Performance Modeling of Web Access over HSPA Networks

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Abstract— **HSPA (High Speed Packet Access) technologies have become an attractive solution for broadband wireless Internet access. This article evaluates the quality of service experimented by one HSPA user in the presence of multiple terminals sharing the cell capacity. The study focuses on Web traffic and includes analytical and simulation results, providing a basis for dimensioning and admission control in HSPA networks given the intended user quality of experience. The results show that the downlink channel capacity can be shared by several tens of Web users with a satisfactory quality. This is possible because the activity factor of this application (i.e. the time spent in downloading pages compared to the time spent in reading them) is low. However, the results also indicate that the page download time is penalized by the delay associated with the initial procedure for allocating resources on the traffic channels. This problem can be alleviated by an adequate configuration of the timers associated to the resource allocation procedures in HSPA.**

Keywords-component; HSPA, Web, Simulation, Quality of Experience

I. INTRODUCTION

HSPA [1] (High Speed Packet Access) is an umbrella term covering a set of extensions to the original UMTS (Universal Mobile Telecommunications System) radio interface aimed to improve the throughput for packet-switched services. The first two HSPA extensions are HSDPA (High Speed Downlink Packet Access) and EUL (Enhanced Uplink), respectively defined in 3GPP Release 5 and 6 specifications. The evolution of 3GPP systems continues and operators are already preparing for the introduction of new extensions such as Evolved HSPA (also known as HSPA+) and LTE (Long Term Evolution).

This article focuses on the performance evaluation of mobile Web access over HSPA from the user point of view. Although UMTS operators have been introducing HSPA extensions gradually since 2006, there is still little practical knowledge on how to properly dimension HSPA networks so that users are guaranteed a given quality of experience.

HSDPA [2] provides downlink throughputs up to 14.4 Mbit/s (theoretical) for packet-switched services. This contrasts with the maximum of 384 kbit/s usually supported in UMTS Release 99. Other advantages of HSDPA are lower latency and more efficient use of spectrum. These improvements are achieved by introducing a number of enhancements in the radio access network. They include the use of a downstream shared channel HS-DSCH (High Speed Downlink Shared Channel), along with a number of features added to the Node-B which are grouped under a new layer of media access control MAC-hs. These features include a fast packet scheduling mechanism combined with the use of adaptive modulation and coding (AMC) and a hybrid retransmission scheme (H-ARQ).

Fig. 1 illustrates the traffic channels used in HSPA. In the downlink, the HS-DSCH provides a high capacity channel which is dynamically shared between the users in the cell. In the uplink, HSPA terminals can use either a DCH (Dedicated Channel) or an E-DCH (Enhanced DCH). The latter option depends on whether the cell supports EUL or not.

The downlink shared channel HS-DSCH is a transport channel that may be associated to one or more physical channels, i.e. OVSF (Orthogonal Variable Spreading Factor) codes, with a fixed spreading factor value of 16. This value allows up to 15 codes for the HS-DSCH channel on a 5 MHz W-CDMA carrier. An operator can devote a full carrier to HSPA, or share it between HSPA and UMTS Release 99 services. In this second option, quite common in initial HSPA deployments, the number of codes for high speed packet services is typically 5 or 10. For areas with high service demand, operators are currently considering the deployment of dedicated carriers for HSPA with 15 codes.

EUL improves the uplink performance by combining a number of techniques similar to HSDPA, including H-ARQ retransmissions, a fast link adaption mechanism, and an advanced packet scheduler. Unlike HSDPA, the allocation of radio resources in the uplink is not set on the basis of a shared channel, but by controlling the distribution of power between the terminals. The packet scheduler operates on a request-grant principle where the UEs (User Equipment) request permission to send data and the scheduler decides when they can transmit and how much power they can use on the E-DCH.

In practice, the actual performance of HSPA depends on many factors: number of codes available in the cell, allocated power, propagation conditions, terminal category, etc. As an orientation, an HSPA cell with 10 codes provides a typical aggregated download throughput at IP level between 2 and 3 Mbit/s. Additionally, a key aspect to consider is the number of users simultaneously accessing the cell since, as noted above, the radio resources are shared dynamically either in terms of codes (downlink) or power (uplink).

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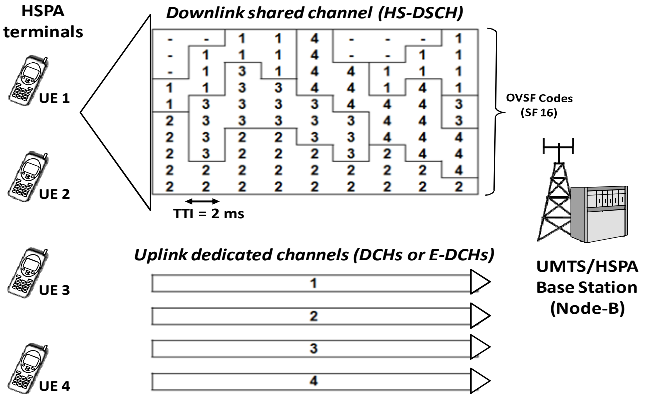

Fig. 1. Overview of HSPA traffic channels

Focusing in the downlink, the capacity of the HS-DSCH channel is shared dynamically between the users of the cell under the control of the fast scheduling algorithm in the Node-B. Intuitively, this means that the capacity per user is inversely proportional to the number of users in the cell. This is the key aspect investigated in this article.

More specifically, the paper focuses on the problem of assessing the equivalent dedicated capacity (C_{eq}) effectively utilized by a user, given the total capacity of the downlink shared channel and the number of users in the cell. C_{eq} is defined as the capacity value exclusively dedicated to one user that would provide the same quality of experience as on the shared HSPA channel.

In the case of Web navigation, C_{eq} is the capacity that each user has for downloading pages. Thus C_{eq} determines the waiting time until Web pages are downloaded and displayed on the browser, which is the typical performance indicator for measuring the quality of experience of Web access. In the literature, there are similar studies for Web access over other shared media access technologies, such as cable networks and GPRS [3][4].

To evaluate the equivalent capacity and the Web page download time, we present results obtained with an analytical model, and compare them with results obtained by simulation. Given the global capacity of the HS-DSCH channel, we estimate the maximum number of simultaneous users that guarantees a minimum equivalent capacity, so that the mean page download time is kept under a given value.

The rest of the article is organized as follows. Section II describes the analytical model and the results obtained with it. Section III describes the HSPA simulator and section IV presents the most relevant simulation results, which are compared with those provided by the analytical model. Finally, section V summarizes the main findings of the study.

II. EQUIVALENT CAPACITY ANALYSIS

This section analyses the relationship between the equivalent capacity C_{eq}, the total capacity C of the downlink channel HS-DSCH, the number of users N, and the characteristics of the Web traffic they generate. The analysis considers each user downloads Web pages of average length L bits, with mean reading time T_{off} seconds between consecutive pages. L is assumed to be the sum of the sizes of the HTML page plus all objects it includes (e.g. images). The analysis is made at the IP layer. Thus, C is the total capacity available for transmission of IP packets in the downlink direction, and L includes the overhead due to IP and higher layer protocols.

At any given time, C is shared among the UEs (User Equipment) that are concurrently downloading Web pages. However, when a user requests a new page download, the UE cannot immediately utilize the HS-DSCH channel. To do so, the UE must transition from its current RRC (Radio Resource Control) state, for example “idle”, to the state “dedicated” in which the UE is allowed to send information on the HS-DSCH channel.

More details on the RRC states and the delays associated to transitions among those states are provided in section III and section IV, respectively. In the analysis, this effect is modeled by introducing a delay Δ from the instant a new page is requested to the instant the download on the HS-DSCH channel starts. By choosing an adequate value for Δ we can consider not only the time required to transition to the RRC dedicated state, but also the delays introduced by upper protocol layers (e.g. TCP connection setup and slow start) .

After the initial delay Δ, the page is downloaded at C_{av} bit/s, which is defined as the fraction of the shared downlink capacity C that is available to each user. Note that the average time spent downloading a Web page on the HS-DSCH channel is only L/C_{av}, but the download time observed by the user is $\Delta+L/C_{av}$. Therefore, the equivalent capacity C_{eq} observed by the user will be smaller than C_{av}.

According to the above described behavior, each user generates L bits in a time equal to $\Delta+L/C_{av}+T_{off}$ s. The utilization factor (U) of the downlink shared channel can then be calculated as the aggregated traffic generated by the N users divided by the total available capacity C:

$$U = \frac{N \cdot L / C}{\Delta + T_{off} + L / C_{av}} \tag{1}$$

Let α be the activity factor of a user assuming no one else is using the downlink capacity C. Note that α is an ideal parameter, independent of N, which characterizes the behavior of a single user on a channel of capacity C. In this case, the average page download time is L/C s, so α is given by:

$$\alpha = \frac{L/C}{\Delta + T_{off} + L / C} \tag{2}$$

Combining (1) and (2) and clearing C_{av} / C, we obtain:

$$\frac{C_{av}}{C} = \frac{\alpha \cdot U}{\alpha \cdot N - (1-\alpha) \cdot U} \tag{3}$$

Equation (3) serves to calculate the available capacity C_{av} as a fraction of the total capacity C, in terms of the number of users N, the activity factor α and the channel utilization U. α can be obtained using (2) with L and T_{off} set according to the considered Web traffic model. It remains the problem of how to calculate the average channel utilization U for a given number of users N. In [4], U is analytically estimated as:

$$U = 1 - \left(\sum_{i=0}^{N} \left(\frac{\alpha}{1-\alpha} \right)^{i} \cdot \frac{N!}{(N-i)!} \right)^{-1} \tag{4}$$

Note that for a single user (N = 1), the channel utilization U coincides with the user activity α, as expected.

Once C_{av} has been obtained, the average page download time (T) perceived by the user is simply:

$$T = \frac{L}{C_{av}} + \Delta \tag{5}$$

and the corresponding value of the equivalent capacity is:

$$C_{eq} = \frac{L}{T} = \frac{L \cdot C_{av}}{L + \Delta \cdot C_{av}} \tag{6}$$

Fixing the values of C, L, T_{off}, and Δ in these equations, we can obtain curves of C_{av}, T, and C_{eq} as a function of N.

Figs. 2 and 3 show the impact of Δ on the page download time and on the equivalent capacity, respectively, for a variable number of users N between 1 and 120. The results correspond to C=2.8 Mbit/s, L=128.4 kbytes, and T_{off}=45 s, which are the same parameter values considered in the simulation experiments of section III.

When $\Delta \cdot C_{av}$ is large compared to the page length L, C_{eq} is significantly smaller than C_{av}, as shown in Fig. 3. If Δ is reduced C_{eq} increases. In the limit, if Δ=0 we have C_{eq}=C_{av}. Additionally, the curves show that the difference between C_{eq} and C_{av} is reduced when N increases. In that case C_{av} is small, so the impact of Δ is less noticeable.

The following sections present the simulator developed for HSPA and compare the simulation results with the analytical results obtained above. In addition to the average page download time T obtained analytically and the corresponding values of the capacities C_{eq} and C_{av}, the simulator allows us to estimate the initial delay Δ, as well as distribution functions of the page download time in various scenarios. These estimates can be used, for example, for network dimensioning taking into account quality of service requirements expressed as percentiles instead of average values.

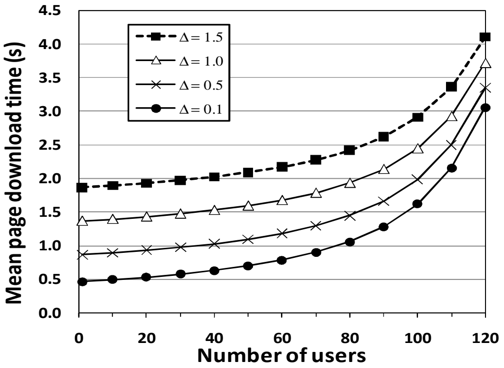

Fig. 2. Analysis. Mean page download time vs. number of users.

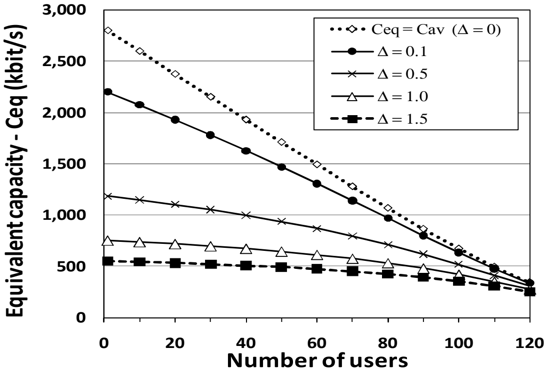

Fig. 3. Analysis. Equivalent capacity vs. number of users

III. SIMULATION FRAMEWORK

A. *Simulation model*

To study the performance of Web access over HSPA in more detail, we have developed a simulator based on the OPNET Modeler simulation tool [5]. The architecture of the simulation model is illustrated in Fig. 4.

The simulator consists of several nodes, some of them directly taken from the library of models provided by OPNET Modeler, and others specifically developed for this study. The experiments consider scenarios of up to 100 mobile terminals, downloading Web pages according to the traffic model described in section B. The Applications and Profile modules of Modeler are used for this purpose. The models of the application (http), transport (TCP) and network (IP) protocols are also provided by Modeler. The connectivity from the UTRAN to the remote Web server (Remote_Server) is modeled by an IP network with a variable number of hops. The IP_Cloud node of the model library is used for that purpose.

In this study, the primary goal is to assess the performance impact of sharing the capacity of the HSPA cell among several users in similar transmission conditions. In the simulations, the capacity values used (see section IV) have been selected to reflect typical operation conditions, so low-level aspects of the radio links such as propagation, fading, power control, modulation, etc. need not be simulated in detail.

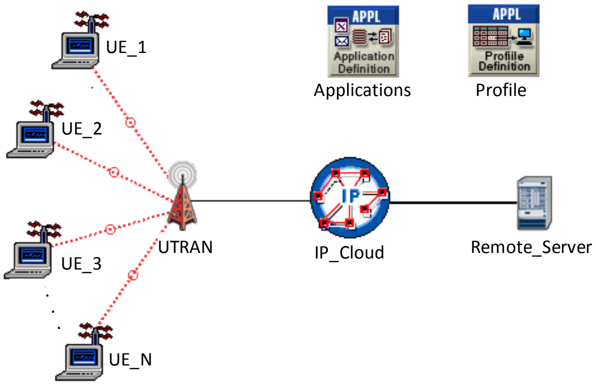

Fig. 4. Architecture of the simulation model

The simulator models the capacity of the HSPA traffic channels (FACH/RACH, DCH, HS-DSCH, and E-DCH) and the transmission over them scheduled according to the TTI (Transmission Time Interval) values: 2 ms for HS-DSCH, and 10 ms for the rest of channels. Several types of UEs are supported, including HSDPA (Categories 6, 8, and 12) and EUL (Cat. 4).

Fig. 5 shows the simplified RRC (Radio Resource Control) state model [6] considered in the simulator. UEs can be in one out of three states, which are characterized by the types of associated radio channels for the uplink and the downlink directions. The idle state represents an UE with no activity, so that it does not have any associated channel. An active UE is characterized for having access grant to traffic channels. Two states are considered for an active UE. In the dedicated state, terminals make use of the HS-DSCH channel in the downlink direction, and an E-DCH or a DCH in the uplink direction, depending on whether they support EUL (e.g. Cat. 8 UEs) or not (e.g Cat. 12 and Cat. 6 UEs).

The transition from idle to dedicated is governed by a simple algorithm that monitors the volume of user packets queued for uplink transmission at the UE. If the volume exceeds a certain threshold, the UE requests the RNC to switch to dedicated state, which is accompanied by the appropriate allocation of traffic channels as described above. Being in dedicated mode, if the activity level is below a certain threshold, the UE is switched to the common state. In this state, the UE can transmit small amounts of traffic on the common channels RACH (Random Access Channel) and FACH (Forward Access Channel). The traffic volumes in the uplink and downlink directions are monitored so that if they exceed a certain threshold, the UE is switched back to the dedicated state. Conversely, if there is no traffic exchange for a certain period of time, the terminal is switched to idle mode.

The delay and threshold values of each of the above described mechanisms can be configured in the simulator. For the purpose of the simulation study carried out in section IV, there are two simulation parameters of particular relevance. These are the parameters I2D Delay and C2D Delay that define the delays of the state transitions idle-to-dedicated and common-to-dedicated. In a real network, these delays are not negligible and, as discussed later on, they can significantly affect the performance perceived by the users.

Fig. 6 shows an example illustrating the behavior of the mechanisms and the main parameters involved.

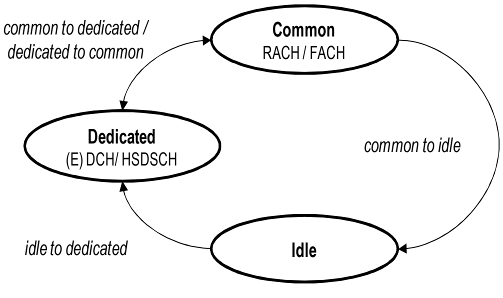

Fig. 5. Modeled RRC states and transitions

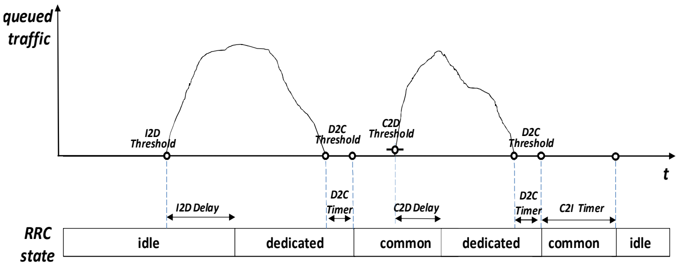

Fig. 6. Example of RRC state transitions

The number of HSDPA codes in the cell can be set from 5 to 15. The effective bit rate per code is modeled as a function of the UE category and its reported CQI (Channel Quality Indicator) value, according to [7]. The indicated bit rates are defined at IP level, as the low-level details of the radio interface (e.g. the RLC and MAC protocols) have not been considered in the simulation tool.

The simulator supports several HSDPA packet scheduling mechanism [8], including maximum C/I, round-robin, fair throughput, and proportional fair. In the experiments reported here, the impact of the scheduling mechanism is not significant as the CQI is set to a common fixed value for all UEs in the cell. Optionally, code multiplexing on the HS-DSCH channel can be enabled so that several users can transmit on the same TTI (see Fig. 1.)

The model also implements a simplified EUL packet scheduler operating on a request-grant procedure. The maximum aggregated uplink capacity at IP level is set to 1 Mbit/s, which correspond to the practical figure measured in commercial networks.

The simulator calculates numerous results, including: channel utilization, number of simultaneous active users, number of pages downloaded per user, page download time, equivalent capacity perceived by the user, etc. The simulation results are summarized in section IV.

B. *Web traffic modeling*

The Web traffic generator used in this paper follows a structured model in which users download sequences of Web pages, each one consisting of a main object (HTML) and other additional objects (e.g. images) [9]. After the page has been completely downloaded, the user spends some reading time before the next download starts.

The traffic parameters considered in our work are based on [10], which proposes lognormal probability distributions for the size of the main page object (L_p), the number of objects associated to the page (N_{obj}), the size of the objects (L_o), and the reading time (T_{off}).

Table I indicates the corresponding values of the mean (m) and the standard deviation (s), from which the parameters μ and σ of the lognormal distributions can be derived.

The average page length that results from these parameters is $L_p + N_{obj} \cdot L_o = 125$ kbyte. Including packet headers the average number of bytes transmitted per page is 128.4 kbyte.

TABLE I. WEB TRAFFIC MODELING

	Parameter	Simulated values	
T_{off}	reading time (s)	lognormal	m=45, s=100 (max. 1800)
L_p	page size (kbyte)	lognormal	m=25, s=50 (max. 2000)
N_{obj}	objects per page	lognormal	m=8, s=20 (max. 250)
L_o	object size (kbyte)	lognormal	m=12.5, s=120 (max. 3000)

IV. SIMULATION RESULTS

This section presents the experiments and results carried out with the simulation model described in the preceding section. Table II provides a summary of the parameter values considered in the simulation experiments.

To model a realistic situation, a cell with 10 OSVF codes for HSDPA is selected. This configuration is frequent in existing networks. The experiments consider UEs supporting both HSDPA (Cat. 8, 7.2 Mbit/s) and EUL (Cat. 4, 2 Mbit/s), which is in line with the fastest terminals currently available.

The proportional fair algorithm for the HSDPA packet scheduler is simulated, although this aspect is not relevant in this study, as all UEs are assumed to have the same CQI value. This value is fixed so that the resulting bit rate per code at IP level is 280 kbit/s. This gives a maximum aggregated downlink throughput on the cell of C=2.8 Mbit/s, which can be considered a typical capacity value to be expected from current HSPA networks. The values of I2D Delay and C2D Delay have also been taken from HSPA equipment used in real networks.

For EUL, an aggregated cell throughput of 1 Mbit/s is configured. (This aspect has no special relevance in the study, as the performance of Web access over HSPA is dominated by the downlink capacity).

Fig. 7 shows the results of the mean page download time as a function of the number of HSPA users. As expected, the download time increases with N. For a moderate number of users, the rising is relatively small. However, as N continues to grow the curve slope increases significantly.

TABLE II. SUMMARY OF SIMULATION PARAMETER VALUES USED IN EXPERIMENTS

Parameter name	Simulated values
Number of UEs (N)	1 to 100
UE Category	HSDPA Cat 8 / EUL Cat 4
HSDPA OSVF Codes	10
Max. DL Cell Throughput (C)	2.8 Mbit/s (280 kbit/s per code) [a]
Max. UL Cell Throughput	1.0 Mbit/s [a]
HSDPA Scheduling Algorithm	Proportional Fair
I2D Delay	1.5 s
C2D Delay	0.5 s

a. Values at IP level

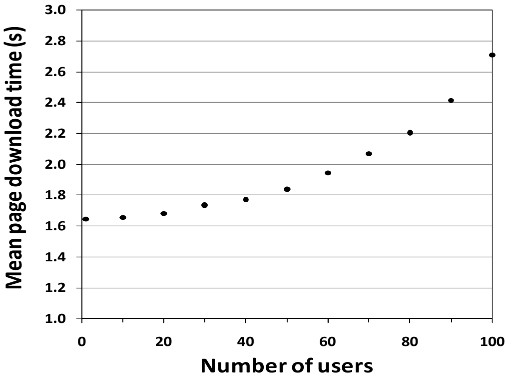

Fig. 7. Simulation results. Mean page download time.

Fig. 8 shows the individual page download times for one of the users in an experiment with N=30 users. Note the great dispersion of values. This can be seen in more detail in Fig. 9, which shows the cumulative distribution functions of the download time for 30 and 80 users. Distribution functions can be useful if we are interested in guaranteeing a specific quality of experience. For example, the curve for N=30 crosses the 90% value around 2.5s. For N=80 and the same probability, the corresponding delay value increases to 4.8 s.

Fig. 10 shows results for the equivalent capacity C_{eq} and the available capacity C_{av} (see section II) measured at IP level, as a function of the number of HSPA users. As expected, C_{eq} decreases with N, although not in a direct proportion. Thus, for example, the value of C_{eq} for N=10 is more than a tenth of the value for N=1 (a single user in the cell), due to the statistical multiplexing gain when several Web users share the capacity in the HSPA cell.

There is a noticeable reduction of C_{eq} due to the initial delays associated with the RRC state transitions and the TCP behavior. For example, according to Fig. 10, the C_{eq} value for N=1 user is approximately 630 kbit/s, far below the total downlink capacity simulated, which was fixed to 2.8 Mbit/s.

Fig. 11 shows a simulation trace of a Web page download indicating the instants of transmission of the uplink and the downlink packets on the corresponding HSPA channels.

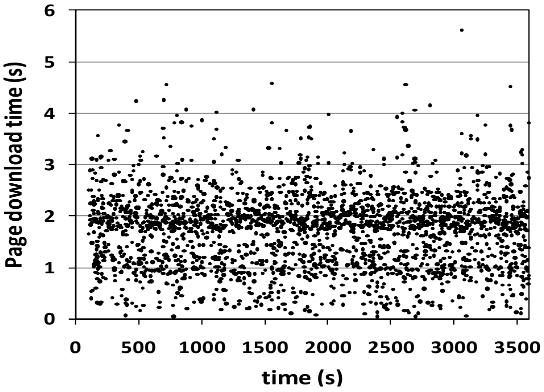

Fig. 8. Simulation results. Web page download times.

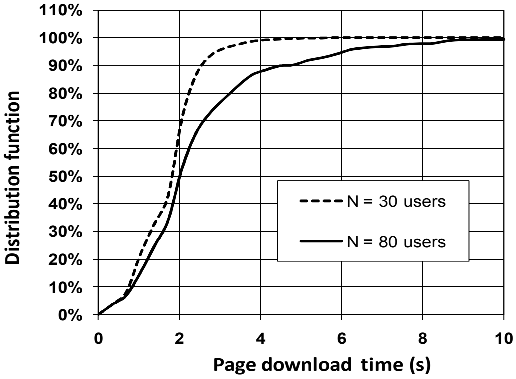

Fig. 9. Simulation results. Cumulative distribution function.

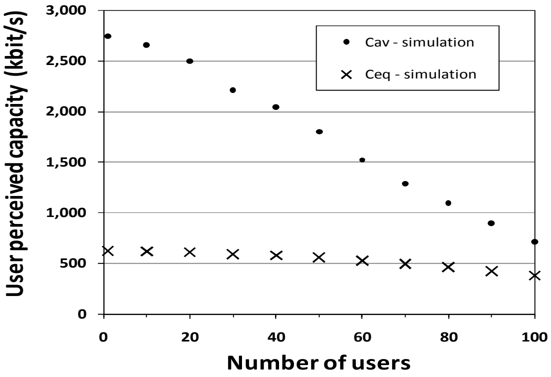

Fig. 10. Simulation results. Capacity per user.

The trace starts when the user requests the page download in the Web browser. Then, the packet exchange is delayed until the UE enters into the dedicated state. The delay depends on the previous RRC state of the terminal, which can be either idle or common, according to the duration of the reading time for the last downloaded page. In any case, the state transition has an associated delay (I2D Delay or C2D Delay) during which the transmission of the initial packet is delayed.

The page download begins with the TCP setup handshaking procedure, which adds a delay equivalent to the round-trip time between the UE and the Web server. The UE then sends the HTTP request packet and, after some time, the page download starts. The initial data packet exchange is regulated by the TCP slow-start algorithm, so the maximum download throughput is not achieved until the slow-start phase ends. In summary, when evaluating C_{eq} it is necessary to take into account the existence of time periods in which the traffic exchange is either interrupted or performed at lower bit rates.

If the initial periods illustrated in Fig. 11 are excluded, and the calculation of capacity is made from the end of the slow-start phase to the end of the page download only, we obtain the values of available capacity (C_{av}) shown in Fig. 10.

We note that the values of C_{av} are significantly greater than those of C_{eq}. As explained above, C_{av} is the fraction of the shared downlink capacity that is available to the user, while C_{eq} is the capacity effectively utilized to download the page.

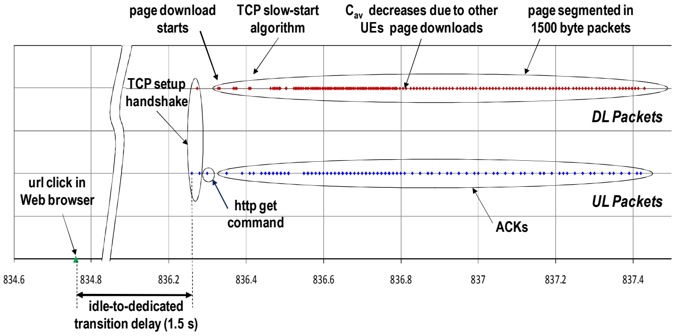

Fig. 11. Simulation trace. Packet transmission times.

From the simulation results, an average value for the initial delay Δ can be obtained. Recall that Δ was introduced in the analysis presented in section II in order to model the time required to enter the RRC dedicated state and the other delays discussed above. The resulting value is Δ=1.27 s. Introducing this value in the analytical expressions, the agreement between the analysis and the simulation results is very good, as shown in Figs. 12 and 13. In the case of C_{eq}, the difference is almost unnoticeable at the scale displayed.

In summary, according to the above results, HSPA offers reasonably short Web page download times even for a relatively high number of users per cell. However, due to the existence of an initial delay before the actual start of the page download, the resulting performance is worse than expected. This delay is largely due to the RRC transition to the dedicated state and depends on the particular state of the UE when the page is requested.

The best case is when the UE is in dedicated mode, so that no transition is required. In such circumstances, the initial delay is minimal and we get the smallest download times. On the contrary, if the UE is in the states common or idle, it is necessary to consider the transitions to dedicated state and their associated delays. As a result, the page download time is prolonged by the corresponding transition delays. Looking back to the distribution functions shown in Fig. 9, and in spite of the variability of download times caused by the different sizes of the pages and additional objects, it is possible to identify the inflection points associated with the three situations described above.

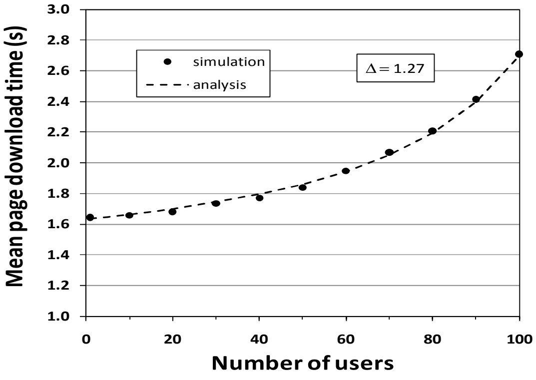

Fig. 12. Analytical vs. simulation results. Mean page download time.

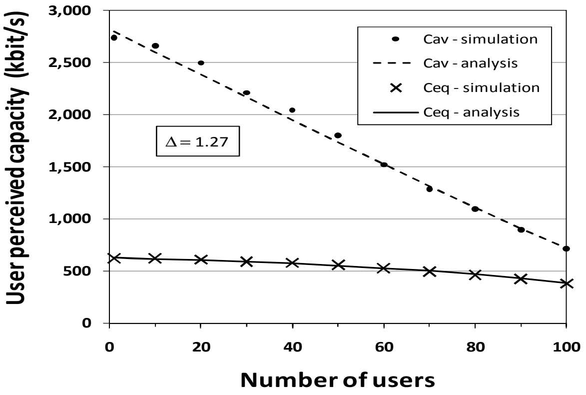

Fig. 13. Analytical vs. simulation results. Capacity per user.

Some possible solutions for reducing the page download time would be to keep the terminal in dedicated state longer or to avoid the transition to idle state. These solutions can be analyzed with the simulation model developed. In the first case, it would be appropriate to evaluate the eventual congestion in the uplink due to the maximum number of dedicated channels admissible in the cell. In the second case, it would be necessary to assess the impact of increased traffic on the Forward Access Channel (FACH).

A third alternative is the Enhanced Cell FACH feature defined in the HSPA evolution, known as HSPA+ [11]. The basic idea consists in sending the user data packets on the HS-DSCH channel rather than on the FACH channel while the UE is in the common state. This avoids overloading the FACH channel with user traffic and also reduces the duration of the transition into dedicated state.

V. CONCLUSIONS

This paper has studied the performance experienced by a variable number of Web users sharing the capacity provided by an HSPA cell. Firstly, we have presented an analytical estimate of the average performance individually perceived by each user. Secondly, we have developed a simulator, based on OPNET Modeler, that includes a more detailed model of the HSPA behavior and the Web traffic generated by the users.

The results of the study provide guidelines for the dimensioning of HSPA cells for Web traffic, based on key performance indicators such as the equivalent capacity and the page download time perceived by the users. The average values of capacity and download times predicted by the analysis are similar to those obtained in the simulation experiments. In addition to average values, the simulator provides distribution functions for the main performance indicators, which are useful to validate quality of service requirements.

The results show that the downlink channel capacity can be shared by several tens of Web users with good performance. This is possible because the activity factor of this application (i.e. the time spent in downloading pages compared to the time spent in reading them) is low.

Nevertheless, when a user requests a new Web page, the download start is delayed when the terminal has to change from the idle or common state to the dedicated state. For this reason, the performance observed by the user is worse than expected. This problem can be alleviated by increasing the time that the HSPA terminal remains in the dedicated state after the page download, so that when the next page is requested there is a higher probability of being in the dedicated state already. This can be done by adjusting the RRC timers in the HSPA equipment. Another solution is to implement the Enhanced Cell FACH feature defined in HSPA+.

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