A User-Centric Approach for Dynamic Resource Allocation in CDMA systems based on Hopfield Neural Networks

N. García *, R. Agustí**, J. Pérez-Romero**
*Universitat Pompeu Fabra (UPF), **Universitat Politècnica de Catalunya (UPC)
Barcelona, Spain
email: nuria.garcia@upf.edu, ramon@tsc.upc.edu ,jorperez@tsc.upc.edu

Abstract— **This paper introduces a novel approach for considering the Dynamic Resource Allocation (DRA) in a multi-rate DS-CDMA wireless network supporting non real-time (NRT) communication. The allocated bit rate obeys to a user-centric approach by introducing a non-satisfaction user probability that has to be maintained below its targeted value while still keeping the best exploitation of the maximum available bandwidth. To this purpose different classes of users with different Contracted User Profiles are introduced and a Hopfield Neural Network optimization methodology is used under both user and network restrictions. Significant and promising results are finally shown for a single isolated cell DS-CDMA scenario including realistic propagation and mobility models.**

Index terms— **CDMA, Hopfield Neural Networks, Resource Allocation**

I. INTRODUCTION

Research in multi-rate direct-sequence code-division multiple access (DS-CDMA) networks for future wireless communication systems has recently attracted a lot of attention in the light of the new high bit rate data services that will be provided through 3G and 4G systems, including video, multimedia, circuit and packet mode data, together with the traditional speech services and low bit rate data. In such a scenario, it becomes crucial a proper management of the available radio resources in order to benefit from the traffic multiplexing to maximise the channel utilisation while at the same time keeping the specific service requirements. Specifically, in a DS-CDMA system, the amount of radio resources allocated to each user is controlled by regulating the transmission powers and the spreading gains (equivalently the transmission rates).

The problem of dynamic resource allocation (DRA) in a multi-service DS-CDMA wireless network supporting non real-time (NRT) communication services has been widely treated in the literature (see [1][2] and references therein). However, in most of the cases, a network-centric vision has been the common way to face the DRA, usually with the objective of maximizing the aggregate NRT throughput under different network constraints. As a consequence of that, in many cases users are treated according the propagation losses they suffer, so that throughput is maximised by allowing the transmissions of the users with the lowest path loss. Therefore, static and pedestrian users located far from the base station could be discriminated against other closer users.

In this paper, a user-centric approach is incorporated in the dynamic resource allocation problem, meaning that the users' needs, expectations and requirements are considered and supported by the wireless network. In this way, the system can continue providing an optimized throughput, but now including users' service profiles. Specifically, users will be serviced according to the bit rates that they have contracted with their mobile operator in an uplink CDMA wireless network. The actual bit rate allocated will be granted according to a fair mechanism. Moreover, the closed loop power control algorithm will provide to each user the required Eb/No target regardless of its position in a given instant. An isolated cell and realistic propagation and mobility models will be considered to illustrate these concepts.

On the other hand, in such user-centric approach with different users' service profiles, performance indicators other than the traditional ones (e.g. outage probability, BLER, etc.) must be considered to capture the degree of fulfilment of the contracted bit rate. Specifically, in this paper the probability that a user is not satisfied with the obtained bit rate will be retained as a mechanism to assess the system performance [3].

The remainder of the paper is organized as follows. In Section II, we describe the system model and formulate the resource allocation problem by introducing the fairness criterion and some DS-CDMA wireless network restrictions. In Section III, we present an optimization procedure able to allocate as many resources as possible but still guaranteeing a certain user satisfaction probability in agreement with the user profile. A Hopfield Neural Network will be used for that purpose. In Section IV, we present numerical results, and in Section V conclusions are summarised.

II. DRA PROBLEM FORMULATION

In this work a CDMA wireless network is considered where specific bit rates have to be allocated to a set of NRT users already admitted in the network. Different types of users with different rights coexist in the system according to their user profiles. In particular, each user belongs to a user class characterised by the contractual bit rate, which is the maximum bit rate that can be allocated to the user.

In particular, it is assumed that the allocation process is carried out periodically in periods of T_a s, denoted in the following as frames. Let assume that there are N users i=1,..., N in the cell in the current frame, and that the i-th user has a set of M possible bit rates. The objective of the DRA problem is then to select for each user an optimum allocated bit rate $R_{b,i}$, taking into account a set of constraints as explained in the following.

The optimization approach is performed through the use of Hopfield Neural Networks (HNN) already addressed in multimedia Wireless ATM [4] and in Dynamic Radio Planning [5]. HNN can actually be implemented in hardware devices at a low complexity cost, thus constituting an efficient approach to deal with the DRA problem in real time compared with other approaches like genetic algorithms, which may have more limitations [4][6].

As CDMA is an interference-limited technique, the aim of the DRA algorithm is to allocate the highest possible bit rate per user subject to a maximum planned uplink cell load factor, which allows keeping the total interference under certain limits [7]. A fast closed loop power control strategy is assumed like in UMTS [8] aiming to keep the required Eb/No target.

The user's satisfaction degree with the experienced service is measured with the non-satisfaction probability, which is defined for the i-th user as:

$$P_{ns,i} = \Pr\left(R_{b,i} < \frac{R_{b,i\ \max}}{D_i} \right) \tag{1}$$

where $R_{b,i}$ is the bit rate experienced by the i-th user, $R_{b,i\ max}$, is the maximum contractual bit rate for the i-th user according to its user class and D_i is a parameter to be selected according to the user contract and represents the fraction of the maximum bit rate with which the user is satisfied. A plausible fairness rule will be included in the HNN formulation in order to guarantee the above probability $P_{ns,i}$ according to the agreed user contract.

On the other hand, the CDMA technique imposes certain restrictions to the above optimization as follows:

A. Load Restriction

In any CDMA system, it is required to limit the maximum amount of interference generated by the different transmissions. This can be achieved by limiting the so-called uplink load factor η_{UL} to a maximum value $\eta_{UL\max}$. In the case of a single isolated cell, the load factor is related to the number of instantaneous transmissions N by means of the following expression [7].

$$\eta_{UL} = \sum_{i=1}^{N} \frac{1}{1 + \dfrac{W}{\left(\dfrac{E_b}{N_0}\right)_i R_{b,i}}} \le \eta_{UL\max} \tag{2}$$

where W is the total transmission bandwidth, $(E_b/N_0)_i$ is the target for the i-th user and $R_{b,i}$ is the bit rate allocated to the i-th user. The power control ensures that each user attains the (E_b/N_0) target provided that it has enough power to achieve it. That means it is not unfairly treated.

The above expression (2) can be approximated assuming that, usually, it holds:

$$\frac{W}{\left(\dfrac{E_b}{N_0}\right)_i R_{b,i}} >> 1 \tag{3}$$

It is worth mentioning that, when increasing the bit rate $R_{b,i}$, the last approximation becomes less valid. Nevertheless, it holds reasonably well even for the highest bit rates that will be considered in this paper.

Then, assuming for simplicity that the (E_b/N_0) target is the same for all the users, the sum of allocated bit rates must fulfil the following inequality:

$$\sum_{i=1}^{N} R_{b,i} \le \frac{W \eta_{UL\max}}{\left(\dfrac{E_b}{N_0}\right)} = B_T \tag{4}$$

Notice that B_T can be regarded as the total bandwidth to be partitioned among the different users.

B. Power Restriction

This condition takes into account the fact that the maximum available power in a mobile terminal is limited and, therefore, some bit rates may not be achievable for terminals located at the cell edge.

In particular, the power requirement of a terminal is given by [9] :

$$P_{T,i} = \frac{L_{p,i} P_N}{\dfrac{W}{\left(\dfrac{E_b}{N_o}\right)_i R_{b,i}} + 1} \frac{1}{1-\eta_{UL}} \approx \frac{L_{p,i} P_N}{\dfrac{W}{\left(\dfrac{E_b}{N_o}\right)_i R_{b,i}}} \frac{1}{1-\eta_{UL}} \tag{5}$$

where $L_{p,i}$ is the path loss corresponding to the i-th user and P_N is the background noise. Consequently, assuming a maximum available power of $P_{T\max}$ the bit rate allocation must take into account the following constraint for the i-th user:

$$P_{T\max} \ge \left(\frac{E_b}{N_o}\right)_i \frac{R_{b,i} L_{p,i} P_N}{W} \frac{1}{1-\eta_{UL}} \tag{6}$$

III. Optimization Formulation

The DRA problem formulated in the previous section turns into the requirement to find the optimal bit rate allocation for the N different users given the available bandwidth B_T, the user satisfaction degree and the constraints posed by the CDMA technique given by (4) and (6). In particular, the efficient exploitation of the available bandwidth B_T in terms of the allocated bit rate $R_{b,i}$ to the i-th user can be obtained by minimizing:

$$\left(B_T - \sum_{i=1}^{N} R_{b,i}\right)^2 \tag{7}$$

which ensures that the maximum aggregated throughput is still attained in this scenario.

The bit rate allocated to one user should be one out of M possible bit rates. In the following, the notation $R_{b,i}^{(j)}$ will be used, indicating the allocation of the j-th bit rate, j=1,..., M, to the i-th user, i=1,..., N.

According to (1), the i-th user is not satisfied in the k-th frame whenever the allocated bit rate $R_{b,i}^{(j)}$ is below the satisfaction bound $R_{b,i,max}/D_i$. Then, the fairness rule taking into account the user satisfaction degree is formulated through a suitable cost function $C_{i,j}^{k}$ associated to the i-th user, in the k-th frame and for an allocated j-th possible bit rate $R_{b,i}^{(j)}$ as:

$$C_{i,j}^{k} = \begin{cases} 0 & \text{if} \quad R_{b,i}^{(j)} \geq \dfrac{R_{b,i\ \max}}{D_i} \\ p_{ns,i}^{*} - \hat{p}_{ns,i}^{k-1} & \text{if} \left(\hat{p}_{ns,i}^{k-1} < p_{ns,i}^{*}\right) \text{ and } R_{b,i}^{(j)} < \dfrac{R_{b,i\ \max}}{D_i} \\ 1 & \text{if} \left(\hat{p}_{ns,i}^{k-1} \geq p_{ns,i}^{*}\right) \text{ and } R_{b,i}^{(j)} < \dfrac{R_{b,i\ \max}}{D_i} \end{cases} \tag{8}$$

where $p_{ns,i}^{*}$ is the target probability that the i-th user is not satisfied. In turn, $\hat{p}_{ns,i}^{k-1}$ is an estimation of the current non-satisfaction probability, measured up to frame k-1. It is computed as the ratio of non-satisfied users belonging to the same user class of the i-th user with respect to the total number of users of this class.

Notice that, for bit rates j above the satisfaction bit rate bound $R_{b,i,max}/D_i$, the cost function is low (i.e. 0) meaning that these bit rates are suitable for the i-th user. In turn, for lower bit rates, it depends on the non-satisfaction experienced by the user up to frame k-1: if the non-satisfaction is above the desired target, the cost is high (i.e. 1), meaning that higher bit rates are desirable, while if the non-satisfaction is below the target, the cost decreases meaning that the user could still accept these low bit rates.

The above optimization problem subject to the mentioned restrictions can be formulated in terms of a fast and parallel combinational optimiser known as Hopfield Neural Network (HNN) [10]. In particular, a two-dimensional $L=N\times M$ neural network can be considered for this problem. In a 2D HNN each neuron is modelled as a nonlinear device with a sigmoid monotonically increasing function defined by the logistic function:

$$V_{i,j} = f\left(U_{i,j}\right) = \frac{1}{1+e^{-\alpha U_{i,j}}} \tag{9}$$

where $U_{i,j}$ and $V_{i,j}$ are the input and output, respectively, of the i,j-th neuron, and α is the corresponding gain of the amplifier of the neuron.

The optimization process of the HNN is carried out on a frame basis and relies on minimizing an energy function E through the convergence of the expression:

$$\frac{dU_{i,j}}{dt} = -\frac{U_{i,j}}{\tau} - \frac{\partial E}{\partial V_{i,j}} \tag{10}$$

which characterizes the HNN behaviour [11]. The minima of the Energy occur at the 2L corners inside the L-dimensional hypercube defined on $V_{i,j}\in\{0,1\}$ [12]. By solving numerically (10) and after reaching a stable state each neuron is either ON (i.e. 1 if $V_{i,j}$ is greater or equal than 0.5) or OFF (i.e. 0, if $V_{i,j}$ lower than 0.5).

According to [4][5] a valid expression for the energy function E follows as:

$$E = \frac{\mu_1}{2}\sum_{i=1}^{N}\sum_{j=1}^{M} C^{k}_{i,j} V_{i,j} + \frac{\eta^{\varsigma}\mu_2}{2}\left|1-\sum_{i=1}^{N}\sum_{j=1}^{M}\frac{R_{b,i}^{(j)}}{B_T}V_{i,j}\right| + \\ + \frac{\mu_3}{2}\sum_{i=1}^{N}\sum_{j=1}^{M}\psi_{i,j}V_{i,j} + \frac{\mu_4}{2}\sum_{i=1}^{N}\sum_{j=1}^{M}V_{i,j}\left(1-V_{i,j}\right) + \frac{\mu_5}{2}\sum_{i=1}^{N}\left(1-\sum_{j=1}^{M}V_{i,j}\right)^2 \tag{11}$$

The minimisation of this function provides the allocation of the i-th user given by $V_{i,j}$, which takes the value 1 for the j-th bit rate (i.e. $R_{b,i}^{(j)}$) and 0 for the rest of bit rates.

The first summand in (11) contains the cost functions defined in (8). In turn, the second summand includes the exponent:

$$\varsigma = u\left(\sum_{i=1}^{N}\sum_{j=1}^{M}\frac{R_{b,i}^{(j)}}{B_T}V_{i,j} - 1\right) \tag{12}$$

where u(.) is the unit step function. This summand penalizes the undesired situations in which:

$$\sum_{i=1}^{N}\sum_{j=1}^{M} R_{b,i}^{(j)} V_{i,j} \geq B_T \tag{13}$$

and, at the same time, it drives the above expression to the equality.

The third summand simply penalizes non allowed bit rates according to the contractual user profile. That is, for the allowed bit rates $R_{b,i}^{(j)}$ of the i-th user, $\psi_{i,j}$=0, while for the non allowed bit rates $\psi_{i,j}$=1, thus increasing their contribution to the energy function and then bringing these bit rates out of the energy minima. The non-allowed bit rates include both those given the user profile and those caused by the power constraints given in (6).

That fourth and five summands were introduced in [5] in order to ensure rapid convergence to correct and stable states of neurons. Specifically, the fourth term forces convergence towards $V_{i,j}\in\{0,1\}$ and the last term forces the physical condition that only one bit rate $R_{b,i}^{(j)}$ is possible for the i-th connection.

IV. Results

This section presents some illustrative results obtained with the proposed allocation strategy. The CDMA wireless network scenario consists of one isolated circular cell with radius 2 km. The propagation and mobility models defined in [3] are considered. In particular, the path loss at distance d(km) is given by L(dB)= 128.1 + 37.6 $\log_{10}$(d), with a log-normal distributed shadowing with deviation 10 dB. The mobile speed is 60 km/h and the shadowing decorrelation length is 20 m. The wrap-around technique is considered in the simulations in order to avoid that terminals leave the simulated scenario due to mobility. The transmission bandwidth is W=3.84 Mchips/s and the maximum load factor is $\eta_{UL,max}$=0.7. Furthermore, the Eb/No target is 5 dB, which leads to an available bandwidth B_T=850 kb/s. The available set of bit rates is given by: {256 kb/s, 128 kb/s, 64 kb/s, 32 kb/s and 16 kb/s}. The noise power is -102 dBm.

The selected parameters appearing in the formulation of the HNN are μ_1=1000, μ_2=4000, μ_3=8000, μ_4=800, μ_5=6000, τ=1, α=1.0 and η=10. These values have been set based on [4]. In turn, the non-satisfaction probability is the same for all the users, $p_{ns,i}^{*}$=20% and is measured with respect to the fraction D_i=2 of the maximum bit rate.

A user is blocked whenever the maximum allowed bit rate taking into account transmission power constraints is below the minimum of 16 kb/s. A blocking situation would also occur in HNN enabled systems when all the active users were assigned the minimum 16 kb/s bit rate, occupying all available bandwidth B_T, and a new user requested a link to get through.

The session durations are exponentially distributed with average duration $T_{m,i}$=0.5 s for the i-th user. It is assumed that the session duration is independent of the allocated bit rate like in e.g. streaming services. Furthermore, the average session arrival rate is given by:

$$\lambda_i = \frac{1}{T_{m,i} + T_i} \tag{14}$$

where T_i=0.3s is the average time between the end of one session and the beginning of the next one for the i-th user, also exponentially distributed. Then the total traffic is given by:

$$\rho = \sum_i \lambda_i T_{m,i} = \sum_i \frac{1}{T_i + T_{m,i}} T_{m,i} = N \frac{T_{m,i}}{T_i + T_{m,i}} \tag{15}$$

The allocation algorithm is executed in frames of T_a=0.1 s, and the bit rate is kept during the whole frame time, although it can change from frame to frame. So, at the beginning of each active frame a Hopfield optimization is carried out. When a user finishes a session it is moved randomly to another location within the scenario just to simulate a different user when it comes to activity. It is worth mentioning, that the computational complexity associated with HNN is small enough to be executed in very short periods of time, so that the considered update period of T_a=0.1s has been mainly chosen in accordance with the time required to signal the users the new bit rate to be used and not with the execution time of the HNN algorithm, much lower than 0.1s. In that sense, some studies regarding the execution time of HNN algorithms are presented in [13].

Two scenarios are considered in the simulations:

- **Homogeneous scenario**: All the users belong to the same user class. The maximum bit rate is 256 kb/s.
- **Heterogeneous scenario:** In this case, two different user classes are considered. Class 1 users have a maximum bit rate of 256 kb/s and class 2 users of 128 kb/s. 20% of the users in the scenario belong to class 1 and 80% to class 2.

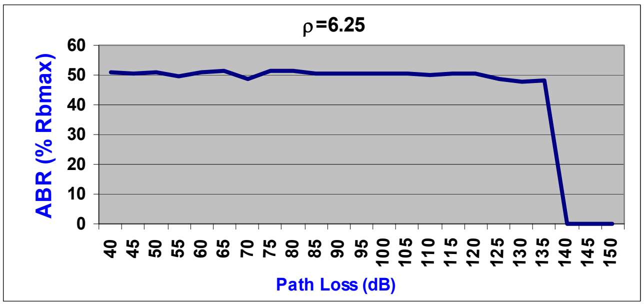


Fig. 1 Average Bit Rate (ABR) for the Homogenous scenario measured as the percentage of the maximum bit rate

Fig. 1 shows the average bit rate allocated depending on the propagation loss for the homogenous case with ρ=6.25, corresponding to N=10 users. It can be noticed the shrinking effect for propagation losses above 135 dB approximately, with a reduction in the average bit rate.

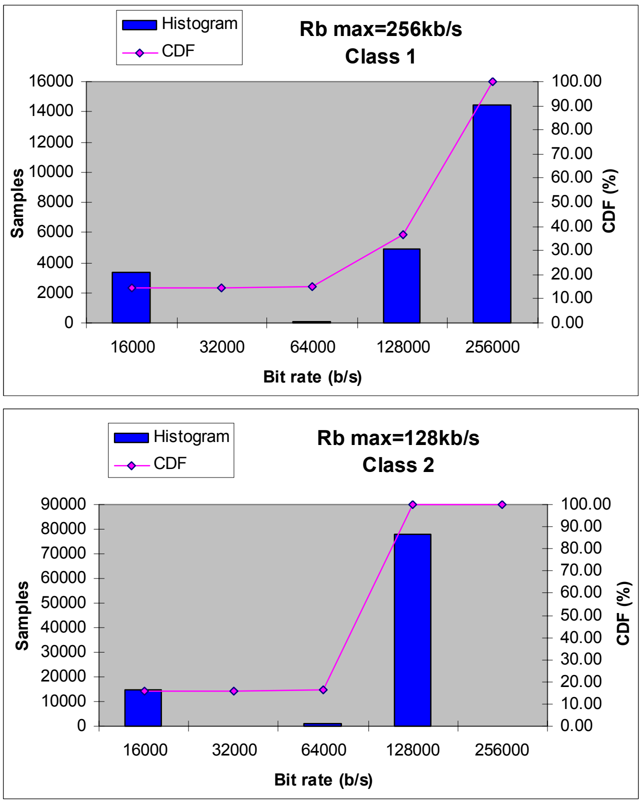
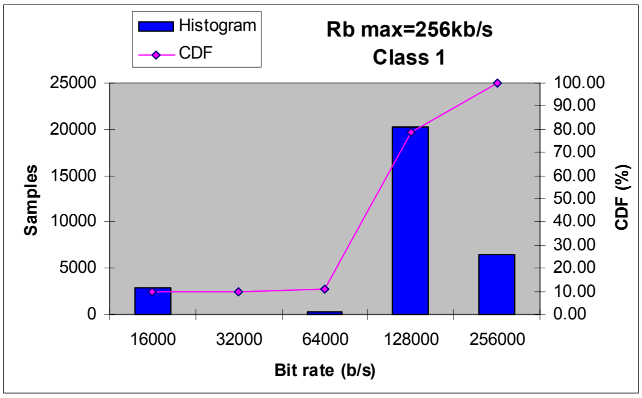


Fig. 2 Histogram and CDF of the allocated bit rates for the two user classes with ρ=6.25

In turn, for the heterogeneous scenario Fig. 2 shows the histogram and the cumulative distribution function (CDF) of the bit rate allocated to Class 1 and 2 users for a moderate-high load of ρ=6.25. It can be noticed in the CDF that the non-satisfaction probability (i.e. the probability of having a bit rate below 128 kb/s for class 1 users and 64 kb/s for class 2 users) is below the target value of 20% and the allocated bit rates are most of the time the maximum permitted. In turn, in Fig. 3, the load has significantly increased up to ρ=8.25 and the maximum permitted bit rates are allocated in a lower number of situations, but the target objective of 20% non-satisfaction probability is still kept.

In all the cases, the blocking probability results in very low values below 0.5%.



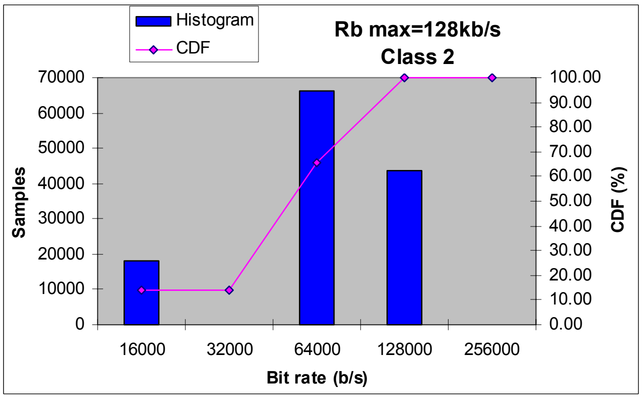


Fig. 3 Histogram and CDF of the allocated bit rates for the two user classes with ρ=8.25

It can be noticed in the above figures that a trade-off appears resulting from the Cost function (first term in (11)) and the best bandwidth partitioning among users (second term in (11)). In other words the algorithm tends to exploit the maximum available bandwidth (i.e. allocating the maximum permitted bit rates whenever possible), while keeping at the same time the target non-satisfaction probability.

V. Conclusions

This paper has presented a novel Dynamic Resource Allocation approach for a multi-rate DS-CDMA wireless network supporting non real-time communication. A user-centric instead of a network-centric approach has been considered aimed at developing a fair mechanism that allocates the available resources according to the specific contracted user profile. For this purpose, a Hopfield Neural Network optimization methodology has been retained with the introduction of a proper cost function characterising the user requirements. It has been shown that the considered approach is able to maintain the so-called non-satisfaction user probability below its targeted value while still keeping a good exploitation of the maximum available bandwidth. Significant and promising results have been obtained revealing that the proposed strategy performs satisfactorily.

Acknowledgements

This work has been carried out in the framework of the European Network of Excellence NEWCOM (Contract number 507325), and is partially funded by the Spanish Research Council under the COSMOS grant.

References

[1] S.A.Jafar, A. Goldsmith, "Adaptive Multirate CDMA for Uplink Throughput Maximization", *IEEE Transactions on Wireless Communications*, Vol. 2, No. 2, March, 2003, pp. 218-228.

[2] Seong-Jun Oh, Danlu Zhang, and Kimberly M. Wasserman, "Optimal Resource Allocation in Multiservice CDMA Networks", *IEEE Transactions on Wireless Communications*, Vol. 2, No. 4, July 2003.

[3] UMTS 30.03 v3.2.0 TR 101 112 "Selection procedures for the choice of radio transmission technologies of the UMTS", ETSI, April, 1998.

[4] C.W.Ahan, R.S.Ramakrishna, "QoS Provisioning Dynamic Connection-Admission Control for Multimedia Wireless Networks Using Hopfield Neural Networks", *IEEE Transactions on Vehicular Technology*, Vol 53, Jan 2004

[5] E. Del Re, R. Fantacci, L. Ronga, "A Dynamic Channel Allocation Technique Based on Hopfield Neural Networks", *IEEE Transactions on Vehicular Technology*, February 1996.

[6] M.R. Sherif, I. W. Habib, M. Nagshineh, P. Kermani, "Adaptive allocation of resources and call admission control for wireless ATM using genetic algorithms", IEEE Journal on Selected Areas in Communications, vol. 18, pp. 262-282, February, 2000.

[7] H. Holma, A. Toskala, *WCDMA for UMTS*, John Wiley & Sons,2nd edition, 2002.

[8] 3GPP TS 25.214 "Physical layer procedures (FDD)"

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

[10] J.J. Hopfield, *Neural Networks and physical systems with emergent collective computational abilities*, Proc. Nat.Acad. Sci.,1982, vol 79, pp2554-2558.

[11] Haykin, Neural Networks. *A Comprehensive Foundation*, New York: Mac Millan,1994

[12] S J.J. Hopfield , "Networks with graded response have collective computational properties like those of two state neurons", *Proc. Nat. Acad. Sci.*, vol 81, May 1984

[13] C.W.Ahn, R.S. Ramakrishna, C.G. Kang, I.C.Choi, "Shortest path routing algorithm using Hopfield neural network", IEE Electronics Letters, vol. 37, no. 19, pp. 1176-1178, 2001.