Qualcomm Technologies, Inc.

Qualcomm Research

Dual-Band Dual-Cell HSDPA

February 2015

Qualcomm Research is a division of Qualcomm Technologies, Inc.

Qualcomm Technologies, Inc.

Qualcomm Technologies, Inc.

5775 Morehouse Drive

San Diego, CA 92121

U.S.A.

Table of Contents

Introduction **5**

DB-DC-HSDPA Overview **5**

Co-existence and Deployment scenarios 6

Timing and Physical Channels 7

Scheduling and Upper Layers 8

Mobility 9

Peak Rate 9

Benefits of Carrier Aggregation **9**

Capacity Gain with Full Buffer Traffic 9

Improved User Experience with Bursty Traffic 10

Load Balancing Gain 10

Simulation and Lab Results for DB-DC-HSDPA **11**

User Experience Gain 11

Cell Edge Throughput Gain 12

Cell Edge Power Consumption Reduction 13

Conclusion **14**

Figures

Figure 1 : DB-DC-HSDPA concept 6
Figure 2: DB-DC-HSDPA deployment with Voice and Data on F1 and Data only on F2 7
Figure 3: DB-DC-HSDPA Downlink Physical Channels 7
Figure 4: HS-DPCCH uplink physical channel structure with DB-DC-HSDPA 8
Figure 5: Scheduling packets in DB-DC-HSDPA 8
Figure 6: Average UE burst rate vs. Number of UE's per cell (simulation) 12
Figure 7: Throughput vs. RSCP (lab test) 13
Figure 8: Power consumption reduction vs. UE transmit power (lab test) 14

Tables

Table 1: DB-DC-HSDPA band combination support introduced in 3GPP Release 9 6
Table 2: DB-DC-HSDPA band combination support introduced in 3GPP Release 10 6
Table 3: Lab setup for throughput test 13

Introduction

The WCDMA standard developed under 3rd Generation Partnership Project (3GPP) is a widely deployed technology for carrying data traffic over mobile networks. The standard was enhanced with High Speed Downlink Packet Access (HSDPA) in 3GPP Rel-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 computers 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) was 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.

DC-HSDPA has garnered considerable adoption across the WCDMA ecosystem as a way to increase peak rates, improve system capacity and enhance the user experience. However, an inherent limitation of DC-HSDPA requires the two carriers being aggregated to be occupying contiguous spectrum. For some cellular operators, this may not be option as the owned spectrum may not be contiguous, and in some cases may even lie in different frequency bands. To alleviate this limitation, Dual-Band Dual-Cell HSDPA (DB-DC-HSDPA) has been introduced in 3GPP Rel-9, which enables the UE to receive downlink data on two HSDPA carrier aggregated across different frequency bands.

This paper provides a high level description of DB-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. Simulation results as well as lab measurements are presented subsequently, followed by concluding remarks.

DB-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. Dual-Band Dual-Cell HSDPA (DB-DC-HSDPA) further enables aggregation across two frequency bands. The following diagram illustrates the concept behind DB-DC-HSDPA.

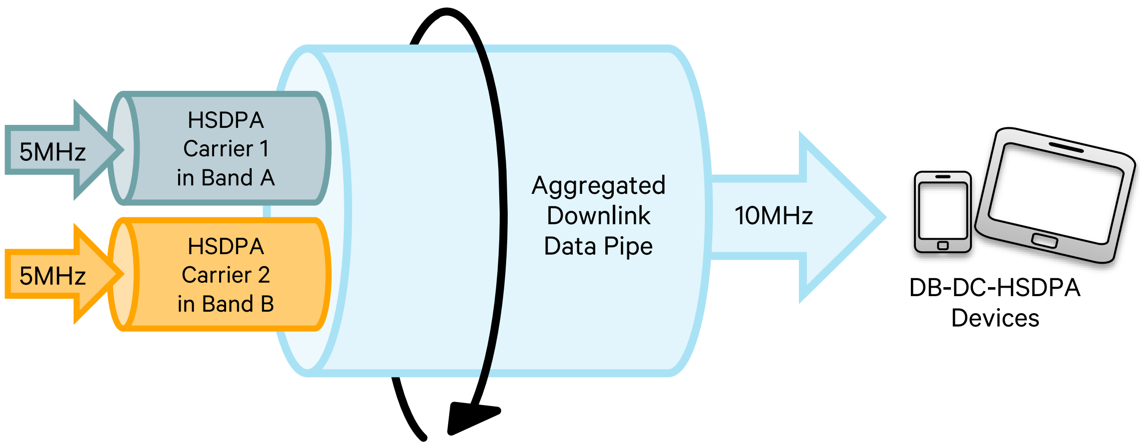

Figure 1 : DB-DC-HSDPA concept

DB-DC-HSDPA was initially standardized in 3GPP Release 9 to support the following band combinations:

Table 1: DB-DC-HSDPA band combination support introduced in 3GPP Release 9

Carrier 1	Carrier 2
Band 1 (2100MHz)	Band 8 (900MHz)
Band 2 (1900MHz)	Band 4 (2100/1700MHz)
Band 1 (2100MHz)	Band 5 (850MHz)

It was further extended in 3GPP Release 10 to support these new band combinations:

Table 2: DB-DC-HSDPA band combination support introduced in 3GPP Release 10

Carrier 1	Carrier 2
Band 1 (2100MHz)	Band 11 (1450MHz)
Band 2 (1900MHz)	Band 5 (850MHz)

Under most of the above band combinations, DB-DC-HSDPA aggregates a high band carrier with a low band carrier. 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 DB-DC-HSDPA UE's.

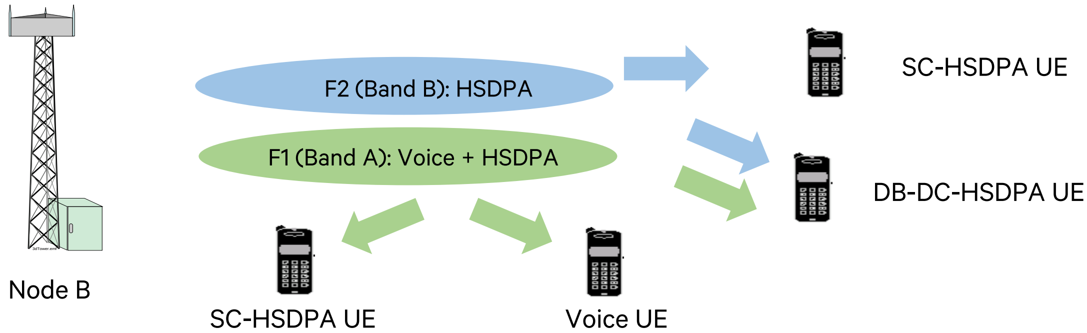

Figure 2: DB-DC-HSDPA deployment with Voice and Data on F1 and Data only on F2

Figure 2 depicts and exemplary deployment scenario with voice and HSDPA on carrier F1 and HSDPA only on F2. In this scenario, DB-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 DB-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.

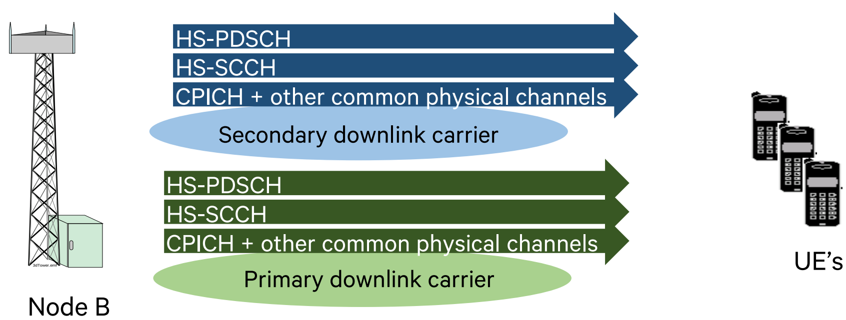

Figure 3: DB-DC-HSDPA Downlink Physical Channels

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.

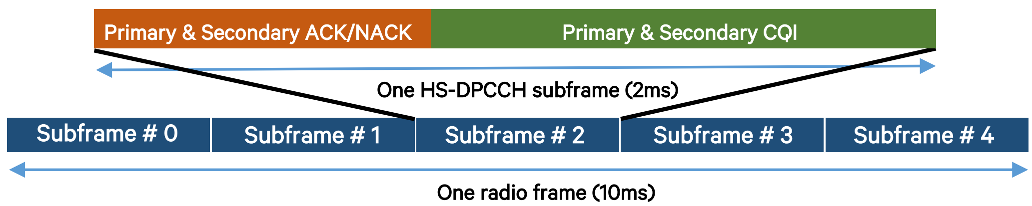

Figure 4: HS-DPCCH uplink physical channel structure with DB-DC-HSDPA

Scheduling and Upper Layers

In DB-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.

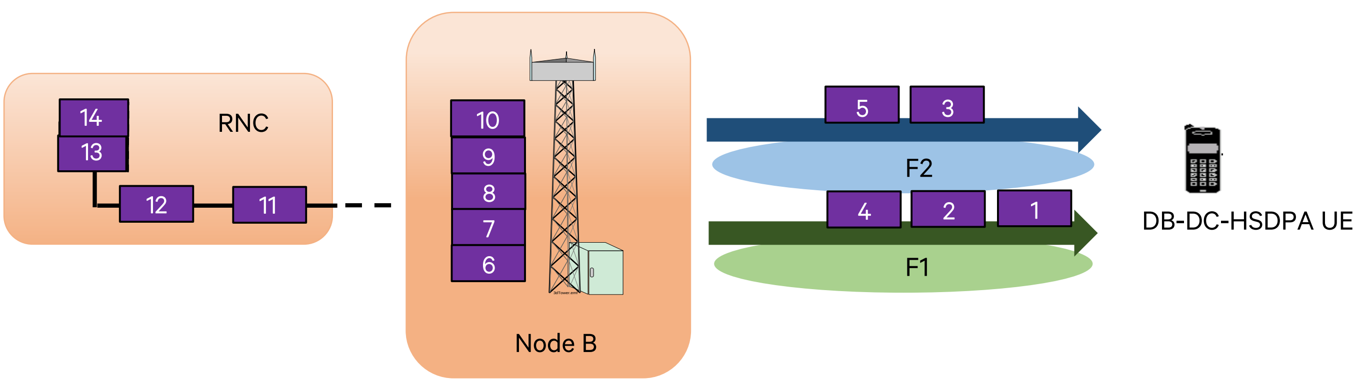

Figure 5: Scheduling packets in DB-DC-HSDPA

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 DB-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 DB-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 DB-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 DB-DC-HSDPA. When combined with 64-QAM and MIMO operation, the highest category DB-DC-HSDPA UE supports a peak rate of 84.4Mbps on the downlink.

Benefits of Carrier Aggregation

Dual-Band Dual-Cell HSDPA (DB-DC-HSDPA) enables carrier aggregation across two frequency bands. 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 two bands. 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 will provide 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 ensures 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 source, 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 i.e. latency is cut 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.

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, thereby improving the fairness amongst the users.

Simulation and Lab Results for DB-DC-HSDPA

In this section we present simulation as well as lab data on the gains from DB-DC-HSDPA.

User Experience Gain

Figure 6 shows the average user burst rate for DB-DC-HSDPA and SC-HSDPA plotted against the number of users per cell (per sector per carrier) from simulation. ‘Burst rate’ is 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 the Node B. The average user burst rate is simply the average of the burst rate over all users in the system. DB-DC (B8, B1) represents a scenario where all users in the system are DB-DC-HSDPA with one carrier in Band 8 (900MHz) and the other carrier in Band 1 (2100MHz). In the SC (B8, B1) case, all the users in the system are single carrier and equally split between one carrier in Band 8 and one carrier in Band 1. Other simulation assumptions are as per the 3GPP simulation methodology described in R1-090572. As argued in the previous section, it can be seen that DB-DC-HSDPA provides double the average burst rate compared to SC-HSDPA, thereby enhancing the user experience for bursty data applications.

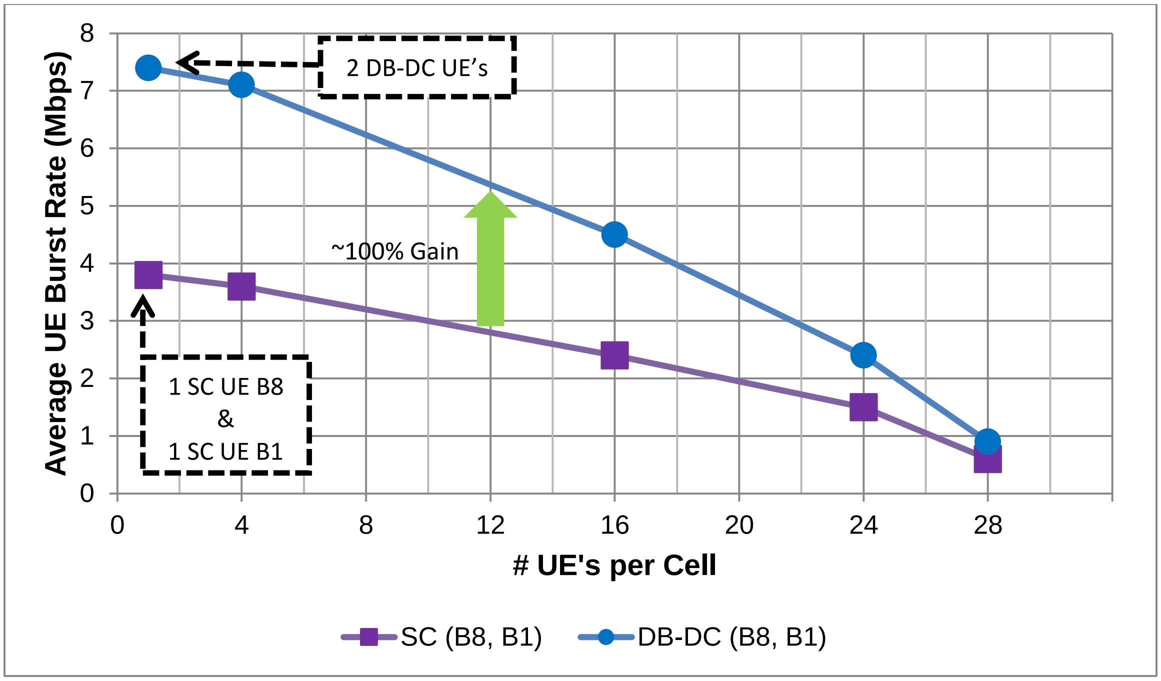

Figure 6: Average UE burst rate vs. Number of UE's per cell (simulation)

Cell Edge Throughput Gain

Under most scenarios, DB-DC-HSDPA aggregates a high band carrier with a low band carrier. Figure 7 compares the cell edge throughput performance of DB-DC-HSDPA with one carrier in Band 8 (900MHz) and the other carrier in Band 1 (2100MHz) against DC-HSDPA with two adjacent carriers in Band 1 in a lab setup. Also shown is the performance of SC-HSDPA with single carrier in Band 8. Other details of the lab setup are listed in Table 3. A 10dB difference in coverage is anticipated between Band 8 and Band 1 based on measurements conducted in actual deployments. This is captured in terms of Received Signal Code Power (RSCP) difference on the horizontal axis in Figure 7. Due to improved coverage and higher RSCP on the low band carrier, DB-DC (B8, B1) shows throughput improvement at cell edge compared to DC (B1). In fact, it can be seen that at the lower RSCP range, SC (B8) also outperforms DC (B1).

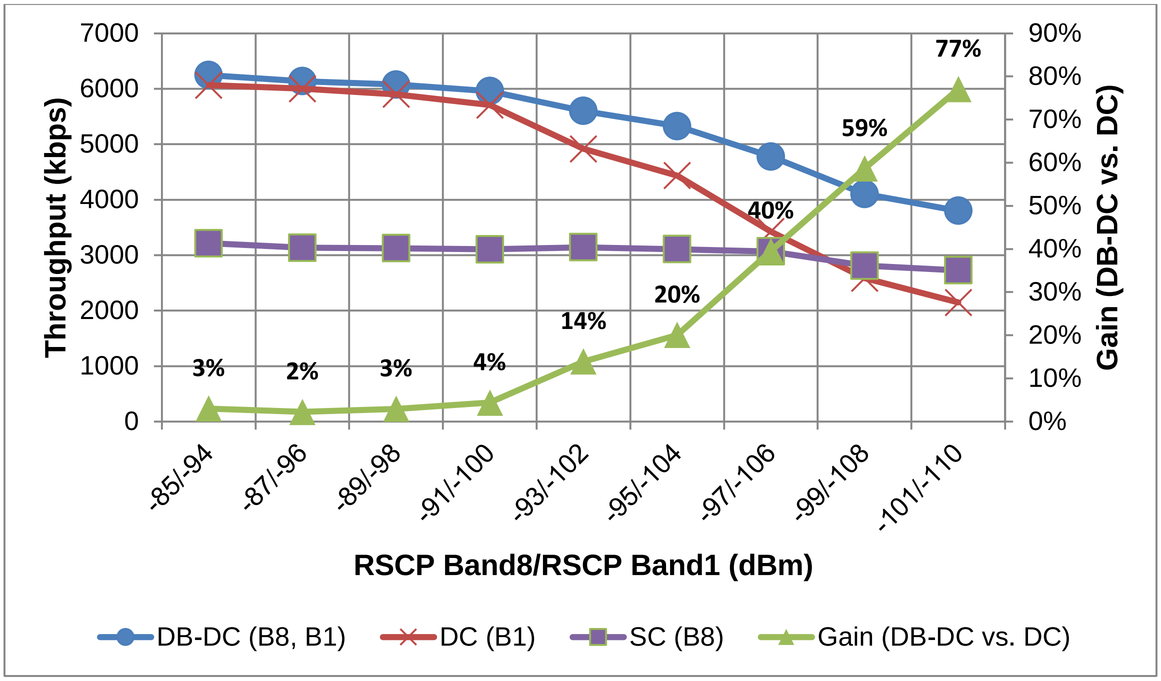

Figure 7: Throughput vs. RSCP (lab test)

Table 3: Lab setup for throughput test

Parameter	Value
Number of UE's	Single
UE Configuration	SC (B8) or DC (B1) or DB-DC (B8, B1)
3GPP Channel Model	PA3
Traffic	Downlink: UDP Uplink: None
Geometry	0dB
Interference	Single interfering cell

Cell Edge Power Consumption Reduction

DB-DC-HSDPA operation with anchor carrier in a lower frequency band requires less UE transmit power when compared with DC-HSDPA or SC-HSDPA operation in a higher frequency band due to better coverage on the lower frequency.

Lower transmit power requirement helps reduce the UE's power consumption, thereby improving battery life. This is depicted in Figure 8. Based on measurements conducted in actual deployments, we anticipate a

~10dB difference in UE transmit power between Band 8 and Band 1, which is captured on the horizontal axis. It can be observed that DB-DC-HSDPA with primary carrier in Band 8 (900MHz) and secondary carrier in Band 1 (2100MHz) reduces the cell-edge power consumption when compared with DC-HSDPA with two adjacent carriers in Band 1. At cell center, where the transmit powers are low and do not contribute much to the overall modem power consumption, DB-DC (B8, B1) causes an increase in the power consumption due to a second RF chain. This increase in power consumption is not as significant because the modem consumes less power in absolute terms at cell center, and so the savings at cell edge outweigh the increase at cell center. It is also worth noting that depending on operator deployment, the UE could be moved to a DC-HSDPA configuration at cell center to limit this impact.

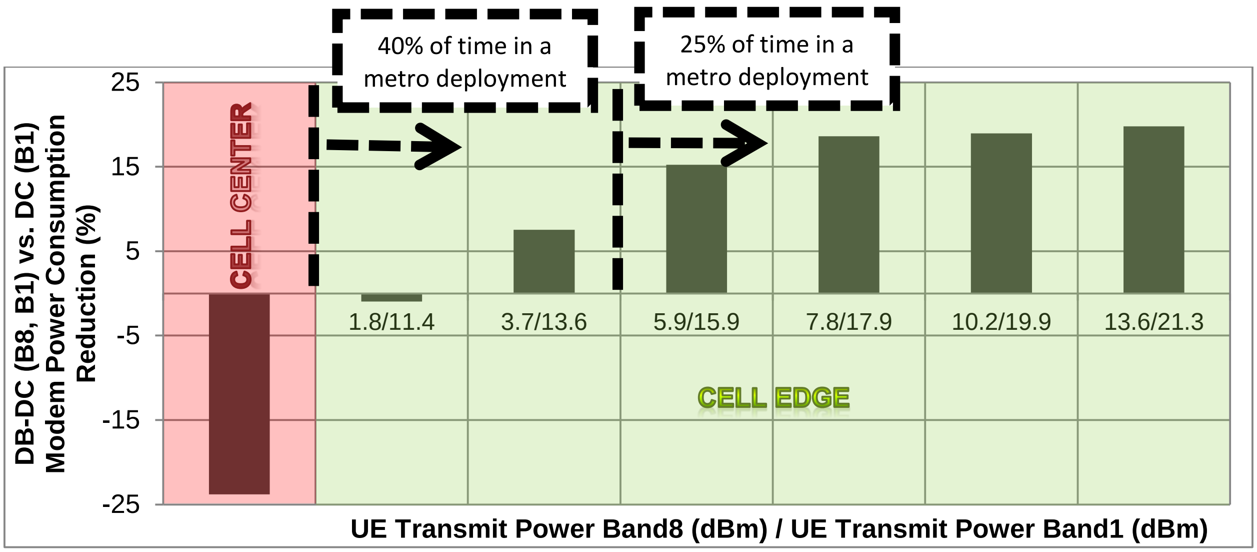

Figure 8: Power consumption reduction vs. UE transmit power (lab test)

Conclusion

Dual-Band Dual-Cell HSDPA (DB-DC-HSDPA) enables aggregation of two carriers across two frequency bands, typically one low band and one high band carrier.

Carrier aggregation provides higher peak rate compared to single carrier operation. A peak rate of 84.4Mbps is supported with DB-DC-HSDPA operation when combined with 64-QAM and MIMO operation. In addition to peak rate benefit, carrier aggregation also increases system capacity and provides superior user experience for full-buffer and bursty data applications. 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 uplink in DB-DC-HSDPA is transmitted only on one carrier. If the uplink is associated with the low band carrier, then DB-DC-HSDPA also provides cell edge throughput improvement compared to DC-HSDPA with two high band carriers and SC-HSDPA. This is because the low band carrier typically has better coverage at cell edge than the high band carrier(s). Further, the coverage benefit also manifests itself in terms of lower UE transmit power requirement. At cell edge, lower transmit power reduces the overall modem power consumption for DB-DC-HSDPA compared to DC-HSDPA. At cell center, where the transmit powers are low to begin with and do not contribute much to the overall modem power consumption, DB-DC-HSDPA causes an increase in the power consumption due to a second RF chain. This increase in power consumption is not as significant because the modem consumes less power in absolute terms at cell center, and so the savings as cell edge outweigh the increase at cell center. Also, depending on operator deployment, the UE could be moved to a DC-HSDPA configuration at cell center to limit the impact.