Efficient QoS-Driven Resource Allocation in Integrated CDMA/WLAN Networks - An Autonomic Architecture

Georgios Aristomenopoulos, Timotheos Kastrinogiannis,
and Symeon Papavassiliou

Institute of Communications and Computer Systems (ICCS)
School of Electrical and Computer Engineering, National Technical University of Athens,
Zografou, 15780, Greece
`{aristome,timothe}@netmode.ntua.gr, papavass@mail.ntua.gr`

Abstract. In this paper the problem of proficient joint radio resource management in an integrated WLAN/CDMA-cellular heterogeneous environment is considered. Nodes'/Networks' autonomicity is envisioned as the enabler for devising a proficient QoS-aware service orientated wireless interworking architecture founded on a common utility based framework that provides enhanced flexibility in reflecting different access networks' type of resources and diverse QoS prerequisites under common optimization problems. A decentralized node-networks assignment mechanism is introduced, aiming at QoS provisioning and efficient resource utilization. Numerical results are presented that validate the efficacy of the proposed architecture.

Keywords: Integrated WLAN/CDMA-cellular networks, autonomic networking, QoS provisioning, load balancing, self-optimization.

1 Introduction

The complementary characteristics of broadband Wireless Local Area Networks (WLANs) and Code Division Multiple Access (CDMA) cellular networks have recently attained much interest towards realizing an integrated system that efficiently enables seamless broadband Internet access for mobile users with multimode access capabilities [1]. However, when aiming at satisfying various Quality of Service (QoS) constraints within the integrated system, separate and independent studies on optimal resource allocation and QoS provisioning in either network, may prove inadequate. Heading towards optimal utilization of resources over an integrated CDMA/WLAN network, current research efforts are targeting on QoS traffic class mapping among different access networks [2] and on proficient call admission control mechanisms aiming at services' seamless continuity [3], [4], or load balancing [5].

Due to the heterogeneity of the wireless environment, in most cases only the mobile node has the complete view of its own environment, in terms of available access networks in its locality, the corresponding available resources and QoS support mechanisms. This becomes even more critical when the available networks belong to different operators. Therefore, contrary to traditional architectures where network/nodes' performance is controlled in a centralized way, future wireless networking [10]

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envisions as its foundation element an autonomic self-optimized wireless node with enhanced capabilities in terms of acting/re-acting to mobility, connectivity or even QoS- performance related events.

Such a vision and evolution, makes the design of a flexible autonomic QoS-aware joint network selection mechanism, a promising alternative service oriented paradigm that allows to fully exploit the proliferation of wireless networks, as opposed to the more conventional existing access oriented designs. In this paper, we describe an autonomic QoS-aware joint resource allocation architecture for integrated WLAN/CDMA-cellular systems that aims at maximizing the overall integrated network's revenue, while enabling users to efficiently self-adapt at QoS-triggered occurrences towards self-optimizing their services' performance.

The rest of the paper is organized as follows. In Section 2, we present the key features of the introduced autonomic joint WLAN/CDMA architecture. In Section 3, intra-cell autonomic resource allocation and QoS provisioning mechanisms are presented, followed by the introduction of an autonomic QoS and service oriented joint network selection mechanism. In Section 4, some quantitative comparative results are presented that demonstrate the efficacy of the proposed approach, while Section 5 concludes the paper.

2 Towards Autonomic Integrated WLAN/CDMA Networks – Motivation and Goals

Our approach in this paper is motivated by the fact that future autonomic networking aims at implementing self-* functions for self-optimization and self-adaptation to context or situation driven behavior changes in systems, services or applications [6]. In order to provide the needed flexibility and functional scalability in the joint resource management process in an integrated WLAN/CDMA network, we introduce autonomicity as the vehicle allowing the design of a novel autonomic framework that maximizes overall integrated network's revenue, enabling self-adaptation and self-optimization functionalities in both mobile nodes and base stations or access points.

The fundamental concept of an autonomic system is a control loop(s). Inputs to the control loop consist of various status signals, information and views continuously exposed from the system, component(s) or resource(s) being controlled (e.g. protocols, nodes, functionalities, etc.), along with (usually policy-driven) management rules that orchestrate the behavior of the system or component. Outputs are commands to the system or component(s) to adjust its operation, along with status to other autonomic systems or components.

Henceforth, future autonomics envisions the aggregation of node-scoped control loops, i.e. within a single node, in terms of interacting intra/inter-node control loops or triggered/managed low level control loops by higher level control loops within the node or the network as a system. Intuitively, the above view leads to a hierarchal control loops paradigm that enables the efficient design of autonomic nodes, systems and architectures. In this paper, node/network's atomicity is employed as an enabler en route for devising a flexible and proficient QoS-aware service orientated wireless interworking architecture.

The distinct features of the proposed architecture are summarized as follows:

- Optimal utility-based resource allocation and QoS provisioning within each system's cell (WLAN or CDMA). Thus, an Autonomic Radio Recourse Management (ARRM) mechanism is introduced to achieve the above goal.
- Efficient joint resource management via a flexible network selection mechanism, which determines whether or not to admit and to which network cell (WLAN or CDMA network) a new or vertical/horizontal handoff service arrival. Towards enabling that, an Autonomic JOint Network Selection (AJONS) decentralized mechanism is introduced.

3 Autonomic QoS-Aware Joint Resource Control

In the proposed integrated CDMA/WLAN architecture a proper Autonomic Radio Resource Management mechanism (ARRM) residing at the base station of each cell in the network is responsible for optimally and independently allocating cell's available radio resources among all active users already attached to the specific network. Moreover, a new user entering the network or an already attached user willing to perform vertical or horizontal handoff due to connectivity, mobility or QoS-triggered events, is accountable for selecting the most appropriate access network type to be attached to, as well as the corresponding base station (cell) from the ones available in his locality using only locally available information. Such a Self-optimization behavior is enabled via a new novel scheme Autonomic JOint Network Selection (AJONS).

3.1 Towards Optimal Resource Allocation

Due to the different wireless access technologies type of resources, as well as the users' services diverse expectations the concept of utilities from the field of economics has been adopted for developing QoS-aware resource allocation mechanisms. A utility function reflects a user's degree of satisfaction with respect to his service performance, and therefore services with assorted QoS prerequisites can be represented in a normalized way. The presented architecture is founded on a common utility-based framework in order to reflect users' QoS requirements in both network types in a unified way, towards achieving seamless and efficient integration.

We consider a set S_{CDMA} (S_{WLAN}) of N_{CDMA} (N_{WLAN}) continuously backlogged users attached to a cell of the CDMA (WLAN) network. Each mobile user is associated with a proper utility function U_i which represents his degree of satisfaction in accordance to his expected actual downlink transmission rate R_i. We assume that U_i has the following properties.

1. U_i is an increasing, twice continuous differentiable function of R_i.
2. $U_i(0) = 0$ and also upper bounded.
3. U_i is a sigmoidal-like or strictly concave or convex function of its rate allocation.

Typically, most utility functions that have been used in wired or wireless networks can be represented by the latter three types of functions illustrated in Fig. 1 [7].

In current CDMA cellular systems QoS-aware resource allocation is commonly performed via power control. Periodically (T_s), resource allocation utility-based optimization problems are set and solved by each cell's ARRM to acquire optimal user's resource assignment. To obtain users' power vector $\overline{P}$ that maximizes total

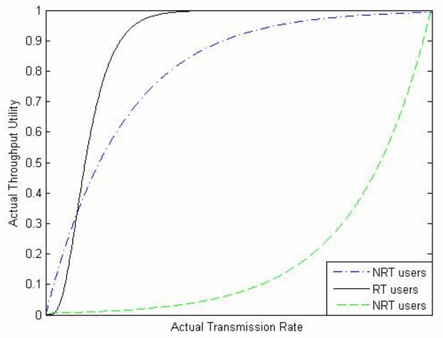

Fig. 1. Basic utilities types as a function of a user's achieved goodput

system utility, the solution of the following non-convex maximization problem must must be derived [7]:

$$\max_{\bar{P}} \sum_{i=1}^{N_{CDMA}} U_i\,(R_i(\bar{P})) \quad s.t. \ \sum\nolimits_{i=1}^{N_{CDMA}} P_i \le P_{\max},\ 0 \le P_i \le P_{\max} \tag{1}$$

where P_{max} denotes the maximum transmission power of a CDMA base station.

To support QoS in WLANs, IEEE 802.11e [8] has been introduced which allows specific parameters that affect a user's *j* performance (e.g. its maximum (minimum) contention window) to be altered by the access point. The corresponding non-convex utility based optimization problem can be formally defined as:

$$\max_{\bar{R}} \sum_{j=1}^{N_{WLAN}} U_j\,(R_j) \quad s.t. \ \sum\nolimits_{j=1}^{N_{WLAN}} R_j \le C_{\max},\ 0 \le R_j \le C_{\max} \tag{2}$$

where C_{max} is system's maximum effective capacity. Problem (2) is set and solved within short-term time periods denoted as WLAN's time-frame (T_f). Mapping the derived optimal rate vector $\bar{R}^*$ to appropriate users' contention windows can be easily achieved as described in [8].

Towards solving (1) and (2), each user already attached to a cell $b \in \{CDMA\ or\ WLAN\}$ solely computes (the Lagrange) $\lambda_{i,b}^{\max} = \min\left\{\lambda \ge 0 \mid \max\limits_{0 \le R \le R_{\max}} \{U_{i,b}(R_i) - \lambda R_i\} = 0\right\}$ towards maximizing its net utility (i.e. the utility minus a corresponding cost), which represents user's *i* maximum willingness to pay per unit resource [7]. It is shown that each mobile has a unique $\lambda_i^{\max}$ which can be calculated as follows:

$$\lambda_i^{\max} = \begin{cases} \left.\dfrac{\partial U_{i,b}(R_i)}{\partial R_i}\right|_{R=0} & if\ U_{i,b}\ is\ concave \\ \left.\dfrac{\partial U_{i,b}(R_i)}{\partial R_i}\right|_{R=R^*} & if\ U_{i,b} is\ a\ sigmoidal\ function\ and\ \mathrm{R}^*\ exists \\ \dfrac{U_{i,b}(R_{\max})}{R_{\max}} & otherwise \end{cases} . \tag{3}$$

where R_i^* is the unique positive solution of:

$$U_{i,b}(R_i) - R_i \frac{\partial U_{i,b}(R_i)}{\partial R_i} = 0 \quad for\ 0 \le R_i \le R_{\max} \,. \tag{4}$$

Then, the base station obtains a unique equilibrium price per unit of resource λ_b^* that optimizes cell's resource allocation and broadcasts it. Finally, for those users that $\lambda_{i,b}^{\max} \ge \lambda^*$, their allocated resources can be easily derived, following the approaches provided in [7] and [8]. It is noted that the value of a user's willingness to pay $\lambda_{i,b}^{\max}$ defines his superiority against others (i.e. higher values of $\lambda_{i,b}^{\max}$ declare higher possibility in QoS requirement fulfillment when attached to cell *b*), while at the same time cell's equilibrium price per unit of resource λ_b^* indicates its congestion level (i.e. lower values of λ_b^* dictate higher availability in resources).

3.2 Autonomic Intra-cell QoS-Aware Radio Resource Allocation in WLAN and CDMA Cellular Networks

In order to enable intra-cell mobile nodes'/network autonomicity we introduce two control loops residing at mobile nodes and base stations. The first manages a node's QoS performance and the second one manages a cell's resource control mechanism, while their collaboration realizes autonomic QoS radio resource management within the cells of an integrated WLAN/CDMA system (ARRM), as depicted in Fig.2.

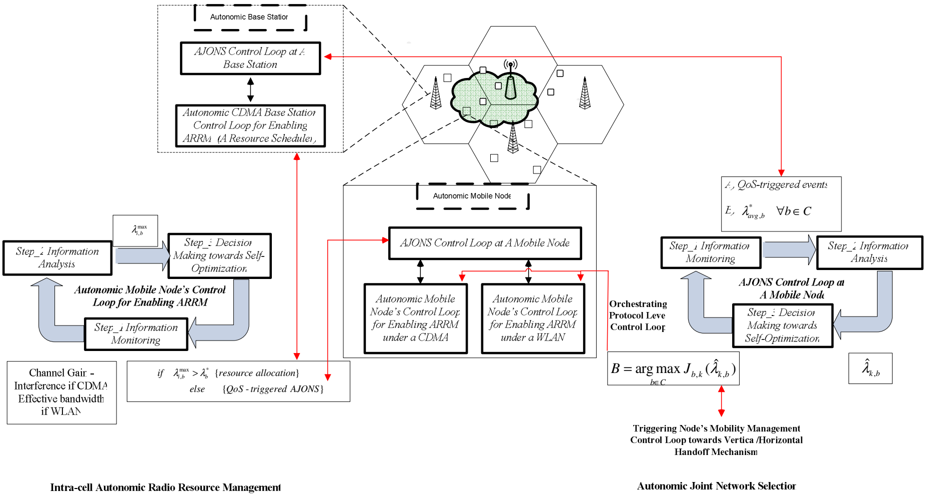

Fig. 2. Autonomic intra-cell QoS-aware radio resource management & Autonomic Joint Network Selection Mechanism (AJONS)

Autonomic Base Station Control Loop for Enabling ARRM

Periodically (i.e. on a time-slot basis regarding a CDMA cell (T_s) and every time-frame concerning a WLAN (T_f)), a control loop residing at a base station performs the following steps:

Step_1. Monitors its environment and gathers QoS related information concerning: a) active mobile users' services' QoS requirements (i.e. users' utilities) b) active mobile nodes' channel conditions and overall interference (CDMA cell) or current cell's maximum effective capacity (WLAN).
Step_2. Sets the corresponding constrained non-convex utility-based optimization problem, as defined in (1) or (2) and obtains its solution.
Step_3. Disseminates the acquired optimal resource allocation vectors to the cell's active autonomic nodes.

Autonomic Mobile Node's Control Loop for Enabling ARRM

Mobile node *i* is already attached to cell $b \in \{CDMA, WLAN\}$

Step_1 Information Monitoring: Constantly monitors a user's service performance and networking environment conditions (i.e. user's channel quality and overall attached cell interference or effective capacity).
Step_2 Information Analysis: Analyzes its current status with respect to QoS requirements and computes its current willingness to pay $\lambda_{i,b}^{\max}$.
Step_3 Decision Making towards Self-Optimization: Interacts with the cell's *b* base station towards determining cell's equilibrium price per unit of resource λ_b^* .Thus:
If $\lambda_{i,b}^{\max} < \lambda_b^*$, and the user is currently not selected to access system's resources and thus triggers user's network selection algorithm towards performing a QoS-triggered handoff (as detailed in the following section). Otherwise, determines its allocated resources.

Establishing control loops that steer node's and base stations' QoS resource allocation mechanisms allows us to further enhance them with self-optimization attributes and manageability attributes. The necessity of the latter emerges by the heterogeneity of the wireless environment where multiple access networks' mechanisms regarding a node's service QoS functionalities must simultaneously coexist and/or collaborate. To effectively accomplish that, an orchestrator is required. Such an orchestrator should also be a control loop, superior in a hierarchy of control loops, with advanced accountabilities that manages inferior in the hierarchy control loops within a mobile node. The operation, the liabilities, the goals and the algorithms that enable such a superior control loop, and thus an autonomic mobile node, to make QoS-aware self-optimization decisions are studied in the following.

3.3 Autonomic Joint Network Selection Mechanism (AJONS)

The goal of Autonomic JOint Network Selection mechanism (AJONS) is to enable autonomic mobile nodes to exploit locally available information from the corresponding base stations of the existing cells in their locality in order to dynamically determine whether or not, and to which network to be attached to, either when entering the system or at the event of a QoS-triggered handoff. Such a procedure mainly aims at guarantying the services' QoS constraints in both WLANs and CDMA networks as well as maximizing the average network revenue via endorsing cell's load balancing. The short-time intervals that both CDMA (T_s) and WLAN's (T_f) ARRM mechanisms set and solve the corresponding resource allocation problems, towards exploiting multi-users' diversity, makes the use of the instantaneous short-term pricing values λ^* as a cell's congestion indicator insufficient, since it would be undesirably sensitive to short-term cell's status variation. Moreover, this would lead users to constantly alter access network or cell preference; thus triggering QoS-driven ping-pong effects.

To overcome such a drawback, AJONS mechanism requires the setup and solution, of both CDMA and WLAN QoS and resource allocation problems, as defined in (1) and (2) in such time intervals that allows to the derived equilibrium price per unit of resource λ^*, denoted as λ^*_{avg}, to efficiently reflect long-term cells' load and environmental variations, in parallel to cell's ARRM mechanism. We refer to the above long-term time period as AJONS time frame (T_{AJONS}) and is defined as $T_{AJONS} = M \cdot \max(T_s, T_f)$ $M \in \aleph$. The smaller the value of M, the more sensitive AJONS mechanism is in short-term variations of the interworking environment.

As the system evolves, periodically, every T_{AJONS}, each base station solves problem (1) in the case of a CDMA cell or problem (2) in the case of a WLAN cell, regarding its already attached users and considering exponentially averaged values for nodes' and cells' characteristics respectively. Subsequently, each cell's b averaged equilibrium price per unit of resource, $\lambda^*_{avg,b}$ is disseminated via broadcasting to the mobile nodes. Each autonomous node k, either entering the integrated system or reacting to QoS-triggered events computes its maximum willingness to pay per resource unit $\lambda^{\max}_{k,b}$ that he would acquire if he selected cell b to attach to, for each of the corresponding existing cells in his locality. In the following we assume a set C of N_C network cells, belonging to either of the considered access technologies, to be available for the user to receive service from. In this way the user possesses all the necessary required information to compute for each cell $b \in C$ the normalized indicator $\hat{\lambda}_{k,b}$, defined as follows:

$$\hat{\lambda}_{k,b} = \begin{cases} \dfrac{\lambda^{\max}_{k,b} - \lambda^*_{avg,b}}{\lambda^*_{avg,b}} & if\ \lambda^{\max}_{k,b} \geq \lambda^*_{avg,b} \\ 0 & otherwise \end{cases} . \tag{5}$$

Since $\lambda^{\max}_{k,b}$ can be interpreted as the maximum value of resource unit of user k at cell b and $\lambda^*_{avg,b}$ as the long-term price of resource unit at cell b, then $\hat{\lambda}_{k,b}$ can be interpreted as the normalized profit per resource unit that user k can acquire once selecting cell b to attach to. Afterwards, the node selects the cell $B \in C$ at which he will be finally attached to, in accordance to the following policy:

$$B = \arg\max_{b \in C} J_{b,k}(\hat{\lambda}_{k,b}) \tag{6}$$

where $J_{b,k}$, is an non-negative, increasing, concave function of $\hat{\lambda}_{k,b}$ and is employed to either reflect network type related parameters or to allow network's operator to impose specific policies regarding billing, access priorities, and congestion avoidance.

The intuition behind the proposed network selection strategy is twofold. From network's perspective, the higher the congestion of a cell, the higher its equilibrium price per unit $\lambda^*_{avg,b}$ will be in the event that a user selects to attach to the cell, thus discouraging or preventing the user from being attached to that cell. Such an approach will eventually lead towards a load balanced integrated network. From user's perspective, the higher his utility-based satisfaction from being attached to a cell is (i.e. his service QoS-aware performance), the higher his maximum willingness to pay will be for the specific offered service quality, steering him to select the most profitable cell and network type. In the rest of this section we outline two control loops (illustrated in Fig.2) for accomplishing the above described distributed asynchronous QoS-triggered joint network selection.

AJONS Control Loop at a Base Station

- ***Step_1.*** Periodically, every T_{AJONS}, sets and obtains the solution of cell's b constrained non-convex utility-based resource allocation optimization problem defined in (1) and (2) using exponentially averaging, within a T_{AJONS} time interval, for the parameters: users' channel quality regarding all users already attached to cell b when b is a CDMA cell, or effective capacity when b is a WLAN, respectively.
- ***Step_2.*** Disseminates the acquired equilibrium price per unit of resource $\lambda^*_{avg,b}$ to the autonomous mobile nodes/users in the cell.

AJONS Control Loop at a Mobile Node

- ***Step_1.*** Constantly monitors user's services performance and reacts to QoS-triggered events (i.e. Step_3 of Autonomic Mobile Node's Control Loop for Enabling ARRM) or mobility triggered events.
- ***Step_2.*** Obtains locally available networks' average equilibrium price per unit of resource $\lambda^*_{avg,b}$, disseminated from all network's cells in his locality (i.e. $b \in C$).
- ***Step_3.*** Computes the normalized profit per resource unit $\hat{\lambda}_{k,b}$ for each $b \in C$ and selects the most profitable network to handover/attach (i.e. cell B in accordance to (4)).
- ***Step_4.*** Disseminates this decision to lower level control loops that execute the attachment/handoff.

4 Numerical Results and Discussions

In this section we present some indicative numerical results considering an integrated CDMA/WLAN (IEEE 802.11e) system with one CDMA cell, and one WLAN network overlapping with the CDMA cell. We assume that the CDMA network's base station is located at the cell's center and that its maximum transmission power is $P_{max}=10$. Moreover, we assume that CDMA system's spreading bandwidth is $W = 10^8$ and all users' maximum downlink rate is $R_i^{\max} = 2 \cdot 10^3\, kbps$. Regarding the

WLAN, the system's access point is also located at the center of its coverage area and operates in *5GHz* band with maximum network data rate of *54Mbit/s*. WLAN effective capacity, C_{max} is dynamically calculated using a simulator that incorporates the IEEE 802.11e scheme. We model the path gain from the CDMA base station to user i as $G_i = K_i / s_i^n$ where s_i is the distance of user i from the base station and n is the path loss exponent ($n=4$) and K_i is a log-normal distributed random variable with mean 0 and variance $\sigma^2 = 8(dB)$. New users periodically enter the system (i.e. every T_{AJONS}) requesting Real Time (RT) and Non-Real Time (NRT) services in a random manner while moving in arbitrary patterns. We use the following sigmoidal function to represent real-time users' $U_i(R_i)$, i.e $U_i(R_i) = \mathrm{m}\{1/1 + e^{-a(R_i - p)} - d\}$, where we set $m = (1 + e^{ap})/e^{ap}$ and $d = 1/(1 + e^{ap})$ for normalization purposes (i.e. $U(0) = 0$ and $U(\infty) = 1$), while regarding non-real-time services a concave function $U_i(R_i)=1-exp(-gR_i)$ is applied, with $g=0.8$. For demonstration only purposes we set $a=3$ and $p=3$ [7].

In order to better illustrate the efficacy of the proposed autonomic joint network selection and QoS-triggered handoff mechanism in terms of achieved overall integrated network utility-based performance, we compare the performance of ARRM/AJONS architecture against three other network selection schemes. The first one makes use of Radio Signal Strength quality for determining the cell that a user should be attached to (referred as RSS) [9]. The second approach applies a Service Differentiation scheme (SDiff), where RT users are served by the CDMA cellular network while NRT by the WLAN [3]. Finally, INS scheme performs only Initial Network Selection at the time of a new user's arrival adopting AJONS mechanism, while vertical handovers are not permitted over the duration of its service. Let us underline that under all examined schemes optimal intra-cells' radio resource management is achieved by ARRM scheme. Finally, for demonstration purposes we set $J_{b,k}(\hat{\lambda}_{k,b}) = \hat{\lambda}_{k,b}$ and $M=1$.

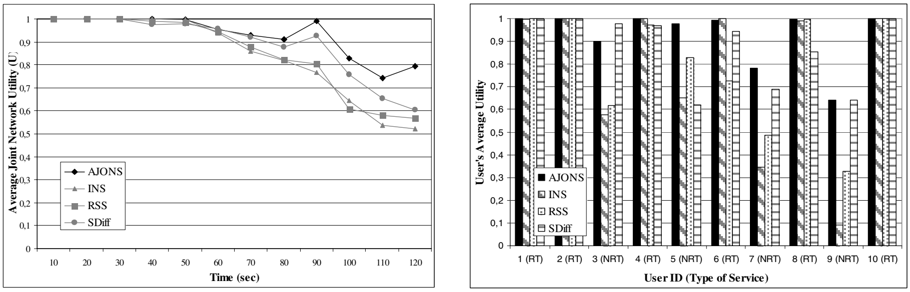

Fig. 3. a) Overall system utility and **b)** Users' average utility based performance

Fig.3a illustrates average joint integrated network's utility performance achieved under ARRM/AJONS, INS, RSS and SDiff schemes. The results reveal the superiority of the proposed autonomic scheme in terms of overall system performance, especially as the system evolves and the overall load increases. Moreover, the normalized profit per resource unit ($\hat{\lambda}$) exploited by ARRM/AJONS scheme is able to reflect not only performance parameters regarding both types of networks (i.e. congestion level, available resources and channel conditions), but more importantly user's service QoS-aware metrics, thus steering users towards making appropriate attachment decisions. On the other hand, myopic network selection criteria (i.e. RSS, SDiff) or even static network attachment schemes where no vertical handoffs are allowed (i.e. INS) are not capable of responding to networking environment variation (e.g. network cells' load and or users' channels time-varying nature) resulting to low overall system's performance, and thus to users' service QoS degradation. The latter behaviour is revealed in Fig.3b where users' average utility based performance is illustrated as a function of their ID and requested type of service.

5 Conclusions

In this paper, a novel QoS-centric joint resource allocation architecture for a WLAN/CDMA integrated network, founded on nodes/networks' autonomicity is discussed and evaluated. Autonomicity is deployed to facilitate the realization of multiple self-optimization functionalities towards integrated system's proficient utilization and efficient support of QoS provisioning and services' continuity.

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