter is organized as follows. Section 2 surveys the JRRM research activity. Section 3 explains our approach and summarizes the main articulations of the model. We describe the Network Model and Radio Model respectively in Sections 4 and 5. Sections 6 and 7 describe the QoS considerations and the admission control in WiMAX and UMTS RATs respectively. In Section 8, we describe the SMDP and the policy iteration algorithm. Section 9 gives some numerical applications and shows how the optimal policy outperforms a common sense policy. Finally, conclusions are presented in Section 10.

# 2. Overview on JRRM and its theoretical approaches

Several projects treated the problem of advanced resource management as a key element in all solutions that propose the coexistence of multiple access networks. Nokia in [17] coined the term Common Radio Resource Management (CRRM). The CRRM ensures interoperability and improves efficiency in multi-standard networks, by placing the radio resource control for several radio network access standards into a single server. Nokia targets ubiquitous 3G services over all major existing and future radio interfaces, such as WCDMA, GSM/EDGE, TDMA/EDGE, 1XEV-DV and WLAN.

The CRRM is also studied by 3GPP RAN working group 3 [18], in the context of heterogeneous 3G/2G systems (UTRAN/GERAN - RNS/BSS). It is intended to direct users in idle and connected mode to the cell and resource pool which are most suitable, depending on the user QoS requirements/classes and the network features (load balancing, minimizing interference, avoidance of needless handovers/cell changes etc.). Authors in [19] evaluated the CRRM proposed by 3GPP in UTRA/GERAN and showed that CRRM improves the conversational, streaming, and interactive capacity.

The Wireless World Initiative (WWI) [20] initiated a series of projects (WINNER [21] [22] and Ambient Networks [23], etc.) in the purpose of defining B3G mobile systems and investigating the mechanisms to be used in such networks. All these projects undertook the radio resource management problem in multi-radio networks and proposed methods to efficiently share resources between co-localized access networks.

Similarly, CRRM is used by the Open Radio Access Network (OpenRAN) model of Mobile Wireless Internet Forum [24]. The long term vision of the OpenRAN architecture is to extend the peer-to-peer and distributed Internet architecture to radio access networks, so that a radio access network becomes just another access network, like cable, DSL, Ethernet, etc.

As we mentioned above, there has been a significant research effort to propose solutions for WLAN-3G coexistence. For that purpose, many papers proposed JRRM algorithms based on various mathematical frameworks. The authors in [14] use fuzzy logic framework to elaborate fuzzy neural algorithm to ensure given QoS constraints in a multi-cell scenario deployment with three different RATs (WLAN, UMTS, and GSM/EDGE). A combined analytic hierarchy process (AHP) and grey relational analysis (GRA) is proposed by [25] to perform network selection in integrated cellular/wireless LAN systems, taking into account network conditions, users’ preference, and minimizing handoffs. Another approach using the combinatorial optimization framework is exposed in [26]. An iterative heuristic algorithm is derived to compute the association of wireless stations to either 3G BSs or WLAN access points.

The Semi Markov Decision Process (SMDP) [4] has been proposed as a framework for WLAN-UMTS user-network association in [15]. The SMDP model was used to obtain global optimality while individual optimality is computed using a non-cooperative dynamic game framework. This approach has been further exploited by other works. The work in [27] proposes an optimal joint session admission control scheme for multimedia traffic that maximizes overall network revenue with QoS constraints for WLAN/CDMA networks. In this work, physical layer and classes of traffic were integrated into the model. In [16] [28], heterogeneous WLAN/HSDPA configuration is considered and the SMDP model of JRRM takes into account the users geographical location by decomposing the cell into rings.

Finally, some works were interested in the WiMAX/3G coexistence. Markovian models were derived in [29] to study the dynamics of elastic sessions in a cell served by HSDPA and WiMAX systems. The proposed JRRM strategies give the possibility to perform inter-system vertical handovers. Another paper [30] tackles the same problem through of game-theory based approach that allows mobiles to single out the appropriate RAT in a distributed manner.

# 3. Explaining our JRRM Procedure

We consider a cell where WiMAX and UMTS RATs coexist. UMTS uses DS-WCDMA access scheme while WiMAX uses OFDMA. WiMAX base station and UMTS Node B are assumed to be co-localized and having the same coverage. This assumption is realistic not only for small cells (e.g. micro or femto cells), but also in the case where an operator chooses to deploy a heterogeneous WiMAX/UMTS network with co-localized base stations for economical and technical reasons, implying geographical cells coincidence. Note that this assumption is only necessary for our detailed radio computation, but the Markov Decision Process framework can be extended to the general case.

The cell is divided into zones where new sessions (users) arrive as a Poisson process, and will stay in the system for an exponentially distributed time. The sessions belong to a finite number of traffic classes, thus the arrival and service rates depend on the session class. The term *session* will be generically multimedia calls (telephony, video) as well as data sessions. In this work we consider one elastic data class and a finite number of streaming classes with different QoS requirements. Moreover, the admission control that we propose is done in the downlink.

Due to the Poissonian arrivals and exponential services, the network evolution will be modeled by a Markov process where transitions occur when new sessions arrive or quit the system. A state of the Markov process is a multidimensional vector containing the number of users per class, per zone and per RAT. It can be seen as the combination of two sub-states: WiMAX state and UMTS state. A RAT state is a vector containing the number of users in this RAT per class per zone. The transition between two states  and  depends upon both  and .

Each RAT performs its proper admission control. The number of users connected to a RAT is therefore limited and depends on the current state of the RAT. Hence, the set of system *admissible states* is limited by the admission control of RATs. For example, an UMTS cell may be able to handle a certain number of users that are close to the Node B but not when they are located at the cell border. An *admission policy* consists in taking a decision when a session arrives on whether to accept or reject a new session.

A trivial admission policy would be a policy that routes all incoming sessions to WiMAX RAT. When WiMAX is saturated, the sessions are routed to UMTS as an alternate solution. When both RATs are full, sessions are simply rejected. This raises the following question: is that the optimal way to control the admission of sessions. The answer to that question is not absolute, but depends on the objectives we set. If we aim to find the easiest way to accept sessions, than, the trivial policy would be probably optimal. But, for a more ambitious target, one must define its objective function and then find the policy that would fulfill it.

In our approach, we use the Markov Decision Process technique [4] in order to model the decisional process. We define a reward function that, for each state of the system, gives a reward that accounts for current rates and blocking probability. In addition, each state has a set of possible decisions (actions) that can be taken. The optimal policy has to find for each state, the decision to make in order to optimize the total discounted reward for each state.

Given the characteristics of the network, radio and traffic parameters, the computation of the optimal policy is done offline and then applied to the system. This corresponds to a network-centric approach where the network is the only responsible for routing incoming sessions and sending the order to the terminal.

Finally, we will summarize the modeling steps that are exposed in the following sections:

* Define the topology, the zone decomposition, and the traffic characteristics QoS requirements, and determine the expression of system states.
* Find the admissible states by defining the admission control procedure in each RAT:
  + Define radio conditions and compute the signal to interference plus noise ratio () probability distribution (the complementary cumulative distribution function precisely) in each zone of the cell. This is useful for computing data rates in the zones.
  + Compute, for a given RAT state, the rates that are available for each user in that state. If QoS requirements are met for all users, the state is admissible; otherwise, the state is omitted. Note that for WiMAX, the available resources to allocate for users are subchannels while in UMTS, they are the amount of power emitted by the base station to a given mobile. The quantity of allocated resources depends on users’ requirements and their radio conditions.
* Applying the admission control scheme in each RAT, we obtain the set of system admissible states that constitutes the states of our SMDP.
* Determine the transition rates between states and define the actions and the reward function for each state.
* Compute, using the policy iteration algorithm, the optimal policy.

# 4. Network Model

## 1. Network Topology

The reference cell we study is called . As stated before, the UMTS and WiMAX base stations are co-localized in . Note that the term base station (BS) will be generically used for Node B and WiMAX base station. The  index is used throughout the chapter to designate a given RAT:  for WiMAX and  for UMTS.  denotes the base station of RAT  in our reference cell.

In the general case, our cell  will not be orphan, but an element of UMTS and WiMAX deployment. Let then  be the set of the  BSs that constitute the deployment of RAT . There is no assumption concerning the location of those BSs.

Our reference cell  will be logically divided into  zones called . These zones could for example be concentric rings. The reason behind this decomposition is to make the number of system states finite by assuming that all users in a zone have the same geometrical properties. Therefore,  denotes the distance from any user in  to the BS, while  represents the distance from users in  to  and will be used to determine the interference of other cells.

## 2. Traffic Model on the downlink

Sessions in our model belong to traffic classes, each class having different requirements in terms of bit rate. As we mentioned before, our JRRM is done on the downlink channel, thus the traffic considered is on the downlink. This corresponds to streaming services on downlink and elastic traffic such as FTP and HTTP for which the uplink traffic is less constraining the downlink one.

For simplicity, we suppose that one user generates one session, and so, we will use interchangeably the terms session and user. Thus, a real user having  sessions is formally considered as  users. It is all a matter of conventions.

A session will not be admitted in the system if its QoS constraint cannot be met. Let  be the number of traffic classes. In both RATs, the  classes are divided into two categories:  streaming (or constant bit rate CBR) classes requiring a constant bit rate  for  and one elastic class indexed by  (where ), that is able to tolerate variable bit rates. However, the bit rate of elastic traffic must always be greater than a minimal value. (see sections 6 and 7 for details).

Class  arrivals in zone  follow a Poisson process of rate. Session duration for CBR classes and session size for elastic users are exponentially distributed with mean resp. equal to  and.

## 3. Network States

We define a state of RAT  at time  as being the -tuple denoted by  for:

 (1)

where  is a stochastic process giving the number of class  users in zone  of  at time . In the remaining we will omit  as we assume stationarity.

The structure of the state vector is defined as follows:  is the  element of .  can also be viewed as a  matrix where the element of coordinates  is the number of class  users in zone .

To illustrate this definition, consider a cell  compounded of 2 zones and servicing 2 traffic classes. The state  corresponds to a UMTS RAT state with  user of class 1 in zone 1,  users of class 2 in zone 2,  user of class 1 in zone 1, and  users of class 2 in zone 2.

A state  of the total system in  will be the combination of the corresponding UMTS and WiMAX states

 (2)

An admission control scheme is later defined, giving the admissible states for each RAT.

# 5. Radio Model

In this section, the radio conditions are described based on path loss and Rayleigh fading models. The main goal is to derive the probability distribution, more precisely the complementary cumulative distribution function (CCDF), of the Signal to Interference plus Noise Ratio () of users. This distribution surely depends on the user location in the cell and is the key element to carry out the zone decomposition and hence to determine feasible bit rates of each zone. Recall that all computations are done in the downlink channel.

## 1. The Propagation model

Recall that users in zone  are assumed to have the same distance  to their BS, which means that they have the same attenuation characteristics. We will use the path loss model combined to Rayleigh fading.

In RAT , the power received by a class  user in zone  depends on the BS emitted power and radio channel attenuation, and varies with time due to fading effects. Let  be the power emitted by  at time  to a class  user in . **In WiMAX, the emitted power**  **is the same for all users and can be simply denoted by** **. In UMTS, this power depends upon**  **and**  **due to power control.** The received power is then:

 (3)

where the fading process  is i.i.d. and follows an exponential distribution of parameter  as we consider fast fading [31]. , which is the path loss for zone , depends on the distance  from the reference BS and is given by:

 (4)

where  is the path loss exponent and  a constant characterizing the radio propagation in RAT .

As we work in stationary conditions, the time  will be emitted from power computations and the fading becomes an exponentially distributed random variable of parameter. **Note that the received power is not the same for two users in the same zone due to the random fading parameter**.

## 2. The Signal to Interference plus Noise Ratio ()

### 1. Expression

Given a state  of the system, the  of a class  user in RAT  in zone  is computed by dividing the power received by that user by the sum of interference and noise power. We first give the expression of  that is formally valid for both RATs, and then we explain and detail its elements:

 (5)

The numerator is clearly the received power by the class  user in zone . The denominator is the sum of the background noise power (), the intra-cell interference (), and the other-cells interference ().

#### 1. Intra-Cell Interference:

The intra-cell interference is the interference incurred by the user due to the power emitted by its BS (common channels and other users).

 (6)

with  being the own cell orthogonality factor experienced by users in  and  the power dedicated to common channels in RAT . **Note that the intra-cell interference is null for WiMAX, which mean that** **; however, we keep the general expressions in order to obtain a unified formula for the**  **CCDF.**

 is the total power emitted by  and will be denoted by .

#### 2. Inter-Cell Interference:

The inter-cell interference is the impact of other cells emissions. The interfering cells are those having the same transmission frequency as the reference cell, and called co-channel cells. The notation  means that the cell  is a co-channel cell with our reference cell. For UMTS, all cells use the same frequency since the reuse factor is in general equal to 1. In WiMAX, the co-channel cells are in different frequency clusters.

 (7)

 is the total power emitted by co-channel cell  and is assumed to be constant.  is the path loss between  and a user in  and is given by:

 (8)

where  is the other cell orthogonality factor experienced in . Note that for WiMAX RAT,  .

### 2. CCDF

Let  be the complementary cumulative distribution function (CCDF) of the  of class  users in zone. By defining:

 (9)

a simple calculation will prove that:

 (10)

With this form, we can use the Lemma 11 in the appendix to obtain:

 (11)

The exact expression will be approximated by the following CCDF function:

 (12)

**Finally, note that the**  **CCDF depends on the network state in UMTS RAT due to intra-cell interference and on the user class due to the power control. This is not the case in WiMAX RAT.**

# 6. Admission Control in WiMAX

The goal behind the admission control in WiMAX is to be able, for a given WiMAX state , to verify if all users are getting the QoS requirements, and thus concluding that  is a possible substate of the system. We proceed as follows for a state :

* Define the OFDMA access parameters in WiMAX.
* Use the  CCDF to compute the mean value of the  in each zone.
* Use this mean value to determine the modulation scheme that will be used in each ring (adaptive rate).
* Determine the number of subchannels to be allocated for each user in the current state, in order to satisfy its requirements.
* Verify that the resources are sufficient for that state.

## 1. WiMAX Modulation/Coding Parameters per Zone

Note that we omit the index  from  expressions as in WiMAX, the  depends only on the user location. The equation (12) of the  CCDF rewrites for WiMAX as follows:

 (13)

### 1. Adaptive Modulation/Coding Scheme

In the 802.16 standard, Adaptive Modulation and Coding (AMC) determines the modulation scheme and coding rate to be used depending on the value taken by the . Let  be the number of modulation/coding schemes used in WiMAX (=7).  is the  the modulation/coding that will be used if the value of  lies within the interval  (by convention ). The values used by the standard [2] are shown in Table 1.

|  |  |  |
| --- | --- | --- |
|  |  |  |
| 1\*BPSK | 1/2 | 6.4 |
| 2\*QPSK | 1/2 | 9.4 |
|  | 3/4 | 11.2 |
| 2\*16 QAM | 1/2 | 16.4 |
|  | 3/4 | 18.2 |
| 2\*64 QAM | 2/3 | 22.7 |
|  | 3/4 | 24.4 |

Table 1. The set of  (dB) thresholds in WiMAX

The modulation/coding scheme of a user situated in zone  is then:

(14)

### 2. Determining Modulation/Coding in Zone

In a given zone, the  can surely take all possible values, which means that the modulation/coding scheme varies in the same zone. However, we will choose one scheme that best fits the reality.

We can for example choose the most probable  interval in zone . In fact, the probability that the  lies within the interval  is given by:

 (15)

Using equation (13), we can choose the interval  that maximizes . The corresponding modulation/coding is thus assumed to be the one used in .

Another approach consists in computing the average  in . Using the Fubini theorem, we have that:

 (16)

By integrating the equation (13) between 0 and , we get:

 (17)

The corresponding modulation/coding scheme is then chosen from Table 1.

 and  denote respectively the alphabet size of modulation and the coding rate chosen for .

## 2. WiMAX Admission Procedure using OFDMA

WiMAX RAT uses OFDMA as an access scheme. Let  denote the total number of subchannels that can be allocated to users, each subchannel containing  subcarriers. Resources are allocated in WiMAX on both time and frequency basis: the frequency is allocated on the basis of subchannels, each consisting of several subcarriers. In turn, a user shares in time a subchannel with other users within a frame structure. Let  be the WiMAX downlink frame duration.

The atomic bit rate  that can be provided to a user in  corresponds to one allocated subchannel per frame. It depends on  modulation/coding through the following relation (see [32]):

 (18)

where  is the bloc error rate; it can be obtained as a function of .

Since a class  streaming session requires a bit rate of , we obtain the number of subchannels to be allocated to class  streaming sessions in ring , denoted by :

 (19)

We are now able to establish our admission control scheme that will be implemented in WiMAX RAT. Consider a state . The total number of subchannels allocated to streaming sessions is:

 (20)

For elastic traffic, TCP/IP protocol is typically used at the transport layer and the remaining resources will be shared in a manner to insure fair access among elastic users. Therefore, the remaining subchannels, are equally shared by all elastic sessions, which is equivalent to a fair-access scheduling scheme. The number of those sub-channels is denoted by  and hence The number of subchannels per elastic session will then be:

 (21)

An elastic session in zone  will then have the following bit rate:

 (22)

When a new session arrives, WiMAX RAT runs the following algorithm:

1. Get the location  and the traffic class  of the new session.
2. If it is a streaming session, compute  using equation (19). If no  subchannels are available, reject the session. Otherwise:
3. If it is an elastic session, compute  using equation (21).
4. Verify the two following constraints:
   1. Streaming sessions are not allowed to obtain more than a fraction  of total resources. Hence, the condition  must be respected.
   2. The rate of an elastic session should not be less than a minimum value, thus  for all .
5. If both conditions (4b) and (4a) are met accept the session, otherwise, reject it.

Consequently, the set of admissible states in WiMAX is:

(23)

# 7. Admission Control in UMTS

## 1. Power Control Model

The UMTS RAT has to perform a power control in order to meet users QoS requirements, which are expressed in terms of target . Streaming users must obtain constant  targets denoted by , while elastic users have a finite set of  targets ordered decreasingly  where  is the maximal number of possible elastic  targets in UMTS. Note that elastic sessions share fairly the same target .

The model of the power control operates at state level; in a given state , the power allocated to users is fixed. In order to satisfy all users, the power allocation must guarantee that all users get their target  with a high probability . According to our radio model, the power allocated to a class  user in  must then verify:

 (24)

Replacing  by its expression in (12), and then taking the logarithm of equation (24), a simple algebraic calculation shows that equation (24) rewrites to:

 (25)

where  is the total power emitted to all users given by:

 (26)

and

 (27)

Equations in (25) and (26) form a linear system of  equations and where the unknowns are the various powers  and the total allocated power . The system can be solved by writing  as a function of  in equation (25), then solving for  in equation (26). The solutions are:

 (28)

and

 (29)

We denote by  the rate obtained by a class  user in  to whom an amount  of power is allocated.

To protect elastic users, streaming traffic are not allowed to acquire more than a fraction  of total resources . Hence, the admission control policy in UMTS RAT whenever a new session arrives becomes:

1. Get the traffic class and the location of the new session. Update the UMTS state. The new state is .
2. Set the variable . This is the index of elastic target 
3. Set the elastic target  to its  value ().
4. Solve the system of equations in (25) and (26).
5. If  or , then:
   1. If , . Go to step 3
   2. If , reject the new session.

Otherwise:

1. If , reject the session, otherwise
2. Accept the session.

Rejecting a session implies that the state  is not feasible. Thus, the set of admissible states in UMTS is

 (30)

# 8. The JRRM as a Semi-Markov Decision Process

A joint radio resource management policy is an algorithm that decides when a new session arrives, whether or not to admit the arrival and through which RAT. We formulate the problem as a semi-Markov decision process (SMDP) [4], where the decision making is bound to the process that describes the system dynamics.

The arrival times are called decision epochs since the decision is taken whenever an arrival occurs. Note that decisions are called actions in the SMDP framework. Hence, the SMDP goal is to associate an action to each state of the system. The optimality criterion is an objective function to be maximized, which is in our case, indicative of the discounted system reward. In fact, we define for each state a reward function that accounts for the current bandwidth being used as an image of the network revenue and users satisfaction, and for the blocking as a penalty.

In order to obtain the optimal solution, it is necessary to identify the state space, decision epochs, actions, state dynamics, and the reward function.

## 1. States of the SMDP

Let the -tuple  be the state of the joint system defined as the concatenation of the CDMA and WiMAX substates. The state space  of the system comprises all states such that the CAC constraints in the both RATs are met. Thus, the state space of the SMDP is defined as:

 (31)

The transitions between states occur whenever a session arrives or quit the system. In order to represent transitions, we define the vector  as -tuple containing all zeros except for the  component, which is equal to one. Hence, given a state , if for example a class  session is accepted in zone  of UMTS, the sytem will move to the state . If a class  session located in  leaves the WiMAX RAT, the system will be then in state .

## 2. Action Set

At each call arrival, an action is taken by the system relative to the rejection/admission of the session. An action  is a -tuple (or a  matrix) defined by:

 (32)

where  represents the decision to be taken when the arriving session is of class  and is located in zone . It takes the following values:

 (33)

It is obvious that there are  possible actions. We denote by  the set all possible actions. However, given a state , not all actions are feasible. For instance, if the WiMAX reached its maximum capacity and thus cannot accept any session in any zone, then all actions containing  are not valid. We denote by  the subset of all possible actions in state .

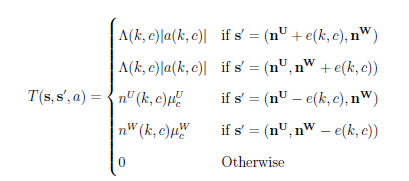
Consequently, the goal of the optimal policy is to choose, for every state , an action from  to be performed each time a session arrives while the system is in 

## 3. State Dynamics

The state dynamics of the underlying Markov process can be characterized by the transition rates or equivalently by the state transition probabilities of the embedded chain and the expected sojourn time for each state-action pair.

The transition  between states  and  depends on arrival and departure rates defined in the traffic model (see subsection 4.2) and on the action  chosen in state. The transition rates originating from a state  are given by:

(34)



In Markov processes, the expected sojourn time in state , denoted by , is the inverse of the sum of transitions from  to other states.

 (35)

The state transition probabilities of the embedded Markov chain are given by:

 (36)

## 4. Reward Function

The discounted reward is considered as the performance criterion in this chapter. Let  be the reward incurred if action  is chosen in state . This reward could be any function that represents the gain and the penalty of being in . In this work the chosen reward  is the sum of network revenue and a blocking cost:

 (37)

The network revenue per unit time is taken to be:

 (38)

with  being the data rate of class  sessions in  and  being the class  revenue in RAT  earned in a time unit.

The blocking cost estimates the penalty due to rejected calls in state :

 (39)

where  is the cost per unit time inflicted upon the network for blocking a class  user in zone . We see that the blocking cost depends on the sojourn time in the state. This means that the penalty of blocking sessions increases with the duration of that blocking.

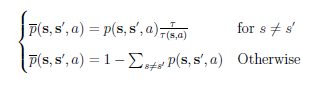
## 5. Uniformization

In order to find the optimal policy with the algorithm *Policy Iteration*, one could transform the continuous-time Markov Process into a discrete-time Markov chain using uniformization ([4]). This is done by discretizing the time into intervals of constant duration  that is smaller than all states expected sojourn times:

 (40)

Transition probabilities are modified as follows:

(41)



The reward is modified as follows: . This is the reward earned for a time .

## 6. Solving MDP using Policy Iteration

Our objective is to find what action to choose when the system is in state . We define a policy  as a mapping from  to .  is the action to take in state . In order to find an optimal policy, one must first construct an objective function that maps infinite sequences of rewards to single real numbers. For a given policy , such function is called *value function* and denoted by . maps  to the real numbers set .  is the expected objective value of state  when policy  is being used.

An optimal policy is a policy  that verifies:



In our case, the expected discounted reward is set to be a value function. Let  be a trajectory of the process given a policy . The discounted reward  of state  is the discounted sum of the rewards earned on that trajectory:



where  is the discounting factor (). The value function at state ,  will be the expected value of  over all possible trajectories.

The policy iteration algorithm is applied to find out the optimal JRRM policy. It operates as follows

* **step 0:**  We choose an arbitrary policy .
* **step 1:**  For the current policy , we compute the value function  for all states by solving the following system of linear equations:



* **step 2:**  For each , we find:



* **step 3:**  If , the algorithm is stopped with , otherwise, go to step

# 9. Numerical Evaluation

This section describes, through numerical applications, how the optimal policy functions and how its parameters could be tuned to attain given performance objectives. In order to see the improvements made by the optimal JRRM policy, we define a common sense policy, denoted by *max-rev policy*, that consists in accepting the arrival in the RAT that maximizes locally the network profit . When only one RAT has enough resources, it is naturally chosen. When both RATs have reached their capacity limit, all new arrivals are blocked.

The numerical results were obtained using Matlab simulation that takes all system parameters as input and determines the space of admissible states. The SMDP computations were done using the MDP toolbox developed by the decision team of the biometry and artificial intelligence unit of INRA Toulouse [33]. We made slight modifications to the MDP toolbox to adapt it to the big number of states in our problem.

## 1. Scenarios Description

In our simulations, we consider a WiMAX/UMTS deployment covering a circular geographical area of radius. The cells of both technologies coincide and form a regular honeycomb structure where each hexagonal cell has a side length of  (cell radius). The reference cell will be the one located in the center of the network.

Two scenarios will be studied each involving two traffic classes: CBR and elastic. In scenario 1, the cell will be divided into two zones while in scenario 2, three zones will be considered. Note that zones are simply concentric rings. The Table 1 summarizes the systems parameters for both scenarios.

## 2. Discount Factor

We start by inspecting the impact of the discount factor  on the system mean reward. Recall that our optimal policy maximizes the discounted reward for any given state , and not the global mean reward. This is illustrated in Figure 1 where the max-rev policy outperforms the optimal policy for  and . The factor  can be seen as the weight of next states reward in the gain earned in state . The higher the value of , the larger is the number of states involved in the reward function, hence, the mean reward of the system will be improved. Inversely, smaller values of  imply more short-run optimization. The discount factor is therefore a parameter that can be tuned to control the optimization scope. This behavior is drawn in Figure 1, showing clearly the increase of the mean reward with .

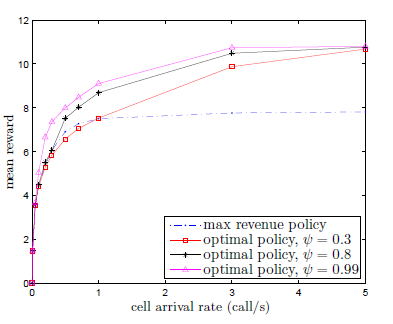


Figure 1: The impact of discount factor on mean reward (Scenario 1)

## 3. Blocking cost

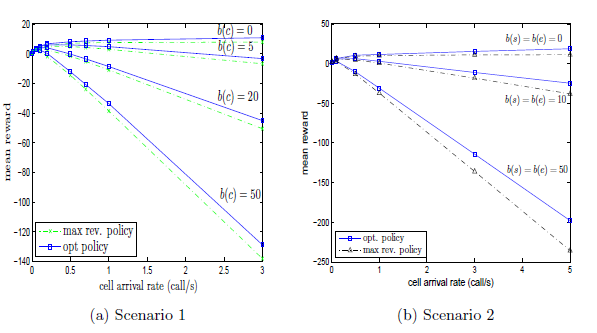


Figure 2: The impact of blocking cost on Mean Reward

For both scenarios, Figure 1 shows the mean reward as a function of arrival rate for various values of the blocking cost. We first notice that the mean reward for both policies decreases with increasing blocking penalty. More importantly, the proposed policy always outperforms the maximum network revenue policy. In the figure, the blocking cost is the same for streaming and elastic traffic. However, it can be differentiated to privilege a given class.

## 4. Performance Evaluation

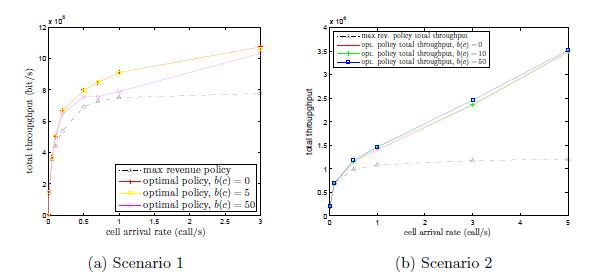


Figure 3. Total Throughput vs. Arrival Rate

As for performance, we depict in Figures 2 and 3 the system total throughput and blocking probability as a function of arrival rate. We notice that the optimal policy improves these two performance indicators in comparison with the maxim network revenue policy. Moreover, we see that the difference between policies in terms of total throughput increases with system load. Hence, the higher the number of possible simultaneous sessions, the greater the performance gain earned in the optimal policy. We deduce also that it is possible to reduce the blocking probability by fine tuning the blocking cost. However, increasing  reduces the blocking probability at the expense of total throughput. This result is intuitive as accepting fewer users reduces the total allocated resources.

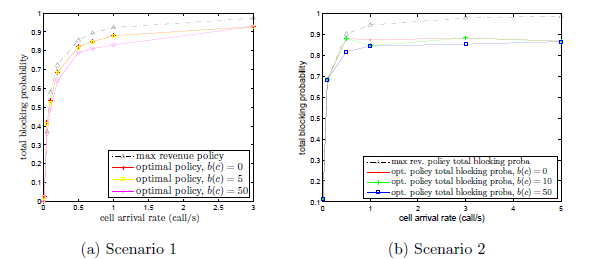


Figure 4. Blocking Probability vs. Arrival Rate

# 10. Discussion and Conclusion

In this chapter, the SMDP theory is used to devise an optimal JRRM policy for a heterogeneous WiMAX/UMTS multi-class network. The first step is to model the admission control in individual RATs in order to obtain the set of admissible system states. This is done using an analytical radio model that accounts for fading effects and interference by segmenting the studied cell into zones. This model is integrated into WiMAX OFDMA and UMTS W-CDMA access schemes and offers a suitable tool to derive an admission control for each RAT.

The second step consists in defining a SMDP process as a general framework for routing decision making. After defining an objective function accounting for user satisfaction and network revenue, the SMDP theory is used to find the set of decisions that maximizes this function. The SMDP model offer several parameters that could be tuned to customize the optimization process: The discount factor controls the scope of the optimization, while the blocking cost might be used to differentiate traffic classes. In addition, from the figures above, it is clear that the enhancement of the optimal policy is accentuated with the arrival rate. This is a satisfactory result since the need of an optimized decision becomes more vital whenever the system load increases. Note that mobility could be integrated to our SMDP model. In fact, if the dwell time in zones is exponentially distributed, the mobility will have the effect of adding transitions to the model corresponding to users mobility.

Nevertheless, the price of a centralized decision making is the complexity and the high dimensionality of the model. In fact, increasing the number of zones and traffic classes yields a large number of states, which implies an increasing computational cost. It is then interesting to investigate reducing techniques to solve large MDP problems (e.g. [34]). Finally, further investigations must be done in order to compare optimal network-centric approach to other distributed approaches (e.g. [30]).

# 11. Lemma Used for Exact CCDF Computation

Let  be a series of  independent random variables with the same exponential distribution of parameter . We define the random variable  as follows:

 (1)

where , , and  are non-null positive real numbers. We define the random variable . Finally, for a given random variable ,  (resp. ) denotes the probability density function (resp. probability distribution function).

The following theorem gives the analytical expression of the complementary cumulative distribution function (CCDF) of .

**Theorem 1.**



## Proof

 (2)

The obtained integral form is simply the expectation of the random variable , hence:

 (3)

Defining  and expanding  that is a sum of independent random variables,  becomes:

 (4)

To conclude the proof, we combine formulae 4 and 3 to obtain:

 (5)

# 

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|  |  |  |  |
| --- | --- | --- | --- |
| **Param.** | **Description (unit)** | **Scenario 1 values** | **Scenario 2 values** |
|  | Network Radius (km) |  |  |
|  | Cell radius (km) | ou | - |
|  | Frequency reuse factor of RAT . | 7,1 | 7,1 |
|  | Path loss exponent | 4 | 3 |
|  | Path loss constant in RAT |  |  |
|  | Total Power of RAT  (W) |  |  |
|  | UMTS common channels power (W) |  |  |
|  | Background noise power (W) |  |  |
|  | Fading parameter |  |  |
|  | Radius of zone  (Km) |  |  |
|  | Own cell orthogonality factor in |  |  |
|  | Other cell orthogonality factor in |  |  |
|  | UMTS  threshold probability |  |  |
|  | Maximum proportion of total resources allocated to streaming traffic |  |  |
|  | Number of traffic classes |  |  |
|  | Mean streaming sessions duration (s) |  |  |
|  | Mean elastic session size (Mbits) |  |  |
|  | Number of subcarriers/subchannel |  |  |
|  | Number of subchannels |  |  |
|  | Streaming target bit rate in RAT  (Kbps) |  |  |
|  | Elastic minimum bit rate (Kbps) |  |  |
|  | WiMAX frame duration(ms) |  |  |
|  | Modulation in zone | 4, 2 | 4, 2 |
|  | Coding rate in zone |  |  |
|  | Streaming  target for (dB) |  |  |
|  | Elastic  targets (dB) | 4.3, 13.16, 12.5, 11.3 | 4.3, 13.16, 12.5, 11.3 |

Table 2. System Parameters for Scenarios 1 and 2.