Towards Balancing User Satisfaction and Operator Revenue in Beyond 3G Cognitive Networks

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Abstract – **An economic driven JRRM algorithm is introduced in a multicell scenario based on guaranteeing a certain user acceptance probability of a given service while at the same time increasing the network provider revenue. It includes both service price and user utility and allows an operator to envisage the price impact on the final revenue attained. The paper focuses on two profiles, namely consumer and business and reflects that the proposed algorithm is able to adapt to the needs of each profile. A realistic UMTS, GERAN and WLAN scenario is considered.**

I. Introduction

Today's wireless communications comprise a broad variety of Radio Access Technology (RAT) standards. In Europe, the success of second-generation (2G) cellular system GSM (Global System for Mobile Communications) and the IP data connectivity support provided by GPRS (General Packet Radio System) paved the way towards evolved systems with higher data rate capabilities, such as the Enhanced Data rates for GSM Evolution (EDGE) and finally the third-generation (3G) Universal Mobile Telecommunications System (UMTS). Moreover, in parallel with the evolution of cellular systems, several types of Wireless Local Area Networks (WLANs) like, e.g., the IEEE 802.11x standard emerged and became profusely used in home environments.

These new scenarios must indeed be regarded as a new challenge to offer services to the users over an efficient and ubiquitous radio access by means of coordinating the available RATs. In this way, not only the user can be served through the RAT that fits better the terminal capabilities and service requirements, but also a more efficient use of the available radio resources can be achieved. On the other hand, the introduction of reconfigurability capabilities at different levels of the network (end user terminal, radio access points, etc) [1] opens new perspectives in the manner all the today's and next future available RATs are managed. Indeed, in a multi radio environment, the capabilities brought by reconfigurable equipments offer the possibility to increase spectrum efficiency by developing appropriate mechanisms allowing a better management of radio resources in near real time (i.e. at frame level scale). This challenge calls for the introduction of new radio resource management (RRM) algorithms operating from a common perspective that takes into account the overall amount of resources offered by the available RATs, and therefore are referred to as JRRM (Joint Radio Resource Management) algorithms. Furthermore, for a proper support of such algorithms, suitable network architectures and procedures must ensure the desired interworking capabilities between the different technologies.

In this framework, introducing cognition processes is of up most importance. They are associated with technologies that operate in a complex environment, observe it, make behaviour choices, and receive feedback from it, while learning to help determining future behaviour based on past and current feedbacks [2].

Clearly, the objective of the network operator is to support its customers with the required QoS in a profitable way. Operator's profit depends, on one hand, on a large variety of CAPEX (Capital Expenditure) and OPEX (Operational Expenditure) components, while on the other hand on the revenue, which is directly influenced by the pricing strategy. In more detail, coverage, radio link quality (e.g. bit error rate) and maximum capacity are the result of the operator's investment on radio network infrastructure [3] as well as the dynamic management of the radio resources (through JRRM strategies in the case of heterogeneous RANs).

Even though technical issues related to the dynamic operation of the network have traditionally been targeted quite independently from economic aspects, research community has already identified the need for a major interaction. In this context, this paper represents a step forward in this direction by introducing revenue considerations into radio-interface management decisions. In particular, a complete framework for JRRM in a UMTS/GERAN/WLAN scenario is proposed, including the user's satisfaction and the operator's revenue into the decision making process for the RAT selection and bandwidth allocation. It is worth noting that the proposed approach introduces techno-economic cognitive mechanisms, so that the JRRM decisions auto-adapt themselves to the changing traffic, mobility and propagation conditions in order to keep the target on user's satisfaction, which in turn is mainly driven by the price and the utility given to the offered service. It is shown that this leads to improved revenue for the operator compared to the case where only technical aspects are considered.

The rest of the paper is organised as follows. In Section II, the traditional approach for JRRM is described, accompanied by reference solutions. Section III is devoted to describe how pricing and revenue mechanisms have been considered so far in the wireless communications arena. In turn, Section IV develops the proposed solution based on a techno-economic fuzzy-neural machine. Section V presents some illustrative simulation results supporting the rationale of the proposed approach. Finally, Section VI summarises the conclusions.

II. JOINT RADIO RESOURCE MANAGEMENT

JRRM refers to the set of functions that are devoted to ensure an efficient use of the available radio resources in heterogeneous networks scenarios by means of a proper coordination between the different RATs. In turn, when a heterogeneous scenario is considered, some additional functionalities arise, like the initial RAT selection (i.e. the functionality devoted to decide to which RAT a given service request should be allocated at the set-up phase) and the vertical (inter-system) handover (i.e. the functionality devoted to decide a seamless RAT switching for an on-going service) [2]. JRRM strategies may be useful to support a variety of objectives, such as avoiding disconnections due to lack of coverage in the current RAT, blocking due to overload in the current RAT, possible improvement of QoS by changing the RAT, support of user's preferences in terms of RATs, support of operator's preferences for RATs usage or load balancing among RATs.

JRRM entity is responsible for the QoS guarantee and monitoring of the different radio interfaces. The QoS may be expressed in a variety of parameters, ranging from system-level performance indicators (e.g. blocking probability), to connection level figures (e.g. average bit error rate, average packet delay, etc.). Furthermore, smart JRRM algorithms may lead to capacity gains, thanks to the exploitation of the resource sharing leading to a potential trunking gain.

It is worth mentioning that JRRM has been identified as an important issue by the 3GPP from an architectural point of view [5][6], as well as by the research community. The literature has covered the effects of load balancing in inter-RAT handover procedures. In particular, in [7], the effect of tuning the load-based handover (HO) thresholds depending on the load of inter-system/inter-layer/inter-frequency cells is studied. In [8], a force-based load balancing approach is proposed for initial RAT selection and vertical HO decision making. In turn, in [9] the authors compare the load balancing principles with respect to service-based policies. Similarly, Lincke discusses the problem from a more general perspective in e.g. [10] and references therein, comparing several substitution policies and evaluating them by means of simulations. Finally, in [11] a fuzzy-neural based strategy for JRRM operation was presented by the authors, including a reinforcement learning mechanism to adapt the algorithm in order to achieve the desired QoS constraints. In this context, the user satisfaction was associated with the minimum bandwidth allocated to the users. Consequently, a user was considered dissatisfied if its bandwidth allocated was below the contracted one. However, the users' feelings also depend on the price paid for the service, so that both the users' and the operator satisfaction depend on the bandwidth allocated and pricing policies. In this sense, this paper aims at including in the technical framework presented in [11] microeconomic considerations.

III. PRICING AND REVENUE IN WIRELESS NETWORKS

Several works in the open literature have addressed the inclusion of economic concepts in the development of different types of algorithms for wireless networks [12]. In that sense, one of the key driving indicators is the notion of *user acceptance* of a given service. This can be defined as the probability that the users are satisfied with the service obtained from the network in accordance with the price they are paying, and therefore they stick to the network [13]. Therefore, the acceptance depends on the one hand on the utility that the user perceives from the network for a given service, which is related mainly with QoS parameters like, e.g. bandwidth, delay, etc., and on the other hand on the price that the user is paying for that service. Furthermore, the acceptance should be an increasing function of the utility and a decreasing function of the price.

The utility is a function that depends on the specific service characteristics and the elasticity of the applications [14]. Particularly, an application can be inelastic, meaning that the utility is modelled as a step function with only two values, either good or bad, depending on e.g. whether the allocated bandwidth *B* is above or below a given threshold, as illustrated in Figure 1. Some examples in this category would be the real time voice or video applications with constant bit rate. On the contrary, other applications, e.g. typically data applications, exhibit more elastic behaviours in the sense that the utility is a smoother function of the allocated bandwidth, as depicted in Figure 1. Some utility models focusing on different quality parameters like delay or signal-to-interference-ratio are presented in [15][16].

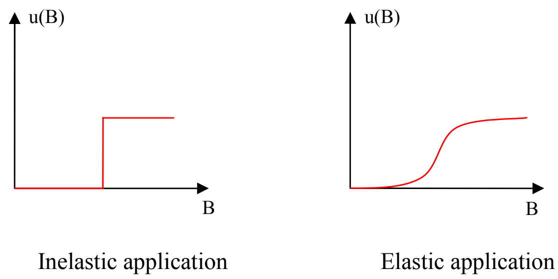

Figure 1 Utility functions for elastic and inelastic applications

From the point of view of the network operator, pricing strategies should be devised in order to determine the price that should be paid for the access to the different services with specific user profiles. Here the objective is to maximize the obtained revenue by taking into account the user behaviour with respect to one or another price, captured with the definition of a proper acceptance function. Then, the revenue can be formulated as a function of the price that the users are paying and of the user acceptance, in the sense that only users accepting the service will be in practice generating revenue. This leads to the following definition of revenue [13]:

$$R = \sum_{i=1}^{N} p_i A(u_i(B_i), p_i) \quad (1)$$

where N is the number of users, p_i is the price paid by the i-th user, B_i its bandwidth and A(u,p) the user acceptance, as a function depending on both utility and price, with a tuning similar to the Cobb-Douglas demand curves widely used in economics, which can be modeled by:

$$A(u,p) = 1 - \exp(-Cu^{\mu} p^{-\varepsilon}) \quad (2)$$

where C, μ and ε are constants representing the different user sensitivity to utility and price. In [13] these economic concepts are used to devise a rate allocation algorithm so that users are satisfied with the received service and the price paid while at the same time revenue can be maximized.

Pricing strategies are typically classified into static and dynamic pricing [17]. In static pricing the price of the different services is either fixed or is only changed at specific periods of the day or the week, i.e. the so-called time-of-day pricing, in which the price is higher during e.g. the working days than during weekends or in the night. In turn, the dynamic pricing strategies consider the price as an additional network parameter that can be changed during relatively short periods of time in order that the network operates always with the optimum price according to the available resources and the existing demand. Some static pricing models were proposed initially in [18] and in [19], where a reservation based pricing is proposed. In [20] a dynamic pricing strategy is applied to devise a network congestion control. Other applications of dynamic pricing are in the development of admission control [21], power control [22] and packet scheduling [23] algorithms. Concerning Dynamic Spectrum Allocation (DSA), the pricing concepts have been introduced in [24] where a scheme for choosing the appropriate pricing in short-term spectrum licenses is presented.

IV. Economic-Driven JRRM

The proposed economic-driven JRRM is based on fuzzy neural methodology and operates in a heterogeneous scenario aiming at selecting the most appropriate RAT and bandwidth for each active use in the system. The proposed scheme is plot in Figure 2 and consists of two main blocks, a Fuzzy Neural Controller (FNC) and a Multiple Objective Decision Maker (MODM). The inputs of the algorithm are of the following nature:

a) Technical inputs: They consist of measurements of the signal strength SS_k and resource availability RA_k for each RAT k. Mobile speed MS is included to take into consideration mobility constraints in the RAT allocation.

b) Economic inputs: They consist of the price p_j to be paid for service j, in the revenue estimation R according to (1) and on the desired total user acceptance A(u,p).

c) Operator policies: They consist in a set of high-level directives that specify the construction of the inference rules in the fuzzy neural block and the operation of the decision maker.

The FNC consists of a Fuzzy Logic Controller (FLC) and a reinforcement learning algorithm. The FLC is organized into three procedures, denoted as fuzzification, inference engine and defuzzification whose mission is to make a selection of the appropriate RAT and bandwidth taking into account the technical inputs. The details of the operation of the FLC are described in [11]. The reinforcement learning procedure aims at tuning the different membership functions in the fuzzification and defuzzification processes in order to adapt the network to the current conditions and to learn from the experience the way to satisfy a target criterion. Then, this procedure embeds the cognitive-based mechanisms letting the network be aware of its current status in terms of user traffic and position variations. More specifically, the criterion considered in the proposed economic-driven JRRM will be to achieve a specific value of the overall user acceptance *A(u,p)*. Notice that, according to (1), for a given price a high user acceptance turns into a high operator revenue. The reinforcement learning algorithm will try then to minimise the following error:

$$E(t)=\frac{1}{2}\left(A^{*}-A(t)\right)^{2} \qquad (3)$$

where $A(t)$ is the user acceptance *A(u,p)* averaged for all the users at the time t and A^* is the target value. For each user, the actual acceptance depends on the FNC allocated bandwidth, as it is explained below, and on the price charged according to the user profile.. For details on the operation of the reinforcement learning algorithm the reader is referred to [11], where only bit rate considerations were made in the definition of the reinforcement signal.

The outputs of the FNC are:

a) The RAT selected by means of the so called FSD parameter (Fuzzy Selected Decision), which is an indicator of the appropriateness of selecting a RAT in front of another one.

b) The most appropriate bandwidth B that should be allocated to the active users in each RAT.

Finally, the MODM is in charge of performing the selection of the specific RAT and bandwidth combining the output of the fuzzy-neural JRRM with revenue considerations in order to maximize revenue while keeping the desired user acceptance. Particularly, the MODM is based on the combination of fuzzy logic with the Analytic Hierarchy Process (AHP) presented in [25][26] and is here used with two decision criteria, namely the FSD values corresponding to the different RATs and the revenue that would be obtained by the operator selecting the different RAT and allocating the corresponding bandwidth suggested by the FNC. The two decision criteria are characterized by the same importance in order to obtain the final decision regarding the RAT and the bandwidth. For details the reader is referred to [25][26]. It is worth noting that *p* is a fixed price parameter in all the above procedure. However, it could also be set in a medium or long term dynamic way, depending on spatial-temporal average traffic fluctuations and operator agreements, if any. Nevertheless, this is out of the scope of this paper,

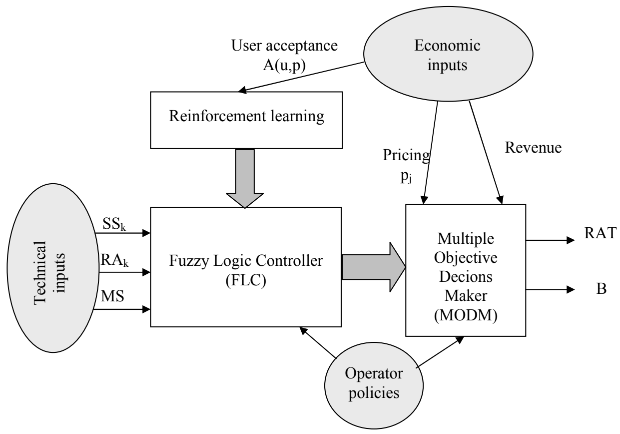

Figure 2 Economic-driven JRRM algorithm

V. Results

The proposed economic-driven JRRM is evaluated in a multicell scenario, with a seven cell deployment, including 4 UMTS base stations, 2 GERAN base stations and one WLAN access point, as it is shown in Figure 3. Each cell is characterized by a given coverage area and its corresponding RAT. The considered scenario consists of circular cells, with radii 150m for WLAN, 650m for UMTS and 1km for

GERAN. A mobility model with users moving according to a random walk model inside the coverage area is adopted with a randomly assigned mobile speed (MS) in the interval [0,50] km/h and a randomly chosen direction. The propagation model considered for UMTS and GERAN is given by L=128,1+37,6 log d (km), which assumes that the frequency band is similar for both systems [27]. For WLAN the propagation losses inside the hotspot are modeled by L= 20 log d(m)+40 [28]. The shadowing model considers a standard deviation of 7 dB and a decorrelation length of 20m.The beginning and the end of the user's activity periods are defined according to a Poisson scheme with an average of 6 calls per hour and user and average call duration of 180 seconds. The set of available bit rates in UMTS are {32 kb/s, 48 kb/s, 64 kb/s, 80 kb/s, 96 kb/s, 112 kb/s, 128 kb/s, 192 kb/s, 256 kb/s, 320 kb/s, 384 kb/s}, considering a single UTRAN FDD carrier with maximum allowed uplink load factor 0.75. For GERAN, the set of bit rates is {32 kb/s, 48 kb/s, 64 kb/s, 80 kb/s, 96 kb/s}, assuming a total of four carriers available and coding scheme CS-4. For WLAN it is considered that the total bandwidth available (11 Mb/s) is equally distributed among the WLAN users (i.e. the higher the number of users the lower the bandwidth per user will be). It is also assumed that no more WLAN users are accepted when the bandwidth per user is less or equal than 384 kb/s. A single access point is considered.

A static pricing is considered in which the price p is proportional to the allocated bandwidth (i.e. $p=0.01\cdot B$). The utility function as a function of the allocated bandwidth B is [13]:

$$u(B)=\frac{\left(B/K\right)^{\xi}}{1+\left(B/K\right)^{\xi}} \quad (4)$$

where K=2 and ξ=2.2 have been set for illustrative purposes. Actually, reliable user utility functions can be obtained through field tests and user survey.

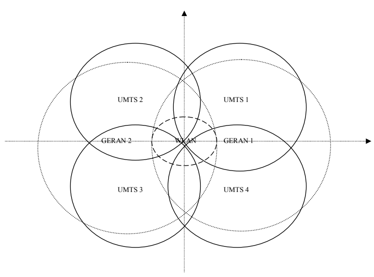

Figure 3 Considered Multicell scenario

From the point of view of user acceptance, and in order to consider that different users may exhibit a different sensitivity to the specific service, two user profiles, are defined for illustration purposes, whose acceptance functions as a function of the allocated bandwidth are plot in Figure 4. (i.e. μ=2 and ε=1.5 for consumer users and μ=40 and ε=2.5 for business users) The consumer profile represents the population segment for which the price may be more relevant than the allocated bandwidth and therefore its acceptance is high even for relatively low bandwidths and decreases very fast for high bandwidths because they are not willing to pay for them. On the contrary, the business profile represents the population segment for which the most important thing is the allocated bandwidth rather than the price. Consequently their acceptance is low for low bandwidths and decreases slowly for high bandwidths.

Table 1 and Table 2 present some illustrative performance figures of the considered algorithm in the cases that the RAT selection decision is made according to the fuzzy neural JRRM presented in [11], which considers only technical criteria (denoted here as technical-driven JRRM), or according to the economic-driven fuzzy neural JRRM. In the later case, two different solutions have been envisaged. The first one bases the JRRM decision just on the fuzzy neural JRRM outputs (i.e. without the MODM block in Figure 2), whereas the second one also includes the MODM block in Figure 2, for revenue maximization. In

Table 1 and 2 a total of 100 consumer and business users have been considered, respectively. In the case of economic driven JRRM, the target user acceptance in the reinforcement algorithm is 0.8. In turn, in case of the technical-driven fuzzy neural JRRM, the satisfaction probability (i.e. the probability that the allocated bandwidth is above the satisfaction bandwidth) is set to 80%, for comparison purposes with the economic driven implementation. Similarly, and to allow a fair comparison, the satisfaction bandwidths in the technical-driven case are selected as the minimum bandwidths allocated in more than 80% of the cases by the economical-driven JRRM (i.e. the 20-th percentile of the allocated bandwidth distribution).

Focusing on the economic-driven JRRM, the higher willingness of business users to pay for high bandwidths turns into an overall increase in the allocated bandwidth with respect to consumer users. Similarly, and due to the higher bit rates available in UMTS, the allocation of business users in UMTS is higher than the allocation in GERAN, particularly when only fuzzy neural JRRM is considered, while the opposite occurs for consumer users. Notice also that the inclusion of the MODM aimed at revenue maximization turns into an increase in the total revenue obtained for both consumer and business users at the expense of slight performance degradation in terms of blocking and dropping rate, which in all cases is below 1%. In addition, notice that the economic-driven JRRM provides higher revenues to the operator and higher bandwidth allocated for the users, than the technical-driven JRRM approach, where the RAT selection and bandwidth allocation do not take into account neither revenue nor price.

VI. CONCLUSIONS AND FUTURE WORK

This paper has included the economic concepts based on user acceptance and pricing in the JRRM problem. To this end, a JRRM algorithm able to select the appropriate RAT and bandwidth in a heterogeneous B3G scenario has been presented. The algorithm keeps a certain constraint in terms of user acceptance, depending on the utility and the price, and is capable of increasing the revenue through a multiple criteria decision making process. Furthermore, different user profiles depending on the sensitivity to price and utility have been considered, showing that the algorithm is able to adapt to the specific user requirements. Further work involves the global optimization of the price to achieve maximum revenues.

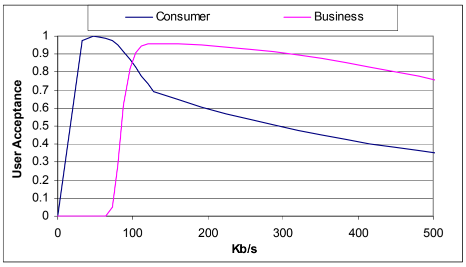

Figure 4 User acceptance for the two user profiles

Table 1 Consumer Performance figures

	Technical-Driven JRRM	Economic-Driven JRRM	
		Fuzzy-Neural JRRM only	Fuzzy-Neural JRRM + Decision Maker
% UMTS Selection	35	45	49
% GERAN Selection	63	54	49
%WLAN Selection	2	1	2
Revenue	1.17	1.66	1.83
Average assigned bandwidth	84.5 Kb/s	115.3 Kb/s	132.8 Kb/s

Table 2 Business Performance figures

	Technical-Driven JRRM	Economic Driven JRRM	
		Fuzzy-Neural JRRM only	Fuzzy-Neural JRRM + Decision Maker
% UMTS Selection	50	54	58
% GERAN Selection	48	45%	35
%WLAN Selection	2	1	7
Revenue	2.5	3.06	3.4
Average assigned bandwidth	157 Kb/s	171.8 Kb/s	203.1 Kb/s

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REFERENCES

[1] E2R Project. http://e2r.motlabs.com

[2] R. W. Thomas, L. A. DaSilva, A. B. MacKenzie, "Cognitive Networks", 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, Baltimore (USA), November 2005

[3] D. Avidor, D. Furman, J. Ling, C. Papadias, "On the Financial Impact of Capacity-Enhancing Technologies to Wireless Operators", IEEE Wireless Communications, Vol. 10, No 4, August 2003.

[4] J. Pérez-Romero, O. Sallent, R. Agustí, M.A. Díaz-Guerra, *Radio Resource Management Strategies in UMTS*, John Wiley&Sons, 2005

[5] 3GPP TR 25.881 v5.0.0 "Improvement of RRM across RNS and RNS/BSS".

[6] 3GPP TR 25.891 v0.3.0 "Improvement of RRM across RNS and RNS/BSS (Post Rel-5) (Release 6)".

[7] A. Tölli, P. Hakalin, "Adaptive load balancing between multiple cell layers", IEEE 56th VTC 2002-Fall, Vol. 3, 24-28 Sept. 2002 pp.1691 – 1695.

[8] A. Pillekeit, F. Derakhshan, E. Jugl, A. Mitschele-Thiel, "Force-based load balancing in co-located UMTS/GSM networks", VTC 2004-Fall. 2004 IEEE 60th Vol. 6, 26-29 Sept. 2004 pp. 4402 – 4406.

[9] X. Gelabert, J. Pérez-Romero, O. Sallent, R. Agustí, "On the suitability of Load Balancing Principles in Heterogeneous Wireless Access Networks", Wireless Personal Multimedia Communications Symposium (WPMC'05), Aalborg, Denmark, September, 2005.

[10] S. J. Lincke "Vertical handover policies for common radio resource management", International Journal of Communication Systems 2005; Published Online: 15 Mar 2005. DOI: 10.1002/dac.715.

[11] L. Giupponi, R. Agusti, J. Pérez-Romero, O. Sallent, "Joint Radio Resource Management algorithm for Multi-RAT networks", IEEE Globecom, San Luis, USA, November, 2005.

[12] T.Giles, J. Markendahl, J.Zander, P. Zetterberg, P. Karlsson, G.Malmgren, J.Nilsson "Cost Drivers and Deployment Scenarios for Future Broadband Wireless Networks -Key Research problems and directions for research", IEEE VTC Spring Conference, 2004.

[13] L. Badia, M. Lindström, J.Zander, M. Zorzi, "Demand and Pricing Effects on the Radio Resource Allocation of Multimedia Communication Services", IEEE Globecom, 2003.

[14] L. A. Dasilva, "Pricing for QoS-Enabled Networks: A Survey", IEEE Communications Surveys, 2nd Quarter, 2000.

[15] Honig, Steigliz, "Usage-Based Pricing of Packet Data Generated by a Heterogeneous User Population", INFOCOM '95. Fourteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Bringing Information to People. Proceedings. IEEE, 2-6 April 1995 Page(s):867 - 874 vol.2

[16] S. Stidham Jr., "Pricing and Congestion Management in a Network with Heterogeneous Users", *IEEE Transactions on Automatic Control*, Volume 49, Issue 6, June 2004 Page(s):976 – 981

[17] I. Ch. Paschalidis, Y. Liu, "Pricing in Multiservice Loss Networks: Static Pricing, Asymptotic Optimality, and Demand Substitution Effects", IEEE/ACM Transactions on Networking, Volume 10, Issue 3, June 2002 Page(s):425 - 438

[18] R. Cocchi, S.Shenker, D. Estrin, L. Zhang, "Pricing in Computer Networks: Motivation, Formulation and Example", *IEEE/ACM Transactions on Networking*, Vol., No. 6, pp. 614-627, December 1993.

[19] C. Parris, S. Keshab, D. Ferrari, "A Framework for the Study of Pricing in Integrated Networks", Technical Report, Tenet Group, ICSI, UC Berkeley, 1994.

[20] Ioanis Ch. Paschalidis, John N. Tstsiklis, "Congestion-Dependent Pricing of Network Services", *IEEE/ACM Transactions on Networking*, Volume 8, Issue 2, April 2000 Page(s):171 – 184

[21] Jingkuan Hou, Jie Yang, Symeon Papavassiliou, "Integration of Pricing with Call Admission Control to Meet QoS Requirements in Cellular Networks", IEEE Transactions on Parallel and Distributed Systems, Volume 13, Issue 9, Sept. 2002 Page(s):898 - 910

[22] Cem. U. Soraydar, Narayan B. Mandayam, David J. Goodman, "Efficient Power Control via Pricing in Wireless Data Networks", IEEE Transactions on Communications, Volume 50, Issue 2, Feb. 2002 Page(s):291 – 303

[23] A. Vïinikaïnen, J. Joutensalo, M. Wikström, T. Hämäläinem, "Bandwidth Allocation and Pricing for Telecommunications Network", Next Generation Internet Networks 2005, 18-20 April 2005, Page(s):165 – 172

[24] V. Rodriguez, K. Moessner, R. Tafazolli, "Market-Driven Dynamic Spectrum Allocation: Optimal End-User Pricing and Admission Control for CDMA", IST Summit, Dresden, 2005

[25] Saaty T.L. Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process. RWS Publications: USA, 2000

[26] R. Agusti, O. Sallent, J. Pérez-Romero, L. Giupponi "A Fuzzy-Neural Based Approach for Joint Radio Resource Management in a Beyond 3G Framework", 1st International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks, Qshine'04, Dallas, USA, October, 2004.

[27] 3GPP TR 25.942 "RF System Scenarios"

[28] J. D. Parson, Mobile Radio Propagation Channel, 2nd Edition, Wiley, 2001