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Dual Cell-high Speed Downlink Packet Access System Benefits and User Experience Gains

S. Chandra Sekhar Srinivas, S.G. Kiran Kumar and K.N. Brahmaji Rao

[1]*Department of Computer Science & Technology, Jawaharlal Nehru Technological University, Visakhapatnam, India.*
[2]*Department of Information Technology, Higher College of Technology Muscat, Sultanate of Oman.*
[3]*Department of CS & SE, Andhra University, Visakhapatnam, India.*

Abstract

Dual Cell-High Speed Downlink Packet Access (DC-HSDPA), which was introduced in Release 8 of the WCDMA specifications, enables the User Equipment (UE) to receive downlink data on two adjacent carriers simultaneously. The doubling of physical layer rate of DC-HSDPA UEs translates to user experience gain for real applications such as web browsing and video streaming in unloaded systems. In this paper, using a real prototype implementation, we focus on gains of DC-HSDPA over two carriers of Single Cell HSDPA (SC-HSDPA) in terms of number of additional supportable users. For a given user experience, we show how many more users DC-HSDPA can support compared to two carriers of SC-HSDPA.

1. Introduction

DC-HSDPA, which was introduced in Release 8 of the HSPA specifications [3][4], doubles the physical channel rate seen by the UE compared to SC-HSDPA. The gains of a DC-HSDPA system can be viewed in two dimensions: either the improvement in user experience for a given number of users, or the gain in number of users for a given user experience. A previous paper [1] evaluated the gains of DC-HSDPA over SC-HSDPA in terms of user experience for applications such as web browsing and video streaming. [1] also showed the ability of DC-HSDPA to improve application performance by taking advantage of uneven loading across carriers.

In this paper, we focus on the gains provided by DC-HSDPA in terms of number of supportable users. We attempt to answer the following question: for a given user experience seen by a user *downloading a file* or *browsing the web* in a system consisting of other Internet users, how many such users can DC-HSDPA support compared to two carriers of SC-HSDPA? To answer this question, we used the aggregate traffic from a number of UEs, whose traffic model is the Closed Loop Bursty traffic model [5], as representative of the traffic from a mix of Internet users (this is further discussed in Section IV). By varying the system load or equivalently the number of bursty traffic users (referred to as *background* users), we evaluate the gains of DC-HSDPA at different levels of user experience for the user *downloading a file* or *browsing the web* (referred to as the *foreground* user). File download is evaluated using files of different sizes to capture any effects due to TCP Slow Start [6]. For web browsing, we use CNN and Google Maps as representative web pages. The paper is organized as follows. Section II provides more details of the applications considered. Section III describes details of the DC-HSDPA prototype. In Section IV, we discuss how we compare the number of supportable background Internet users between SC-HSDPA and DC-HSDPA. In Section V and VI, we compare user experience and number of supportable users for DC-HSDPA compared to SC-HSDPA, for the application of file download and web browsing respectively. Section VII concludes the paper.

2. Application Description

The following applications are considered in this paper:

File Download (FTP): We considered file sizes of 1Mbit, 4Mbits, 8Mbits and 20Mbits to capture effects due to TCP Slow Start. We considered both TCP and UDP as transport protocols for file download. Note that FTP typically runs on TCP; UDP was considered only to provide an upper bound on the performance of the TCP-based file download (since UDP does not have to go through Slow Start). *Download rate* (defined as *file size/time to download*) is used as the metric for user experience. In addition, we also show the *Download rate gain* for DC-HSDPA (defined as ratio of *download rate* of DC-HSDPA to *download rate* of SC-HSDPA expressed in percentage).

Web Browsing: We considered CNN and Google Maps as representative web pages. For CNN, a web browsing session consists of downloading the main page of www.cnn.com. For Google Maps, a web browsing session consists of downloading maps of the cities San Diego, Las Vegas and Los Angeles. To allow repeatability (since server load as well as content could vary at different times), we copied snapshots of www.cnn.com and maps.google.com (for the 3 cities mentioned above) on a local server. The average *page download time* is used as the metric for user experience.

3. DC-HSDPA Prototype Description

3.1 Key features

The DC-HSDPA prototype implements all the layers of the protocol stack (physical, Medium Access Control (MAC), Radio Link Control (RLC), and upper layers) per 3GPP Rel 8 specifications. The following are some of the key features:

1. The prototype UE supports both SC-HSDPA and DC-HSDPA and uses an Linear Minimum Mean Squared Error (LMMSE) Equalizer receiver using either 1 or 2 receive antennas.
2. The Channel Quality Index (CQI) reported by the UE is filtered through an IIR filter at the Node B, with a time constant of 30 Transmission Time Intervals (TTIs).
3. The Node B HS-PDSCH scheduler is Proportional Fair (PF), where the throughput for each UE is filtered with a throughput filter time constant of 100 ms. For DC-HSDPA, a joint PF scheduler is used across carriers.
4. The HS-PDSCH scheduler selects the transport block size based on the filtered CQI value and an outer loop algorithm, which targets 10% Block Error Rate (BLER) after the first Hybrid Automatic Repeat Request (HARQ) transmission.
5. The power used on the High Speed Shared Control Channel (HS-SCCH) channel is fixed at 10% of the total cell power.
6. On the uplink, 10 ms TTI is used for the Enhanced Dedicated Physical Data Channel (E-DPDCH) channel with a maximum of 2 HARQ transmissions. An outer loop power control algorithm, which targets 10% BLER after the first HARQ transmission on the E-DPDCH channel, is implemented at the Node B. With these settings, residual BLER is observed to be less than 1%.

3.2 Downlink User Simulator (DLUS)

A key goal of our testing was to study performance at different levels of system loading. To avoid logistical difficulties in using multiple simultaneously active prototype UEs to create loading, a downlink user simulator (DLUS) was used. DLUS captures the DL resource usage for a user with given channel and traffic conditions. DLUS is implemented at the NodeB scheduler and models UEs by reading their CQIs and ACKs/NAKs from input traces (traces for all DLUS UEs are generated based on a VA30 channel at 5dB geometry; this makes DLUS UEs statistically identical, but temporally, their CQIs and ACKs/NAKs are uncorrelated). DLUS UEs are treated as real UEs by the scheduler in terms of priority of scheduling and power allocated, i.e., the scheduler evaluates and compares their scheduling priority with other DLUS and real UEs, and transmits packets for them on the HS channel with appropriate power and codes. The aggregate effect of the DLUS UEs is a somewhat realistic emulation of DL resource usage in terms of code, power and time. DLUS UEs used in our testing are single carrier UEs.

Traffic for DLUS UEs is input to the scheduler using traces. The traffic is generated per the Closed Loop Bursty Traffic model (as defined by 3GPP in [5]). Specifically, bursts of size 100kbit are generated with a mean inter-arrival time between bursts of 500ms.

Figure 1 shows the system load (TTI utilization percentage) with only the DLUS UEs present, obtained from the prototype. By changing the number of DLUS UEs from 0 to 32, the system load varies from 0% to more than 90%. Note that the TTI utilization does not scale linearly with number of UEs at higher number of UEs due to the increased efficiency of proportional fair scheduler.

3.3 Lab and OTA Setup

In our prototype setup, a laptop is connected to the prototype UE, which can be either a DC-HSDPA or a SC-HSDPA UE. The laptop is the client for the applications evaluated. Our lab tests consider the VA30 channel and a range of geometries. It should be noted that DC-HSDPA gains are not sensitive to the type of fading channel since the transmit duration of the applications considered spans multiple coherence times of the channel. Hence similar gains for DC-HSDPA are expected for other channels such as the slow speed pedestrian PA3 channel. For OTA testing, we chose two stationary locations, one with low CQI (average CQI=14) and one with high CQI (average CQI=23), assuming a Measurement Power Offset of 8dB.

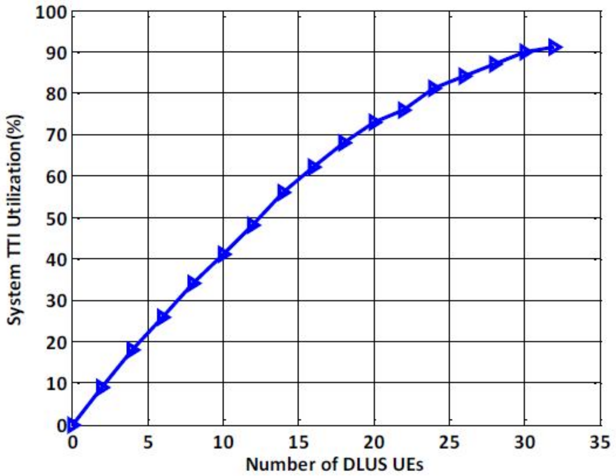


Figure 1: System load (TTI utilization%) versus number of DLUS UEs.

4. Comparing Number of Supportable Users Between SC-HSDPA and DC-HSDPA

To evaluate whether DLUS users can represent a mix of Internet traffic, we compared, through simulations, the user experience of a foreground UE (downloading a file using

UDP), where the background loading comes *(a) only from DLUS UEs*, or *(b) from real UEs doing a mix of Internet applications* (50% UEs doing file download, 50% UEs doing web browsing). As shown in Table 1, the user experience gain provided by DC-HSDPA for the foreground UE, at different background loads, is independent of how the background load is created. Tests with other foreground applications showed similar results.

Table 1: Download Rate Gain (%) of DC-HSDPA over SC-HSDPA for a Dual Rx receiver in a VA30 Channel.

Download Rate Gain (%) for DC-HSDPA with UDP traffic		
TTI Utilization(%)	Mix of Internet traffic as background load	DLUS UE traffic as background load
20	100%	100%
40	100%	100%
80	100%	100%

Thus, given a certain user experience, we use the number of background DLUS UEs at which a foreground SC-HSDPA or DC-HSDPA UE can achieve this user experience, as representative of (or proportional to) the number of supportable background Internet users. The gain of DC-HSDPA over SC-HSDPA in terms of number of additional supportable users is then the increase (in %) in the number of such background DLUS UEs.

5. Results for File Download

In this section, we evaluate (i) gains in download rate and (ii) number of supportable users for DC-HSDPA compared to SC-HSDPA for the file download application.

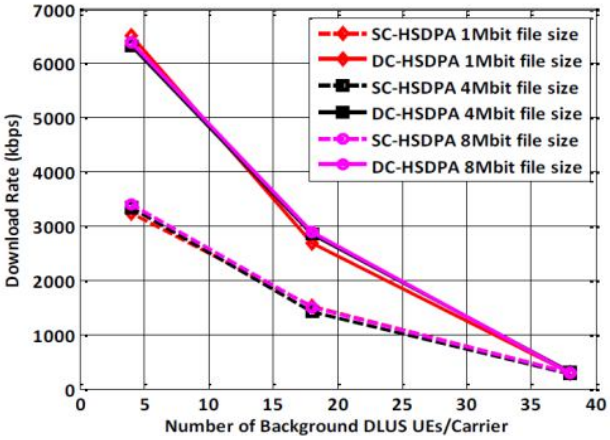


Figure 2: Download Rate as a function of system load with UDP as transport protocol in a VA30 channel at 5dB geometry.

The tests comprise one SC-HSDPA or DC-HSDPA foreground UE and a varying number of background SC-HSDPA DLUS UEs, to create different levels of system loading. When evaluating gains in download rate, we keep the same number of DLUS UEs per carrier to make a fair comparison between SC-HSDPA and DC-HSDPA.

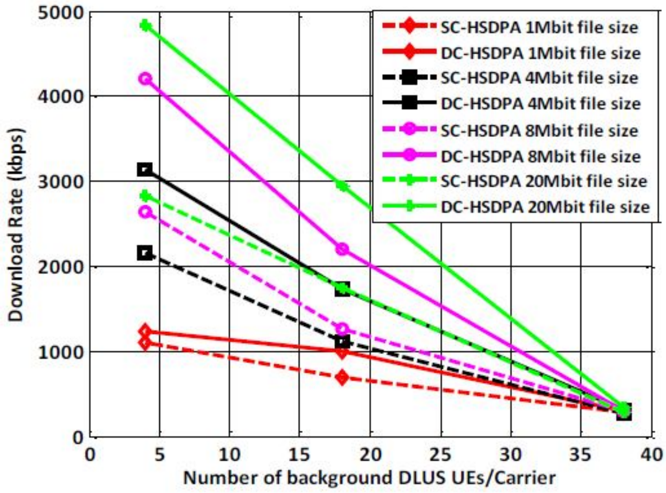
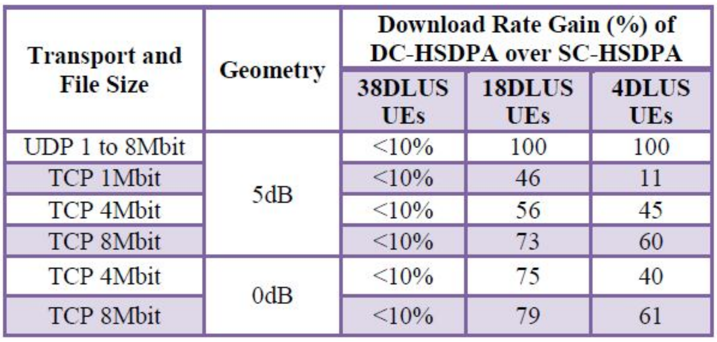


Figure 3: Download Rate as a function of system load with TCP as transport protocol in a VA30 channel at 5dB geometry.

The results in this section are generated using foreground UEs with two receive antennas in a VA30 fading channel at 5dB and 0dB geometry. UDP results, shown in Figure 2, provide an upper bound on TCP based file download rates (shown in Figure 3). Table 2 summarizes the download rate gains seen by DC-HSDPA for UDP and TCP.

Table 2: Download Rate Gain(%) of DC-HSDPA over SC-HSDPA for Dual Rx receiver in a VA30 Channel.



Transport and File Size	Geometry	Download Rate Gain (%) of DC-HSDPA over SC-HSDPA		
		38DLUS UEs	18DLUS UEs	4DLUS UEs
UDP 1 to 8Mbit	5dB	<10%	100	100
TCP 1Mbit		<10%	46	11
TCP 4Mbit		<10%	56	45
TCP 8Mbit		<10%	73	60
TCP 4Mbit	0dB	<10%	75	40
TCP 8Mbit		<10%	79	61

The following are the key observations:

- For a given background load, the absolute download rate for UDP is independent of the file size, as expected. For UDP, the download rate gain of DC-HSDPA over SC-HSDPA is close to 100%, except at very high loads approaching the ~100% loading point.
- With TCP as transport protocol, the absolute download rate as well as download rate gain increases with file size. This is attributed to effects of TCP Slow Start. For small file sizes, the time to download the file is mostly spent in the window-limited region of TCP, i.e., when the congestion window is smaller than that required to saturate the channel rate. This reduces gains for DC-HSDPA. As the file size increases, more of the file download time is spent in the rate-limited region of TCP, i.e., when the congestion window is equal or larger than that required to saturate the channel rate.
- The download rate gain of DC-HSDPA over SC-HSDPA for TCP shows an interesting trend versus system loading: it increases from 4 DLUS UE loading (~20% system load) to 18 DLUS UE loading (~70% system load), then decreases at 38 DLUS UE loading (~100% system loading). There are two opposite effects at work: (a) the relative impact of TCP Slow Start is diminished as the effective channel rate decreases (i.e., system loading increases), leading to higher download rate gains for DC-HSDPA at 70% loading compared to 20% loading, and (b) as also seen in the UDP results, very high system loading (i.e., 100% loading) diminishes the statistical multiplexing gains of DC-HSDPA since there are no empty TTIs that the DC-HSDPA users to take advantage of.

We further elaborate the TCP trend using Figure 4, which shows an analytically-derived progression of file download versus time for a user at 5dB geometry under loading due to 4 DLUS UE (i.e., ~20% system loading). The figure assumes TCP RTT of 100 ms and TCP segment size of 1500 bytes. The window-limited region is to the left of the dotted vertical lines, which denote the time at which the congestion window reaches the rate of the channel. Up to the window-limited region of SC-HSDPA, the congestion window grows similarly for SC-HSDPA and DC-HSDPA. Thus, DC-HSDPA sees no gain during this period. Gains for DC-HSDPA can be observed in the rate-limited region for SC-HSDPA: in this region, a larger congestion window does not increase the rate for SC-HSDPA, since it is rate-limited, while DC-HSDPA sees increased rate. The relative time spent in the window-limited can be decreased compared to the time spent in the rate- limited region by increasing the file size, lowering the geometry or increasing the loading.

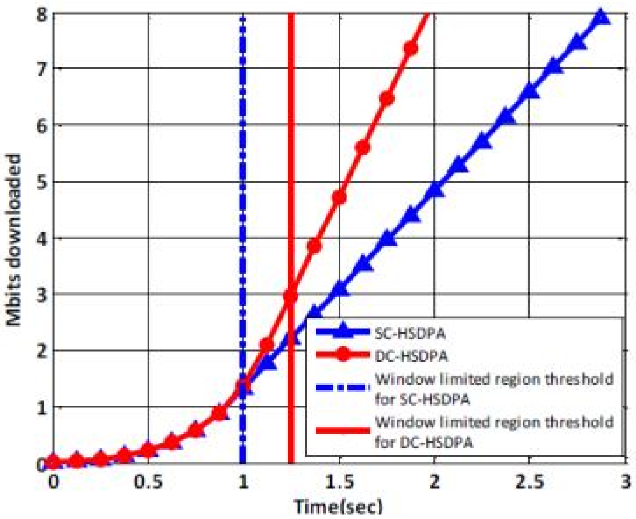


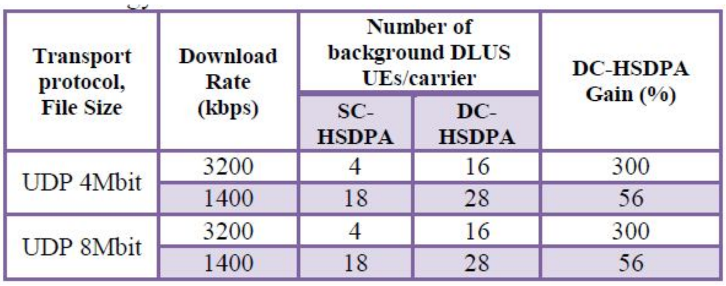
Figure 4: Progression of file download vs time for TCP with 4Mbit file size.

Table 3: Shows that the download rate gain obtained for DC-HSDPA in OTA tests are similar to lab results.

Transport and File Size	OTA location	Download Rate Gain (%) of DC-HSDPA over SC-HSDPA		
		38DLUS UEs	**18DLUS UEs**	**4DLUS UEs**
UDP 1 to 4Mbit	OTA high CQI stationary location	<10%	80	75
TCP 1Mbit			16	8
TCP 4Mbit			34	10
TCP 8Mbit			41	12
UDP 4Mbit	OTA low CQI stationary location	<10%	89	100
TCP 4Mbit			52	78
TCP 8Mbit			76	78

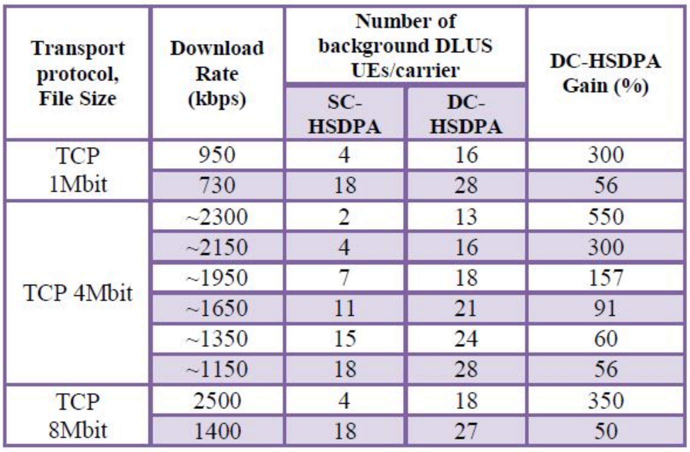
We now show gains of DC-HSDPA in number of supportable background users for the file download application: we compare in Table 4 and Table 5 the system loads at which a DC-HSDPA and a SC-HSDPA foreground UE can achieve the same *download rate*. We use the methodology defined in Section IV.

Table 4: DC-HSDPA gain in number of supportable users for UDP transport protocol from lab tests.



Transport protocol, File Size	Download Rate (kbps)	Number of background DLUS UEs/carrier		DC-HSDPA Gain (%)
		SC-HSDPA	DC-HSDPA	
UDP 4Mbit	3200	4	16	300
	1400	18	28	56
UDP 8Mbit	3200	4	16	300
	1400	18	28	56

Table 5: DC-HSDPA gain in number of supportable users for TCP transport protocol from lab tests.



Transport protocol, File Size	Download Rate (kbps)	Number of background DLUS UEs/carrier		DC-HSDPA Gain (%)
		SC-HSDPA	DC-HSDPA	
TCP 1Mbit	950	4	16	300
	730	18	28	56
TCP 4Mbit	~2300	2	13	550
	~2150	4	16	300
	~1950	7	18	157
	~1650	11	21	91
	~1350	15	24	60
	~1150	18	28	56
TCP 8Mbit	2500	4	18	350
	1400	18	27	50

Table 4 and Table 5 are obtained from Figure 2 and Figure 3 by reading the number of background DLUS UEs/carrier for the same download rate achieved by the foreground SC-HSDPA or DC-HSDPA UE. Note that for TCP with 4 Mbit file size, we have a few additional points of comparison.

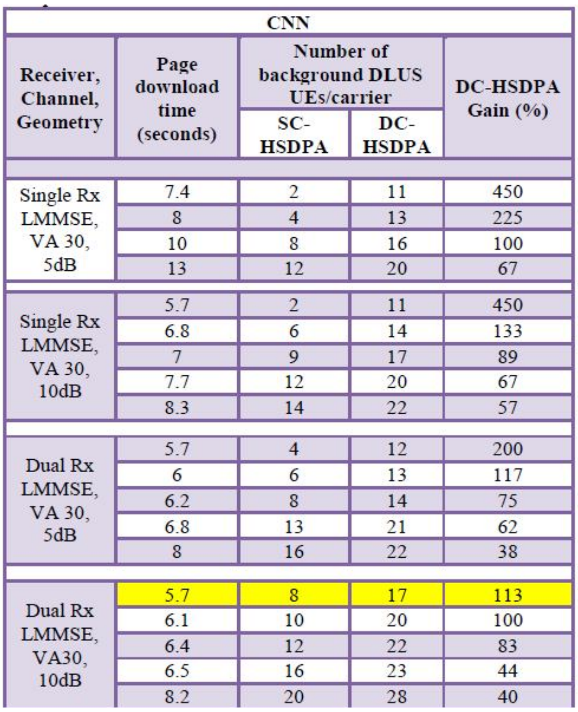
We see that: (i) at the relatively higher download rates, DC-HSDPA can support 4-6 times the number of background DLUS UEs/carrier (300-500% gain) compared to SC-HSDPA (ii) at lower download rates, DC-HSDPA can support ~1.5 times the number of background DLUS UEs/carrier (~50% gain compared to SC-HSDPA. Due to the statistical multiplexing of users that is achieved by joint scheduling across carriers, DC-HSDPA is able to support more than twice the number of users (for a bandwidth increase of 2x) for the same user experience.

We also see that the gain in number of supportable users is nearly independent of the transport protocol (UDP or TCP) or file size. Though the Slow Start algorithm in TCP diluted some of the download rate gains of DC-HSDPA compared to using UDP, the number of supportable users gains are not impacted. In general, the statistical multiplexing capability of DC-HSDPA depends only on TTI utilization, not on file size or transport protocol.

6. Results for Web Browsing

In this section, we evaluate gains in page download time and number of supportable background users for DC-HSDPA over SC-HSDPA for web browsing in a lab setting. Table 6 and Table 7 show results for CNN and Google Maps respectively.

Results presented in [1] have shown that for web browsing, page download times saturate as the channel rate increases (loading decreases). The effective channel rate (accounting for loading) at which CNN saturates was seen to be ~1500kbps; Google Maps was seen to saturate at ~3000kbps~ [1]. We show results only in the region where page download times have not saturated, i.e. the number of UEs have a lower bound, beyond which the page download time saturates. For example, note the highlighted table entry, here 8 background DLUS UEs is the lowest load shown in the case of CNN for a 10dB geometry dual rx UE. Under scenarios where the page download time has not saturated, the lowest load chosen for SC-HSDPA is 2 background DLUS UEs. From Table 6 and Table 7, we see that: (i) at relatively lower page download times, DC-HSDPA can support 3-6 times the number of background DLUS UEs/carrier (200- 500% gain) compared to SC-HSDPA (ii) at higher page download times, DC-HSDPA can support ~1.25-1.5 times the number of background DLUS UEs/carrier (~25-50% gain compared to SC-HSDPA.



CNN

Receiver, Channel, Geometry	Page download time (seconds)	Number of background DLUS UEs/carrier		DC-HSDPA Gain (%)
		SC-HSDPA	DC-HSDPA	
Single Rx LMMSE, VA 30, 5dB	7.4	2	11	450
	8	4	13	225
	10	8	16	100
	13	12	20	67
Single Rx LMMSE, VA 30, 10dB	5.7	2	11	450
	6.8	6	14	133
	7	9	17	89
	7.7	12	20	67
	8.3	14	22	57
Dual Rx LMMSE, VA 30, 5dB	5.7	4	12	200
	6	6	13	117
	6.2	8	14	75
	6.8	13	21	62
	8	16	22	38
Dual Rx LMMSE, VA30, 10dB	5.7	8	17	113
	6.1	10	20	100
	6.4	12	22	83
	6.5	16	23	44
	8.2	20	28	40

Table 6: DC-HSDPA gain in number of supportable users for CNN.

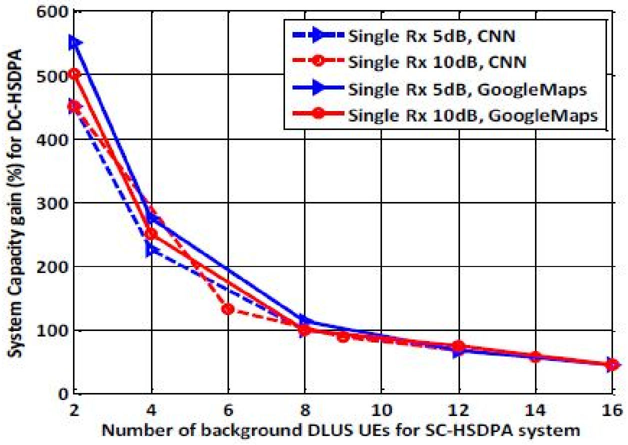
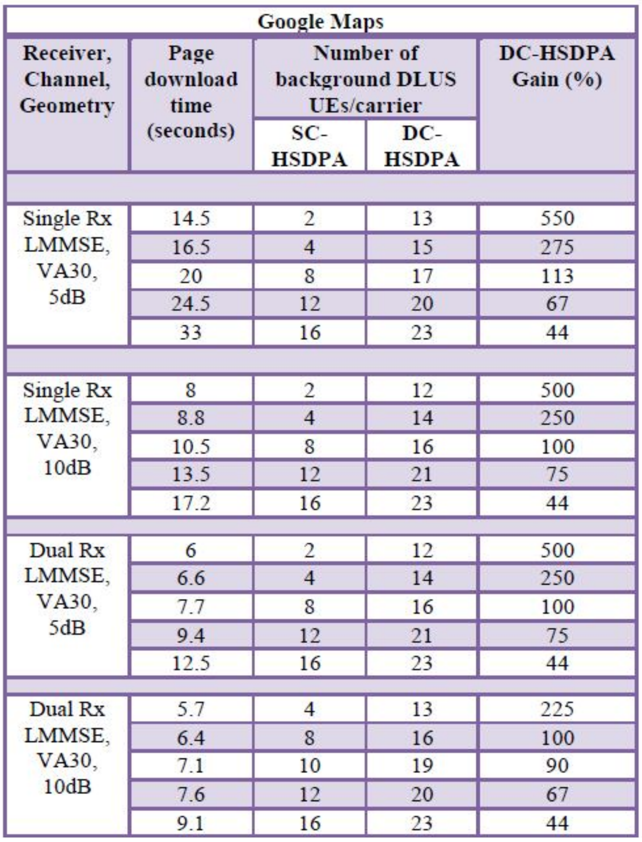


Figure 5: DC-HSDPA gain in number of supportable users for web browsing (Foreground UE has single rx receiver).



Google Maps				
Receiver, Channel, Geometry	**Page download time (seconds)**	**Number of background DLUS UEs/carrier**		**DC-HSDPA Gain (%)**
		SC-HSDPA	**DC-HSDPA**	
Single Rx LMMSE, VA30, 5dB	14.5	2	13	550
	16.5	4	15	275
	20	8	17	113
	24.5	12	20	67
	33	16	23	44
Single Rx LMMSE, VA30, 10dB	8	2	12	500
	8.8	4	14	250
	10.5	8	16	100
	13.5	12	21	75
	17.2	16	23	44
Dual Rx LMMSE, VA30, 5dB	6	2	12	500
	6.6	4	14	250
	7.7	8	16	100
	9.4	12	21	75
	12.5	16	23	44
Dual Rx LMMSE, VA30, 10dB	5.7	4	13	225
	6.4	8	16	100
	7.1	10	19	90
	7.6	12	20	67
	9.1	16	23	44

Table 7: DC-HSDPA gain in number of supportable users for Google Maps.

In Figure 5 and Figure 6, we show the number of supportable users gain of DC-HSDPA compared to SC-HSDPA for single rx and dual rx UEs respectively. Note that Figure 5 and Figure 6 are generated using the data shown in Table 6 and Table 7. We see that the gains are nearly independent of the web page considered (CNN or Google Maps), UE geometry (5 dB or 10 dB) or receiver type (single rx or dual rx).

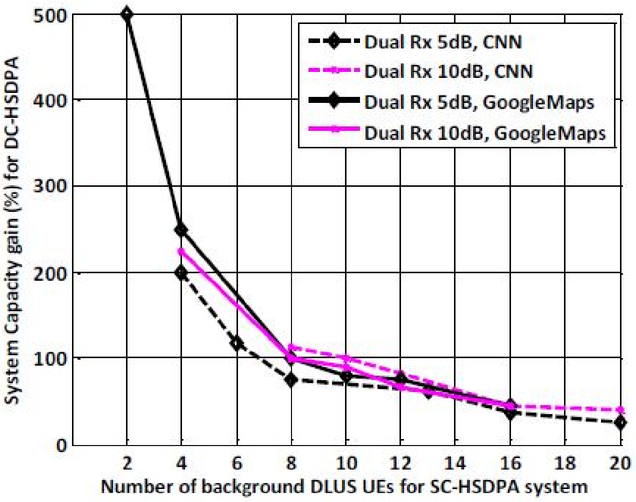


Figure 6: DC-HSDPA gain in number of supportable users for web browsing for web browsing (Foreground UE has dual rx receiver).

7. Conclusion

DC-HSDPA has also shown significant gains in the number of supportable users compared to two carriers of SC-HSDPA. When the foreground user is downloading a file, DC-HSDPA was found to support 300-500% additional background users for the higher download rates (corresponding to lower system loading), and ~50% additional background users for the lower download rates (corresponding to higher system loading). When the foreground user is browsing the web (CNN or Google Maps), our results showed DC-HSDPA gains of 200-500% for the lower page download times, and 25-50% for the higher page download times. At the highest system loads, approaching the ~100% TTI utilization, the gains of DC-HSDPA almost disappear. One interesting observation from our results is that the gains of DC-HSDPA in number of supportable background users are nearly independent of UE geometry, receiver type (single or dual rx) and to a large extent, even the considered application for the foreground user (file download or web browsing). The gains of DC-HSDPA, both in terms of user experience and number of supportable users, make it an attractive upgrade option for HSPA operators.

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