EURASIP Journal on Wireless Communications and Networking 2005:4, 573–578

Optimisation of Downlink Resource Allocation Algorithms for UMTS Networks

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Received 22 October 2004; Revised 3 June 2005; Recommended for Publication by Sayandev Mukherjee

Recent interest in resource allocation algorithms for multiservice CDMA networks has focused on algorithms optimising the aggregate uplink or downlink throughput, sum of all individual throughputs. For a given set of real-time (RT) and non-real-time (NRT) communications services, an upper bound of the uplink throughput has recently been obtained. In this paper, we give the upper bound for the downlink throughput and we introduce two downlink algorithms maximising either downlink throughput, or maximising the number of users connected to the system, when orthogonal variable spreading factors (OVSFs) are limited to the wideband code division multiple access (WCDMA) set.

Keywords and phrases: resource management, capacity optimisation, code division multiple access, OVSF, multiservices.

1. INTRODUCTION

Third generation (3G) wireless mobile systems like UMTS provide a wide variety of packet data services and will probably encounter an even greater success than already successful existing 2G systems like GSM [1]. With the growing number of services, the optimisation of resource allocation mechanisms involved in the medium access control (MAC) layer is a difficult aspect of new radio mobile communications systems. The resource allocation algorithm allocates the available resources to the active users of the network. These resources could be radio resources: they are time-slots in the case of a 2.5G network like (E)GPRS, but in a 3G network like UMTS, using WCDMA technology, they are spreading codes and power. Each user of data services can request, depending on his negotiated transmission rate, a spreading code of variable length with a corresponding transmission power at each moment. In a cell, we have real-time (RT) communications services that are served with the highest priority and non-real-time (NRT) communications services that are served with the lowest priority. Having allocated resources to the RT services, the base station then has to allocate resources to NRT services. In this paper we consider two possible criteria: the greatest number of allocated NRT services and the maximisation of the downlink throughput [2].

Most of notations used in this paper are close to those of [3, 4, 5, 6] where the downlink case was analysed, and of [7, 8, 9, 10] concerning the uplink case.

Compared with these previous papers, we take into consideration the problem of the orthogonal variable spreading factors (OVSF) of UMTS terrestrial radio access network (UTRAN) solution where spreading factors are limited to the wideband code division multiple access (WCDMA) finite set [11, 12, 13, 14]. This constraint was neither introduced in [5, 6] where algorithms presented are then perfectly suited for the UTRAN context, nor in [10] where the spreading factor set used is infinite and yields to a complex search table algorithm.

The UTRAN finite set constraint for spreading factors was previously addressed in [15] through the description of a real-time UMTS network emulator but without developing an optimal allocation algorithm.

Following approach presented in [9] for the uplink, we first introduce in the paper the optimal downlink upper bound, in order to compare performances of proposed algorithm with this upper bound.

The remainder of the paper is organised as follows: main notations are introduced in Section 2. The upper bound for the aggregate downlink throughput is given in Section 3. The solution for the powers to the NRT flows is given in Section 4. Two allocation algorithms are detailed in Section 5. The proof of the optimality of the proposed "downlinkDSF-U algorithm" is given in Section 6. Simulations results are finally presented in Section 7.

2. NOTATIONS

We consider a cell with Q RT terminals and M NRT terminals. Let $0 \leq p_i \leq P_{\max}$ and $N_i \in N^+$ be the transmission power and spreading factor of the ith flow at slot t. $P_{\max}$ is the maximum transmission power of the base station. N^+ is the set of possible spreading factors. Let $g_i > 0$ be the channel gains between the base station and the ith user and I_i the interference level for the ith user. This interference level includes the background, thermal noise power, and the intercell interference power. I_i does not include the intracell interference power due to other flows (RT and NRT) of the cell.

Index $i = 1, 2, \dots, Q$ is devoted to RT terminals while index $i = Q+1, Q+2, \dots, Q+M$ is devoted to NRT terminals. For each NRT user, we introduce a new g_i' variable representing its own "channel quality" defined by the ratio of its channel gain to its interference level: $g_i' = g_i/I_i$. Without loss of generality, we assume $g_{Q+1}' \geq g_{Q+2}' \geq \cdots \geq g_{Q+M}'$, so lower index values correspond to higher channel quality.

We assume that the coherence time of the most rapidly varying channel is greater than the duration of a time slot, so that the variations of the channel are small enough to consider that the gains are constant over a time slot.

We introduce Γ_i representing the target signal-to-noise-plus-interference ratio requested for RT or NRT services.

Finally we introduce the constant $0 \leq \alpha \leq 1$, representing the loss of orthogonality of downlink spreading codes. We consider $\alpha = 0$ for an additive white Gaussian noise channel, where codes stay orthogonal at the input of the terminal receiver, and typically $\alpha = 1/2$ for a multipath channel, where orthogonality is partially lost.

Therefore, for the ith terminal we have

$$\Gamma_i = \frac{N_i p_i g_i'}{1 + \alpha(P_T - p_i)g_i'}, \tag{1}$$

where $P_T = \sum_{k=1}^{Q+M} p_k$ represents the sum of allocated powers either to RT terminals ($k \in [1, Q]$) or to NRT terminals ($k \in [Q+1, Q+M]$).

Constraints are $0 \leq P_T \leq P_{\max}$ and $N_i \in N^+$. The aggregate downlink throughput of NRT terminals $\Omega_{\mathrm{NRT}}^{\downarrow}$ is proportional to the sum of the inverse of the allocated spreading factors: $\Omega_{\mathrm{NRT}}^{\downarrow} \propto \sum_{i=Q+1}^{Q+M} 1/N_i$. In this paper we consider that all NRT terminals correspond to the same service category and request all the same QoS and then the same signal-to-noise-plus-interference ratio. We then have $\Gamma_i = \Gamma$ for all $i \in [Q, Q+1]$.

3. UPPER BOUND FOR THE DOWNLINK THROUGHPUT

The upper bound for the downlink throughput is straightforward. We allocate powers to RT flows considering that residual available power is then allocated to the first NRT flow (having the highest channel quality). Actually we can first consider the choice between allocating the maximal power either to the first NRT flow with a spreading factor N_{Q+1} or to the second NRT flow with a spreading factor N_{Q+2}. Due to the constant term equal to one in (1) and the nondecreasing function $f(x) = ax/(1+bx)$, $a, b > 0$, it appears that $g_{Q+1}' > g_{Q+2}'$ leads to $1/N_{Q+1} > 1/N_{Q+2}$, so the first solution gives a higher throughput. We now consider a solution allocating powers to both flows $Q+1$ and $Q+2$. It is then obvious that the power allocated to the second NRT flow generates a higher throughput if it is transferred to the first NRT flow. Generalising this result to more than two flows gives the solution for maximising the downlink throughput. The ideal and minimal spreading factor N_{Q+1} for the fist NRT flow is obtained using (1) by

$$N_{Q+1} = \frac{\Gamma\left(1 + \alpha P^{\mathrm{RT}} g_{Q+1}'\right)}{\left(P_{\max} - P^{\mathrm{RT}}\right) g_{Q+1}'}, \tag{2}$$

where $P^{\mathrm{RT}} = \sum_{k=1}^{Q} p_k$ represents power allocated to RT terminals.

This allocation leads to the following optimal upper bound for the downlink throughput $\Omega_{\mathrm{NRT}}^{\downarrow *} \propto 1/N_{Q+1}$. However, N_{Q+1} has no reason to be in the set of values $N^+ = \{4, 8, 16, 32, 64, 128, 256, 512\}$ that have been normalised for UTRAN downlink [11, 12, 13, 14]. Consequently, $\Omega_{\mathrm{NRT}}^{\downarrow *}$ is a theoretical upper bound for $\Omega_{\mathrm{NRT}}^{\downarrow}$. In this paper we propose an optimal downlink allocation algorithm where allocated spreading factors belong to the finite set of available spreading factors of UTRAN.

4. POWERS ALLOCATED FOR NRT FLOWS

We propose to split the allocation problem in two steps. First we identify a set of spreading factors $\mathbf{N} = (N_1, N_2, \dots, N_Q, N_{Q+1}, \dots, N_{Q+M})$ suited to the UTRAN constraints and, in a second step, the corresponding powers $\mathbf{p} = (p_1, p_2, \dots, p_Q, p_{Q+1}, \dots, p_{Q+M})$ are computed. For the spreading factors allocation, RT services define rigorously the Q first spreading factors $(N_1, N_2, \dots, N_Q)$ and the degree of freedom of the allocation algorithm concerns only the M last spreading factors $(N_{Q+1}, \dots, N_{Q+M})$.

For the power allocation, whatever the RT or the NRT terminal i taken into consideration, (1) must be verified, we then have

$$p_i = \frac{\Gamma_i(1+\alpha P_T g_i')}{\alpha\Gamma_i g_i' + N_i g_i'}. \tag{3}$$

So by summation,

$$P_T = \sum_{i=1}^{Q+M} p_i = \sum_{i=1}^{Q+M} \frac{\Gamma_i(1+\alpha P_T g_i')}{\alpha\Gamma_i g_i' + N_i g_i'}. \tag{4}$$

Afterstraightforward derivation, we obtain

$$P_T = \frac{\sum_{i=1}^{Q+M} \Gamma_i/g_i'\,(\alpha\Gamma_i + N_i)}{1-\alpha\sum_{i=1}^{Q+M}\Gamma_i/(\alpha\Gamma_i+N_i)}. \tag{5}$$

If $1-\alpha\sum_{i=1}^{Q+M}\Gamma_i/(\alpha\Gamma_i+N_i) > 0$ and $P_T \le P_{\max}$, the solution is "feasible" and, once spreading factors are allocated, p_i is directly obtained by combining (5) and (3). If constraints are not checked, the allocation is not possible and the throughput must be decreased through an increase of the spreading factors.

5. NRT SPREADING FACTORS ALLOCATION ALGORITHMS

In this section we propose two allocation algorithms. In both cases we first allocate RT terminals, then we continue with NRT terminals sorted in ascending order (numbered from $Q+1$ to $Q+M$, corresponding to the channel quality g_{Q+1}' to g_{Q+M}'). Both algorithms check that powers obtained by solving (5) lead to $0 \le P_T \le P_{\max}$. If this condition is not checked, the algorithm stops and keeps the last correct allocation. The first algorithm, so-called downlink discrete spreading factor down (downlinkDSF-D), first allocates the highest spreading factor (SF=512) to the greatest number of NRT terminals in order to maximise the number of served terminals. If possible, it then decreases progressively all the spreading factors, starting with the terminal with the highest channel quality in the cell (N_{Q+1}), then N_{Q+2}, and so forth. If the allocation is not possible, the algorithm ends and the spreading factor of the processed terminal keeps its previous value. In the paper we note $N_i = \infty$ if no spreading factor is allocated to the corresponding terminal. Obviously, this algorithm maximises the number of users simultaneously served and tries, if possible, in a second time, to increase as much as possible the downlink throughput but without decreasing the number of served terminals. The second algorithm, so called downlink discrete spreading factor up (downlinkDSF-U) proceeds terminal by terminal and in order to maximise the aggregate downlink throughput, it allocates the lowest spreading factor (SF=4) to the terminal with the highest channel quality in the cell (N_{Q+1}), then to the second (N_{Q+2}), and so forth. If the allocation is not possible, the spreading factor of the processed terminal is increased until a correct set of $\{N_i\}$ is found; otherwise,the terminal is rejected and the algorithm stops. This second algorithm optimises the downlink throughput. The proof is presented in the next section.

6. OPTIMALITY OF THE DOWNLINKDSF-UP ALGORITHM

Definition 1 (definition of an arranged solution). Arranging a solution $\mathbf{N} = (N_1,\ldots,N_Q,N_{Q+1},\ldots,N_{Q+M})$ consists in considering only M last spreading factors corresponding to NRT terminals and for them (1) reordering spreading factors in increasing order, and (2) in the case of two equal factors $N_k = N_{k+1}(> N_{\min})$ to recombine N_k by $N_k/2$ and N_{k+1} by ∞. The operation is reiterated as many times as possible. At the end of the process the solution is arranged. Throughputs of the original solution and its arranged version are equals. Except for $N_i = N_{\min} = 4$, any NRT spreading factor cannot appear twice in the last spreading factors set of the arranged solution.

Theorem 2. *For any solution $\mathbf{N} = (N_1,\ldots,N_Q,N_{Q+1},\ldots,N_{Q+K})$ the corresponding arranged solution leads to a reduction of the transmitted power $P_T = \sum_{i=1}^{Q+K} p_i$.*

Proof of Theorem 2. (A) Permutation: we consider two solutions $\mathbf{N}^1 = (N_1,\ldots,N_Q,\ldots,N_i,\ldots,N_j,\ldots)$ and $\mathbf{N}^2 = (N_1,\ldots,N_Q,\ldots,N_j,\ldots,N_i,\ldots)$ with $i<j$ and, by hypothesis, $g_i' \ge g_j'$ and $N_i \le N_j$. We introduce the corresponding transmitted powers P_T^1 and P_T^2. Using (5), we notice that denominators of P_T^1 and P_T^2 are equal (we considered $\Gamma = \Gamma_i = \Gamma_j$ for any NRT terminal). For the numerator we notice that $M+Q-2$ terms are similar for these two powers. We then have to analyse 4 terms in order to compare powers corresponding to these two different spreading factors allocations:

$$\operatorname{sign}\left(P_T^2 - P_T^1\right) = \operatorname{sign}\left(\frac{1}{g_i'(N_j+\alpha\Gamma)} + \frac{1}{g_j'(N_i+\alpha\Gamma)} - \frac{1}{g_i'(N_i+\alpha\Gamma)} - \frac{1}{g_j'(N_j+\alpha\Gamma)}\right), \tag{6}$$

and after some easy derivation,

$$\operatorname{sign}\left(P_T^2 - P_T^1\right) = \operatorname{sign}\left(N_i g_j' + N_j g_i' - N_j g_j' - N_i g_i'\right). \tag{7}$$

Since $N_i \le N_j$, we can write $N_j = N_i + \Delta N_{ij}$ with $\Delta N_{ij} \ge 0$. Then $\operatorname{sign}(P_T^2 - P_T^1) = \operatorname{sign}(\Delta N_{ij}(g_i' - g_j'))$. Since by hypothesis $g_i' \ge g_j'$, we have directly $\operatorname{sign}(P_T^2 - P_T^1) \ge 0$, then $P_T^2 \ge P_T^1$.

(B) Recombining: we consider two solutions $\mathbf{N}^1 = (N_1,\ldots,N_Q,\ldots,N_i,\infty,\ldots)$ and $\mathbf{N}^2 = (N_1,\ldots,N_Q,\ldots,2N_i,2N_i,\ldots)$ with the corresponding transmitted powers P_T^1 and P_T^2. Using (5) we can note $P_T^1 = \mathrm{Num}_1/\mathrm{Den}_1$ and $P_T^2 = \mathrm{Num}_2/\mathrm{Den}_2$.

(i) *Analysis of* $\text{Num}_1 - \text{Num}_2$*:*

$$\text{Num}_2 - \text{Num}_1 = \frac{\Gamma}{g_i'(\alpha\Gamma + 2N_i)} + \frac{\Gamma}{g_{i+1}'(\alpha\Gamma + 2N_i)} - \frac{\Gamma}{g_i'(\alpha\Gamma + N_i)}, \tag{8}$$

$$\text{Num}_2 - \text{Num}_1 = \frac{\Gamma N_i(g_i' - g_{i+1}') + \alpha\Gamma^2 g_i'}{g_i' g_{i+1}'(\alpha\Gamma + N_i)(\alpha\Gamma + 2N_i)}.$$

As $g_i' > g_{i+1}'$, we have $\text{Num}_2 > \text{Num}_1$.

(ii) *Analysis of* $\text{Den}_2 - \text{Den}_1$*:*

$$\begin{aligned}\text{Den}_2 - \text{Den}_1 &= \frac{-2\alpha\Gamma}{2N_i + \alpha\Gamma} - \frac{-\alpha\Gamma}{N_i + \alpha\Gamma},\\ \text{Den}_2 - \text{Den}_1 &= \frac{-\alpha^2\Gamma^2}{(2N_i + \alpha\Gamma)(N_i + \alpha\Gamma)}.\end{aligned} \tag{9}$$

Formula (9) gives directly $\text{Den}_2 < \text{Den}_1$. Finally $P_T^2 > P_T^1$. After successive reordering and permuting we obtain the arranged version of the original solution. It has same throughput, lower P_T, and any $N_i \neq 4$ can appear only once. □

Remark 1. If a solution $\mathbf{N}^2$ is possible, it means that $0 \leq P_T^2 \leq P_{\max}$, then we have $\text{Den}_1 > \text{Den}_2 > 0$ and $P_T^1 < P_T^2 \leq P_{\max}$. With (5) we conclude that the arranged version $\mathbf{N}^1$ of any possible solution $\mathbf{N}^2$ exists always and is possible.

Theorem 3. *The downlinkDSF-U algorithm maximises the aggregate downlink throughput.*

Proof of Theorem 3. We consider an exhaustive search among all possible solutions. We identify the solution $\mathbf{N}^{\text{best}}$ giving the highest throughput and minimising, for this throughput, the transmitted power P_T. Because P_T is minimal, this solution is necessarily arranged (cf. Theorem 2). We now compare spreading factors used by this optimal solution $\mathbf{N}^{\text{best}}$ and those used by the downlinkDSF-U algorithm $\mathbf{N}^{\text{Up}}$. If we can find an NRT index i such that $N_i^{\text{best}} > N_i^{\text{Up}}$ then, since W-CDMA spreading factors are successive powers of 2, we have $N_i^{\text{best}} \geq 2N_i^{\text{Up}}$. The corresponding throughput difference is then greater or equal to $(2N_i^{\text{Up}})^{-1}$. At this point, even if for all $j > i$, $N_j^{\text{Up}} = \infty$, this throughput loss cannot be balanced by spreading factors corresponding to indices $j > i$ of the "best" solution. To check this, we just have to consider that for all $j \geq i$, $N_j^{\text{best}} \geq 2^{j-i} N_i^{\text{best}}$. Then the aggregate throughput $\Omega_{i+1\to M}^{\text{best}}$, due to spreading factors $i+1$ to M of the "best" solution, is proportional to $\sum_{j=i+1}^{M}(1/N_j^{\text{best}})$. This additional throughput is maximal when each spreading factor is replaced by its minimal value. Accordingly,

$$\Omega_{i+1\to M}^{\text{best}} \leq \sum_{j=i+1}^{M} \frac{1}{2^{j-i}} \frac{1}{N_i^{\text{best}}}. \tag{10}$$

Using $N_i^{\text{best}} \geq 2N_i^{\text{Up}}$, (10) becomes

$$\Omega_{i+1\to M}^{\text{best}} \leq \sum_{j=i+1}^{M} \frac{1}{2^{j-i+1}} \frac{1}{N_i^{\text{Up}}}. \tag{11}$$

Then (with $m = j - i$),

$$\Omega_{i+1\to M}^{\text{best}} \leq \frac{1}{2N_i^{\text{Up}}} \sum_{m=1}^{M-i} \frac{1}{2^m}. \tag{12}$$

And finally,

$$\Omega_{i+1\to M}^{\text{best}} < \frac{1}{2N_i^{\text{Up}}}. \tag{13}$$

In order to prove Theorem 3, we just have to compare spreading factors $\mathbf{N}^{\text{best}}$ and $\mathbf{N}^{\text{Up}}$.

For $i = Q + 1$, we have three possibilities.

(i) $N_{Q+1}^{\text{best}} > N_{Q+1}^{\text{Up}}$: as mentioned earlier this case is impossible because it leads to $\Omega^{\text{Up}} > \Omega^{\text{best}}$.

(ii) $N_{Q+1}^{\text{best}} < N_{Q+1}^{\text{Up}}$: this case is impossible because the downlinkDSF-U algorithms have minimised N_{Q+1}^{Up}.

(iii) $N_{Q+1}^{\text{best}} = N_{Q+1}^{\text{Up}}$: so the two solutions are equivalent.

Having finally $N_{Q+1}^{\text{best}} = N_{Q+1}^{\text{Up}}$, we can now consider $i = Q + 2$ and so forth following the same argument. At the end, we obtain $\mathbf{N}^{\text{best}} = \mathbf{N}^{\text{Up}}$. The downlinkDSF-U algorithm gives the optimal solution, which maximises then the downlink throughput. □

7. SIMULATION RESULTS

RT and NRT terminals are uniformly distributed in the cell at distances from the base station from 325 m–1.2 km. In order to determine the channel gains, we chose Okumura-Hata propagation model in an urban area with $f = 2$ GHz, $h_{\text{base station}} = 40$ m, and $h_{\text{terminal}} = 1.5$ m. Let $P_{\max} = 10$ W and $I_{\text{inter}} = -63$ dBm (equivalent to 6 base stations situated 2.4 km away from the base station and transmitting at $P_{\max}$). Γ_{RT} and Γ_{NRT} are set to7.4 dB. Q is set to 50 and M varies from 1–500. Finally, $N_{\text{RT}} = 256$ and $\alpha = 0.5$.

Simulation results represent mean values obtained after more than thousand trials. Figure 1 illustrates the variations of $\Omega_{\text{NRT}}^{\downarrow *}$, $\Omega_{\text{NRT}}^{\downarrow}$ obtained with downlinkDSF-U and with downlinkDSF-D. Actually, a constant chip rate (including the radio supervision) of 5120 chips per 10/15 milliseconds is performed with UTRAN. The aggregate downlink throughput of NRT terminals is then equal to $\Omega_{\text{NRT}}^{\downarrow} = \sum_{i=1}^{M} 7.68/N_i$, in Mbps (7.68 is the UTRAN 3.84 chip rate doubled with modulation).

Hence, $\Omega_{\text{NRT}}^{\downarrow}$ and $\Omega_{\text{NRT}}^{\downarrow *}$ are increasing functions of the number of NRT terminals. Finally, $\Omega_{\text{NRT}}^{\downarrow}$ varies from 950 kbps to 1.25 Mbps, that is, from 63%–83% of $\Omega_{\text{NRT}}^{\downarrow *}$ (equal to 1.5 Mbps).

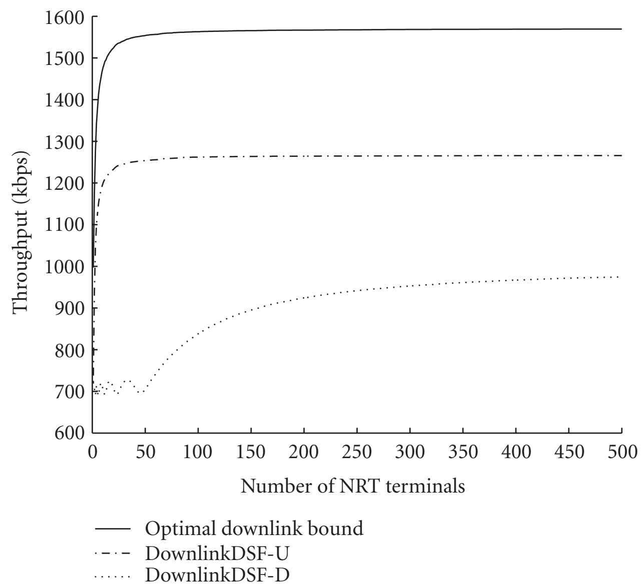

Figure 1: $\Omega^{\downarrow *}_{\mathrm{NRT}}$ and $\Omega^{\downarrow}_{\mathrm{NRT}}$ obtained with downlinkDSF-U and downlinkDSF-D.

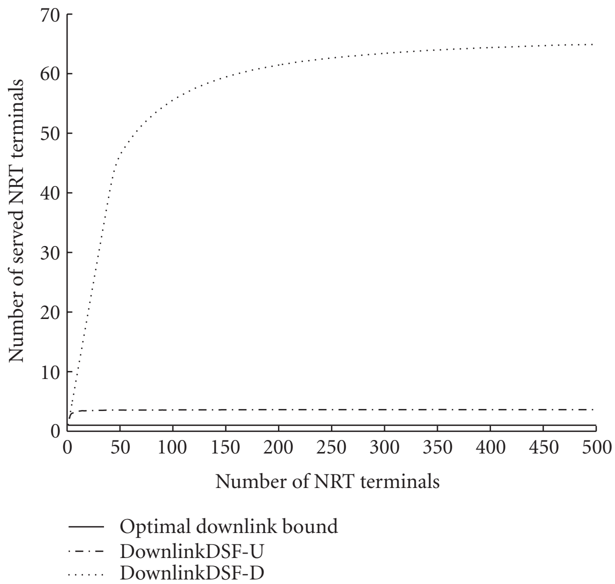

Figure 2: Number of simultaneously transmitted NRT services with downlinkDSF-U and downlinkDSF-D, as a function of the total number of active NRT services in the cell.

Figure 2 gives the number of simultaneously transmitted NRT services with downlinkDSF-U and downlinkDSF-D as a function of the total number of active downlink NRT terminals in the cell. Objectives of the two algorithms are different and this figure is just an illustration more than a performance comparison. It is recalled that with the upper bound, only one NRT terminal is served. It appears that when downlinkDSF-D is applied, the number of simultaneous transmitted NRT services is exactly M when M is low (typically lower than 40). Then, as the base station uses all its power to reach more and more terminals benefiting from worse and worse conditions of propagation, it cannot satisfy all NRT services and the individual rates remain minimum. Therefore, the aggregate throughput is nearly proportional to the number of simultaneously served NRT services. On the opposite, the downlinkDSF-U never transmits simultaneously information to more than 4 NRT terminals. Further more, the probability of having terminals benefiting from better conditions of propagation increases with M increasing.

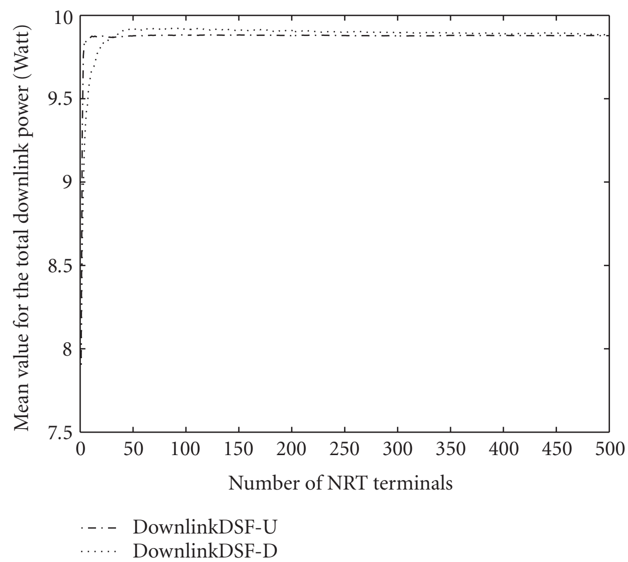

Figure 3: Mean value of the downlink power.

Figure 3 gives the total power radiated by the base station with respect to the number of active NRT services in the cell. It appears that the power is close to the 10 W maximum value. This maximum value is quickly obtained with the downlinkDSF-U, while the downlinkDSF-D seems to be unable to serve all terminals and therefore has to choose terminals with good channel quality in order to reach this maximal power value.

8. CONCLUSION

In this paper two resource allocation algorithms for the W-CDMA downlink of UMTS were presented. These algorithms allocate spreading factors in the set $\{4, 8, 16, 3264, 128, 256, 512\}$; downlinkDSF-U maximises the aggregate downlink NRT throughput whereas downlinkDSF-D maximises the number of simultaneously transmitted NRT services. Simulation results have presented comparisons between an upper bound and the two algorithms in terms of throughput and number of served terminals. This work can be extended to the high-speed downlink packet access (HSDPA) evolution of W-CDMA considering complementary fractional (corresponding to the QAM16 modulation) spreading factors and considering the multicodes allocation principle. The two optimal algorithms are legitimate, respectively, for the operators (seeking maximum revenue) and users (seeking a fair part of the available resources). We have shown that these allocations are quite opposite so that trade off algorithms have to be studied. A suggestion for further work is to look for maximising throughput in short term while looking for fair use of the resources among users in the long term.

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