Qualcomm Technologies, Inc.

Qualcomm Research

Dual-Cell HSDPA

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Introduction

The WCDMA standard developed under 3rd Generation Partnership Project (3GPP) is a widely deployed technology for carrying voice and data traffic over mobile networks. The standard was enhanced with High Speed Downlink Packet Access (HSDPA) in 3GPP Release 5 which enables efficient use of over-the-air (OTA) resources to carry data on the downlink.

During the last few years, mobile networks have experienced considerable increase in data traffic. This has largely been due to the rapid penetration of smartphones, the availability of mobile broadband dongles for laptops and affordable rates for consumers. Increasing demand and the need for improved user experience has necessitated continuous evolution of networks to meet such requirements.

Various enhancements have been introduced to HSDPA to cater to such needs. The deployment of additional network resources, such as a second HSDPA carrier, has created an opportunity for resource pooling as a way to provide benefits above and beyond what would be possible if the two carriers were operating separately. With this in mind, Dual-Cell HSDPA (DC-HSDPA) has been introduced in Release 8 of the WCDMA specifications. DC-HSDPA enables the User Equipment (UE) to receive downlink data on two adjacent HSDPA carriers simultaneously.

This paper provides a high level description of DC-HSDPA feature and its expected benefits. The paper is organized as follows: A high-level description of the feature is provided first, followed by some intuition and theory on the expected benefits from carrier aggregation. A sampling of OTA results from commercial networks are presented subsequently, followed by concluding remarks.

DC-HSDPA Overview

Dual-Cell HSDPA aggregates two adjacent downlink carriers to offer higher peak data rate, and to improve capacity and user experience for data applications. The following diagram illustrates the concept behind DC-HSDPA.

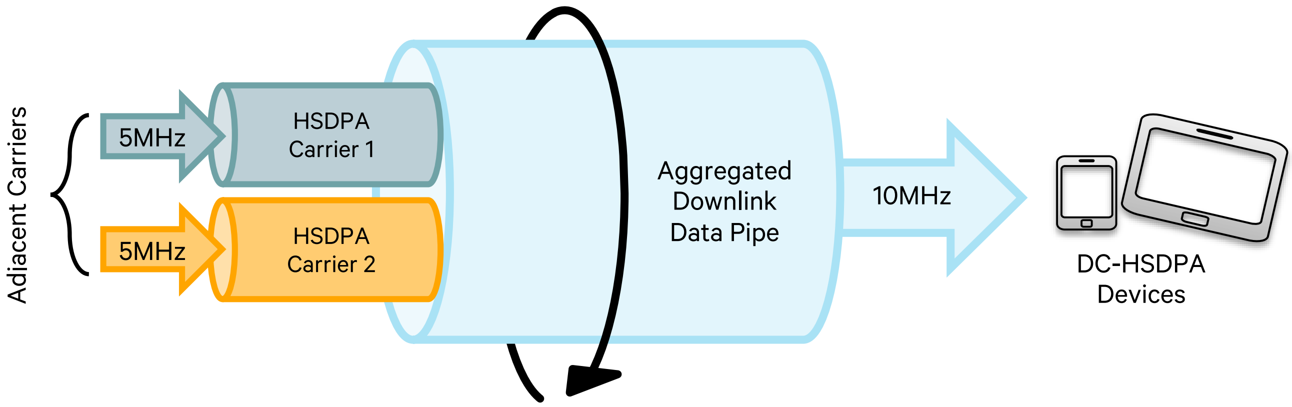

Figure 1 : DC-HSDPA concept

Under DC-HSDPA operation, the uplink is still transmitted only on one carrier, the anchor carrier. The downlink carrier associated with the anchor carrier is referred to as the serving/primary downlink and the other downlink carrier is referred to as the secondary serving downlink carrier.

Co-existence and Deployment scenarios

Legacy UE's can be mixed and co-exist with DC-HSDPA UE's.

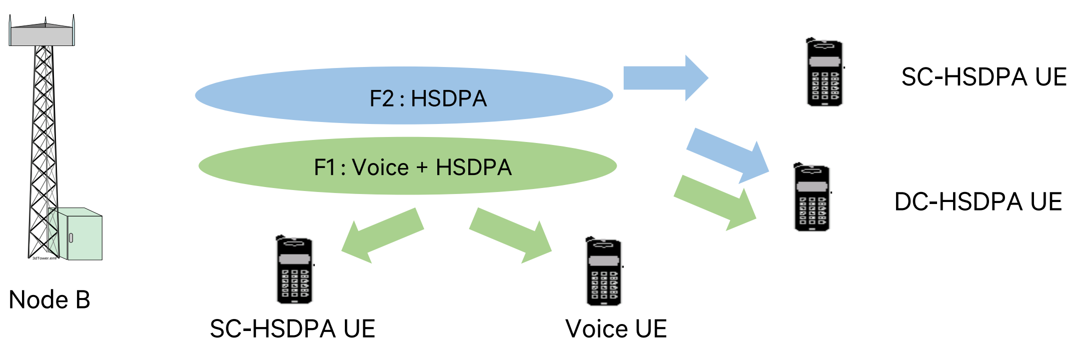

Figure 2: DC-HSDPA deployment with Voice and Data on F1 and Data only on F2

Figure 2 depicts and exemplary deployment scenario with voice and HSDPA on carrier F1 and HSDPA only on F2. In this scenario, DC-HSDPA users co-exist with legacy voice and single-carrier (SC) HSDPA users on F1 and F2. In general, F1 and F2 could have any combination of voice, data (R99 PS and/or HSDPA) and DC-HSDPA UE's co-existing, depending on operator requirements.

Timing and Physical Channels

The pilot channel (CPICH) is required to be transmitted on the secondary downlink carrier. The nominal radio frame timing for CPICH and timing reference are the same for the primary and secondary carriers. The network is free to also transmit other common physical channels such as the broadcast (PCCPCH, SCCPCH) and synchronization (SCH) channel on the secondary carrier depending on the deployment scenario and whether legacy UE's are expected to co-exist on that carrier. Transmitting other common physical channels also enables assigning either carrier as the primary downlink carrier and have its associated uplink as the anchor carrier, thereby balancing the load across the uplink carriers. Figure 3 depicts the typical case where CPICH and other common physical channels are transmitted on both carriers.

HS-SCCH is used to provide downlink scheduling information such as codes, modulation, transport block size etc. to the UE. The UE monitors the HS-SCCH on each carrier separately. Just like SC-HSDPA operation, if the UE detects the presence of HS-SCCH on a carrier, it decodes the HS-PDSCH physical channel on that carrier, carrying the data intended for the UE. Each carrier has its own hybrid ARQ (HARQ) entity, which is responsible for physical layer retransmissions of the packet on that carrier.

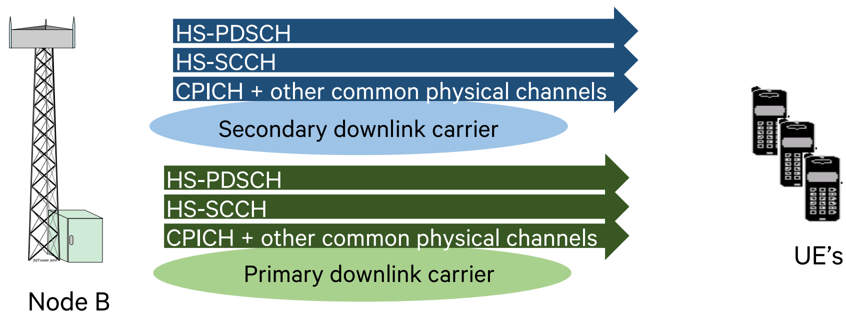

Figure 3: DC-HSDPA Downlink Physical Channels

In addition to the HS-SCCH for scheduling, a new HS-SCCH format called HS-SCCH order has been introduced to activate or de-activate the UE's secondary carrier. The HS-SCCH order enables the Node B to quickly, in one TTI, activate and de-activate the secondary carrier depending on the UE's buffer occupancy and coverage, amongst other considerations.

As stated above, the uplink is transmitted on a single carrier. Further, a single jointly coded HS-DPCCH uplink physical channel carries the HARQ ACK/NACK as well as Channel Quality Information (CQI) for both the primary and secondary downlink carriers. This is depicted in Figure 4 below.

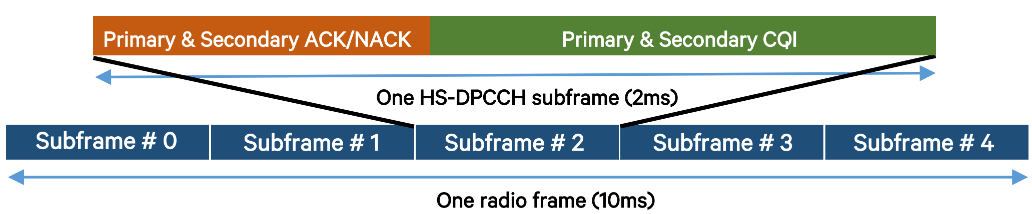

Figure 4: HS-DPCCH uplink physical channel structure with DC-HSDPA

Scheduling and Upper Layers

In DC-HSDPA, the UE receives both the primary and secondary carriers from the same sector. The concept is illustrated in Figure 5. The RNC forwards data packets 1 through 10 for the UE to the Node B. The Node B schedules packets 1, 2 & 4 on carrier F1 and packets 3 & 5 on carrier F2 to the UE, while packets 6 through 10 wait in the Node B queue.

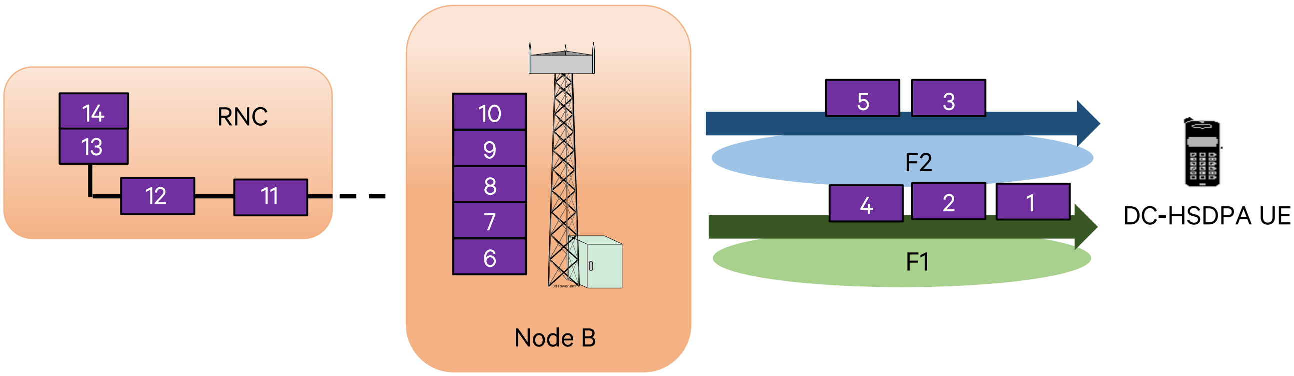

Figure 5: Scheduling packets in DC-HSDPA

The packet split between the carriers as well as time instants of scheduling are implementation dependent. On one extreme, we could visualize schedulers which do not exchange any information regarding CQI etc. between the two carriers and perform independent scheduling of data on each F1 and F2 to the UE. At the other extreme, we could have tightly coupled joint schedulers which exchange information to schedule as much data as possible on the carrier experiencing better fading and interference characteristics as inferred from the reported CQI's. Whilst joint scheduling provides performance improvement, it comes at the cost of additional complexity.

Since the data is transmitted from the same sector in the Node B, the impact to upper layers is limited. The data is transmitted from a single queue and in sequence no matter how it is split and scheduled between the two carriers. At the UE, the data is received in-sequence except for skew caused by HARQ re-transmissions on each of the carriers. Just like single carrier operation, the UE's MAC layer would ensure HARQ reordering and in-sequence delivery to the upper layers.

Mobility

Mobility in DC-HSDPA is based on the primary downlink carrier. The UE maintains an active set only on the primary carrier. For this purpose, legacy events such as Event 1A and Event 1B etc. are used. If the serving cell on the primary carrier is handed over to a new Node B, the serving cell on the secondary carrier is also handed over to the same Node B. This is because the primary and secondary carriers for a UE must be received from the same site due to the timing requirement described above.

Similar to intra-frequency handover described above, inter-frequency mobility is also based on the primary carrier using legacy inter-frequency events. For completeness, we should mention that DC-HSDPA is not supported when handing over to UTRAN from another RAT. This is to say that during inter-RAT PS handover, the UE is first handed over to single carrier HSDPA operation, and subsequently may be reconfigured to DC-HSDPA operation once in UTRAN. This restriction has been removed in 3GPP Release 11.

Peak Rate

Eight new UE categories have been introduced with support for DC-HSDPA. When combined with 64-QAM and MIMO operation, the highest category DC-HSDPA UE supports a peak rate of 84.4Mbps on the downlink.

Dual-Cell HSDPA (DC-HSDPA) enables carrier aggregation across two adjacent frequencies. In this section, we provide intuition on the benefits of carrier aggregation compared to a single carrier systems. The discussion applies generally to any carrier aggregation scheme, not necessarily limited to aggregation across adjacent frequencies. To keep the discussion general, we compare a dual-carrier (DC) aggregation system with one in which two single carriers (2xSC) operate independently.

Capacity Gain with Full Buffer Traffic

For fading channels typical in a wireless system, a DC system provides higher total throughput compared with a 2xSC system for full buffer traffic model. More precisely, we define full buffer capacity gain as the increase in the sum throughput across all users in the DC system compared with the sum throughput across all users in the 2xSC system. For fairness, we assume that we have the same number of users in a geographic area, i.e. per sector, in the two scenarios. For the DC system, there are 2*N users per sector aggregated across two carriers. For the 2xSC system, there are N users on each of the two carriers per sector.

The capacity gain comes from a) improved multi-user diversity gain and potentially b) joint scheduling gain. The multi-user diversity gain is higher in DC because there are 2*N users in each carrier compared with N users in each carrier in the 2xSC system, enabling the scheduler to “ride the users channel peaks” more effectively. Joint scheduling provides another degree of freedom, whereby information exchange across the carriers such as reported CQI’s is used to ensure that users are scheduled and prioritized on the carrier experiencing better fading and interference characteristics.

Improved User Experience with Bursty Traffic

Most real world applications such as web-browsing are inherently bursty in nature. For bursty traffic, a DC system provides latency reduction compared to a single carrier system thereby improving the user experience. The gain can be seen from the queuing analysis presented below.

As an abstract model of a bursty traffic system, let us assume an M/G/1 queuing system. The service rate can be random with any distribution. The arrival process is assumed to be memoryless, i.e. the inter-arrival times are exponentially distributed.

For one single carrier, let us denote the arrival rate as λ and the departure rate as μ. When we have two aggregated carriers and twice the number of users per sector, we have another M/G/1 system with arrival rate 2λ and service rate 2μ. The total time spent in the system by a burst is the sum of its service time and waiting time. It is obvious that the service time of each burst is reduced by half in the aggregated system. Therefore, to quantify the latency, we need to find the waiting time, which in turn depends on the queue length. If we compress a unit of time to half in a new M/G/1 system with 2λ and 2μ, the queue length dynamic is exactly the same as in the original M/G/1 system with λ and μ. Therefore, the average queue length remains the same but the average waiting time is cut in half, thereby reducing the overall latency in half.

The same conclusion can be seen from the Kleinrock-Khinchin formula for M/G/1 queue. The total time for a data burst in the system with arrival rate λ and departure rate μ is given by,

$$T_{total,\lambda,\mu} = T_{service} + T_{waiting} = \frac{1}{\mu} + \frac{\lambda m_2}{2\left(1 - \frac{\lambda}{\mu}\right)}$$

where m_2 is the second moment of the service time. When both λ and μ are doubled, m_2 is reduced to a quarter of its value and the total time in system is given by,

$$T_{total,2\lambda,2\mu} = T_{service} + T_{waiting} = \frac{1}{2\mu} + \frac{2\lambda m_2 / 4}{2\left(1 - \frac{2\lambda}{2\mu}\right)} = T_{total,\lambda,\mu}/2$$

An intuitive performance metric is the 'burst rate' defined as the ratio between the burst size and the total time taken to transfer the burst over the air interface from the time it arrives at Node B, i.e. T_{total}. Since the burst size is presumably the same for the single carrier and aggregated carrier system, the burst rate of the aggregated system becomes twice that the single carrier system. The increase in burst rate is a direct consequence of the reduced latency offered by the aggregated system.

Load Balancing Gain

In reality, the user association in a 2xSC system may not always be balanced between the carriers. When there are unequal number of users, for example, higher number of users in carrier 2 than in carrier 1, carrier 1 will have smaller multi-user diversity gain whereas the users in the carrier 2 suffer throughput reduction relative to users in carrier 1. Even if the users were equally distributed amongst the carriers, most realistic data applications are not full buffer in nature and therefore it is impractical, if not impossible, to equalize the number of "simultaneously active" users across carriers in a single carrier system. On the other hand, a DC system automatically balances the load between the carriers both in terms of number of users in each carrier and data traffic. Since multi-user diversity increases with number of users, load balancing leads to a net gain in capacity. Furthermore, there is no reduction in throughput for those users in the more crowded carrier of the 2xSC system, which improves the fairness amongst the users.

OTA Results for DC-HSDPA

In this section we present over-the-air (OTA) results on the gains from DC-HSDPA. The OTA tests were conducted in two commercial networks at different times of the day to incorporate varying load in the network and at various locations to capture a multitude of RF conditions. We had a single device-under-test (DUT), which was setup for either SC-HSDPA or DC-HSDPA operation.

User Experience Gain

To quantify the user experience gain of DC-HSDPA, we look at three different applications: DASH video streaming, web-browsing and FTP download. Further, we group the results into different RF conditions as identified by the CQI reported by the UE.

Good RF: >25 CQI	Mid RF: [15-20] CQI	Low RF: [13-14] CQI

Figure 6: RF characterization based on CQI reported by UE

DASH Video Streaming

DASH is an HTTP based streaming protocol that adapts the video rate based on the quality of the link. Figure 7 shows the usage of different streaming video rates for DC-HSDPA and SC-HSDPA under mid RF conditions at two different locations.

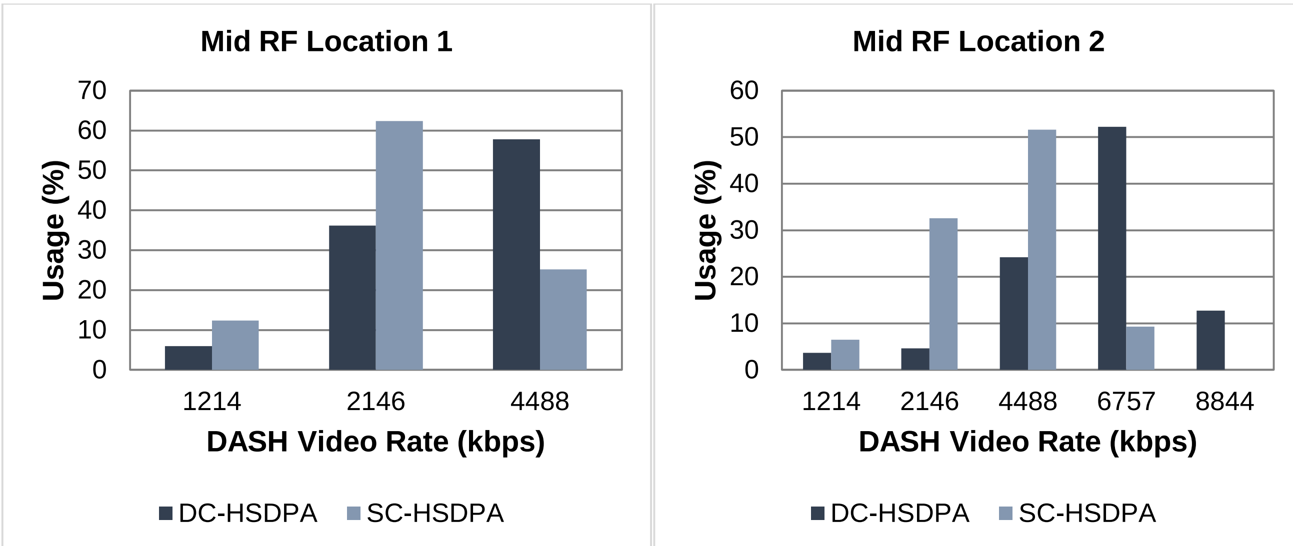

Figure 7: Usage percentage vs. DASH video rate under mid RF conditions for SC-HSDPA and DC-HSDPA

It can be observed that DC-HSDPA increases the usage of higher streaming video rates, thereby improving the user experience. At low RF conditions, this effect is even more pronounced, as shown in Figure 8.

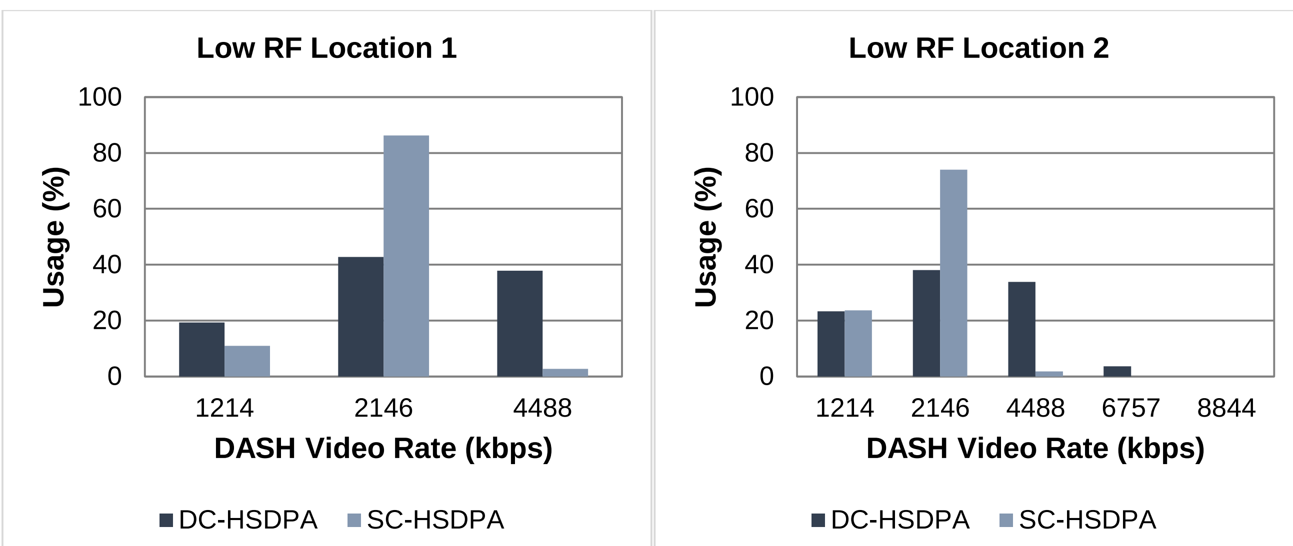

Figure 8: Usage percentage vs. DASH video rate under low RF conditions for SC-HSDPA and DC-HSDPA

Web-browsing

Another popular application that can be used to assess user experience is web-browsing, In particular, we look at the webpage download time, i.e. the time from 'click' to the time the webpage finishes downloading, measured at the application (web-browser) level. Figure 9 shows the webpage download time averaged over multiple visits to www.foxnews.com for different RF conditions.

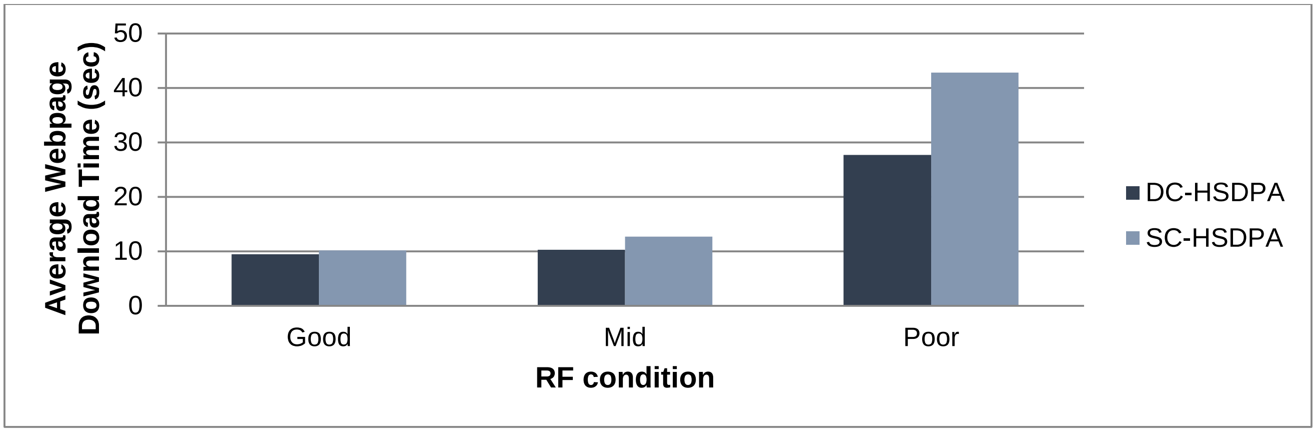

Figure 9: Webpage download time vs. RF condition for SC-HSDPA and DC-HSDPA

First, we notice that under good RF conditions, there is no tangible reduction in webpage download time. This can be explained by a) Request-response nature of HTTP and b) Browser processing delays. The request-response nature of HTTP leads to multiple round trip times being used for sending HTTP requests to download a webpage, introducing instants where the air-link may be underutilized. This, coupled with browser processing delays, leads to web browsing download times saturating once the OTA channel rate is sufficiently high, as is the case in good RF even with a single-carrier. In other words, the application layer throughput for web-browsing is limited by the browser delays and HTTP overheads, and an increase in the OTA rate beyond a certain level does not manifest itself into a corresponding gain at the application layer.

Similar effects also play a part in limiting the reduction in page download time observed at mid RF conditions. However, in low RF conditions, where OTA rates are the bottleneck for realizable throughput for web-browsing, introducing DC-HSDPA provides considerable reduction in webpage download time, thereby improving user experience.

FTP Download

FTP is a popular protocol to transfer files from one host to another. Figure 10 shows the OTA throughput for SC-HSDPA and DC-HSDPA for different RF conditions and locations for FTP file download. Unlike HTTP, FTP protocol utilizes all the available resources of the OTA link for downloading the file. Introducing DC-HSDPA provides a fatter pipe, improving the OTA throughput achieved across all RF conditions and locations.

It should be noted that the experiments at different locations were conducted at different times of the day and as a result may have experienced varying network loading conditions. This could explain the differences in OTA throughput under similar RF conditions as well as the varying gains in throughput observed for DC-HSDPA across different scenarios.

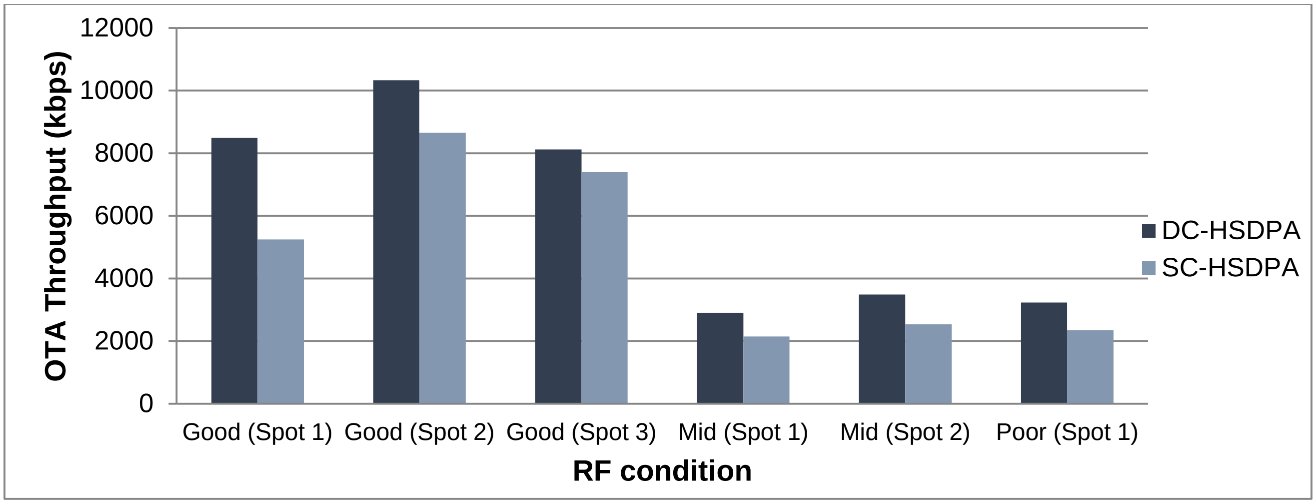

Figure 10: FTP OTA throughput for SC-HSDPA and DC-HSDPA

System Capacity Gain with Bursty Traffic

In this section, we focus on the system capacity gain for bursty traffic with DC-HSDPA in a commercial setting. In case of bursty traffic, we define capacity gain as the increase in number of users that can be simultaneously supported in a system at a given burst rate (burst rate is as defined earlier). To establish the system capacity gain, we performed sequential tests using one device-under-test (DUT), which was setup as either SC-HSDPA or DC-HSDPA. The DUT performed multiple FTP file downloads at different locations and at different times of the day. Since the tests were conducted in a commercial network, the amount of loading could not be controlled and network loading statistics were unavailable. Thus, in order to establish the number of UE's per cell, an extrapolation technique was used based on the fraction of TTI's and HS-codes scheduled for the DUT during active burst transmissions. For example, in SC-HSDPA mode, if the DUT was scheduled on a third of the TTI's with an average of 9 HS-codes (out of a maximum of 15), then the number of UE's per cell was inferred to be $\frac{1}{1/3} \times \frac{15}{9} = 5$. The burst rate was obtained as the average FTP download rate of the DUT, where the average was taken over multiple runs and across different locations for a given number of inferred UE's per cell.

Figure 11 plots the number of HSDPA users per cell (per sector per carrier) versus the average FTP download rate per user. It can be seen that DC-HSDPA increases the number of users that can be supported per cell at a given burst rate compared to SC-HSDPA, thereby providing increased system capacity.

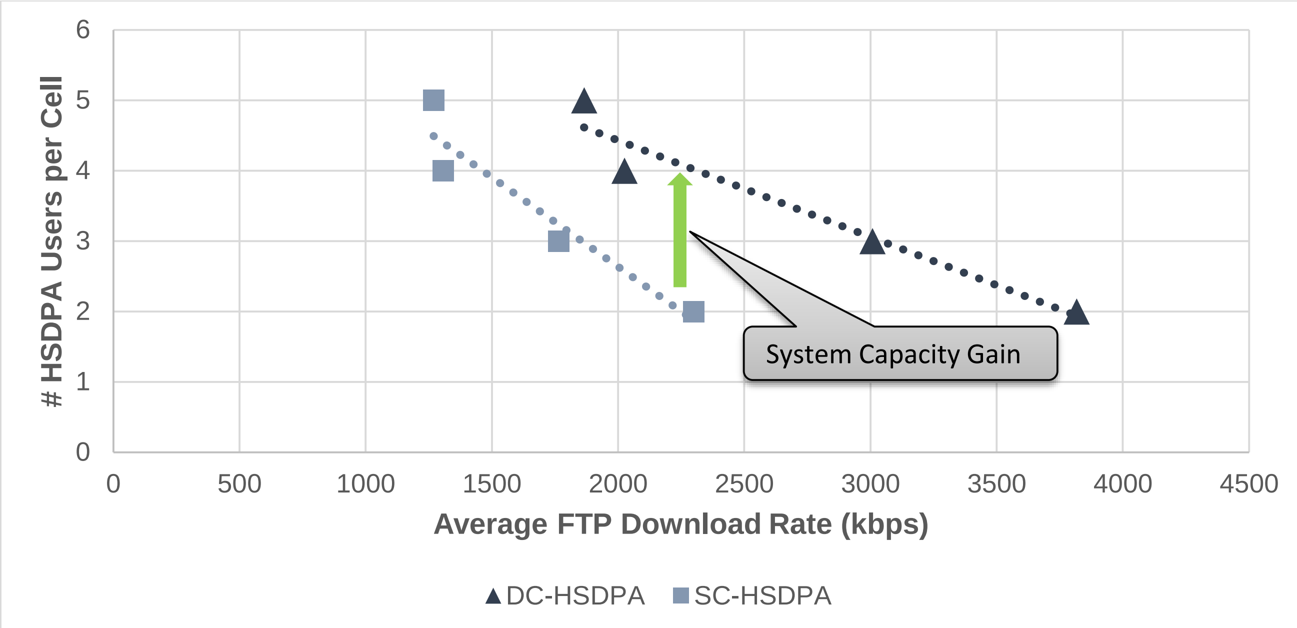

Figure 11: Number of HSDPA users per cell vs. Average FTP download rate per user

Conclusion

Dual-Cell HSDPA (DC-HSDPA) enables aggregation of two adjacent carriers in a single band.

Carrier aggregation provides higher peak rate compared to single carrier operation. A peak rate of 84.4Mbps is supported with DC-HSDPA operation when combined with 64-QAM and MIMO operation. In addition, carrier aggregation increases system capacity and improves user experience. Carrier aggregation also enables load balancing both in terms of number of users and the amount of data traffic. Such load balancing is impractical, if not impossible, in single carrier systems due to the dynamic and unpredictable nature of bursty data applications.

The user experience benefits of DC-HSDPA are validated based on measurements taken in commercial networks for real world applications such as DASH video, web-browsing and FTP download. For DASH video and web-browsing, it is observed that DC-HSDPA provides benefits at mid and low RF conditions. Gains in FTP download rates are observed across all good, mid and low RF conditions. Results are also presented showing system capacity increase for bursty traffic for DC-HSDPA compared to SC-HSDPA in a commercial network.