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Joint Dynamic Resource Allocation for Coupled Heterogeneous Wireless Networks. A New Hopfield Neural Network-based Approach

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Abstract — **This paper proposes an algorithm to solve the problem of Joint Dynamic Resource Allocation in heterogeneous wireless networks. The algorithm is based on Hopfield Neural Networks to achieve fast and suboptimal solutions. The generic formulation is particularized and evaluated in coupled WLAN access points. Some illustrative simulations results are presented to evaluate the performance of the new algorithm as compared with other strategies. The obtained results confirm the validity of the proposal.**

I. INTRODUCTION

The notion of being always best connected, introduced in [1], is an extension for heterogeneous systems of the notion of being always connected. Now, users not only should be connected anywhere, anytime, but also they should be served with the best available connection, what can be only accomplished with the interworking of the different technologies. For that reason, the standardization bodies are doing their best to make the interworking possible. For instance, the 3GPP not only allows UMTS to interwork with GPRS (two 3GPP Radio Access Technologies (RATs)) but also establishes the basis for a WLAN interworking (a non-3GPP RAT). In addition, the IEEE Standards Association is working in the 802.11u standard (scheduled for 2009) which gives WLAN the capacity of interworking with external networks. Likewise, the IPv6 network mobility management protocol (NEMO) enables a fast handover between different RATs, which is currently paving the way for a real implementation of multihoming in WLAN [2].

The multihoming concept provides multiple radio access for a single terminal in order to allow the terminal to maintain simultaneous links with the RATs [3]. Considering the higher level of coupling, the user could receive packets simultaneously from all links, what on the contrary entails an increasing receiver complexity. A simpler solution which keeps the user equipment unaltered consists in dynamically reconfiguring the active connection thus transmitting only through the best link. Since the user is simultaneously connected to all RATs, the reallocation of the active link can be performed in a very short time. This paper is focused on this last scenario for multihoming.

If the dynamic resource allocation (DRA) in a single RAT is a hard optimization problem, when dealing simultaneously with multiple RATs, what is usually referred to as Joint DRA (JDRA), the problem becomes unmanageable, unless real-time sophisticated optimizers employed.

Hopfield Neural Networks (HNNs) have proven useful in solving optimization problems in a short time (see e.g. [4]). HNNs have the capability of finding suboptimal solutions in few microseconds [4], what is fast enough to establish a new resource allocation in a frame-by-frame basis in current wireless communication systems.

This paper proposes a JDRA HNN-based algorithm for the downlink in a multihoming WLAN scenario. Although the employed formulation has been particularized for this scenario, the solution can be easily extended to any other heterogeneous scenario. The algorithm not only decides on which Access Point (AP) services each user in the next time interval (TI), but also on the distribution of resources among users to fulfill their QoS.

The proposed algorithm follows a user-centric approach, since bit rates are not only allocated by network constraints, but also by users' expectations and requirements. This feature allows the system to maximize the utilization of the radio resources as a function of the user service profile.

The rest of the paper is organized as follows: Section II presents the characteristic constraints of any wireless system that the DRA algorithm should take into account. Section III presents the solution adopted for the JDRA problem based on a HNN. Section IV shows some numerical results obtained by simulation. Finally, the most important conclusions are drawn in section V.

II. DRA CONSTRAINTS

This paper assumes a set of feasible bit rates, $\Re$. Each user is characterized by a subset of possible bit rates defined by the type of service he is subscribed to. Thus, the DRA algorithm shall find the optimal bit rate, $R_j \in \Re$, for each user satisfying the following constraints.

II.1. Resources constraint

The total allocated resources must not exceed the maximum available ones. The effective throughput is a function of the channel quality perceived by each user and the resources allocated to him. This dependence is supposed to be known by the algorithm. Hence, if $SNIR_{ik}$ is the Signal to Noise and Interference Ratio (SNIR) perceived by the i-th user in the k-th RAT, then his effective throughput by resource unit (r.u.) in that RAT is $Q_k\left(SNIR_{ik}\right)$, where function Q_k is known. Resource units can be time slots in GSM, spreading codes in UMTS or seconds of channel occupancy in WLAN.

II.2. Bit rate constraint

The algorithm must only allocate to each user one of the bit rates predefined in the associated subset. Therefore, the minimal bit rate ensured is the minimal bit rate in the subset.

II.3. Delay constraint

In order to introduce the delay in the resource allocation process, it is defined a minimum target bit rate for each user in each RAT, $R_{\min,ik}$, that guarantees the transmission of all packets in due time. $R_{\min,ik}$ can be defined as:

$$R_{\min,ik} = P\max_{p}\left(\frac{\beta_p}{t_{\max}-t_p-t_{\text{change},ik}}\right) \tag{1}$$

where P are the number of data units (d.u.) in the buffer, β_p is the size of the p-th d.u., $t_{\max}$ is the maximum delay for the specific type of service, t_p is the time the p-th d.u. is in the buffer and $t_{\text{change},ik}$ is the time needed for the i-th user to change from its current RAT to the k-th RAT. Data units depend on the service, for example for web browsing, FTP service and video calling, the d.u. is a web page, a file and a frame respectively. The formulation of (1) assumes that if several d.u. are stored in a buffer then the allocated bit rate is equally divided to transmit all the d.u. simultaneously. Therefore, (1) reflects the actual behaviour of web browsers, since several opened web pages or file downloads are transmitted all together.

III. HNN-BASED JDRA ALGORITHM

III.1. HNN model

A HNN is composed by a set of interconnected neurons. Neurons will change dynamically their state until reaching an equilibrium point. Hopfield showed that an energy function E can represent the dynamics of the HNN, and that the problem of finding an equilibrium state of the neurons can be solved by finding a local minimum of the energy function [5],[6].

The dynamics of the HNN can be expressed as:

$$\frac{dU_i}{dt} = -\frac{U_i}{\tau} - \frac{\partial E}{\partial V_i} \tag{2}$$

where U_i and V_i are the input and output of the i-th neuron, and τ is the time constant of the circuit. The relationship between the outputs and the inputs of the neurons is non-linear, and is given by the sigmoid function:

$$V_i = f\left(U_i\right) = \frac{1}{1+e^{-\alpha U_i}} \tag{3}$$

where α is the gain of the neurons.

III.2. HNN formulation

Provided a set of feasible bit rates, $\Re$, the JDRA problem can be formulated in terms of a 3D-HNN with $L = IJK$ neurons, being I the number of users in the system, J the number of elements in $\Re$ and K the number of RATs. The neuron states indicate the resource allocation, being the neuron with indices (i,j,k) ON if the i-th user has the j-th bit rate, R_j, allocated in the k-th network. Note that the rest of the neurons of user i, must be OFF. It is important not to confuse the neuron states with the neuron outputs, V_{ijk}. A neuron is ON if $V_{ijk} \geq 0.5$ and is OFF if $V_{ijk} < 0.5$.

The energy function is a quadratic function whose terms make the system converge to the expected solution. For the JDRA problem the energy function proposed in this paper is:

$$\begin{aligned} E = &-\frac{\mu_1}{2}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} B_{ijk}V_{ijk} - \frac{\mu_2}{2}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\frac{R_j}{R_{\max}}V_{ijk} \\ &+\frac{\mu_3}{2}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\eta_k V_{ijk} + \frac{\mu_4}{2}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\xi_{ijk}V_{ijk} \\ &+\frac{\mu_5}{2}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\psi_{ijk}V_{ijk} + \frac{\mu_6}{2}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}V_{ijk}\left(1-V_{ijk}\right) \\ &+\frac{\mu_7}{2}\sum_{i=1}^{I}\left(1-\sum_{j=1}^{J}\sum_{k=1}^{K}V_{ijk}\right)^2 \end{aligned} \tag{4}$$

where μ_n, $n = 1\cdots 7$, are coefficients that weight each term.

The first term of the energy function introduces the benefit function B_{ijk} which measures the benefit of allocating each bit rate to each user in terms of delay. This function is defined as:

$$B_{ijk} = \frac{S\left(R_j, s_{ik}, r_{ik}\right) - S\left(0, s_{ik}, r_{ik}\right)}{S\left(R_{\max}, s_{ik}, r_{ik}\right) - S\left(0, s_{ik}, r_{ik}\right)} \tag{5}$$

$$S\left(x,s,r\right) = \frac{1}{1+e^{-s(x+r)}} \tag{6}$$

$$s_{ik} = \begin{cases} \dfrac{2\ln(9)}{R_{\min,ik}} & R_{\min,ik} \leq R_{\max} \\ \dfrac{2\ln(9)R_{\min,ik}}{\left(R_{\max}\right)^2} & R_{\min,ik} > R_{\max} \end{cases} \tag{7}$$

$$r_{ik} = \begin{cases} -\dfrac{R_{\min,ik}}{2} & R_{\min,ik} \leq R_{\max} \\ -R_{\max} + \dfrac{\left(R_{\max}\right)^2}{2R_{\min,ik}} & R_{\min,ik} > R_{\max} \end{cases} \tag{8}$$

where $R_{\max}$ is the maximum allocable bit rate and s_{ik} and r_{ik} are selected to increase B_{ijk} highly if $R_j > R_{\min,ik}$, reflecting the high benefit of selecting a bit rate higher than the minimum target one.

The second term enforces the algorithm to maximize the allocated bit rates, and thus the total resource utilization. Neurons are favoured proportionally to the corresponding allocated bit rate.

The third term favours those RATs with lower resource consumption. The term η_k is:

$$\eta_k = \sum_{i=1}^{I}\sum_{j=1}^{J}\frac{R_j}{Q_k\left(SNIR_{ik}\right)\rho_k}V_{ijk} \tag{9}$$

where ρ_k are the total amount of available resources in the k-th RAT.

The fourth term penalizes the allocations that imply an excess of the maximum available system resources. Consequently, only the allocations combinations that satisfy the resource constraint introduced in section II.1 are possible equilibrium points of the HNN. ξ_{ijk} is defined as:

$$\xi_{ijk} = u\left(\frac{H_{ijk}}{\rho_k}-1\right) \tag{10}$$

$$H_{ijk} = \sum_{\substack{l=1\\ l\neq i}}^{I}\sum_{m=1}^{J}\frac{R_m}{Q_k\left(SNIR_{lk}\right)}V_{lmk} + \frac{R_j}{Q_k\left(SNIR_{ik}\right)} \tag{11}$$

where u is the step function. Note that H_{ijk} is the total amount of resources needed to allocate to the i-th user the j-th bit rate in the k-th RAT.

The fifth term prevents the use of forbidden bit rates. Therefore, ψ_{ijk} is a permission table with $\psi_{ijk}=1$ if the j-th bit rate in the k-th RAT is forbidden for the i-th user, and $\psi_{ijk}=0$ otherwise. Therefore, it is possible to define different bitrates for different services or RATs. Moreover, in order to prevent the undesirable ping-pong effect, after a RAT reselection, the bit rates of the rest of RATs can be temporally banned.

The last two terms ensure a rapid convergence to correct and stable neuron states. The first one forces the neuron outputs to tend to the extremes 0 and 1, whereas the second one makes users have only one bit rate allocated in only one RAT.

III.3. HNN dynamics

The HNN algorithm starts with random neuron outputs uniformly distributed between 0 and 1. The numerical Euler's technique to solve (2) with $\tau=1$ in a 3D-HNN is:

$$U_{ijk}\left(t+\Delta t\right) = U_{ijk}\left(t\right)+\Delta t\left\{-U_{ijk}\left(t\right)-\frac{\partial E}{\partial V_{ijk}}\right\} \tag{12}$$

where Δt is the time interval over which output voltages of neurons are observed and updated. The gradient of the energy function can be calculated as:

$$\begin{aligned}\frac{\partial E}{\partial V_{ijk}} = &-\frac{\mu_1}{2}B_{ijk}-\frac{\mu_2}{2}\frac{R_j}{R_{\max}}+\frac{\mu_3}{2}\left(\frac{R_j\sum_{l=1}^{I}\sum_{m=1}^{J}V_{lmk}}{Q_k\left(SNIR_{ik}\right)\rho_k}+\eta_k\right)\\ &+\frac{\mu_4}{2}\xi_{ijk}+\frac{\mu_5}{2}\psi_{ijk}+\frac{\mu_6}{2}\left(1-2V_{ijk}\right)-\mu_7\left(1-\sum_{m=1}^{J}\sum_{n=1}^{K}V_{imn}\right)\end{aligned} \tag{13}$$

All the outputs are calculated each iteration using (3) and the solution of (12). The equilibrium state is reached when the outputs V_{ijk} changes less than a certain tolerance, ΔV .

IV. NUMERICAL RESULTS

The employed simulator models a single cell of interest with radius of 50m where users are moving at 10km/h. A specific WLAN scenario with two Access Points (APs) separated by a distance of 50m has been considered. Each AP is located 25m away from the cell centre. 250 web browsing and 100 FTP downloading users are introduced in the simulation. The traffic models are extracted from [7] for both services. The maximum delay is set to 30 s for web browsing and to ∞ for FTP, i.e. the FTP service is supposed to be a background service with no maximum delay.

The path loss for the i-th user is calculated using:

$$L_{ik} = 145+35\log\left(d_{ik}\right) \tag{14}$$

where d_{ik} is the distance in km between the i-th user and the k-th AP. The thermal noise power level is -102 dBm. The allowed bit rates are {16384 kb/s, 8192 kb/s, 4096 kb/s, 1024 kb/s, 512 kb/s, 256 kb/s}, all of them allowed for both services.

The parameters of the HNN network considered are the following:

$$\mu_1=1000 \quad \mu_2=1000 \quad \mu_3=5 \quad \mu_4=11500$$
$$\mu_5=11500 \quad \mu_6=5 \quad \mu_7=5000 \quad \alpha=1$$
$$\Delta V=10^{-4} \quad \tau=1$$

The proposed JDRA algorithm (HNN) has been compared with other common strategies: the Fixed RAT Selection (FRS) policy and the Best Channel Quality (BCQ) policy. Both techniques select the RAT before the resource allocation. The first one selects initially the RAT with best channel quality and changes it only if the coverage in the current RAT is lost. This procedure is the one used in current wireless LAN equipments, so that the potential benefit of the new JDRA algorithm proposed in this paper could be evaluated through direct comparison with it. The second one, BCQ, selects always the RAT with best channel quality although the coverage has not been lost. After the RAT selection, the resources are allocated in each RAT separately with a Round Robin (RR) and a HNN-based technique. The HNN-based algorithm is the same explained in this paper but for only one RAT. This two RAT selection policies and resource allocation techniques lead to four reference algorithms: BCQ-HNN, BCQ-RR, FRS-HNN and FRS-RR.

Fig. 1 and 2 represent the Cumulative Distribution Function (CDF) of the service response time for web and FTP users respectively. The new algorithm proposed in this paper achieves the best performances, reducing the delay for all services. Moreover, Table I shows that the HNN has the best performances in comparison with the RR for both RAT selection techniques, BCQ and FRS.

Fig. 3 depicts the CDF of the normalized allocated resources for both RATs. The differences between HNN and BCQ-HNN reveal the high benefit of performing a JDRA technique. The BCQ-HNN allocates fewer resources than the HNN while the HNN dynamically reallocates users to RATs taking maximum advantage of the available resources and improving the delay of both services.

V. Conclusions

This paper has presented a novel HNN-based JDRA algorithm for packet-switched services with delay constraints in heterogeneous wireless networks. The algorithm has been evaluated through simulations in a basic WLAN scenario with two access points and mobile users. As compared with other static and dynamic strategies, the HNN-based JDRA algorithm is always preferred since it is able to adapt the resource distribution to the variable scenario conditions.

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Table I. Average delay per file download.

	HNN	*BCQ-HNN*	*BCQ-RR*	*FRS-HNN*	*FRS-RR*
Web	1.47 s	2.54 s	4.29 s	3.37 s	6.28 s
FTP	10.23 s	11.86 s	17.71 s	15.73 s	33.36 s

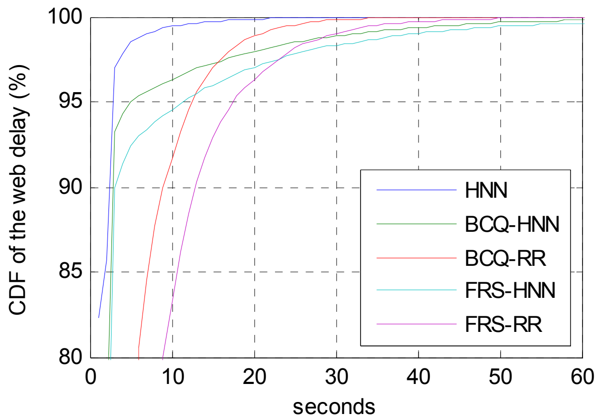

Fig. 1 CDF of the service response time for web service

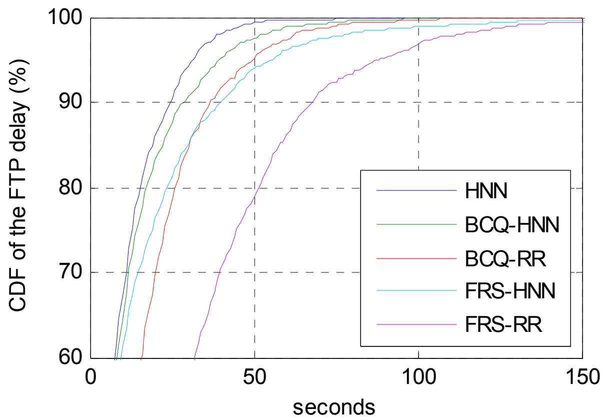

Fig. 2 CDF of the service response time for FTP service

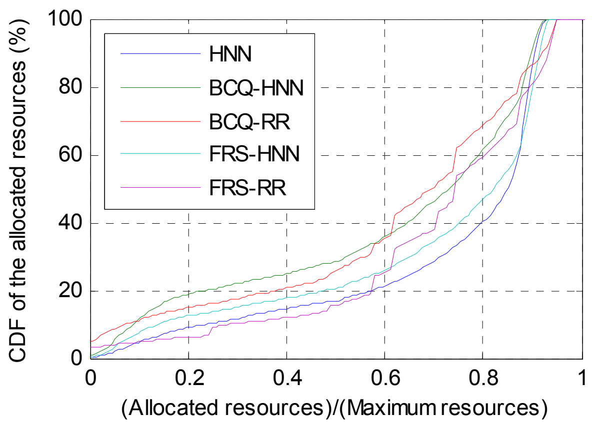

Fig. 3 CDF of the allocated resources