Performance evaluation of dual carrier feature in the uplink of HSPA+ systems

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Abstract –Dual carrier is a feature introduced in HSPA+ that allows scheduling a user on two carriers simultaneously. While this feature has been largely studied, and deployed, in the downlink and it has been proved that it provides significant capacity gains, its performance in the uplink is still to be investigated. This paper fills this gap by estimating the radio capacity improvement provided by dual-carrier feature in the uplink. The proposed method combines link budget simulations to assess the throughputs for a fixed number of users in the cell, and a queuing theory-based statistical capacity model, thereby providing a reliable estimate of the network radio capacity. Simulation results show that dual carrier significantly increases uplink radio capacity.

I. INTRODUCTION

The dual carrier feature has been proved as a successful and very effective improvement in the downlink channel of the new generation High Speed Packet Access (HSPA+). Many studies have analyzed the gain in network performance of Dual Carrier High Speed Downlink packet access (DC-HSDPA). Authors in [1] have shown that DC-HSDPA Release 8, the very first release of dual carrier in HSPA generation, doubles the throughput of dual carrier users only in low loaded network. But this feature still gives a very good gain in high loaded network capacity in comparison to single carrier network HSPA-Rel 7. The paper [2] has assessed this gain. Results showed that we have a 45% improvement in DC-HSDPA capacity, this latter could exceed 160% if dual carrier is combined to MIMO (DC-HSDPA Rel-9).

These satisfying facts led researchers to investigate the possibility of exploiting carrier aggregation enhancement in the uplink. In 2009, the specification of carrier aggregation in the uplink channel was completed and DC-HSUPA was introduced in HSPA Release 9. A DC-HSUPA capable device can transmit simultaneously over two adjacent carriers of 5MHz each as illustrated in Figure 1. This leads to a theoretical throughput of 23 Mbps for 16-QAM capable devices.

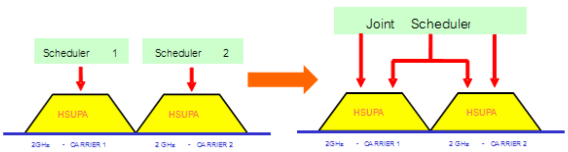

Figure 1: Dual cell scheduling principle

DC-HSDPA is a SNR limited network, but the uplink version, DC-HSUPA, is a power limited network. Indeed, the transmission power of devices is constrained by the same maximal value as in the single cell case (devices are not allowed to double their transmission powers when in dual cell mode). The feasibility of dual carrier in uplink HSUPA has been studied in [3]. This latter paper shows that, in cells with a relative big radius, cell edge users can barely benefit from their dual carrier capabilities.

The purpose of this paper is to evaluate the capacity gain of HSUPA+ network, taking into account the dynamic behavior of users (arrivals/departures). We base our single cell analysis on [4], where single carrier HSUPA throughput has been calculated in a mixed UMTS R99/HSPA network; we extend this work to dual cell in the uplink using recent advances in queuing theory. The major contributions of this work are as follows:

1. We assess the throughputs in DC-HSUPA, taking into account both noise rise and power limitations.
2. We calculate the capacity gains using queuing theory methods, taking into account the multiplexing gain. This latter makes the cell bit rates higher when the number of users increase.
3. We study the intermediate case where there is a mix of legacy, single-carrier devices and HSPA+ dual cell ones.

This paper is organized as follows. Section II presents the uplink throughputs in single cell and dual cell cases. We discuss in section III the methodology to estimate cell radio capacity. The obtained results are shown and discussed in section IV.

II. USER THROUGHPUT EVALUATION METHODOLOGY

HSUPA aims at offering high data rates on the uplink (up to 5.76 Mbps) using key techniques implemented in HSDPA such as fast scheduling, link adaptation and hybrid ARQ. Furthermore, the HSUPA+ technology, introduced in the Release 7 of the 3GPP, aims to offer up to 11.4 Mbps on the uplink thanks to the usage of 16QAM modulation in addition to QPSK.

A. Throughput evaluation in single carrier case

Unlike HSDPA, HSUPA does not use a shared channel for delivering the data calls. By structure, it is considered more as an add-on of UMTS R99 standard than a replacement. The study of HSUPA performance will, consequently, be based on the study for UMTS R99 uplink model. A condition concerning the maximum load is used to allocate the available resources to the HSUPA users [4], knowing that many throughputs are possible. The resulting interference

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configuration is described in Figure 2. A maximal interference level (RoT, Rise over Thermal) is allowed, leading to the following admission control condition on the total noise rise:

$$\nu = \frac{N_0 + I_{tot}}{N_0} < \nu_{\max} \qquad (1)$$

where I_{tot} is the overall power received by the base station and N_0 is the noise power.

The equality holds except for coverage-limited cases where cell edge users are not able to use the overall capacity, even when they transmit with their maximal power.

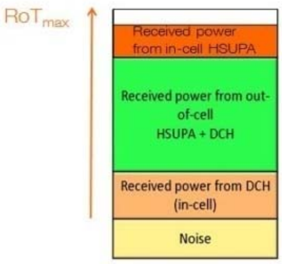

Figure 2: Interference budget for the uplink.

A simple link budget analysis allows calculating the throughput for different positions in the cell. This is shown in Figure 3 for a user that is alone in the cell (system parameters are given in Table I). It can be observed that the throughput is constant until a certain limit (150 meters); this corresponds to the RoT-limited region of the cell. Beyond this limit, the user is limited by its transmission power and its throughput degrades.

PARAMETER	SETTING
Multipath channel	Pedestrian A 3km/h
Maximal uplink output power	24 dBm
RoT max	6 dB
Indoor penetration factor	8 dB
Body loss	4 dB
Frequency band	2.1 GHz
Node B antenna gain	18 dBi

Table 1: Radio parameters used in the calculations

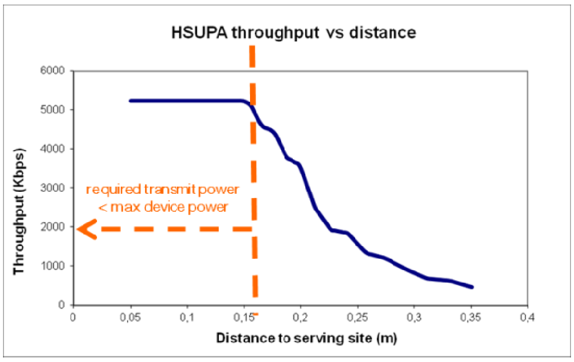

Figure 3: Throughput of an HSUPA user that is alone in the cell: 2 ms HSUPA with RoT limit of 6 dB, Category 6 devices with LMMSE receiver at the base station. The figure shows the limit of the RoT-limited region.

When there are multiple users in the cell, they share the available resources of the cell, i.e. the maximal allowable noise rise. Users are thus multiplexed using scrambling codes, but generate mutual intra-cell interference. Figure 4 shows the user throughputs when two users are present simultaneously in the cell. The user throughput is lower because of the additional intra-cell interference, but the multiplexing gain leads, in this case, to a slightly larger cell throughput.

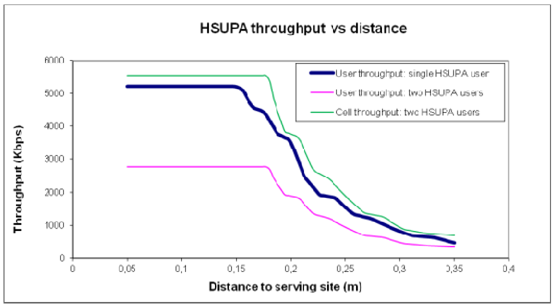

Figure 4: Throughputs when two HSUPA users are present in the cell, compared to the single user case.

B. *Throughput evaluation in dual carrier case*

When dual carrier is activated in the uplink, users can connect to both carriers, and thus profit of twice the available resources than in the case of single carrier. However, unlike in the downlink where the available power is doubled, users will have the same output power, to share between the two carriers; This makes the noise rise limit reached for a smaller distance (120 meters for dual carrier case in Figure 5 compared to 150 meters in the single carrier case). In the RoT-limited region, however, the throughputs are doubled as expected.

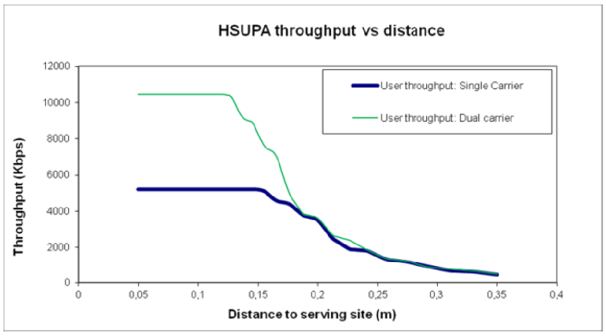

Figure 5: Throughputs when one dual carrier HSUPA user is active. The users has 21 dBm of power available on each of the carriers.

III. Radio Capacity Analysis

HSUPA radio capacity calculation is not as straightforward as one might expect. The common method consists in defining the cell capacity as the served throughput for a given number of users in the cell, using a static simulator ([5] [6]). There are however one key drawback in this method: it does not consider the statistical behavior of the traffic demand. Indeed, in a real network, the number of users in the cell keeps changing, and the activity of each user is not constant over time. We usually refer to these models as “Erlang-like”, since they model the statistical behavior of the traffic, in a similar way as the Erlang B law does.

A. Single carrier case

We start with the simplest case, where only legacy terminals are served by the cell. In the absence of load balancing mechanisms, the traffic demand, denoted by A and expressed in Mbps/cell, can be considered as equally split between the two operating carriers.

Let $T_{user}(n)$ be the (harmonic) average per-user throughput when there are n users in the carrier, as illustrated in Figure 4. We use the harmonic average in order to take into account the fact that users with low throughputs stay longer in the cell, as explained in [7]. As the resources of the cell are equally divided between users, a processor sharing model is a natural choice as for HSDPA [7]. However, the intra-cell interference makes the cell resources dependent on the number of users, as illustrated in Figure 4 where the cell throughput for 2 users is different than the stand-alone user throughput. A Generalized Processor Sharing (GPS) queue is thus the adequate performance model:

$$\pi(n) = \pi(0)\frac{(A/2)^n}{\prod_{m=1}^{N} T(m)} \qquad (2)$$

where N is the maximal number of users in the cell (admission control constraint) , $A/2$ is the traffic per carrier and $T(m)=m^* T_{user}(m)$ the total cell throughput when there are m users.

The QoS measures can thus be extracted. For the blocking rate, it is calculated by:

$$b = \pi(N) \qquad (3)$$

For evaluating the throughputs, we need to calculate the probability that a HSUPA user in the cell has a given throughput. We introduce the set of possible achievable throughputs as:

$$\Delta = \left\{ d > 0 \,\middle|\, \exists\, n \le N; \frac{T(n)}{n} = T_{user}(n) = d \right\}$$

The probability that a HSUPA user in the cell has a throughput d in this set is then given by:

$$\Pr[d] = \frac{n(d)\pi(n(d))}{\sum_{m=1}^{N} m\pi(m)} \qquad (4)$$

where $n(d)$ is the number of HSUPA users in the carrier so that the throughput of each of them is equal to d.

The average flow throughput [7] in the cell is then:

$$\bar{d} = \sum_{d \in \Delta} \frac{d \cdot n(d)\pi(n(d))}{\sum_{m=1}^{N} m\pi(m)} \qquad (5)$$

and the probability of being below a given target d_{min} is:

$$\Pr[d < d_{\min}] = \sum_{d \in \Delta; d < d_{\min}} \frac{n(d)\pi(n(d))}{\sum_{m=1}^{N} m\pi(m)}$$

B. Dual carrier case

When all devices are dual-carrier capable, the same analysis as before can be applied, by substituting the traffic per carrier ($A/2$) by the overall cell traffic (A), and considering the throughputs obtained in the case of dual carrier, $T_{dual}(n)$, obtained by integrating the power restriction and the fact that 10 MHz are available instead of 5 MHZ only (Figure 5). The steady-state probabilities become:

$$\pi_{dual}(n) = \pi_{dual}(0)\frac{(A)^n}{\prod_{m=1}^{N} T_{dual}(m)} \qquad (6)$$

C. Mix of single and dual carrier users

Even if all new UE categories are DC-compliant, they will coexist with legacy SC users. Therefore, the available 2×5 MHz carriers are used to serve both SC and DC users simultaneously.

The cell can then be modelled as three queues: two queues receiving the single carrier traffic, and one queue receiving all the traffic (see Figure 6).

We denote by class 1 the legacy traffic carried by one carrier; by class 2 the legacy traffic carried by the other carrier and by class 3 the dual carrier traffic. The network state is defined by the vector $\mathbf{x} = (x_1, x_2, x_3)$ where x_c is the number of class-c users in progress.

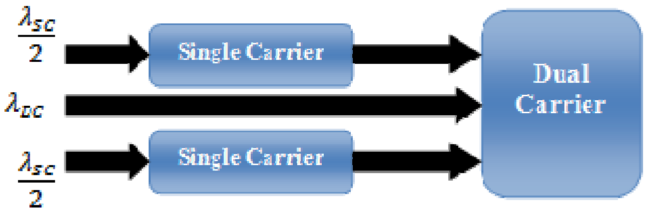

Figure 6: Both SC and DC users coexist in the cell.

These queues share the capacity according to balanced fairness scheme. A balance function $\Phi(x)$ is defined and calculated recursively by:

$$\Phi(x) = \begin{cases} 0, & x_c < 0, \forall c \in \{1,2,3\} \\ 1, & x_c = 0, \forall c \in \{1,2,3\} \\ \max\left[\Phi(\mathbf{x}-e_1),\ \Phi(\mathbf{x}-e_2),\ \sum_{c=1}^{3} \frac{\Phi(\mathbf{x}-e_c)}{2}\right] & otherwise \end{cases} \qquad (7)$$

where e_c is a (3×1) vector with 1 in component c and 0 elsewhere.

The resources allocated to the different classes are the proportion of noise rise power allowed for each class. This latter is given by definition [8]:

$$\varphi_c(\mathbf{x}) = \frac{\Phi(\mathbf{x} - e_c)}{\Phi(\mathbf{x})} \qquad (8)$$

So each queue will have a total throughput dependant of the number of user $T_c(x)$ equal to:

$$T_c(x) = \varphi_c(x) * T(m) \quad c = 1, 2, 3 \tag{9}$$

Someone might be surprised because the double factor in the dual cell capacity (*c=3*) doesn't appear obviously in (9). But they should keep in mind that dual cell users are scheduled on both carriers (1 and 2) so $\varphi_3(x)$ will have two components: $\varphi_{31}(x)$, $\varphi_{32}(x)$ the allowed resources for dual cell users in carrier 1 and 2 respectively. Having $T(m)$ the maximal throughput a dual cell user could attain in each carrier, we will obtain (9) for case c=3 also.

For the evaluation of other performance parameters we need the steady-state probabilities that describe the evolution of the number of calls in the network, $\mathbf{x} = (x_1, x_2, x_3)$. The analysis of [8] was developed for the case where the queue capacity is independent of the number of users it serves. In the case of HSUPA, the cell throughput depends on the number of served users due to the intra-cell interference and the multiplexing gain. So it should be extended in order to be applied to our case. This extension is done by using the Generalized Processor Sharing (GPS) instead of the simple Processor Sharing.

Let us first note that the product form of GPS steady-state probabilities supposes that the capacity of each queue depends only on the number of its own users. This is partially not true in our case as the capacity of the dual carrier queue depends also on the number of single cell users, but this approximation has been shown to be very accurate when we compared the GPS results to exact Markov chain analysis.

We extend the expression in [8] for a GPS case. It can be shown that the steady state probabilities in a mixed HSUPA/DC-HSUPA are calculated by:

$$\pi(\mathbf{x}) = \frac{1}{G}\Phi(\mathbf{x})\frac{\rho_1^{x_1}}{\prod_{m=1}^{x_1} T(m)}\frac{\rho_2^{x_2}}{\prod_{m=1}^{x_2} T(m)}\frac{\rho_3^{x_3}}{\prod_{m=1}^{x_3} T_{dual}^{Sector}(m)} \tag{10}$$

where ρ_c is the offered traffic of class *c* flow ($\rho_3 = A_{DC}$ and $\rho_1 = \rho_2 = \frac{A_{SC}}{2}$ in the case of perfect load balancing), m=x_c the number of users in class *c*, *T(m)* the single carrier throughput when there are *m* single cell in the carrier, $T_{dual}^{Sector}(m)$ the throughput a single dual carrier user can reach on each carrier when there are *m* dual cell users, and G the normalization constant:

$$G = \sum_{\mathbf{x}} \Phi(\mathbf{x})\frac{\rho_1^{x_1}}{\prod_{m=1}^{x_1} T(m)}\frac{\rho_2^{x_2}}{\prod_{m=1}^{x_2} T(m)}\frac{\rho_3^{x_3}}{\prod_{m=1}^{x_3} T_{dual}^{Sector}(m)}$$

Having $\pi(x)$ we can obtain the average flow throughput of a class-*c* user.

$$\overline{T}_c(x) = \frac{\sum_{x_c>0} \varphi_c(x) * T(x_c) * \pi(x_c)}{E[x_c]} \quad c = 1, 2 \; and \; 3 \tag{11}$$

E[xc] is the average number of users of class c.

And the probability of attaining the target throughput T_{min} for an active class-c calls is equal to:

$$\Pr[T_c \geq T_{min}] = \sum_{\mathbf{x}: \frac{T(x_c).\varphi_c(\mathbf{x})}{x_c} > T_{\min}} \frac{x_c.\pi(\mathbf{x})}{\mathrm{E}[x_c]} \tag{12}$$

IV. SIMULATION RESULTS

For the sake of simplicity, we assume that all the devices belong to the same category (same maximal power and same possible modulation schemes). Sector throughputs (aggregated on both carriers) are calculated and given in Table 2. It can be observed that sector throughput remains the same, except in the case of one active user as this user will have to reduce its transmission power per carrier. Note that, in the single carrier case, the number of users is given per carrier, while in the dual carrier case; the number of users is given per sector.

Number of users (per carrier for single carrier case and per sector for dual carrier)	Sector capacity in single carrier case [Kbps]	Sector capacity in dual carrier case [Kbps]
1	1247.3	678.7
2	1522.2	1522.2
3	2335	2335
4	2720.2	2720.2
5	3288.1	3288.1
6	3807.8	3807.8
7	3839.6	3839.6
8	4074.2	4074.2
9	3807.8	3807.8
10	3839.6	3839.6
11	4074.2	4074.2
12	4289.1	4289.1
13	4493	4493
14	4686.9	4686.9
15	4862.1	4862.1
>=16	4941.8	4941.8

Table 2: average sector throughput as a function of number of users. Users are of category 6 and we assume that an LMMSE receiver is implemented at the base station. This harmonic average throughput is computed over the different positions in the cell.

The main purpose of this paper is to assess the gain in the network capacity. We define capacity as the maximal offered traffic so that a target QoS can be reached. QoS is defined as the average user throughput. Figure 7 shows the system capacity evolution for an increasing target throughput.

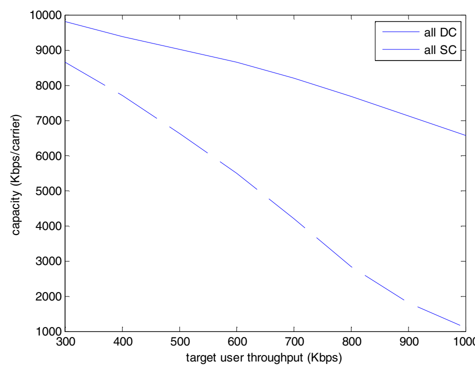

Figure 7: Network capacity for dual carrier and single carrier cases.

Figure 8 shows the capacity gain extracted from the values in Figure 7.

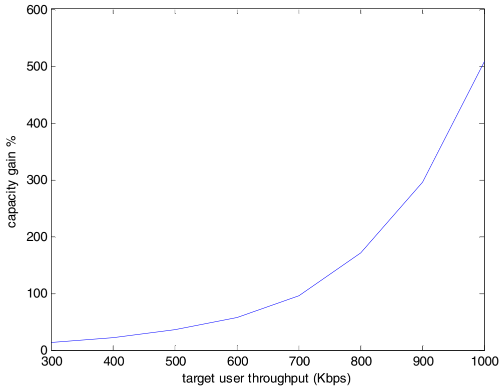

Figure 8: Network capacity Gain

We can conclude from Figures 7 and 8 that dual carrier brings a capacity gain of 13% for a target throughput of 300 Kbps, and this gain increases to 500% when the QoS constraints are more stringent (1000 Kbps average user throughput).

Figure 9 shows the impact of dual carrier terminal penetration on the system capacity. We consider a target throughput of 1000 Kbps and calculate the system capacity when the percentage of dual carrier terminals in the system increases. The two extreme cases (DC penetration of 0 and 1) correspond to a system with single cell and dual cell users only (the capacity of the system corresponds to that given in Figure 8 for the same target throughput). Intuitively, as the dual carrier penetration increases, the capacity increases leading rapidly to large capacity gains (100% gain when half of the devices are DC-capable).

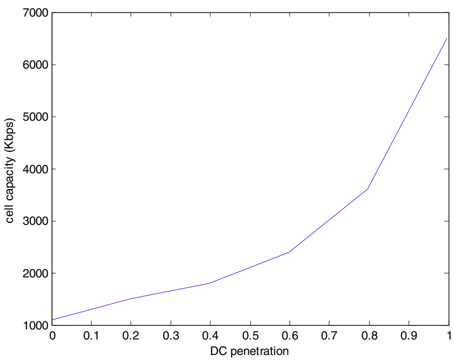

Figure 9: Network capacity for different penetration rates of DC-HSUPA users for a target average throughput of 1000Kbps

V. CONCLUSION

This paper develops a complete methodology to analyze the capacity gain of the dual carrier HSUPA feature. We make use of realistic throughput calculations and calculate the gain introduced by dual carrier feature for a realistic setting where only a proportion of devices are dual carrier capable.

We made use of advanced queuing theory techniques to evaluate the performance of the system and show that dual carrier introduces large capacity gains, especially where stringent QoS targets are considered. Indeed, the gain increases from 13% when a target throughput of 300 Kbps is sought to 500% when the aim is to offer 1 Mbps to the users in average. On the other hand, we show that the system capacity increases gradually when the dual carrier terminal penetration increases in the system.

As of future work, we could investigate the effect of MIMO integration in DC-HSUPA Rel. 11 and extend our model to LTE-Advanced where carrier aggregation is a key feature.

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