Resource allocation and opportunistic scheduling for UMTS-TDD

Illia Racunica, Aawatif Menouni,Christian Bonnet
Eurecom Institut
2229 Route des Cretes - BP 193 06904 Sophia-Antipolis
France
e-mail: Illia.Racunica@eurecom.fr, Aawatif.Menouni@eurecom.fr, Christian.Bonnet@eurecom.fr

***Abstract*— In UMTS-TDD (Universal Mobile Telecommunications System - Time Division Duplex) the data rates and the service quality (bit error rate, delays) are provided by the Radio Resource Management (RRM). The RRM manages the transmission power, the spreading factor and the orthogonal code assignment. The specifications leave open the choice of the RRM strategy. This work proposes a scheme suitable for mixed traffic consisting of Real Time (RT) services and Non Real Time (NRT) services in downlink. The access to the RT services is controlled by the Call Admission Control (CAC) using a Power-based algorithm. This algorithm determines the OVSF (Orthogonal Variable Spreading Factor) codes of a user in order to optimize the sharing of the transmitted power in the downlink in the most uniform manner over the assigned slots in the frame. The OVSF codes given by this algorithm are attributed to a Dedicated Channel. For NRT services, in presence of RT services, a channel allocation power-based strategy is combined at the physical layer with an opportunistic scheduling at the Medium Access Control (MAC) layer to minimize Node-B transmitting power and schedule mixed traffic that benefits of a good radio channel and respects Quality of Service (QoS) constraints and fairness rules. The overall RRM strategy minimizes the number of RT rejected calls and the Block Error Rate (BLER) of NRT services. The NRT services are mapped to Downlink Shared Channel.**

***Keywords*— UMTS, TDD, CAC, scheduling, fairness, DCH, DSCH**

I. INTRODUCTION

UMTS TDD systems are intended to provide a global mobility and wide range of applications with different QoS for multimedia communication. Those applications could be divided in two categories: Real Time (RT) applications, with a constant rate and hard requirements on delays (voice, video), and Non Real Time (NRT) applications, with non constant rate, but with soft requirements on delays (web browsing, file transfer). The RRM part is in charge of determining the usage of radio resources in order to satisfy the various QoS requirements. Related works [1] [2] [3] propose various Call Admission Control (CAC) strategies to allocate resources (OVSF codes to be used on time slots) but only in the case of RT (Real Time) applications. In this work, a suitable scheme for mixed application (RT and NRT) is proposed. The RT applications are handled by CAC that allocates a part of the radio resources based on a minimum power allocation strategy, in order to keep the Node-B transmitting power as well as the power fluctuation from time slot to time slot at the minimum. Other resources are allocated by the scheduler to the NRT application with respect to QoS constraints and fairness rules.

The novelty of this scheme consists, for the CAC part, in joint minimum-power channel allocation strategy to determine precisely the judicious place to allocate resources for RT and NRT application among slots. For the scheduler, it resides in exploiting two constraints: first take into account the presence of RT applications to determine the available capacity, second take into account the radio link quality in order to reduce the transmission error rate. In the presence of mixed applications, NRT application cannot be scheduled freely in the remaining radio resources because it could break the rules used for CAC. The scheduler has to be aware of the constraints on each time slot in a frame in order to determine the subset of radio resources eligible for soft constrained application. The scheduler has to take also into account the radio channel state to avoid transmitting under unfavorable conditions. This feature is called opportunistic scheduling. This opportunistic method may lead to favor only the flows of terminals that are under favorable radio conditions. To mitigate this effect, a fairness rule is introduced. This rule takes into account the relative priorities of the various flows. As a consequence a joint strategy between the physical layer and the MAC layer to allocate resources for RT and NRT applications may improve significantly the performance. This combined approach holds account of a uniform distribution of the transmitted power in downlink on different slots and adopts a scheduling based on channel state knowledge at the transmitter and complies with a fairness rule ensuring the priorities indicated by QoS.

This article is organized as follows: Part II presents the notion of resource and the Transport Channel architecture. Part III describes the RRM CAC minimum power based algorithm that allocates the resource to a user. Part IV covers the adopted opportunistic scheduling over wireless channels with a statistical fairness rule. Part V presents the simulation model based on Eurecom UMTS/TDD platform [10]. Part VI presents simulations and results and part VII concludes.

II. ARCHITECTURE

A. Resource

In this document a resource is an orthogonal code at a given slot that carries user data. A resource could be also called a physical channel. At a given TTI (Transmision Time Interval, 1 TTI = 10 ms), a resource could be used by only one user.

B. TRCH: Dedicated Channel and Downlink Shared Channel

A service is transported on a Transport Channel (TRCH). Transport channels are the services offered by layer 1 to the higher layers. A transport channel is defined by how and with what characteristics data is transferred over the air interface. TRCH include the Block Size, the type of error-correcting code, the rate of the error-correcting code, the CRC size (Cyclic Redundancy Check, for error detection) and the maximum puncturing rate. Two kinds of TRCH are usually used for sending data in the downlink: The Dedicated Channel (DCH) and the Downlink Shared Channel (DSCH).

DCH are TRCH that are used to carry user or control information between the Radio Access Network and a User Equipment (UE). A DCH is created at the start of the service. A DCH is mapped onto one or more physical channels. The set of the physical channels allocated to a DCH is indicated in the CCTRCH (coded composite transport channel). The physical channels of a DCH are reserved to this DCH during all the time of the service. RT applications are transported on DCH, because they are able to provide a continuous rate. The NRT applications are not transported on DCH. The number of physical channels of a DCH will be computed according to the resource required by the RT service.

DSCH are TRCH shared by several UE (User Equipement) carrying dedicated control or traffic data. In a frame, only one UE is allowed to use a DSCH, but the UE can change at every frame. A DSCH is configured during the Base Station initialization. The number of physical channels of a DSCH is variable. The list of the DSCH and the configuration of the DSCH are indicated to each UE at its initialization. In this document, all the DSCH have three physical channels. The UE of a TRCH is indicated in the TFCI field, in the first physical channel of the DSCH. NRT applications are transported on DSCH.

Figure 1 is an example of the resource repartition among DCH and DSCH. Nine slots are reserved for the transport of data on downlink. The Spreading Factor is set to 16, so 16 OVSF code are available by slot. The 8 first resources of each slot are reserved for the DCH. When a DCH is configured, at the start of an RT application, the resources allocated to it are removed from the list of the DCH free resources. The DSCH are configured at the Base Station initialization. Packets are selected from queues and transported by DSCHs according to the scheduling policy.

OVSF 15	DSCH 21	DSCH 21	DSCH 21	DSCH 22	DSCH 22	DSCH 22	DSCH 23	DSCH 23	DSCH 23
OVSF 14	DSCH 18	DSCH 18	DSCH 18	DSCH 19	DSCH 19	DSCH 19	DSCH 20	DSCH 20	DSCH 20
OVSF 13	DSCH 1	DSCH 3	DSCH 5	DSCH 7	DSCH 9	DSCH 11	DSCH 13	DSCH 15	DSCH 17
OVSF 12	DSCH 1	DSCH 3	DSCH 5	DSCH 7	DSCH 9	DSCH 11	DSCH 13	DSCH 15	DSCH 17
OVSF 11	DSCH 1	DSCH 3	DSCH 5	DSCH 7	DSCH 9	DSCH 11	DSCH 13	DSCH 15	DSCH 17
OVSF 10	DSCH 0	DSCH 2	DSCH 4	DSCH 6	DSCH 8	DSCH 10	DSCH 12	DSCH 14	DSCH 16
OVSF 9	DSCH 0	DSCH 2	DSCH 4	DSCH 6	DSCH 8	DSCH 10	DSCH 12	DSCH 14	DSCH 16
OVSF 8	DSCH 0	DSCH 2	DSCH 4	DSCH 6	DSCH 8	DSCH 10	DSCH 12	DSCH 14	DSCH 16
OVSF 7	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH
OVSF 6	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH
OVSF 5	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH
OVSF 4	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH
OVSF 3	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH
OVSF 2	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH
OVSF 1	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH
OVSF 0	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH	DCH
	Slot 0	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6	Slot 7	Slot 8

Fig. 1. Repartition of resource among DCH and DSCH

III. RRM MINIMUM POWER-BASED STRATEGY FOR CHANNEL ALLOCATION

A. RRM minimum power-based algorithm for downlink UMTS/TDD

In UMTS systems the RRM is in charge of handling air interface resources of radio access network in order to respect QoS constraints using techniques such as Power Control (PC), Handover Control (HO), Call Admission Control (CAC) and Load Control (LC). In the downlink, the transmitted power is the critical parameter to manage. Indeed, previous works [5] [6] proposed various RRM CAC entities that accept a user if the new service requires an additional power such that the Base Station maximum power is not exceeded. These approaches respect the constraints but do not guarantee a uniform repartition of power among slots. In this work, a minimum RRM power-based CAC algorithm is proposed. It guarantees a uniform repartition of the transmitted power with minimum fluctuations from one time slot to another. The main steps of this algorithm are:

1) Compute N, the number of resources requested by user for new service.
2) Check if the total number of free DCH resources in the slots allocated for the downlink is greater than the number of resources the user requests for its service.
3) Estimate ΔP, the power needed by a user per resource using power control information.
4) Search the minimum value of power among the slots (the best place where to put the resource). Let be Pi the overall power of the slot i, then:
   - Look for the $Pi + \Delta P$ minimum $\forall i$
   - $Pi + \Delta P$ must be lower than the threshold
   - Keep the best place (slot) found
5) Slot with the minimum power increase is found, if the sum of the power of all the allocated resources of the slot (included the new resource) is lower than a threshold, then allocate there the resource.
6) Repeat this operation for N resources requested by user.
7) If N resources are available, accept the application, otherwise release the DCH resources selected and reject the RT application.

IV. OPPORTUNISTIC SCHEDULING OVER WIRELESS CHANNEL

A. Wireless channel characteristics

Wireless channels are subject to several propagation effects as reflections, diffractions and scattering which cause time varying characteristics like bursty channel errors, location dependent errors. Consequently, the scheduler needs to know the channel state in order to optimize service scheduling and to give the transmission rigth to users with favorable channel conditions. In our scheme, the scheduler infers the channel state from the measurement reports sent by mobiles, relying on the reciprocity of the channel due to TDD operations.

B. Opportunistic scheduling over wireless channel with fairness rules

Scheduling packets over wire-line is a classical problem in network analysis, contrary to wireless network like UMTS which exhibits a time varying behavior because of the radio channel. In addition, providing transmission of multiple data flows with different QoS constraints over wireless channel represents one of the most important requirements of UMTS networks, consequently we have to design scheduling of mixed services and adopt a judicious strategy to jointly allocate resources for RT and NRT flows. Because of its hard constraints, RT traffic has to be treated in priority by the RRM layer which will allocate resources depending on CAC algorithms. When the power among the slots is controlled by the CAC of a RT application, it is supposed that no NRT application is present. Furthermore, at each TTI, before the use of a DSCH by a NRT application, the CAC controls among the slots of this DSCH, if using this DSCH does not make the power exceed the threshold on the slots. This control takes into account the presence of the RT application. If the use of the DSCH makes exceed the threshold, the DSCH is not used. So the number of DSCH available at a TTI is variable. To allocate the available DSCH, we can adopt different approaches. Many works choose to maximize users rate according to the channel condition in a selfish manner [7]. Unfortunately these approaches could be prejudicial to the users facing unfavorable radio conditions and therefore would never get access to the channel. For this reason, we have to consider some fairness rules to guarantee the access for all users. Liu [9] proposes an interesting approach which combines an opportunistic scheduling based on the channel state and one statistical fairness rule to share access to the channel. In our approach, we follow this method to schedule NRT flows and choose to balance the choice of the flow to be served between channel state and fair channel access according to UMTS QoS priorities. We also take into account the fact that NRT flows will not degrade the rule of uniform distribution of the power adopted by the RRM process for RT flows. The scheduling algorithm selects flows according to the equation developed in [9]:

$$f_{p+1} = argmin_{i \in B(p)} \frac{L_i(p) - K_i(p) + U_i(p)}{\phi_i} \quad (1)$$

Where $f_{p+1}(p)$ is the selected flow at time p+1, $B(p)$ is the set of backlogged flows at time p, $L_i(p)$ is the Head Of Line (HOL) packet length of flow i, $K_i(p)$ is the flow associated credit updated according to the Credit Based Fair queuing approach [8], ϕ_i is the weight of flow i given by the QoS priorities and $U_i(p)$ is the cost function at time p. In the implementation of this opportunistic scheduling algorithm, the cost function U_i and channel state E_i are related by:

$$U_i = -\beta log(1 - E_i) \quad (2)$$

Transmission to a user is delayed when he is facing unfavorable radio conditions and has a low credit. During the time when transmission is delayed, his credit is increased. When his credit is high, he is served even if the channel conditions are unfavorable.

By varying the β value of the cost function in equation (2), the importance of the channel state in the service selection algorithm will change. Note that, with β = 0, the scheduling considers only the weight of the services, and not the channel state.

The quality of the fairness could be measured by:

$$\frac{\left(\sum \frac{x_i}{\phi_i}\right)^2}{n * \sum \left(\frac{x_i}{\phi_i}\right)^2} \quad (3)$$

Where ϕ_i is the weight of the user, x_i is the proportion of traffic given to user i, and n is the number of users. When this ratio is close to 1, the scheduling is fair.

When all the users have the same priority, the formula becomes:

$$\frac{\left(\sum x_i\right)^2}{n * \sum {x_i}^2} \quad (4)$$

That is the Jain's fairness index [11].

V. Simulation model

Experiments on the UMTS Eurecom platform have been performed. This platform, which is compliant with the 3GPP specification, offers a Radio Access Network divided into the following layers: RLC (Radio Link Control), MAC (Medium Access Control) and Physical Layer. The RLC receives packets (SDU, Service Data Unit), from the upper layer. It segments them into PDU (Protocol Data Unit) of size 336 bits (320 bits for the data field, and 16 bits for the header). The MAC layer asks a number of PDU from the RLC according to the results of the scheduling. The physical layer is in charge of error correction and detection. The rate 1/2 convolutional code of is used.

The resources are configured as in figure 1. Half the resources are reserved to the DCH, and there are 24 DSCH of 3 resources each. Those DSCH could carry one PDU (So an instantaneous rate of 32 kbit/s). There is no limit to the number of DSCH that a user can listen to in a frame. 10 NRT services are set. To evaluate the quality of the fairness rules, the RLC queues of the NRT services are considered full. The DCH is configured at the initialization of the service, after the authorization of the Access Control. A DCH takes resources with respect to the service requirements between the free resources reserved to the DCH. The rate of the RT services is 196 kbit/s. In this configuration, the DCH of a RT service uses 7 resources. The arrival law of the RT applications and the duration of the services have a Poisson law of rate respectively λ = 0.05 and μ = 0.0083. (respectively average time of 20 and 120 seconds). The following channel model is used: a 10 state Markov chain, from the state 0, channel with few error, to state 9, channel of bad quality. The channel state can increase or decrease with increment 1 with a probability of 1/3, and stay at the same state with a probability of 1/3 (It remains in state 0 with a probability of 2/3, and it goes from the state 9 to the state 8 with a probability of 2/3). The state 0 has an Eb/N0 of 3.3 dB, and the state 9 of 1.5 dB. The step between two states is of 0.2 dB. (2) becomes here:

$$U_i = -\beta log(1 - \frac{1}{S_i}) \quad (5)$$

where S_i is the number of the current state. The value of maximum power by slot is normalized to 1.

VI. Simulations and results

A. CAC and DCH allocation

First the CAC and resource allocation strategy is compared with two other strategies. It is shown that the considered scheme gives the best results in terms of minimum power. In a second step, the trade off (choice of β) is analyzed between the opportunistic scheduling and the fairness rule and the effect on the radio channel efficiency is quantified.

The distribution of the allocated power of the RRM Power Based algorithm was compared to a sequential algorithm: It allocates to a user its required resources columnwise (figure 2). It start to take resources in the first slot, and goes to the next slot, only if the use of a new resource makes exceed the power treshold, or if there is not any free resource in this slot.

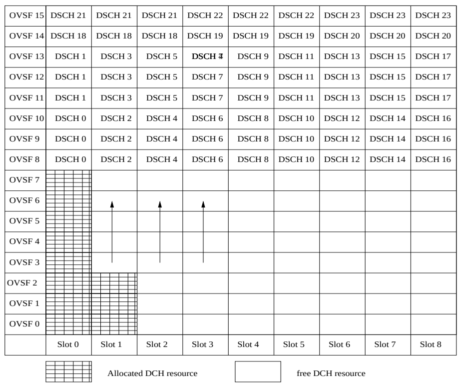

Fig. 2. Sequential algorithm

Figure 3 shows the average normalized power on each slots with respect to the allocation algorithm. The sequential algorithm has an unbalanced power repartition. The slots on the lefts, the ones used first, have a higher power average than the one on the righ, what are used only if there are a large number of simultaneous RT applications. On the contrary, the power based algorithm has a balanced power.

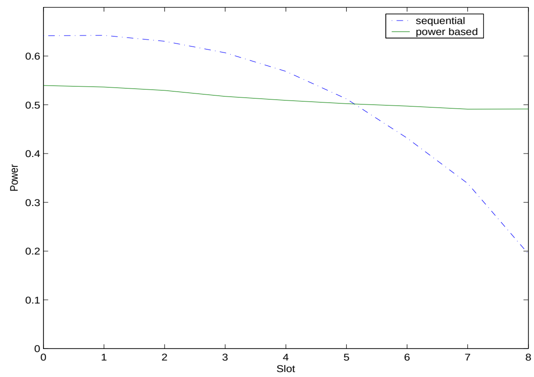

Fig. 3. Average power by slot with respect to the allocation algorithm

The CDF (figure 4) confirms the sequential algorithm as an important deviation in its power distribution when the power based as a distribution more centralized on the average. As the probability to have unused slots is of 14%, the CDF of the sequential algorithm is not null in zero.

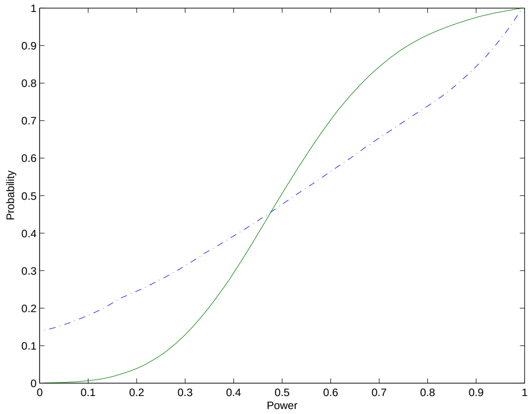

Fig. 4. Average power by slot with respect to the allocation algorithm

Figure 5 shows the reject call rate of the two algorithms. The reject call rate of the power based is better than the one of the sequential algorithm. It is due to more balanced powers among slots. With the sequential algorithm, slots could use all their resources and still have a total power lower than the maximum allowed total power. And at the same time, other slots could have reach the thresholds, but with using only few resources. As a consequence the unused resources are not available. This scenario is not likely with the power based algorithm.

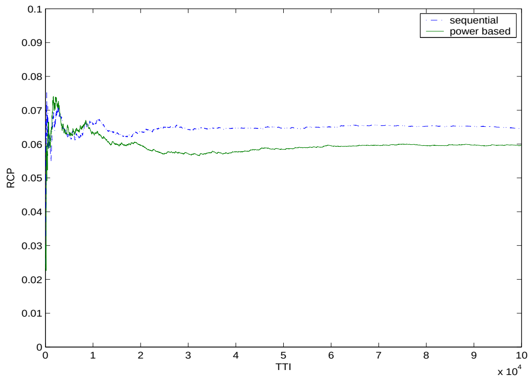

Fig. 5. Rejected Call Rate for RT for RT traffi c

Table 1 shows the effects of the power repartition. The Reject Call Probability (RCP) is calculated by:

$$RCP = \frac{rc}{nc} \quad (6)$$

Where rc is the number of rejected call, and nc is the total number of call. The DSCH load is calculated by:

$$DSCHLoad = \frac{Numblock}{nDSCH * nTTI} \quad (7)$$

Where Numblock is the total number of Transport Block of NRT applications transported, nDSCH is the number of DSCH in the frame configuration, and nTTI is the number of TTI of the experience.

B. Scheduling

Now, the behavior of the scheduling is analyzed. 10 NRT services with various radio channel qualities sharing the DSCH

	RCP	DSCH Load
Sequential	$6.45 * 10^{-2}$	0.464
Power Based	$5.96 * 10^{-2}$	0.479

Tab. 1. Effects of the power repartition

resources have been considered. A DSCH is used only if the additional power induced by the DSCH utilization does not exceed the power threshold limit.

The 10 services are supposed to have different weights. The first 5 have a weight of 0.081, the next 3 have a weight of 0.108, and the last 2 have a weight of 0.135 (the sum of all the weights is 1). But, the scheduling also takes into account the channel state. Thus, a user with a favorable channel will be preferred with respect to a user with an unfavorable one. The objective is to increase the link reliability. By varying the value β of the cost function in equation (2), the importance of the channel state in the service selection algorithm will change. Note that, with $\beta = 0$, the scheduling considers only the weight of the services, and not the channel state. The objective is to assess the performance of the scheduling scheme in terms of BLER while maintaining an acceptable degree of fairness.

Table 2 indicates the average BLER corresponding to PDU Error Rate for a simulation period of $20s$ for NRT services with respect to β. For all β values, the BLER figures given in table 2 are in line with the recommendation of 3GPP specification [12]. The best value is obtained for β = 100 000.

β	Block Error Rate
0	7.9*10 -2
10 000	5.8*10 -2
100 000	2.1*10 -2

Tab. 2. Block Error Rate

Figures 6-8 show the behavior of the scheduler with respect to β. The solid line shows the evolution of the channel state during the simulation time. The bars indicate the number of PDUs served for a given user with respect to the TTI. In figure 6, for (β = 0), the scheduling behavior is similar to a weighted round robin: DSCH are regularly allocated to the service. In figure 7, (β = 10 000),

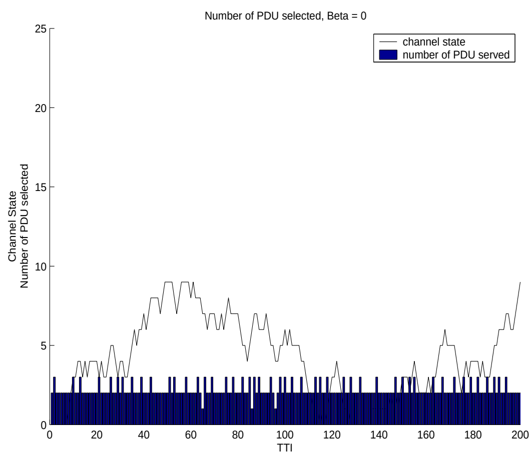

Fig. 6. β = 0

we observe that the service is irregularly served. When the channel conditions are bad, the service could be not served for a short time. However as soon as the channel conditions become little better, the service is allowed to send packets. When the channel of the user is good for a long time, the behavior becomes close to a weighted round robin. In figure 8, (β= 100 000), the scheduling strongly

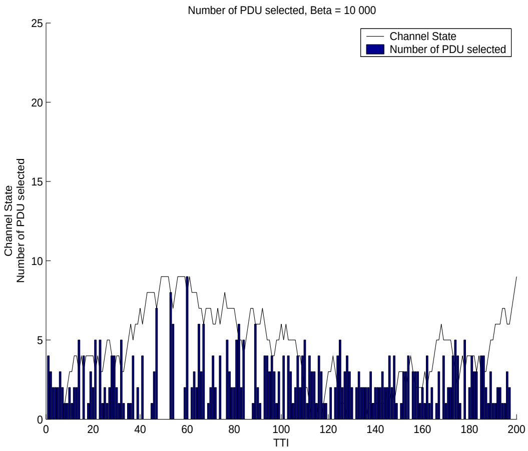

Fig. 7. β = 10 000

follows the channel state. There is an important variation in the way a service is treated over time. When the channel conditions are bad, the appliation is not served for a long time, but when the channel condition becomes better, the service receives a large amount of PDUs (close to the maximum that could be allowed in a frame).

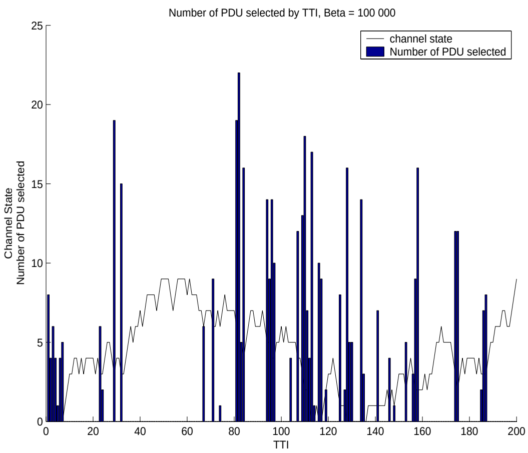

Fig. 8. β = 100 000

Table 2 indicates the proportion of resources allocated to services. For β = 0, the proportion of resources is very close to ϕ_i: The behavior is similar to Weighted Round Robin. The level of fairness is measured using the index (3). The values of the index are 1, 0.9999 and 0.9975 for respectively β = 0, 10^4 and 10^5. The index shows the behavior of the scheduling is fair.

When the RT applications are allowed to be transported on DSCH, the number of resource available for the NRT applications decreases. But the proportion of resources allocated to the services is similar at table 2. The flexible allocation does not change the scheduling behavior.

VII. Conclusions

In this paper, we present a joint RRM channel allocation algorithm with an opportunistic scheduling. This algorithm provides guaranteed resources for RT applications and fair scheduling and priortization for NRT applications.

Service Id	β = 0	β = 10 000	β = 100 000
0	0.081	0.082	0.086
1	0.081	0.081	0.087
2	0.081	0.080	0.084
3	0.081	0.081	0.080
4	0.081	0.081	0.078
5	0.108	0.107	0.105
6	0.108	0.108	0.112
7	0.108	0.109	0.109
8	0.135	0.137	0.137
9	0.135	0.134	0.121

Tab. 3. Proportion of resources allocated to service

Moreover, comparing the power based algorithm with the sequential algorithms, we can see that the power based algorithm better balances the power over the slots. This better balancing decreases the rejected call rate and increases the available resources for NRT applications. The NRT traffic does not disturb the RT traffic, since the opportunistic scheduling and the CAC are joint. The opportunistic scheduling has a fair behavior and reduces the BLER.

References

[1] I. Forkel, T. Kriengchaiyapruk, B. Wegmann, E. Schulz "Dynamic channel allocation in UMTS terrestrial radio access TDD systems", *Vehicular Technology Conference, IEEE VTS 53rd, Volume: 2 , Pages:1032 - 1036 vol.2*, May 2001.

[2] M. Adamou, S. Khanna, Insup Lee, Insik Shin, Shiyu Zhou,"Fair real-time traffi c scheduling over a wireless LAN" *Real-Time Systems Symposium, 2001. (RTSS 2001). Proceedings. 22nd IEEE, Pages:279 - 288*, December 2001.

[3] Elmallah, E.S.; Hassanein, H.S."A power-aware admission control scheme for supporting the assured forwarding model in CDMA cellular networks", *Local Computer Networks, 2002. Proceedings. LCN 2002. 27th Annual IEEE Conference, Pages:211 - 219*, November 2002.

[4] Al-Meshhadany, T.; Al Agha, K.; "A new code allocation scheme for UMTS system", *Vehicular Technology Conference, 2001. VTC 2001 Fall. IEEE VTS 54th ,Volume: 2 , Pages:930 - 933 vol.2*, 7-11 Oct. 2001

[5] H. Holma, A. Toskala,"'WCDMA for UMTS, Radio Access for Third Generation Mobile Communications", *Wiley*, 2000.

[6] I. Forkel,B. Wegmann, E. Schulz,"On the capacity of a UTRA-TDD network with multiple services", *ICC 2002. IEEE International Conference on ,Volume: 1 , Pages:585 - 589*, April 2002.

[7] C. Schurgers,M.B. Srivastava," Energy optimal scheduling under average throughput constraint", *ICC 2003. IEEE International Conference on Communications ,Volume: 3, Pages:1648 - 1652*, May 2003.

[8] B. Bensaou, K. Chan, and D. Tsang, "Credit-based fair queuing (CBFQ): A simple and feasible scheduling algorithm for packet networks," *IEEE ATM97 Workshop, pp. 589594*, May 1997.

[9] Yonghe Liu, S. Gruhl, E.W. Knightly,"WCFQ: an opportunistic wireless scheduler with statistical fairness bounds", *IEEE Transactions on Wireless Communications, Volume: 2 , Issue: 5, Pages:1017 - 1028*, September 2003.

[10] C. Bonnet, H. Callewaert,L. Gauthier,R. Knopp, A. Menouni Hayar,Y. Moret,D. Nussbaum, I. Racunica, M. Wetterwald,"Open-source experimental B3G networks based on software-radio technology ", *Software Digital Radio Forum*, Orlando, USA, November 2003.

[11] Jain Raj, "The art of computer systems performance analysis : techniques for experimental design , measurement , simulation , and modeling", *John Wiley & Sons*, 1991.

[12] 3GPP 25102-530, "UE Radio Transmission and Reception (TDD)"