

## Research Article

# A New OFDMA Scheduler for Delay-Sensitive Traffic Based on Hopfield Neural Networks

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This paper introduces a novel joint channel and queuing-aware OFDMA scheduler for delay-sensitive traffic based on a hopfield neural network (HNN) scheme. It allows providing an optimum OFDMA performance by solving a complex combinational problem. The algorithm is based on distributing the available subcarriers among the users depending, on the one hand, on the time left for the transmission of the different packets in due time, so that packet droppings are avoided. On the other hand, it also accounts for the available channel capacity in each subcarrier depending on the channel status reported by the different users. The different requirements are captured in the form of an energy function that is minimized by the algorithm. In that respect, the paper illustrates two different algorithms coming from two settings of this energy function. The algorithms have been evaluated for delay-sensitive traffic and they have been compared against other state-of-the-art algorithms existing in the literature, exhibiting a better behavior in terms of packet-dropping probability.

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## 1. INTRODUCTION

Orthogonal frequency division multiple access (OFDMA) has emerged as one of the most promising schemes for broadband wireless networks. By using multiple parallel low-rate subcarriers, OFDMA can offer satisfactory high-speed data rate, robust wireless transmission, and flexible radio resource management, among other remarkable features, as it is widely documented in the open literature. In fact, current standards like DVB-T, wireless LAN IEEE.802.11a, and fixed-mobile broadband access system IEEE 802.16 have adopted OFDMA scheme. In addition to that, OFDMA has also been selected as access technology for the future 3G long-term evolution (LTE) in the evolved universal telecommunication radio access (EUTRA) [1], and most of the 4G initiatives also consider OFDMA as a prime access strategy. As a result of this current trend and from the radio resource allocation point of view, there has recently been a lot of attention to manage dynamically the inherent flexibility offered by OFDMA in an

optimal and still practical way, either in isolated [2] or in multicell OFDMA systems [3].

Concerning packet data transmission, most of the subcarrier allocation strategies proposed in OFDMA-based wireless multimedia networks intent somehow to maximize the system throughput or minimize the overall transmitted power while achieving the terminal bit rate requirements [4]. A recent good survey on these topics can be found in [5]. Unfortunately, the traffic-related queuing impact when considering dynamic resource allocation (DRA) scheduling schemes is not covered at the same extent. That is particularly relevant for interactive services and in general terms for delay-bounded services, in which packets should be delivered within specified deadlines. In that respect, there has been little work on these relevant performance measures such as the delay bound and the delay violation probability, which are indicative of the worst-case delay behavior. To the best of our knowledge, [6, 7] are among the first papers to face the constrained delay issue in managing the OFDMA system

resources using for this purpose a heuristic approach based on utility and priority functions when assigning resources to users.

OFDMA scheduling should actually include both joint subcarrier and power allocations. This is a rather complex problem, and usually it is simplified by separating these two allocations. Subcarrier allocation provides more gain than power allocation in [8], and in fact it is shown in [9, 10] that waterfilling allocation only brings marginal performance improvement over fixed power allocation with adaptive code and modulation (ACM). Then, in this paper, we focus on a subcarrier allocation strategy that is aware of the queuing state per each user and that retains a fixed power allocation as well as adaptive quadrature amplitude modulation (QAM).

Subcarrier allocation in OFDMA can be seen as a combinatorial problem where there are plenty of possible combinations associated to a given user. A user can be granted with many subcarriers at a given point of the time. In turn, each subcarrier provides a given channel capacity depending on the current fading and interference, so that multiuser diversity can be exploited. Also, a given subcarrier can only be assigned to one user. This is a natural choice, based on [9], that proves that the optimum OFDMA performance is reached by assigning each subcarrier to one user only in a cell among the many users trying to get access. In queuing-aware OFDMA systems like the one considered here, the information about queuing and channel status is exploited to efficiently allocate resources through proper cross-layer designs of the data scheduler. As a matter of fact, like in general OFDMA, DRA proposals, heuristic algorithms are usually selected to circumvent the fact that NP-hard algorithms would be necessary to obtain the optimum solutions. This is the case of [11], where a heuristic two-step algorithm is proposed to first allocate a number of subcarriers to each user and then to assign the specific subcarrier to each terminal. Similarly, in [12], an alternative approximate asymptotic mechanism is exploited. It relies on the fact that in a heavy traffic scenario minimizing delay violation is approximately equivalent to minimizing mean waiting time. Similarly, in [13], an allocation strategy depending on the queue size of each terminal relative to the overall data queued at the access point is presented for video streams. It is shown that this allocation achieves significant improvements with respect to static allocation methods, in spite of not including in the allocation neither channel gain information nor any stream specific knowledge. In [14], a cross-layer DRA strategy is presented that combines the channel status information together with the queue status and quality requirements in order to maximize power efficiency and ensure user fairness using a virtual clock scheduling algorithm, an adaptive subcarrier, and power allocation.

In this paper, due to the fact that the typical DRA in OFDMA turns out to be actually a combinatorial problem among all subcarriers involved, we have devised the collective computation property featured by the hopfield neural networks (HNN) which provide an optimal solution for many combinatorial problems [15, 16], as a very suitable approach for the problem addressed here. In fact, the HNN approach provides feasible solutions to complex optimization prob-

lems, like the NP-hard algorithms mentioned above. Under the proper conditions we can take advantage of the fact that the so-called HNN energy evolves toward a minimum value [17] providing a final neuron state that includes, in a natural way, the optimal subcarrier combination to be allocated. Consequently, this optimal allocation can be obtained by properly including different constraints (i.e., channel and queue status for the different users) in the definition of the HNN energy. From an implementation point of view, HNN methodology can be carried out either by solving iteratively a numerical differential equation based on the Euler technique or by means of hardware implementations (HNN is derived with an initial hardware implementation in mind) such as the field-programmable gate array (FPGA) chip [18] that has been proved practically for implementation purposes.

Under this framework, this paper proposes a novel HNN-based joint channel and queue-aware scheduling strategy for downlink OFDMA systems suitable for delay-bounded services. A multiuser scenario with statistically independent fading channels and an isolated cell is considered. Then, the subcarrier allocation is directly related to the remaining time before the agreed bounded delay service per user is violated for each packet as well as to the channel state. The proposed algorithm is compared against other approaches existing in the literature [11] and against a heuristic algorithm, also proposed in this paper as a first simple step in the provision of a joint channel and queue-aware strategy, which simply prioritizes the users according to their remaining packet lifetime and assigns subcarriers until they are exhausted.

The rest of the paper is organized as follows. Section 2 describes the considered system model, including the queuing behavior and the OFDMA considerations. Section 3 describes the proposed HNN-based algorithm with two different possibilities depending on the definition of the energy function. The proposed algorithm will be compared against the reference schemes presented in Section 4. Results are given in Section 5 and finally, conclusions are summarized in Section 6.

## 2. SYSTEM MODEL

The considered DRA problem assumes a set of  $N$  users,  $i = 1, \dots, N$ , with their corresponding queues located at the base station of the access network which contains the packets pending to be transmitted in the downlink direction of an OFDMA system, as illustrated in Figure 1. It is considered that nonshaped traffic is arriving to the queues, so that all the incurred packet delay is introduced at the network level. Also the model allows for differentiating among different classes of traffic (services classes) as will be discussed later. When a packet cannot be delivered within this bounded delay it is dropped and therefore, a dropping probability appears as a key performance indicator of the scheduling behavior.

The envisaged HNN-based scheduling algorithm operates in frames of duration  $T$  and allocates a certain bit rate to each user by assigning to him a set of subcarriers. Multiple transmissions of different users in parallel are allowed by making use of different subcarrier combinations. A granularity of one subcarrier is considered in the assignment process.

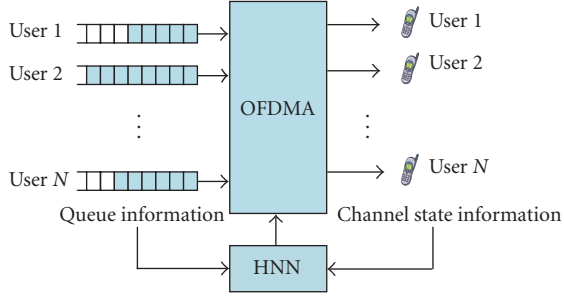
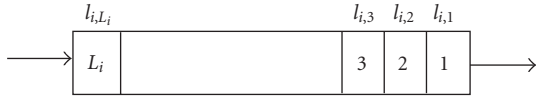


FIGURE 1: System model.

FIGURE 2: Queue of the  $i$ th user (for simplicity, the dependency with the number of frame  $k$  has been omitted).

The bit rate allocation will be executed by means of an optimal mechanism based on HNN, through the minimization of a properly defined energy function which includes a main function associated to the eligible bit rate per user according to the queue status and service-class requirements, as well as other terms to include the OFDMA downlink network restrictions. These considerations related with queue status and OFDMA model are explained in the following.

### 2.1. Queuing model

With respect to the queue model, let us assume that at the beginning of the  $k$ th frame, the  $i$ th user has  $L_i$  packets in the queue as depicted in Figure 2.  $l_{i,m}(k)$  denotes the number of bits of the  $m$ th packet of the  $i$ th user in the  $k$ th frame.

Assuming a first input first output (FIFO) policy for the queue of each user, the amount of bits that should be transmitted until the transmission of the  $m$ th packet of the complete  $i$ th user is given by

$$B_{i,m}(k) = \sum_{n=1}^m l_{i,n}(k). \quad (1)$$

On the other hand, the delay constraint is given by  $D_{\max,i}$ , measured as the maximum packet delay measured in frames specified in the contract of each user. Let  $f_{i,m}(k)$  be the elapsed time at the beginning of the  $k$ th frame since the arrival of the  $m$ th packet in the queue of the  $i$ th user. Then, the maximum timeout left for transmission of this packet is

$$TO_{i,m}(k) = D_{\max,i} - f_{i,m}(k). \quad (2)$$

Consequently, the minimum bit rate required to guarantee the transmission in due time of this packet is given by

$$v_{i,m}(k) = \frac{B_{i,m}(k)}{TO_{i,m}(k)}. \quad (3)$$

We define the *optimum bit rate* (OBR) for the  $i$ th user in the  $k$ th frame as the one that allows transmitting all the packets in due time, given by

$$R_{b,i,\text{opt}}(k) = \max_{m=1,\dots,L_i} \{v_{i,m}(k)\} \cdot (1 + \theta), \quad (4)$$

where  $\theta$  ( $\geq 0$ ) is a safety empirical factor introduced to face fluctuations in the packet generation of the successive frames. This OBR should be provided to each user by the OFDMA scheduler. To this end, it will perform the most suitable aggregation of a given number of subcarriers. Notice that a continuous transmission at the OBR would avoid packet losses for this user. However, it cannot always be guaranteed for all the users because of the total bandwidth restrictions.

### 2.2. OFDMA system model

The system model assumes a total of  $S$  subcarriers with separation  $\Delta f$  (Hz) to be allocated to the  $N$  users. It is assumed that the transmitter knows the channel state at the terminal side, and in particular, the receiver signal-to-noise ratio of the  $i$ th user in the  $j$ th subcarrier  $\rho_{ij}(k)$  in the  $k$ th frame. This value should be transmitted regularly by the mobile to the base station via a feedback channel, as illustrated in Figure 1, being the elapsed time lower than the channel coherence time. Then the actual capacity  $c_{ij}(k)$  of the  $j$ th QAM modulated subcarrier with Gray bit mapping in the  $k$ th frame for the  $i$ th user can be approximated by [18]

$$c_{ij}(k) = \log_2(1 + \beta \rho_{ij}(k)) \text{ bits/s/Hz} \quad (5)$$

$$\beta = -1,6 / \ln(5 \text{ BER}),$$

where BER is the target bit-error rate. Then, the throughput of the OFDMA system in the  $k$ th frame is given by

$$R(k) = \sum_{i=1}^N \sum_{j=1}^S \chi_{ij}(k) c_{ij}(k) \Delta f, \quad (6)$$

where  $\chi_{ij}(k)$  is set to 1 when the  $j$ th subcarrier is assigned to the  $i$ th user and is set to 0, otherwise. Finally, as not all the  $c_{ij}(k)$  values are allowed in a QAM modulation, the value obtained in (5) will be rounded to the highest integer lower than or equal to  $c_{ij}(k)$  from the set  $\{0, 1, 2, 4, 6\}$  bits/s/Hz.

### 3. HNN-BASED SCHEDULING MODEL

This section presents the proposed HNN-based scheduling algorithm to be executed in each frame  $k$  in order to determine the subcarrier allocation in accordance with the channel status for each user captured in the capacity  $c_{ij}(k)$  seen by the  $i$ th user in the  $j$ th subcarrier in the  $k$ th frame, and the buffer status captured in the value of the OBR for the  $i$ th user in the  $k$ th frame,  $R_{b,i,\text{opt}}(k)$ . For simplicity in the notation, the explicit dependency with the number of frame  $k$  will be omitted in the following.

The above DRA problem subject to the mentioned restrictions can be formulated in terms of a two-dimensional neural network with  $L = N \times S$  neurons [15]. The output

values of the neurons, denoted by  $V_{ij}$ , will be equal to 1, if the  $j$ th subcarrier is assigned to the  $i$ th user and 0, otherwise.

In a 2D HNN, each neuron is modeled as a nonlinear device with a sigmoid monotonically increasing function defined by the logistic function

$$V_{ij} = f(U_{ij}) = \frac{1}{1 + e^{-\alpha U_{ij}}}, \quad (7)$$

where  $U_{ij}$  and  $V_{ij}$  are the input and output, respectively, of the  $(i, j)$  neuron, and  $\alpha$  is the corresponding gain of the amplifier of the neuron.

Each neuron receives resistive connections from other neurons and these connections are fully described by the interconnection matrix  $T = [T_{ij,pq}]$ , where  $T_{ij,pq}$  is the interconnection weight from the  $(i, j)$  neuron to the  $(p, q)$  neuron. Each neuron also receives an input bias current  $I_{ij}$  that is an adjustable parameter. The dynamics of the HNN are represented by [15]

$$\frac{dU_{ij}}{dt} = -\frac{U_{ij}}{\tau} + \sum_{p=1}^N \sum_{q=1}^S T_{ij,pq} V_{pq} + I_{ij}, \quad (8)$$

where  $\tau$  is a time constant. Furthermore, the quadratic energy function is defined as

$$E = -\frac{1}{2} \sum_{i=1}^N \sum_{j=1}^S \sum_{p=1}^N \sum_{q=1}^S T_{ij,pq} V_{ij} V_{pq} - \sum_{i=1}^N \sum_{j=1}^S I_{ij} V_{ij}. \quad (9)$$

Then, taking into account the derivative of the energy function  $E$  in (9), the HNN dynamics represented by (8) can be formulated in a more compact way by the following differential equation:

$$\frac{dU_{ij}}{dt} = -\frac{U_{ij}}{\tau} - \frac{\partial E}{\partial V_{ij}}. \quad (10)$$

It is shown in [20] that, for a symmetric matrix  $T$  and sufficiently high gain  $\alpha$ , neurons in HNN evolve along a trajectory over which the energy function decreases monotonically to a minimum occurring at the  $2^{N \times S}$  corners inside the  $N \times S$ -dimensional hypercube defined on  $V_{ij} \in \{0, 1\}$ , thus providing the allocation of subcarriers to users.

It is worth noticing that by selecting a suitable expression for the energy function  $E$ , a queuing-aware OFDMA embedded optimization can be achieved. The optimization process of the HNN is carried out on a frame-by-frame basis and relies on minimizing the energy function through the convergence of the above differential equation. In the following, two suitable expressions for the energy function compliant with the definition in (9) are introduced, which will give rise to two different scheduling HNN-based algorithms.

### 3.1. HNN1 algorithm

A first expression proposed for the energy  $E$  follows as

$$E = \frac{\mu_1}{2} \sum_{i=1}^N \left( 1 - \frac{\sum_{j=1}^S c_{ij} V_{ij} \Delta f}{\bar{m}_i} \right)^2 + \frac{\mu_2}{2} \sum_{i=1}^N \sum_{j=1}^S \psi_{ij} V_{ij} + \frac{\mu_3}{2} \sum_{i=1}^N \sum_{j=1}^S V_{ij} (1 - V_{ij}) + \frac{\mu_4}{2} \sum_{j=1}^S \left( 1 - \sum_{i=1}^N V_{ij} \right)^2. \quad (11)$$

The first term is a cost function intended to be minimized by a proper setting of  $V_{ij}$ . It includes the expression

$$\bar{m}_i = \left( \left\lceil \frac{R_{b,i,\text{opt}}}{\Delta f} \right\rceil + 1 \right) \cdot \Delta f, \quad (12)$$

where  $\lceil \cdot \rceil$  denotes the integer part, so that (12) is actually a quantification of the OBR value  $R_{b,i,\text{opt}}$  in multiples of  $\Delta f$ . The minimum value of the energy  $E$  would be achieved for specific combinations of  $V_{ij}$  that minimize each summand, so that each user tends to be allocated with its OBR. Notice that OBR can be changed at each frame depending on the traffic dynamics and the packets evolution in the queues. Similarly, the channel fading also impacts OBR dynamics as the capacity of the different subcarriers can be changed on a frame basis.

The second summand in (11) simply penalizes the allocated subcarriers with bit rates equal to zero. That is, when the  $i$ th user is considered with a subcarrier  $j$ th in which  $c_{ij} = 0$ ,  $\psi_{ij} = 1$ , thus increasing their contribution to the energy function. In this way, the corresponding subcarriers are brought out of the energy minima and become available for other users. Otherwise, it is set to  $\psi_{ij} = 0$ .

The third summand of (11) was introduced in [21] in order to force convergence toward  $V_{ij} \in \{0, 1\}$  and the fourth term is introduced to reflect the physical OFDMA constraint that a given subcarrier can only be allocated to one user. The relationship between the energy function (11), the HNN interconnection matrix  $T = [T_{ij,pq}]$ , and the input bias current  $I_{ij}$  values in the general expression of the energy function in (9) can be obtained according to the details shown in the appendix.

The terms  $\mu_1$ ,  $\mu_2$ ,  $\mu_3$ , and  $\mu_4$  are constants to be set.

The numerical iterative solution of (10) is obtained following the Euler technique as

$$U_{ij}(n+1) = U_{ij}(n) + \Delta \left[ -\frac{U_{ij}(n)}{\tau} - \frac{\partial E}{\partial V_{ij}} \right], \quad (13)$$

where  $\Delta$  denotes the discrete step and neuron's voltage is updated at each  $n$ th iteration using (7). After reaching a final state, each neuron is either ON (i.e.,  $V_{ij}$  is set to 1 if  $V_{ij} \geq 0.5$ ) or OFF (i.e.,  $V_{ij}$  is set to 0 if  $V_{ij} < 0.5$ ).

Then, once the final  $V_{ij}$  values are achieved as solution of (7) and (10), the final bit rate assigned to the  $i$ th user after the execution of the algorithm in one frame follows:

$$R_{b,i} = \sum_{j=1}^S V_{ij} c_{ij} \Delta f. \quad (14)$$

### 3.2. HNN2 algorithm

A second expression for the energy function that captures additional features concerning both users and channel subcarrier status not considered in algorithm HNN1 is

$$E = \frac{\mu_1}{2} \sum_{i=1}^N \omega_i \left( 1 - \frac{\sum_{j=1}^S c_{ij} V_{ij} \Delta f}{\bar{m}_i} \right)^2 + \frac{\mu_3}{2} \sum_{i=1}^N \sum_{j=1}^S V_{ij} (1 - V_{ij}) + \frac{\mu_4}{2} \sum_{j=1}^S \left( 1 - \sum_{i=1}^N V_{ij} \right)^2. \quad (15)$$



In this case, the first term has been modified with respect to the HNN1 algorithm with the inclusion of a new coefficient  $\omega_i$  introduced with a two-fold objective. First, it should favor the users with high OBR that the former formulation of the term could not capture. Second, it should favor the allocation of subcarriers to the users with the best channel capacity thus making a better exploitation of the multiuser diversity. For that purpose, the users are first ordered in decreasing value of their OBR  $R_{b,i,\text{opt}}$ , and  $\text{order}_i$  is defined as the position of the  $i$ th user in this ordered list. Then, the coefficient  $\omega_i$  is empirically defined as

$$\omega_i = \left(2 - \frac{1}{\text{order}_i}\right) \cdot \left(1 - \frac{\sum_{j=1}^S c_{ij}}{\sum_{i'=1}^N \sum_{j=1}^S c_{i'j}}\right). \quad (16)$$

Notice that, with this definition, users with either a high OBR (i.e., a low value of  $\text{order}_i$ ) or a good channel status in the different subcarriers will tend to have smaller values of  $\omega_i$  and consequently, the minima of the energy function will tend to occur in  $V_{ij}$  values, so that a certain number of subcarriers is allocated to these users.

On the other hand, notice also that the effect of coefficient  $\omega_i$  already captures to some extent the avoidance to allocate the subcarriers to the users with a bad channel status, which was intended by the second summand in the energy function of the HNN1 algorithm in (11), and consequently, this summand is not included in the definition of the energy function for the HNN2 algorithm in (15). The Appendix shows the relationship between the energy function in (15) and the interconnection matrix and input bias currents.

#### 4. REFERENCE SCHEDULING SCHEMES

The proposed HNN-based algorithms described in the previous section have been compared against other approaches. First, a simple heuristic reference scheduling algorithm has been considered which exploits the OBR concept, but does not take into consideration the optimization in accordance with the HNN procedure. This algorithm, denoted in the following as reference scheduling scheme 1 (RSS1), simply tries to allocate to each user its optimum bit rate OBR as defined in (4). The algorithm operates then in the following steps in each frame.

*Step 1.* Order the users in the increasing value of  $R_{b,i,\text{opt}}$ .

*Step 2.* Allocate sequentially to each user  $i$ th the necessary number of subcarriers, so that its final scheduled bit rate is higher than or equal to  $\bar{m}_i$  from (12). This allocation is carried out by ordering first all the available subcarriers still pending to be allocated in the increasing value of  $c_{ij}$ .

*Step 3.* Once all the  $S$  available subcarriers have been allocated, assign a bit rate equal to 0 kb/s (i.e., no transmission) to the remaining users.

Notice that, as far as the OFDMA capacity can satisfy the required OBR per user and frame, the reference system would lead to a quite satisfactory scheduling approach from a delay point of view.

Furthermore, focusing on the existing approaches in the literature, the proposed algorithm has also been compared against the recent proposal introduced in [11], which will be denoted in the following as reference scheduling scheme 2 (RSS2). This algorithm also focuses on delay-sensitive traffic and operates on two different steps.

The first step is the subcarrier allocation algorithm which determines the number of subcarriers to be allocated to each user. For that purpose, it accounts for different average channel conditions in all subcarriers as well as for the delay requirements of the different packets in the queue. After an initial computation, the algorithm executes several iterations in order to ensure that the total number of allocated subcarriers equals the number of available subcarriers  $S$ .

In the second step, the subcarrier assignment algorithm is executed which decides the specific subcarriers allocated to each user. This is done by creating a priority list ordering the different users in accordance with the history of packet droppings experienced by each one, so that users with a higher number of droppings have a higher priority. In turn, for users with equal number of droppings, the priority is computed in accordance with the channel quality (i.e., users with better quality have a higher priority). Then, according to the priority list, each user selects the best available subcarriers up to the number of subcarriers computed in the first step.

For details of the algorithm, the reader is referred to [11]. It is worth mentioning that this algorithm was in turn compared in [11] against other previous references, such as [13], exhibiting better performance. Consequently, this algorithm has been retained here for comparison purposes as an appropriate reference representative of the state-of-the art in OFDMA dynamic resource allocation algorithms for delay-sensitive traffic.

#### 5. RESULTS AND DISCUSSION

A single cell scenario has been considered to assess the proposed HNN-based DRA strategy for a downlink OFDMA wireless access. We consider  $S = 128$  subcarriers and  $\Delta f = 15$  kHz. In the simulation, the scheduling algorithm operates in frames of  $T = 10$  milliseconds. We will also assume that the coherence time is larger than the frame time, so within a frame it is assumed that the channel impulse response does not vary. In our simulation, each user channel suffers from multipath Rayleigh fading with a delay profile characterized by a time variant impulse response following the pedestrian model of [22] with a mobile speed of 5 km/h and an average signal-to-noise ratio equal to 17 dB. We let a target BER =  $10^{-4}$  and assume a set of possible transmission bit rates: 15  $m$  kb/s per subcarrier ( $m = 0,1,2,4,6$ ) by properly adjusting the modulation levels of a  $2^m$  QAM-adopted signalling format.

The selected parameters appearing in the formulation of the HNN are  $\mu_1 = 4000$ ,  $\mu_2 = 30000$ ,  $\mu_3 = 800$ ,  $\mu_4 = 18000$ ,  $\tau = 1$ , and  $\alpha = 1.0$ . Simulations not shown here for the sake of brevity concerning the variation of these parameters have revealed that they are actually robust values, so that changing them to a certain extent (i.e., variations as large as 50% have been tested) does not impact significantly the final results.

The only conditions are that these parameters should be positive and satisfy  $\mu_3 < \mu_4$ , as it is shown in the appendix.

On the other hand, the iterative numerical solution in (13) is finalized when iterations  $n$  and  $n - 1$  satisfy  $\|\mathbf{V}^n - \mathbf{V}^{n-1}\|_2 < \varepsilon$ , where  $\|\cdot\|_2$  is the Euclidean norm and  $\mathbf{V}$  is a matrix which includes all the elements  $V_{ij}$ . We have set  $\Delta = 10^{-4}$  in (13) and  $\varepsilon = 10^{-5}$ . The convergence to a stable value is attained in practice in most of the situations between 1000 and 1500 iterations. As a result of that, a maximum of 2000 iterations has been used to stop the iterative process. If all these conditions are fulfilled, we decide that the process converges and the values  $V_{ij}$  provide us the inputs to calculate the total bit rate allocated to each user in each frame  $R_{b,i}$  according to (14).

An interactive service following the WWW traffic model from [22] has been considered as a representative of a delay-sensitive service. Specifically, WWW sessions are composed of an average of 5 pages with an average time between pages of 30 seconds. In each page, the average number of packets is 25 with an average time between packets of 0.0277 second. The packet length follows a Pareto with cutoff distribution with parameters  $\alpha = 1.1$ , minimum packet size 81.5 bytes and maximum packet size 6000 bytes. The average time between WWW sessions is 0.1 second (i.e., it is assumed that a user is continuously generating sessions). Two interactive user classes, namely, Class 1 and Class 2, have been included, as representatives of two different user profiles, with maximum allowed delays of 120 milliseconds and 60 milliseconds, respectively; 60% of the users belong to class 1 and 40% to class 2.

By setting the parameter  $\theta > 0$  for the OBR in (4), queues are forced to be emptied faster than for  $\theta = 0$ , which is particularly true for low-loaded systems. However, there is not an optimum  $\theta$  setting unique for all the loads. Then, from the obtained results,  $\theta = 0.6$  has been retained as a satisfactory value in all the studied cases. Let us notice that, in general, high values of  $\theta$  could end up at assigning bandwidth in excess to some users in detriment of others. This is clearly pointed out in the RSS1 scheme, where the first-ordered users could be provided with an excessive bandwidth (and actually not required), which would prevent the allocation to other users in the ordered list.

Figure 3 plots the comparison between the considered strategies in terms of packet dropping probability for class-1 users as a function of the total number of users in the scenario (similar results not shown here for the sake of brevity would be observed for class-2 users). It can be observed that the worst performance is obtained with the RSS1 scheme, and that the two approaches based on HNN are able to outperform both RSS1 and RSS2 strategies, thanks to the consideration of both queuing time constraints and channel status in the optimization carried out by hopfield neural networks. Notice that, for low dropping probability values, the reduction achieved by HNN-based strategies is in around one order of magnitude with respect to both RSS1 and RSS2. In that respect, notice also that the energy function from HNN2 is able to achieve always a lower dropping probability than the energy function from HNN1. Equivalently, the performance in terms of dropping probability can be translated into a cer-

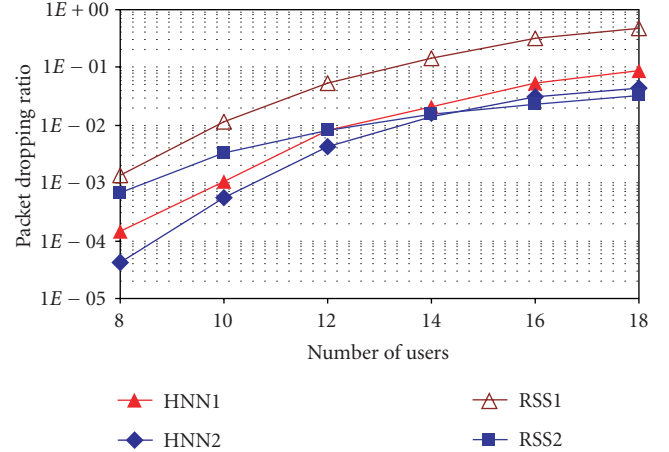


FIGURE 3: Packet dropping ratio for class-1 users as a function of the number of users in the scenario.

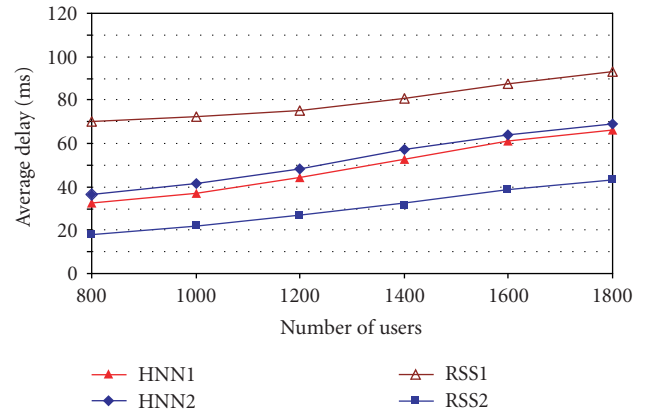


FIGURE 4: Average packet delay for class-1 users as a function of the number of users in the scenario.

tain system capacity (i.e., maximum number of users that the system can handle for a certain maximum dropping probability of, for example, 1%). Specifically, while RSS2 would exhibit a capacity of around 1200 users, in the case of HNN2 the capacity is increased up to around 1350 users (i.e., a capacity gain of 13%).

With respect to the performance on average terms, Figure 4 compares the average packet delay measured for class-1 users with different approaches. In this case, the comparison reveals that HNN-based approaches achieve an average delay that lies between the RSS1 and RSS2 schemes. However, Figure 5 which plots the ratio between standard deviation and average delay for each strategy indicates that RSS2 is actually the strategy with the highest dispersion in terms of delay, which eventually justifies that, in spite of having a good performance on average terms, the packet dropping ratio is higher than with the HNN-based algorithms. Consequently, whenever delay-sensitive traffic is considered, the performance should not be optimized only on average terms but also specific conditions in terms of maximum allowed delays should be considered. Finally, it is worth mentioning

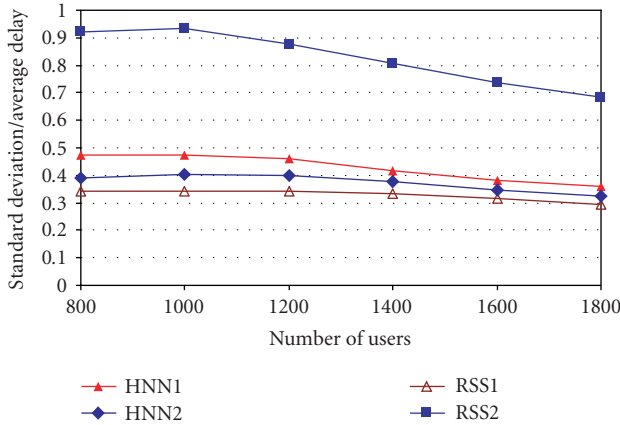


FIGURE 5: Ratio between the standard deviation and the average of the packet delay for class-1 users.

that actually both HNN1 and HNN2 provide just an upper bound of the dropping probability due to the above-mentioned truncation of the iterative Euler technique and the existence of a minimum in the energy function. So, even better results could be expected by exploring other numerical solutions or alternative improved energy function definitions, what is left for future work.

As an illustrative result of how the different algorithms operate, Figure 6 plots the cumulative distribution function (CDF) of the bit rate allocated per user with the different approaches for a situation with 1000 users in the scenario (for illustrative purposes, only the bit rate of class-1 users is presented, but the performance for class-2 users would be similar). Actually, only the most relevant part of CDF relative to the highest percentile is stressed in Figure 6 to better differentiate the reference and the HNN-based scheduler algorithms operation. It can be observed that both HNN-based strategies are able to make allocations of higher bit rates, thanks to the HNN-optimization accounting for the joint queue and channel status, which ensures that the subcarriers are allocated to the most suitable users. In that respect, the main difference between HNN1 and HNN2 would be for the lowest bit rates (i.e., below 30 kb/s, not shown in the graph, and where the crossing point between the HNN1 and HNN2 curves occurs), in which HNN1 would exhibit a higher probability than HNN2 of allocating low bit rates.

Finally, Figure 7 plots the comparison in terms of the CDF of the total allocated bandwidth obtained with HNN1 with respect to the total requested bandwidth (i.e., the sum of all the OBRs of the different users) for the cases with 1200 users and 1600 users. It can be observed how the total requested bandwidth increases with the number of users, but the total allocated bandwidth remains approximately the same; meaning that the system has reached its maximum capacity. However, in spite of the fact that the total requested bandwidth is higher than the total allocated bandwidth, the algorithm carries out a smart allocation that keeps the packet dropping probability at low values, as illustrated in Figure 3. Similar results are obtained with HNN2.

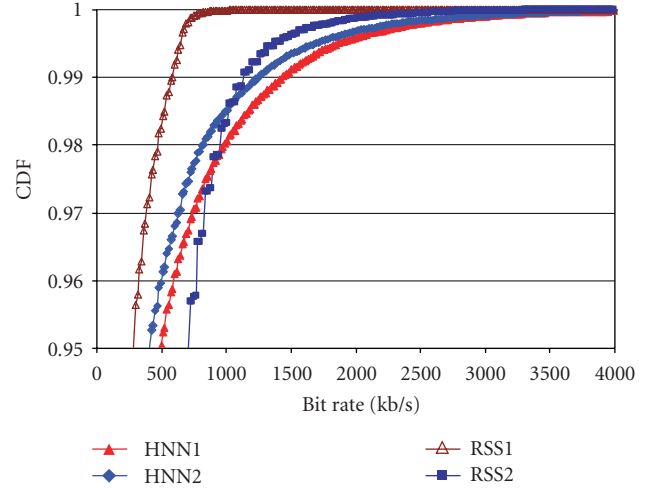


FIGURE 6: CDF of the allocated bit rate for class-1 users for the different strategies with 1000 users in the scenario.

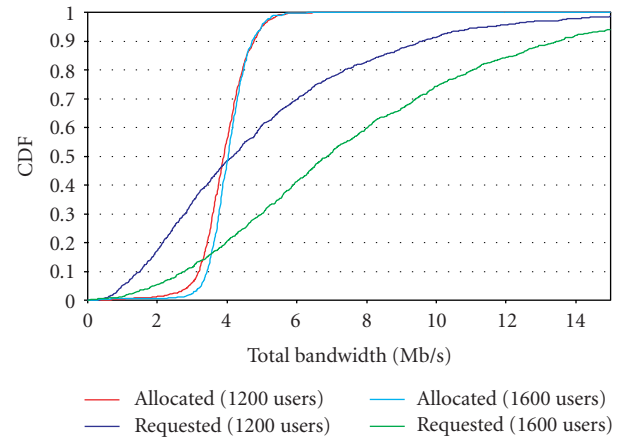


FIGURE 7: Cumulative distribution function of the total allocated and requested bandwidth for the HNN1 algorithm with 1200 and 1600 users.

## 6. CONCLUSIONS

This paper has presented a novel strategy to carry out the dynamic resource allocation of subcarriers to users in OFDMA systems with delay-sensitive service in which packets should be transmitted within a specific maximum delay bound. It is based on hopfield neural network methodology which is a powerful optimization technique and takes into account both service-class constraints in terms of maximum allowed delay as well as channel capacity limitation in each subcarrier. Actually, HNN methodology has been carried out by solving iteratively a numerical differential equation having a hardware implementation in mind, and the different delay requirements are captured in the form of an energy function that is minimized by the algorithm. In that respect, two different energy functions have been analyzed by means of simulations and compared against two reference schemes revealing a better behavior in terms of packet-dropping probability,

which eventually turns into system capacity increase. Specifically, capacity gains of around 13% for a maximum dropping probability of 1% have been observed with respect to a representative state-of-the-art algorithm existing in the literature.

## APPENDIX

### INTERCONNECTION MATRIX AND INPUT BIAS CURRENT FOR THE PROPOSED HNN MODEL

This appendix presents the relationship between the energy functions considered in the two HNN-based algorithms and the general expression of the energy function for an HNN given in (9), so that both the interconnection matrix  $T_{ij} = [T_{ij,pq}]_{p=1,\dots,N, q=1,\dots,S}$  and the input bias current  $I_{ij}$  can be obtained.

In order to make the derivation valid for both HNN1 and HNN2 algorithms, let us consider the following common definition of the energy function  $E$ :

$$E = \frac{\mu_1}{2} \sum_{i=1}^N \omega_i \left( 1 - \frac{\sum_{j=1}^S c_{ij} V_{ij} \Delta f}{\bar{m}_i} \right)^2 + \frac{\mu_2}{2} \sum_{i=1}^N \sum_{j=1}^S \psi_{ij} V_{ij} + \frac{\mu_3}{2} \sum_{i=1}^N \sum_{j=1}^S V_{ij} (1 - V_{ij}) + \frac{\mu_4}{2} \sum_{j=1}^S \left( 1 - \sum_{i=1}^N V_{ij} \right)^2. \quad (\text{A.1})$$

Notice that, the energy function of HNN1 in (11) is obtained by taking  $\omega_i = 1$  in (A.1), while the energy function of HNN2 in (15) is obtained by taking  $\mu_2 = 0$  in (A.1).

For the energy function defined as (15) and a given  $V_{i^*j^*}$  neuron we obtain

$$\begin{aligned} \frac{\partial E}{\partial V_{i^*j^*}} &= \frac{\mu_1}{2} \sum_{i=1}^N 2\omega_i \left( 1 - \frac{\sum_{j=1}^S c_{ij} V_{ij} \Delta f}{\bar{m}_i} \right) \\ &\times \left( - \sum_{j=1}^S \frac{c_{ij} \Delta f}{\bar{m}_i} \frac{\partial V_{ij}}{\partial V_{i^*j^*}} \right) + \frac{\mu_2}{2} \sum_{i=1}^N \sum_{j=1}^S \psi_{ij} \frac{\partial V_{ij}}{\partial V_{i^*j^*}} \\ &+ \frac{\mu_3}{2} \sum_{i=1}^N \sum_{j=1}^S \left[ \frac{\partial V_{ij}}{\partial V_{i^*j^*}} (1 - V_{ij}) + V_{ij} \frac{\partial (1 - V_{ij})}{\partial V_{i^*j^*}} \right] \\ &+ \frac{\mu_4}{2} \sum_{j=1}^S 2 \left( 1 - \sum_{i=1}^N V_{ij} \right) \left( - \sum_{i=1}^N \frac{\partial V_{ij}}{\partial V_{i^*j^*}} \right). \end{aligned} \quad (\text{A.2})$$

Furthermore, since  $\partial V_{ij} / \partial V_{i^*j^*} = 1$  for  $i = i^*$ ,  $j = j^*$ , and  $\partial V_{ij} / \partial V_{i^*j^*} = 0$  for  $i \neq i^*$ ,  $j \neq j^*$  (A.2) can be expressed as

$$\begin{aligned} \frac{\partial E}{\partial V_{i^*j^*}} &= -\mu_1 \frac{c_{i^*j^*} \Delta f \omega_{i^*}}{\bar{m}_{i^*}} \left( 1 - \frac{\sum_{j=1}^S c_{i^*j} V_{i^*j} \Delta f}{\bar{m}_{i^*}} \right) + \frac{\mu_2}{2} \psi_{i^*j^*} \\ &+ \frac{\mu_3}{2} (1 - 2V_{i^*j^*}) - \mu_4 \left( 1 - \sum_{i=1}^N V_{ij^*} \right). \end{aligned} \quad (\text{A.3})$$

By substituting (A.3) into (10) it is obtained that

$$\begin{aligned} \frac{\partial E}{\partial U_{i^*j^*}} &= -\frac{U_{i^*j^*}}{\tau} + \mu_1 \frac{c_{i^*j^*} \Delta f \omega_{i^*}}{\bar{m}_{i^*}} \left( 1 - \frac{\sum_{j=1}^S c_{i^*j} V_{i^*j} \Delta f}{\bar{m}_{i^*}} \right) \\ &- \frac{\mu_2}{2} \psi_{i^*j^*} - \frac{\mu_3}{2} (1 - 2V_{i^*j^*}) + \mu_4 \left( 1 - \sum_{i=1}^N V_{ij^*} \right). \end{aligned} \quad (\text{A.4})$$

By identifying the coefficients in (A.4) with the corresponding coefficients in (8), it is possible to obtain the interconnection weights and bias currents as

$$\begin{aligned} T_{ij,pq} &= -\mu_1 \frac{c_{ij} c_{iq} (\Delta f)^2 \omega_i}{(\bar{m}_i)^2} \delta_{ip} + \mu_3 \delta_{ip} \delta_{jq} - \mu_4 \delta_{jq}, \\ I_{ij} &= \mu_1 \frac{c_{ij} \Delta f \omega_i}{\bar{m}_i} - \frac{\mu_2}{2} \psi_{ij} - \frac{\mu_3}{2} + \mu_4, \end{aligned} \quad (\text{A.5})$$

where function  $\delta_{ip}$  is 1 if  $i = p$  and 0 otherwise.

It is worth mentioning that a solution for the selection of the optimal bit rate per user can be easily performed simply by changing the input bias current  $I_{ij}$  and the interconnections values  $T_{ij,pq}$  at a frame basis.

In order to have minimum points with respect to output voltages  $V_{ij}$  of neurons, it is necessary that the second derivatives be positive, or equivalently

$$\frac{\partial^2 E}{\partial V_{ij}^2} > 0 \iff \mu_1 \frac{c_{ij} c_{iq} (\Delta f)^2}{(\bar{m}_i)^2} - \mu_3 + \mu_4 > 0, \quad (\text{A.6})$$

Condition (A.6) is satisfied if we ensure always that  $-\mu_3 + \mu_4 > 0$ , which yields the following relationship between the parameters of the energy function

$$\mu_3 < \mu_4. \quad (\text{A.7})$$

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Although the technical requirements are more and more fulfilled for a commercial success, there is still a need of sophisticated algorithms to handle 3D image information. The amount of data is extremely high, requiring efficient techniques for coding, transmission, and processing. Similarly, the estimation of 3D geometry and other meta data from multiple views, the augmentation of real and synthetic scene content, and the estimation of 3D object or face/body motion have been addressed mainly for restricted scenarios but often lack robustness in a general environment. This leaves many interesting research areas in order to enhance and optimize 3D imaging and to enable fully new applications. Therefore, this special issue targets at bringing together leading experts in the field of 3D image and video processing to discuss and investigate this interesting topic.

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A cellular neural/nonlinear network (CNN) is any spatial arrangement of mainly locally coupled cells, where each cell has an input, an output, and a state that evolves according to some prescribed dynamical laws. CNN represents a paradigm for nonlinear spatial-temporal dynamics and the core of the cellular wave computing (also called CNN technology). Partial differential equations (PDEs) or wave-like phenomena are the computing primitives of CNN. Besides, their suitability for physical implementation due to their local connectivity makes CNNs very appropriate for high-speed parallel signal processing.

Early CNN applications were mainly in image processing. The possible availability of cellular processor arrays with a high number of processing elements opened a new window for the development of new applications and the recovery of techniques traditionally conditioned by the slow speed of conventional computers. Let us name as example image processing techniques based on active contours or active wave propagation, or applications within the medical image processing framework (echocardiography, retinal image processing, etc.) where fast processing provides new capabilities for medical disease diagnosis.

On the other hand, emerging applications exploit the complex spatiotemporal phenomena exhibited by multilayer CNN and extend to the modelling of neural circuits for biological vision, motion, and higher brain function.

The aim of this special issue is to bring forth the synergy between CNN and spatiotemporal signal processing through new and significant contributions from active researchers in these fields. Topics of interest include, but are not limited to:

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Radio resource management (RRM) techniques (such as admission control, scheduling, sub-carrier allocation, channel assignment, power allocation, and rate control) are essential for maximizing the resource utilization and providing quality of service (QoS) in wireless networks.

In many cases, the performance metrics (e.g., overall throughput) can be optimized if opportunistic algorithms are employed. However, opportunistic RRM techniques always favor advantaged users who have good channel conditions and/or low interference levels. The problem becomes even worse when the wireless terminals have low mobility since the channel conditions become slowly varying (or even static), which might lead to long-term unfairness. The problem of fair resource allocation is more challenging in multi-hop wireless networks (e.g., mesh and multihop cellular networks).

The performance fairness can be introduced as one of the QoS requirements (e.g., as a condition on the minimum throughput per user). Fair RRM schemes might penalize advantaged users; hence, there should be a tradeoff between the overall system performance and the fairness requirements.

We are soliciting high-quality unpublished research papers addressing the problem of fairness of RRM techniques in wireless communication systems. Topics include (but are not limited to):

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## Special Issue on Broadcasting and Telecommunications at Crossroads: Impacts of NGN and Web 2.0 Concepts on the Future of IPTV

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Broadcasting, telecommunications, and the Internet are converging. As transporting the traditional broadcast TV just over the Internet is probably not generating significant benefits for the customers, IPTV contemporary deployments provide additional capabilities, such as video-on-demand, network-based personal video recorders, time-shifted TV, and so forth. However, key values of IPTV probably originate from the availability of back control channel, allowing for interactive TV, as well as the integration with emerging multimedia group communication services, such as buddy lists featuring presence information and instant messaging, voice over IP, emailing, video conferencing and many more, enabling a new community TV experience. In this context, the notion of *IP multimedia subsystem- (IMS-) based IPTV* is currently gaining momentum in the international NGN and IPTV standardization, by providing the middleware to glue network intelligence and directly to the home or on the move, that is, wire or wireless, respectively, TV service provision.

In light of *Web 2.0*, The internet has become a user-generated multimedia content distribution medium for many different communities, including different types of video services: for example, YouTube, Apple Podcasts, or P2P video architectures like Joost. As the Internet is currently challenging many business cases for the provision of NGN communication services, it will also do so in the field of broadcasting and TV. There is no doubt that in the future NGN- and Web 2.0-enabled IPTV environments will be in a position to provide the required flexibility for supporting adequately the converged markets.

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## Special Issue on Formal Techniques for Embedded Systems Design and Validation

### Call for Papers

Computing platforms that are embedded within larger systems they control, called embedded systems, are inherently very complex as they are responsible for controlling and regulating multiple system functionalities. Often embedded systems are also safety-critical requiring high degree of reliability and fault tolerance. Examples include distributed microprocessors controlling the modern cars or aircrafts and airport baggage handling system that track and trace unsafe baggage. To address this growing need for safety and reliability, formal techniques are increasingly being adapted to suit embedded platforms. There has been widespread use of synchronous languages such as Esterel for the design of automotive and flight control software that requires stronger guarantees. Languages like Esterel not only provide nice features for high-level specification but also enable model checking-based verification due to their formal semantics. Other semi-formal notations are also being proposed as standards to specify industrial embedded systems using, for example, the newly developed IEC61499 standard for process control. This standard primarily focuses on component-oriented description of embedded control systems. The goal of this special issue is to bring together a set of high-quality research articles looking at different applications of formal or semiformal techniques in specification, verification, and synthesis of embedded systems.

Topics of interest are (but not limited to):

- Verification of system-level languages
- Verification of embedded processors
- Models of computation and verification
- Models of computation for heterogeneous embedded systems
- IP verification issues
- Open system verification techniques such as module checking and applications of module checking
- Formal techniques for protocol matching and interface process generation
- Applications of DES control theory in open system verification

- Adaptive techniques for open system verification
- Verification techniques for automatic debugging of embedded systems
- Formal approaches for secure embedded systems
- Hardware-software coverification of embedded systems
- Compositional approaches for SOC verification
- Verification of distributed embedded system

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Manuscript Due	August 1, 2008
First Round of Reviews	November 1, 2008
Publication Date	February 1, 2009

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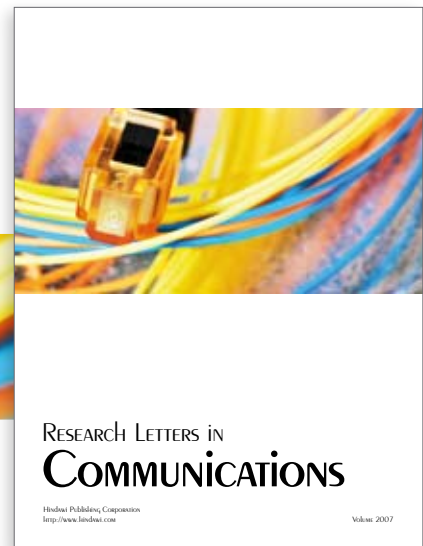
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