The Evolution of HSPA

The 3GPP standards progress for fast mobile broadband using HSPA+

4G americas™

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1 INTRODUCTION

1.1 MOBILE DATA EXPLOSION AND 3GPP FEATURES

Mobile broadband traffic has surpassed voice traffic and is continuing to grow rapidly.

This trend is set to continue, with global traffic figures expected to double annually over the next five years[1]. By 2014, the average subscriber will consume about 1GB of data per month compared with today's average figures that are around some hundred MB per month. This traffic growth, driven by new services and terminal capabilities, is paralleled by user expectations for data rates similar to those of fixed broadband. Actual figures per subscriber can vary greatly depending on geographical market, terminal type and subscription type; some users with mobile devices are already creating traffic in the order of gigabytes and predictions are estimated to be several GB per month for some devices and certain user behavior. This user behavior continues to evolve as expanded mobile broadband usage over time is responded to by operators and vendors with enhanced technology to meet these new demands, thus leading to more enhanced technology that is more capable and enables new usages that then drive additional demand. Faster mobile broadband connections, more powerful smart phones, connected tablets, networked laptops as well as new consumer and enterprise applications are all driving the wireless industry to provide new technical capabilities. The mobile industry is, therefore, preparing for data rates in the order of tens of Mbps for indoor use as well as outside and gigabyte traffic volumes. With the expected explosion of mobile broadband data, it is therefore of great interest for the mobile industry to continually seek the introduction and improvement of advanced features that improve network and user-equipment efficiencies and increase the overall quality of the end user experience. 4G Americas is positively "bullish" on the continued development, enhancement, standardization and deployment of both HSPA and LTE. 3GPP Rel-11 offers exciting technical enhancements to the 3GPP mobile broadband technologies and particularly several areas that evolve HSPA even further.

Whereas, LTE has tremendous momentum in the marketplace and it is clearly the next generation OFDMA based technology of choice for operators gaining new spectrum, HSPA will continue to be a leader in mobile broadband subscriptions for the next five to ten years. Some forecasts put HSPA at over 3.5 billion subscribers by the end of 2016, almost five times as many LTE subscribers predicted. Clearly, operators with HSPA and LTE infrastructure and users with HSPA and LTE multi-mode devices will be commonplace. As of October 2011, there are 412 commercial deployments of HSPA in 157 countries, including 165 HSPA+ networks. Thus, with the continued deployment of LTE throughout the world, and the existing ubiquitous coverage of HSPA in the world, HSPA+ will continue to be enhanced through the 3GPP standards process to provide a seamless solution for operators as they upgrade their networks.

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[1] Mobile data traffic surpasses voice, http://www.ericsson.com/news/1396928

1.2 SCOPE

This white paper will highlight some of the key HSPA+ features that have been approved by 3GPP and have been standardized from Rel-7 to Rel-10 to address the Mobile Data Explosion as previously described. In addition, it will examine a number of upcoming important work and study items that are being considered for Rel-11 to further improve Mobile Broadband capabilities. Study items that have not been approved by 3GPP, proprietary solutions, or operator-specific implementations are outside the scope of this paper, since the implementation details may be complicated to describe and necessarily unique to each operator. However, the study item *HSPA+LTE Carrier Aggregation* is included separately in an annex, since this feature was originally considered for this whitepaper but was not ultimately included in the Rel-11 work plan as decided by the September 2011 3GPP RAN #53.

1.3 3GPP RELEASES AND HSPA+ CONTENT

As 3GPP specifications evolve, the advanced features that they describe help to further the capabilities of today's modern Mobile Broadband networks. With each release, there have been improvements such as better cell edge performance, increased system efficiencies, higher peak data rates and an overall improved end-user experience. The figure below illustrates the evolution of HSPA standards and performance as measured by increases to the potential uplink and downlink peak data rates per 3GPP release.

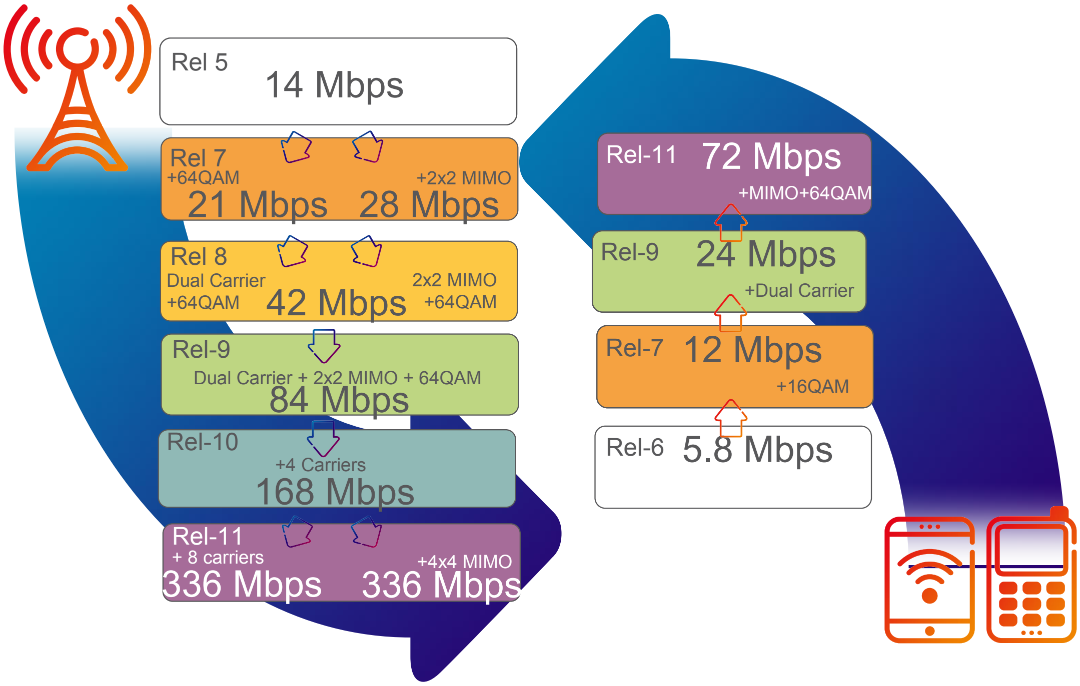

Figure 1: HSPA evolution – Peak data rates

2 KEY HSPA+ FEATURE CONTENT IN REL-7 TO REL-10

2.1 HSPA+ ENHANCEMENTS FOR REL-7

This section provides a high level overview of the main HSPA+ enhancements introduced in 3GPP Rel-7. Further details on the Rel-7 HSPA+ discussed in this section can be found in [1] and [2].

2.1.1 MULTIPLE INPUT MULTIPLE OUTPUT (MIMO)

The term “MIMO” is an acronym for multiple-input, multiple-output, and it is used to refer to any wireless system with multiple antennas at the transmitter and receiver. At the transmitter, multiple antennas can be used to mitigate the effects of fading via transmit diversity and to increase throughput via spatial division multiple access (SDMA). Beamforming and sectorization are two examples of SDMA. Beamforming can also be used for range extension. At the receiver, multiple antennas can be used for receiver combining which provides diversity and combining gains. If multiple antennas are available at both the transmitter and receiver, then different data streams can be transmitted from each antenna, with each stream carrying different information but using the same frequency resources. This technique, known as spatial multiplexing (SM), can potentially increase a user's peak data rate compared to conventional single-stream transmission.

HSDPA uses rate adaptation based on a user’s channel quality information (CQI), which is fed back from the UE to the Node B. In conventional single-antenna HSDPA, the highest rate achievable under realistic conditions in Rel-7 employs 64QAM providing 21 Mbps. In Rel-7, an SM MIMO mode was introduced. Spatial multiplexing achieves higher data rates by reusing spectral resources over multiple spatial dimensions. For example, using two transmit antennas, one could transmit two separate data streams, each with data rate 14.4 Mbps resulting in a peak rate of 28.8Mbps. Because the two data streams are modulated in the same bandwidth using the same set of spreading codes, MIMO for HSDPA is sometimes called “code reuse”. At the receiver, multiple antennas are required to demodulate the data streams based on their spatial characteristics. In general, the minimum number of receiver antennas required is equal to the number of separate data streams. Different receiver techniques can be used, but they typically employ a minimum mean-squared error (MMSE) linear processor followed by a non-linear interference canceller.

Rel-7 defined a MIMO technique called Double Transmit Adaptive Array (D-TxAA). The baseband block diagram is shown in Figure 2, which consists of a single-stream mode and a SM mode. The information bits are first demultiplexed, prior to coding. Because the rate for each antenna can be adapted independently, the number of bits sent to each antenna can be different. For D-TxAA, the single-stream mode uses Rel-’99 TxAA precoders to achieve closed-loop transmit diversity. The signals for each antenna are weighted by a complex amplitude chosen to best match the instantaneous channel characteristics. The pairs of amplitudes are chosen from a pre-defined set. Spatial multiplexing for D-TxAA transmits two simultaneous streams whose weight vectors are mutually orthogonal.

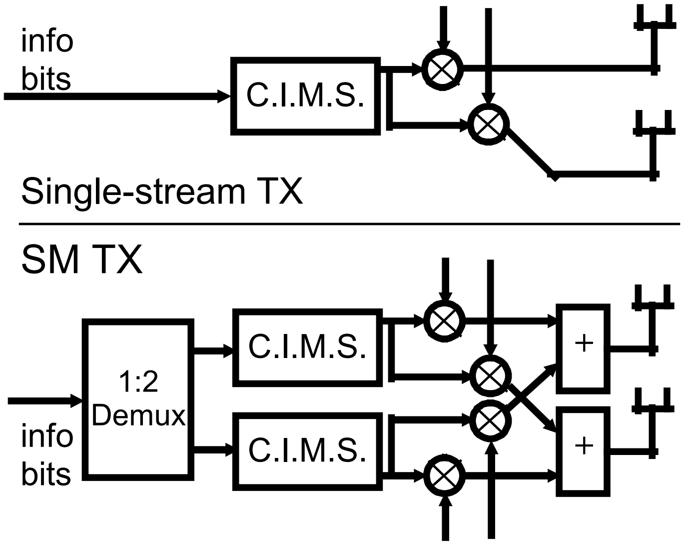

Figure 2: D-TxA

2.1.2 CONTINUOUS PACKET CONNECTIVITY (CPC)

The main goal of the CPC feature is to reduce control channel overhead for low bit rate, “always on” types of applications. The objectives with CPC are to (1) reduce overhead for HSPA users, (2) significantly increase the number of HSPA users that can be kept efficiently in active mode (i.e. CELL_DCH state) (3) reduce latency for restart after temporary inactivity and (4) reduce UE power consumption. The was achieved in Rel-7 through Uplink discontinuous transmission (UL DTX), CQI reporting reduction, downlink discontinuous reception (DL DRX), blind decoding of some DL control channels (HS-SCCH-less operation) and a new control channel (DPCCH) slot format. It is helpful to consider the state diagram in Figure 3 to understand the benefits of CPC.

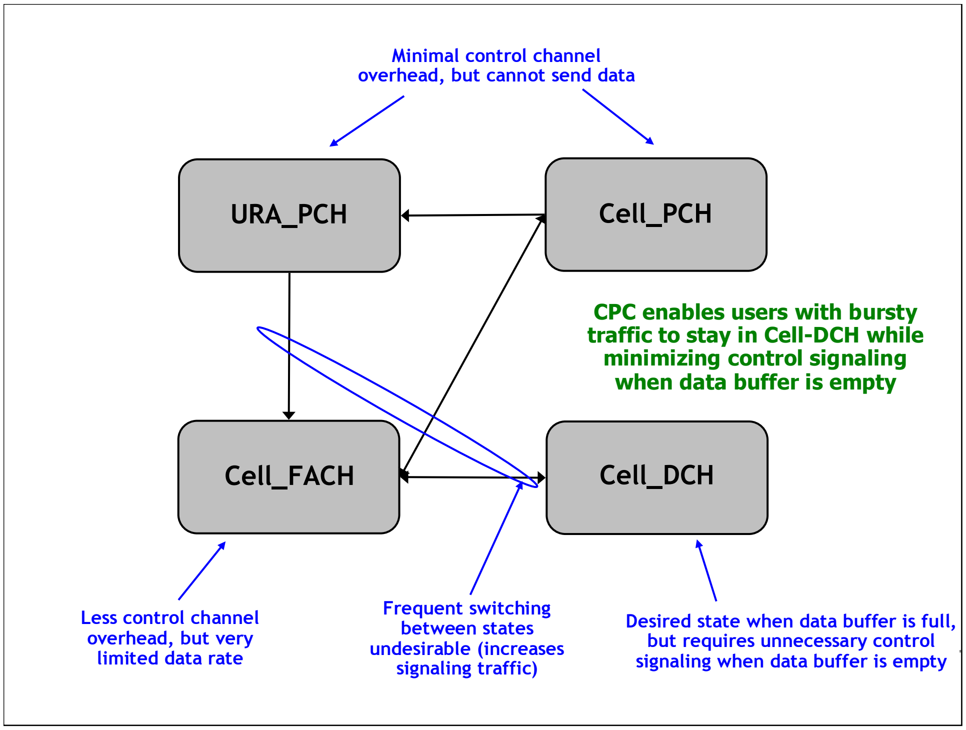

Figure 3: UTRAN state diagram

Figure 3 shows the state diagram when a user is in RRC connected mode. Users that have significant data to send are typically in the CELL_DCH state, however if the user's data buffer has emptied and remained empty for a period of time, the user is typically sent to one of the remaining three states which have less control channel overhead which conserves battery life. Switching to FACH, CELL_PCH or URA_PCH mode may be fine for applications that have data to send very infrequently, however for very bursty applications (such as VoIP) continuous switching between CELL_DCH and CELL_FACH/CELL_PCH/URA_PCH modes can occur, leading to excessive signaling. For such applications it is desirable to keep the user in CELL_DCH mode, yet reduce the control channel overhead when the user does not have data to send like during a silence burst for VoIP. The feature UL DTX and the new DPCCH slot format enable the UE can be configured to switch off the UL DPCCH (i.e. the uplink control channel) when there is no data to transmit, (e.g. between web browsing events, or VoIP packets). This is also known as UL DPCCH gating. UL DTX reduces both the interference from inactive users, and the UE power consumption. To prevent severe impact on synchronization performance and power control, a UL DPCCH burst pattern (UE DTX cycle) is transmitted even when there is no data to transmit.

Figure 4 demonstrates the benefits of CPC.

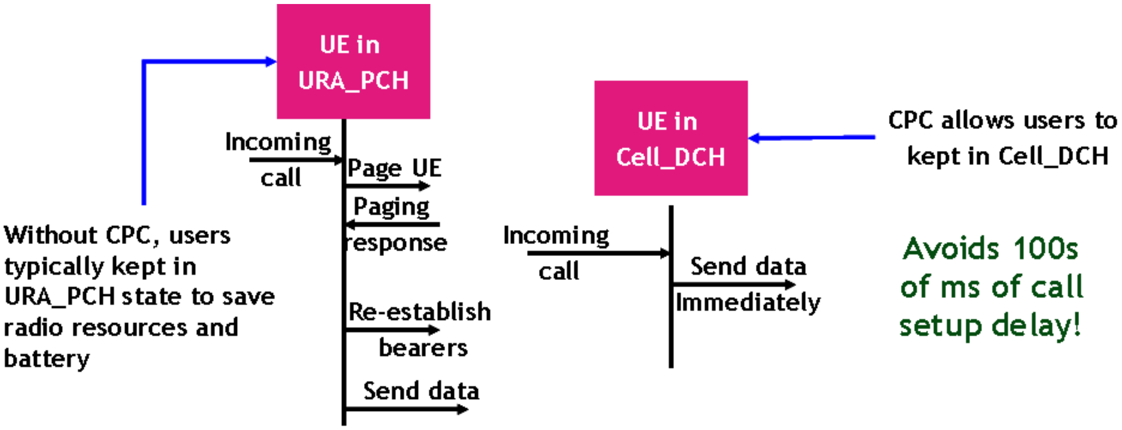

Figure 4: Demonstration of benefit of CPC

2.1.3 HIGHER ORDER MODULATIONS (64QAM DL, 16QAM UL)

The use of higher order modulations (HOMs) such as 64QAM (Quadrature Amplitude Modulation) is an attractive complement to multi-antenna techniques (MIMO), QAM is a modulation scheme which conveys data by changing (modulating) the amplitude of two carrier waves. HOMs provide more bits per symbol in order to increase the spectral efficiency of the transmitted signal, therefore enabling more information to be transmitted during the same symbol period over the air. Figure 5 illustrates a typical constellation for both 64QAM and 16QAM.

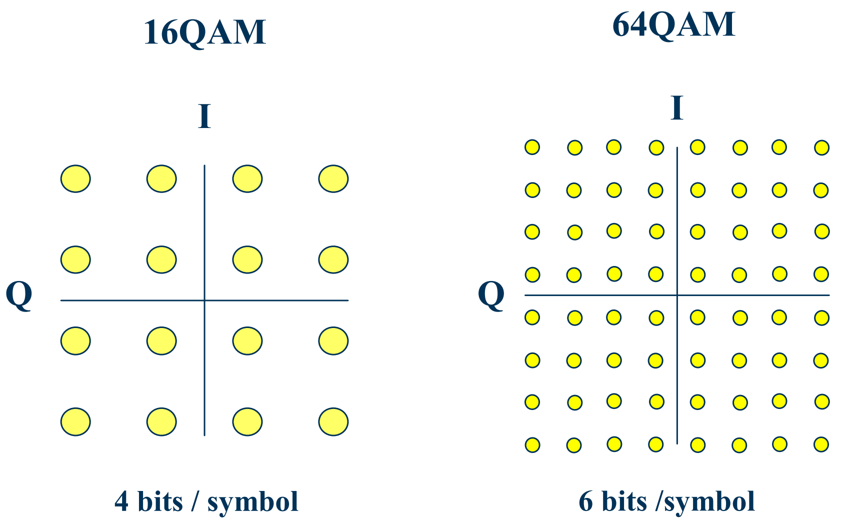

Figure 5: Typical 16QAM and 64QAM Constellations

In Rel-6 HSPA systems there was support for the use of 16QAM in the downlink and QPSK in the uplink. These modulation schemes provide higher data rates in situations where the received symbol SINRs are higher, such as areas close in proximity to the macrocell towers. It's also possible to experience higher SINRs when near small cell deployments (e.g. in the home where a femto cell has been deployed or when close in proximity to where pico/microcells have been deployed). Modulation and Coding Scheme (MCS) tables determine the best combination of modulation and coding rate for a given SINR. With existing MCS tables, high symbol SINRs may "max out" the choice of MCS, giving the highest order modulation with the least amount of coding. As a result, these high SINR systems become peak rate limited. Besides MIMO, another means to increase this peak rate is to extend the MCS tables into higher SINRs with the introduction of even higher order modulations: 64QAM in the downlink and 16QAM in the uplink. While HOM can be used in conjunction with MIMO, it is important in its own right in those cases where deployment of MIMO systems is prohibited by physical, zoning, or budgetary limitations at the transmitter.

The feasibility and performance impact of 64QAM modulation in HSDPA networks was extensively investigated in 3GPP in 2001. However, with the introduction of several new reference receivers, there was renewed interest in understanding the performance and impact of the 64QAM modulation in HSDPA. The various types of Receivers defined in 3GPP for UMTS/HSPA are:

- Type 0 – RAKE
- Type 1 – Diversity RAKE
- Type 2 – Equalizer
- Type 2i – Equalizer with Interference Awareness
- Type 3 – Diversity Equalizer
- Type 3i – Diversity Equalizer with Interference Awareness

As can be seen, the Type 2i and 3i receivers were added in order to add "interference awareness", meaning that the receiver performs some form of interference suppression/rejection in order to improve the post-detection SINR. This type of receiver significantly increases the percentage of time that HOMs can provide gains.

2.1.4 ENHANCED CELL_FACH STATE

Although CPC (described in 2.1.2) helps to keep HSPA users in the CELL_DCH state, eventually users who have not had data to send for a period of time will be moved to the CELL_FACH state (see Figure 6). Users can send data over the FACH channel, but the data rate is very limited. Thus, if the user has a significant amount of data to send, it is preferred to move the user back to CELL_DCH state so they can send the data over the HS-DSCH channel (i.e. the HSDPA traffic channel) to experience improved throughput rates. However, moving users back to the CELL_DCH state requires signaling over the limited data rate FACH channel, and thus can take some time. In order to reduce the latency associated with moving from CELL_FACH to CELL-DCH state, Rel-7 defined an enhanced CELL_FACH state that allows the users to transmit on the HS-DSCH channel while in CELL_FACH state. This enables the user to send the signaling required to move from CELL_FACH to CELL_DCH over the much faster HS-DSCH channel, greatly reducing setup times and improves user experience.

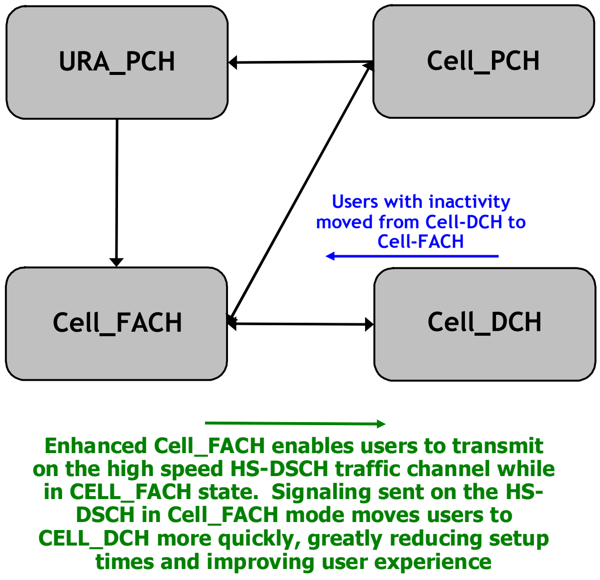

Figure 6: Benefits of Enhanced Cell-FACH

2.2 HSPA+ ENHANCEMENTS FOR REL-8

This section provides a high level overview of the main HSPA+ enhancements introduced in 3GPP Rel-8. Further details on the Rel-8 HSPA+ discussed in this section can be found in [3].

2.2.1 COMBINATION OF 64QAM AND MIMO FOR HSDPA

Rel-8 combines MIMO and 64QAM modulation (two features in Rel-7) to boost the peak downlink rate over a single 5MHz carrier to 42Mbps. In Rel-7, 16QAM was the highest-order modulation used in combination with MIMO. Therefore, four bits can be transmitted per modulation symbol, resulting in a peak rate of 28Mbps. The upgrade to 64QAM in Rel-8 allows six bits to be transmitted per symbol, which increases the peak rate by 50% to 42Mbps. To the greatest possible extent, the introduction of MIMO with 64QAM modulation reuses the protocol changes introduced in Rel-7 for MIMO and 64QAM respectively.

2.2.2 DUAL-CELL HSDPA OPERATION ON ADJACENT CARRIERS

In deployments where multiple downlink carriers are available, the new multicarrier operation offers an attractive way of increasing coverage for high bit rates. Rel-8 introduces dual-carrier operation, as shown in Figure 7, in the downlink on adjacent carriers. This technique doubles the peak rate (with 64QAM) from 21Mbps to 42Mbps without the use of MIMO.

Figure 7: Dual Cell HSDPA combines multiple downlink 5 MHz carriers

A dual-carrier user can be scheduled over either of the 5 MHz carriers. All non-HSDPA-related channels reside in the primary serving cell, and all physical layer procedures are essentially based on the primary serving cell. Either carrier can be configured to function as the primary serving cell for a particular user. As a consequence, the dual-carrier feature also facilitates an efficient load balancing between carriers in one sector. As with MIMO, the two transport channels perform Hybrid Automatic Repeat request (HARQ) retransmissions, coding and modulation independently. A difference compared to MIMO is that the two transport blocks can be transmitted on their respective carriers using a different number of channelization codes. In terms of complexity, adding a dual-carrier receiver to UEs is roughly comparable to adding a MIMO receiver.

2.2.3 ENHANCED UPLINK FOR CELL_FACH STATE

Users should always be kept in the state that gives the best trade-off between data rate availability, latency, battery consumption and usage of network resources. As a complement to the data rate enhancements made to the dedicated state (CELL_DCH), 3GPP has also made significant enhancements to the common states (URA_PCH, CELL_PCH and CELL_FACH).

Rel-7 introduced HSDPA mechanisms in the common states in order to improve their data rates, latency and code usage (e.g. Cell_FACH feature). Rel-8 introduced corresponding enhancements in the uplink, allowing base stations to configure and dynamically manage up to 32 common E-DCH resources in each cell. This enhancement improves latency and data rates for keep-alive messages (for example, from VPN or messenger applications) as well as web-browsing events, providing a seamless transition from E-DCH in common state (i.e. URA_PCH, CELL_PCH or CELL_FACH) to E-DCH in dedicated state (i.e. CELL_DCH) as shown in Figure 6.

2.2.4 ENHANCED UE DRX

As a further improvement of the CELL_FACH state, Rel-8 introduces discontinuous reception (DRX), which enables UEs to restrict the downlink reception times. This significantly reduces battery consumption by allowing the UEs to go into “sleep mode” during periods of time where downlink reception has been restricted. Therefore, UEs can now remain in CELL_FACH for long periods of time with greatly reduced battery drain experience. Figure 8 demonstrates the Enhanced UE DRX concept, showing a DRX cycle of 4. The gray boxes indicate times when the UE is required to be awake for downlink transmissions, while the UE can go to sleep during the period of times shown by the white boxes.

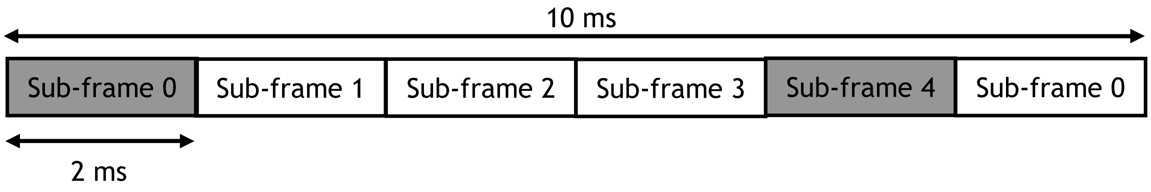

Figure 8: Enhanced UE DRX with DRX cycle of 4

2.2.5 CS VOICE OVER HSPA

The traditional mechanism of mapping the CS voice connection over the DCH channels in the radio network has been in place since the very first WCDMA standard release, version 3.0.0 of Rel-’99. The HSPA radio was later introduced to specifically apply for high speed packet access and thus only PS data could be mapped to HSPA. Subsequently a number of VoIP related optimizations were introduced to HSPA radio making radio’s VoIP over HSPA significantly more efficient than the traditional CS voice over DCH both in terms of system capacity and UE power consumption. As from radio perspective there is no difference whether data bits are relate to CS or PS connection, in order to be able to benefit from the voice related HSPA radio improvements, the artificial limitation to not allow the CS connections to be mapped to HSPA radio was lifted in Rel-8.

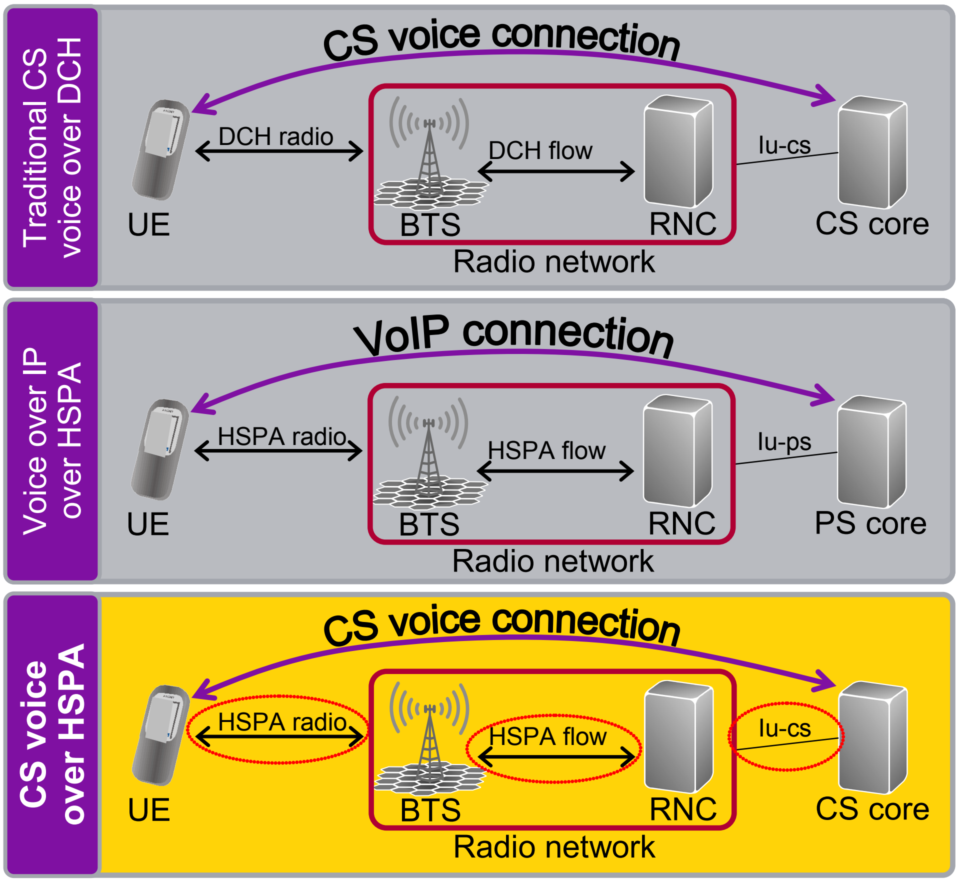

Figure 9: Illustration of CS voice over HSPA relation to VoIP and traditional CS voice

Notably the feature capability indication bit for UE support of CS voice over HSPA was introduced to Rel-7 specifications making the feature ‘early implementable’, that is, a Rel-7 compliant UE is able to support CS voice over HSPA even though the feature is technically part of Rel-8 specifications.

2.2.6 FAST DORMANCY FEATURES

In order improve battery life, users that have been in the CELL_FACH state for a period of time without sending any data can be moved to either CELL_PCH or URA_PCH state as shown in Figure 3. This allows the mobile to go into "dormant" or "sleep" modes to conserve batter life. In general, this process is controlled by the network. Prior to Rel-8, the only possibility for the UE to have some control of the state changes was to terminate the RLC connection and go to idle mode. In Rel-8, a more sophisticated mechanism was introduced whereby the UE explicitly indicates to the network that it wants to go into a dormant mode. With this extra information, the network can decide to move the UE to any state, preferably CELL_PCH or URA_PCH.

2.3 HSPA+ ENHANCEMENTS FOR REL-9

This section provides a high level overview of the main HSPA+ enhancements introduced in 3GPP Rel-9. Further details on the Rel-9 HSPA+ discussed in this section can be found in [4].

2.3.1 COMBINATION OF DC-HSDPA, MIMO AND 64 QAM

Rel-8 introduced two ways to achieve a theoretical peak rate of 42 Mbps: 1) dual-carrier HSDPA operation as mentioned above, or 2) 2x2 MIMO in combination with 64QAM. Rel-9 combines dual-carrier HSDPA operation with MIMO and 64-QAM. The peak downlink rate is thus doubled to 84 Mbps and the spectral efficiency is boosted compared to dual-carrier HSDPA operation without MIMO. Again, the L1/L2 solutions from earlier releases are reused to a large extent with only minor modifications to the L1 feedback channel (HS-DPCCH) and the L2 transmission sequence numbering (TSN) in order to handle the doubled amount of transport blocks. In order to provide maximum deployment flexibility for the operator, the MIMO configuration is carrier-specific, meaning that, if desired, one carrier can be operated in non-MIMO mode and the other carrier in MIMO mode.

2.3.2 DUAL-CELL HSUPA

The data rate improvements in the downlink call for improved data rates also in the uplink. Therefore, support for dual-carrier HSUPA operation on adjacent uplink carriers is introduced in Rel-9. This is essentially the same concept as shown in Figure 7 but now for the uplink. This doubles the uplink peak rate to 23 Mbps for the highest modulation scheme (16QAM). The achievable uplink data rate is often more limited by the available bandwidth than by UE transmit power, and in these scenarios both availability and coverage of high data rates in the uplink are substantially increased by multi-carrier HSUPA operation.

The dual-carrier HSUPA user is able to transmit two E-DCH transport channels with 2ms TTI, one on each uplink carrier. The user has two serving cells corresponding to two carriers in the same sector of a serving base station, and the serving base station has the ability to activate and deactivate the secondary carrier dynamically using so-called HS-SCCH orders. When two uplink carriers are active, they are to a large extent operating independently from each other in a way that is very similar to the single-carrier HSUPA operation specified in earlier releases. For example, mechanisms for grant signaling, power control and soft handover toward non-serving cells have been re-used.

Dual-carrier HSUPA operation can only be configured together with dual-carrier HSDPA operation and the secondary uplink carrier can only be active when the secondary downlink carrier is also active. This is because the secondary downlink carrier carries information that is vital for the operation of the secondary uplink carrier (F-DPCH, E-AGCH, E-RGCH, E-HICH). The secondary downlink carrier can, on the other hand, be active without a secondary uplink carrier being active or even configured, since all information that is vital for the operation of both downlink carriers (HS-DPCCH) is always only carried on the primary uplink carrier.

2.3.3 TRANSMIT ANTENNA ARRAY EXTENSION FOR NON-MIMO UES

The 2x2 MIMO operation for HSDPA specified in Rel-7 allows transmission of up to two parallel data streams to a MIMO UE over a single carrier. If and when the HSDPA scheduler in the base station decides to only transmit a single stream to the UE for any reason (e.g. because the radio channel temporarily does not support dual-stream transmission), the two transmit antennas in the base station will be used to improve the downlink coverage by single-stream transmission using BF. Notably the "single-stream MIMO" transmissions can be received by a single antenna UE, whereas support for dual-stream reception requires two receive antennas in the UE, hence the feature enables single antenna UEs to benefit from the MIMO networks' two transmit antennas.

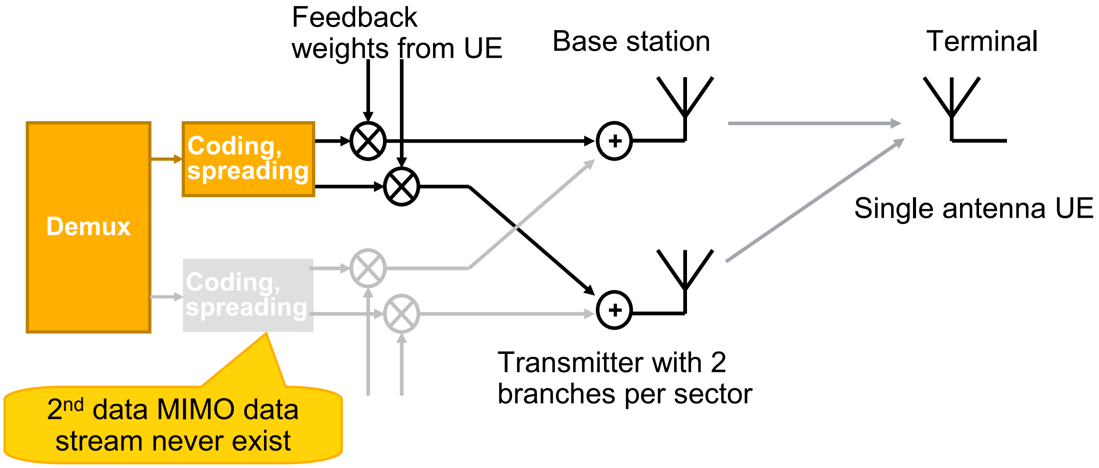

Figure 10: Transmitter configuration for "Single-stream MIMO [5]

One of the limitations in Rel-7 is that the single stream transmission mode shown in Figure 2 still requires MIMO capable UEs. Since technically a single stream transmission can be decoded by a single Rx antenna, it is highly desirable to have single-stream transmission using BF also support non-MIMO UEs that reside in MIMO cells. Therefore, this option has been introduced in Rel-9, re-using L1/L2 solutions from Rel-7 MIMO to as large extent as possible. This is referred to as TxAA extension for non-MIMO UEs, and provides the benefit of TxAA to UEs with only a single Rx antenna. For a Rel-9 dual-carrier HSDPA user, the usage of single-stream MIMO can be configured independently per carrier.

2.3.4 SUPPORT FOR DIFFERENT BANDS FOR DC-HSDPA (DUAL BAND DC-HSDPA)

In deployments where multiple downlink carriers are available, multi-carrier HSDPA operation offers an attractive way of increasing coverage for high bit rates. Dual-carrier (or dual-cell) HSDPA operation was introduced in Rel-8, enabling a base station to schedule HSDPA transmissions over two adjacent 5 MHz carriers simultaneously to the same user, thereby reaching a peak rate of 42 Mbps for the highest modulation scheme (64QAM) without the use of MIMO. Furthermore, it doubles the rate for users with typical bursty traffic and therefore it typically doubles the average user throughput, which results in a substantial increase in cell capacity.

In order to provide the benefits of dual-carrier HSDPA operation also in deployment scenarios where two adjacent carriers cannot be made available to the user, (e.g. due to spectrum distributed over different bands), Rel-9 introduces dual-band DC-HSDPA (DB-DC-HSDPA) operation, where in the downlink the primary serving cell resides on a carrier in one frequency band and the secondary serving cell on a carrier in another frequency band. In the uplink transmission takes place only on one carrier, which can be configured by the network on any of the two frequency bands.

In Rel-9, dual-band HSDPA operation is introduced for three different band combinations, one for each ITU region:

- Band I (2100MHz) and Band VIII (900MHz)
- Band II (1900MHz) and Band IV (2100/1700MHz)
- Band I (2100MHz) and Band V (850MHz)

Introduction of additional band combinations will be possible to do in a release independent manner (i.e. can be added to any quarterly update of a frozen release). In the Rel-10 specifications, the following dual-band HSDPA combinations were added:

- Band I (2100MHz) and Band XI (1450MHz)
- Band II (1900MHz) and Band V (850MHz)

Note that even though these additional bands were included after the freezing of the Rel-9 specifications, the release independent nature of new DB-DC-HSDPA combinations means that new Rel-9 UEs can be developed and deployed that support these new bands without having to support all the mandatory Rel-10 functions/capabilities.

2.4 HSPA+ ENHANCEMENTS FOR REL-10

This section provides a high level overview of the main HSPA+ enhancements introduced in 3GPP Rel-10. Further details on the Rel-10 HSPA+ discussed in this section can be found in [6].

2.4.1 FOUR CARRIER HSDPA

Motivated by surging traffic volumes and growing demand for increased data rates, support for non-contiguous four carrier HSDPA (4C-HSDPA) operation was introduced in Rel-10. Relying on the same principles as Rel-8 DC-HSDPA and the Rel-9 extensions of DC-HSDPA operation together with dual-band operation or MIMO operation, 4C-HSDPA enables the base station to schedule HSDPA transmissions on up to four 5 MHz carriers simultaneously. With the highest modulation scheme (64 QAM) and 2X2 downlink MIMO configured on all downlink carriers this enables a peak data rate of 168 Mbps. However, besides doubling the peak data rate, 4C-HSDPA operation will also double end-user data rates (burst rates) for a typical bursty traffic model when compared to Rel-9 DC-HSDPA with MIMO.

The performance gain from multi-carrier operation is based on the resource pooling principle.[2] If multiple downlink carriers are pooled an increased spectrum utilization efficiency can be achieved since the probability of having unused resources reduces. This phenomenon is sometimes also referred to "trunking efficiency." It is interesting to note that in a system using 4X5 MHz carriers (but where only single-carrier operation and load balancing are supported), 4C-HSDPA will yield a fourfold increase in both peak and end-user data rates.[3] [4]

For 4C-HSDPA the configured system can be spread over two frequency bands. Similarly as in Rel-9 DB-DC-HSDPA operation the following band combinations are supported (one for each ITU region):[5]

- **Band I (2100 MHz) and Band VIII (900 MHz)**: Two or three 5 MHz carriers can be configured in Band I simultaneously as one 5 MHz carrier is configured in Band VIII
- **Band II (1900 MHz) and Band IV (2100/1700 MHz)**: One or two 5 MHz carriers are configured in Band II simultaneously as one or two 5 MHz carriers are configured in Band IV
- **Band I (2100 MHz) and Band V (850 MHz)**: One or two 5 MHz carriers are configured in Band I simultaneously as one or two 5 MHz carriers are configured in Band V

In addition to these dual-band configurations, it is also possible to configure three adjacent carriers in Band I (2100 MHz) only (i.e. without configuring any carriers in another frequency band). The different configurations for 4C-HSDPA in Rel-10 are illustrated in Figure 11. Introduction of additional band combinations can be done in a release-independent manner.

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[2] D. Wischik, M. Handley, M. Bagnulo Braun, *The Resource Sharing Principle*, ACM SIGCOMM Computer Communication Review, Vol 38, No 5, October, 2008.

[3] 3GPP Tdoc R1-091082, *RAN1 findings of the UTRA Multi-Carrier Evolution study.*

[4] K. Johansson et al, *Multi.Carrier HSPA Evolution*, In Proceedings of VTC spring, 2009.

[5] 3GPP Tdoc R4-103975, *Introduction of frequency bands for 4C-HSDPA*, Ericsson, RAN4 Adhc meeting, Xian, China, October 11th – 15th, 2010.

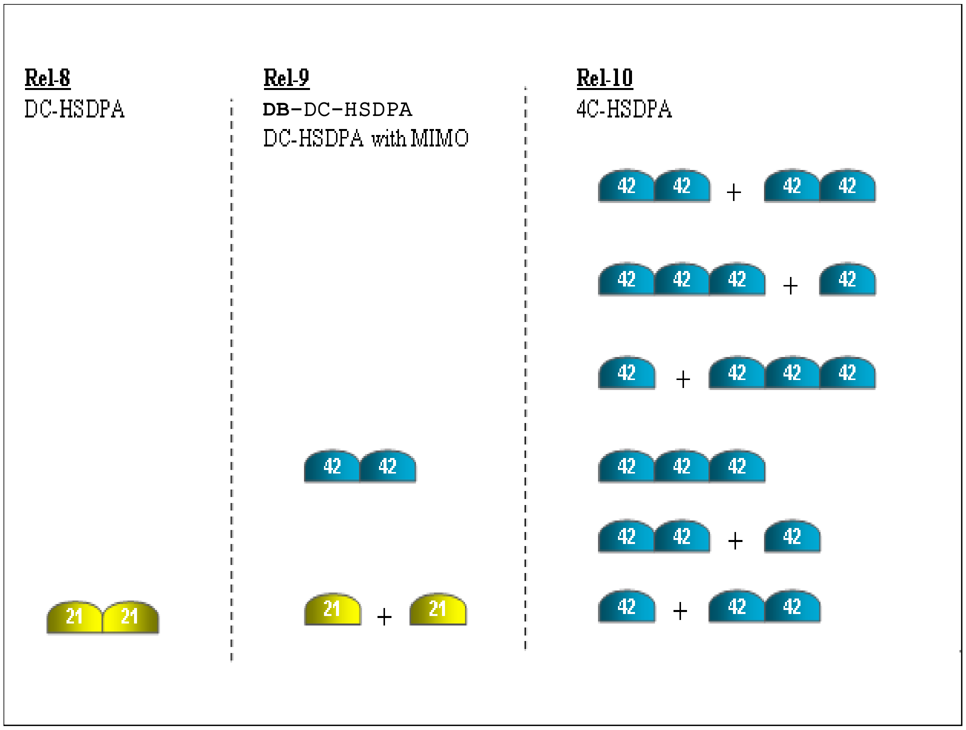


Figure 11: Illustration of the supported configurations in Rel-8 DC-HSDPA, Rel-9 DB-DC-HSDPA and DC-HSDPA with MIMO, and Rel-10 4C-HSDPA with MIMO

As shown in Figure 11, all carriers configured in a frequency band need to be adjacent in Rel-10 4C-HSDPA. This is because only supporting adjacent configured carriers will facilitate a simplified UE design employing a single receiver chain per band. However, it should be noted that the protocol specifications in principle support non-contiguous configurations of downlink carriers within a band.

To a large extent 4C-HSDPA operation reuses the L1/L2 solutions standardized for Rel-8 DC-HSDPA, and Rel-9 DC-HSDPA with MIMO. L1 changes are limited to changes of the L1 feedback channel (HS-DPCCH). More specifically, to accommodate the doubling in L1 feedback information, the spreading factor for this physical channel was reduced from 256 to 128. The L2 changes are limited to increased UE buffer sizes for the RLC AM and MAC-(e)hs buffers, for example, and with 4C-HSDPA, this means that a UE can be scheduled in both the primary serving cell and the secondary serving cells over a total of four HS-DSCH transport channels. As in previous multi-carrier features, HARQ retransmissions, coding and modulation are performed independently for activated downlink carriers and streams. One configuration that received special attention within Rel-10 is the configuration where three carriers are configured without MIMO. In order to maintain similar HS-DPCCH uplink coverage as in Rel-8 and Rel-9, a new HARQ-ACK codebook was designed for this configuration.

As for the multi-carrier features standardized in Rel-8 and Rel-9, all secondary serving carriers can be dynamically deactivated and reactivated in a fully flexible manner by means of HS-SCCH orders transmitted by the serving base station. Thus, HS-SCCH orders enable an efficient means for:

- **Dynamic load balancing.** This is possible since different users can be configured by the S-RNC to have different primary serving cells. This may increase user data rates.
- **UE battery savings.** Deactivating all downlink carriers in a frequency band enables that the UE switches off the receiver chain for this particular band. This can yield significant battery savings in traffic scenarios where the data arrives in bursts.

These two advantages are illustrated in Figure 12.

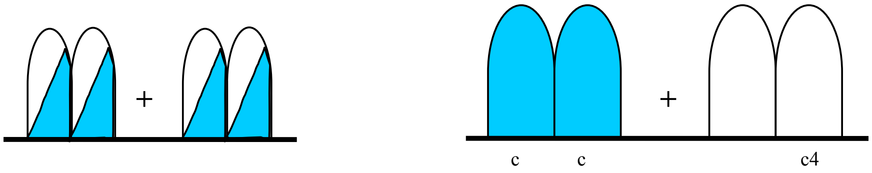
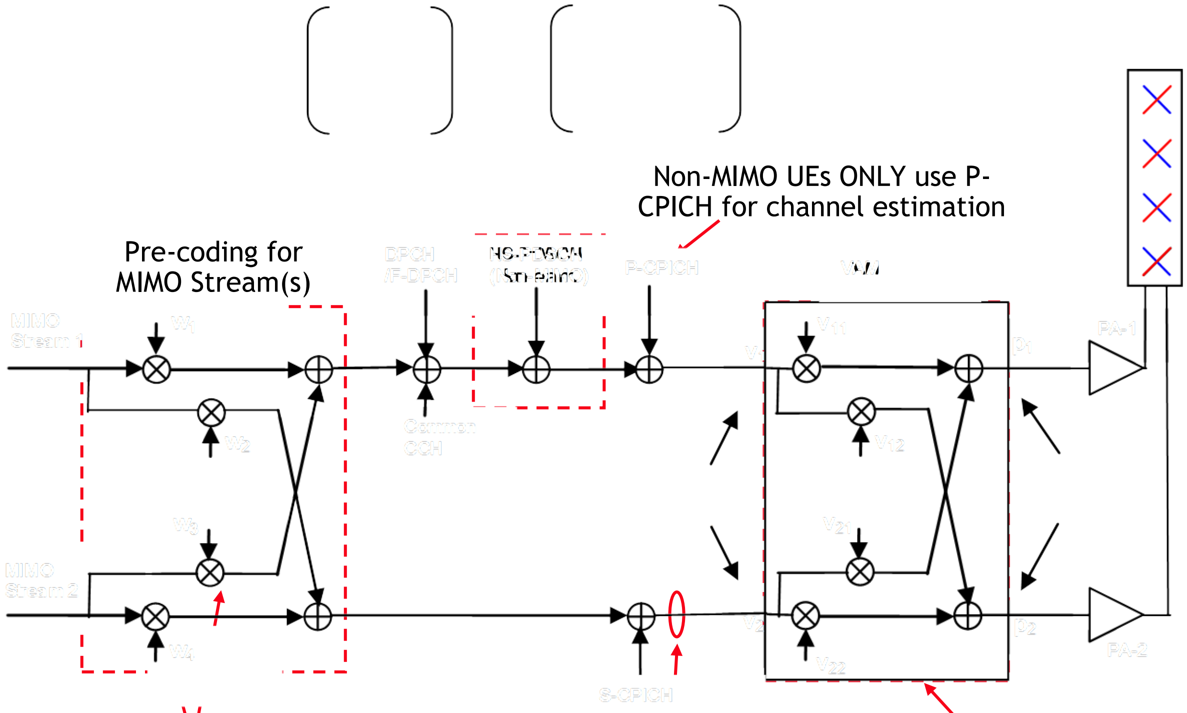


Figure 12: Illustration of the Conceptual Gains that can be Achieved by Dynamic Deactivating Secondary Carriers by Means of HS-SCCH Orders

In Figure 12, user 1 (white) has carrier c3 as its primary serving cell and user 2 (light blue) has carrier c1 as its primary frequency. The left side of the figure depicts a scenario where both users have all carriers activated and the users are scheduled in a CDM fashion. The right side of the figure illustrates the scenario where the serving Node-B has deactivated part of the secondary serving cells. This may increase data rates (due to less intra-cell interference) as well as enable significant UE battery savings (since they can switch off one of its receiver chains).

2.4.2 MIMO OPERATION WITH NON-MIMO COEXISTENCE IN HSDPA

The support of Rel-7 MIMO requires a second pilot channel (S-CPICH) to be sent on the second transmit antenna. This second pilot channel can actually have a detrimental impact on legacy non-MIMO UEs whose equalizer/receiver designs assumed only a single pilot channel (P-CPICH) is being sent, In order to minimize the potential negative performance impact of the introduction of MIMO in the network on legacy non-MIMO UEs, Rel-10 introduced some workarounds. For example, power offsets and power balancing between the two pilot channels was made possible, This enables a power balancing network, sometimes called a Virtual Antenna Matrix (VAM), to be implemented before the two transmit amplifiers which can reduce the negative performance impact of MIMO to the legacy non-MIMO UEs. The concept of VAM is illustrated in Figure 13.



Pre-coding for MIMO Stream(s)

Non-MIMO UEs ONLY use P-CPICH for channel estimation

$W_3=W_4=0$ in CLSS

Cause power reduction and interference to non-MIMO UEs

Tune VAM to balance between MIMO and non-MIMO UEs

Figure 13: Virtual Antenna Matrix Concept

3 THE PROJECTED REL-11 HSPA+ FEATURES

This section provides a high level overview of the main HSPA+ enhancements introduced in 3GPP Rel-11. These new enhancements were approved at 3GPP in September of 2011 and provide wide ranging technical enhancements.

3.1 NEW REL-11 FEATURES SPECIFIC TO DOWNLINK

3.1.1 8-CARRIER HSDPA – 40 MHZ OF CARRIER AGGREGATION

The 8-carrier HSDPA feature extends the HSDPA carrier aggregation potential up to 40 MHz aggregate bandwidth by enabling simultaneous transmission on up to eight carriers towards a single UE. The carriers do not necessarily need to reside adjacent to each other on a contiguous frequency block, as it is possible to aggregate carriers together from more than one frequency band.

Eight-carrier HSDPA is expected to increase the peak HSDPA data rate by a factor of 2 compared to 4-carrier HSDPA, and it can be expected to bring similar gains as achieved by the other multi-carrier features standardized in Rel-8 to Rel-10. Hence, user bitrates will be increased throughout the cell, leading to a clear improvement in user experience. The pooling of resources will also increase the system capacity.

The standardization of 8C-HSDPA will reuse the framework developed during the previous rounds of multi-carrier standardization in 3GPP. As much as possible will be reused to ease implementation of the standard.

It will be possible to deploy 8C-HSDPA using only one uplink carrier. The associated uplink signaling, which carries the CQI and ACK/NACKs will be carried over two HS-DPCCHs. The 4C-HSDPA solution standardized in Rel-10 will be duplicated: two SF128 channelization codes will be used to transmit the associated signaling.

To handle the increased bit rates, a few changes will be required in L2. It is clear that the MAC-ehs window size will be increased. It is also likely that the RLC SN space needs to be increased.

MIMO can be configured independently per carrier. The same is true for STTD and single-stream MIMO described in section 2.1.1.

Mobility will be handled as in Rel-10: it will be based only on the primary carrier.

The serving nodeB will have the possibility to dynamically switch on and off carriers using HS-SCCH orders. This procedure will be increasingly important with the increased number of carriers.

So far, band combinations have not been discussed for 8C-HSDPA. It is however likely that it will be possible to split the 8C-HSDPA over no more than two bands.

3.1.2 HSDPA MULTIPOINT TRANSMISSION

The Multi-Point Study Item in RAN 1 of 3GPP [7] & [13] aims to assess the benefit from various downlink data transmission schemes that involve transmission of data from more than a single cell to the UE. The basic objective is to improve data rates to edge of cell users, i.e. those UEs in the soft or softer handoff regions by making un-utilized resources from neighboring cells available to them.

One family of such schemes parses the incoming data for the user into multiple (restricted to two cells in the study) data streams or flows, each of which is transmitted from a different cell [8] Concurrent transmission of data from the two cells may either be permitted or the UE may be restricted to receiving data from only one cell during a given TTI. The former type of scheme is designated an aggregation scheme while the latter is termed a switching scheme. The aggregation scheme can be seen as subsuming the switching scheme at the network when scheduling to the user is restricted to the cell with better channel quality.

Figure 14 illustrates the basic multi-flow concept with both cells operating on the same carrier frequency F1.

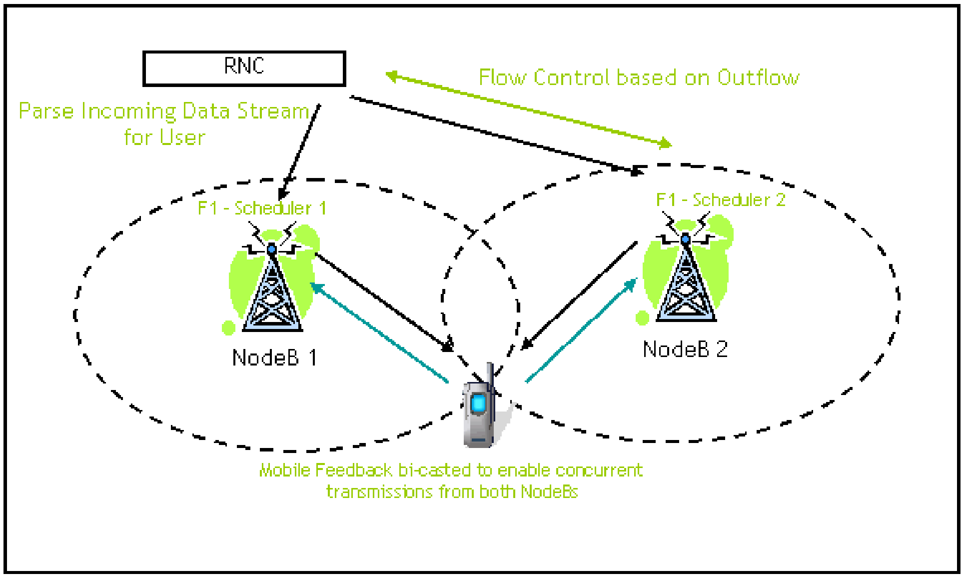


Figure 14: Multi-Flow Transmission with non-collocated cells

The second family of schemes relies on the transmission of either an identical waveform to the user from two cells, i.e. an SFN (Single Frequency Network) type transmission, or muting one the cells while a transmission is being made on the other, i.e. using a form of interference co-ordination between cells. Figure 15 illustrates the use of SFN transmission for a UE in softer handoff. It should be noted that the scheme continues to allow conventional, i.e. non-SFN transmissions to other UEs that are not in softer handoff.

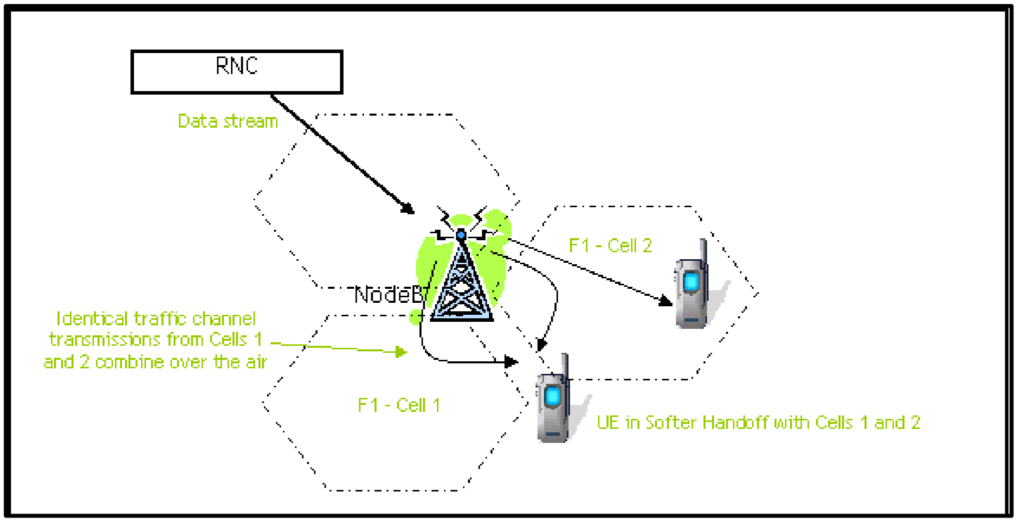


Figure 15: SFN Transmission to UE in Softer Handoff from collocated cells

Performance Assessment

Fundamental to deriving the benefits of such schemes is the recognition firstly that most data transfers are intermittent not continuous. These are therefore not well modeled by the full buffer model which is more appropriate to an assessment of the absolute limits of spectral efficiency of a system. For realistic scenarios, the arrival processes of finite sized data blocks create significant multiplexing opportunities across cells, which can be used to increase the effective data rates to edge of cell users and reduce the times taken for data file or web page delivery.

The second relevant observation is that cell load, as characterized by the number of users attached to each cell, shows significant spatial variability across cells. Recognizing the existence of such imbalances to transfer load from heavily loaded to lightly loaded cells, one may improve both edge of cell performance and network throughput.

Finally, allowing edge of cell users to receive data from multiple cells results in getting multi-server diversity for such users.

Although there are numerous multi-point algorithms, we focus on the performance of the multi-point scheme called Single Frequency Dual Carrier (SF-DC) aggregation since it is a good proxy for multi-point schemes overall in addition to being the solution that applies to the most spectrum-constrained environments. SF-DC aggregation refers to transmission of two data streams on a common carrier frequency by two cells that may or may not be collocated.

Figure 16 [9] shows the benefits of SF-DC transmission as a percent gain in data burst rates for soft handoff users over the baseline where such users are not allowed to receive data from a secondary cell. The system in this case is uniformly loaded and all the users in soft handoff are assumed to be capable of supporting SF-DC operation. At low loads a significant gain of between 20 – 33% in burst rate is observed.

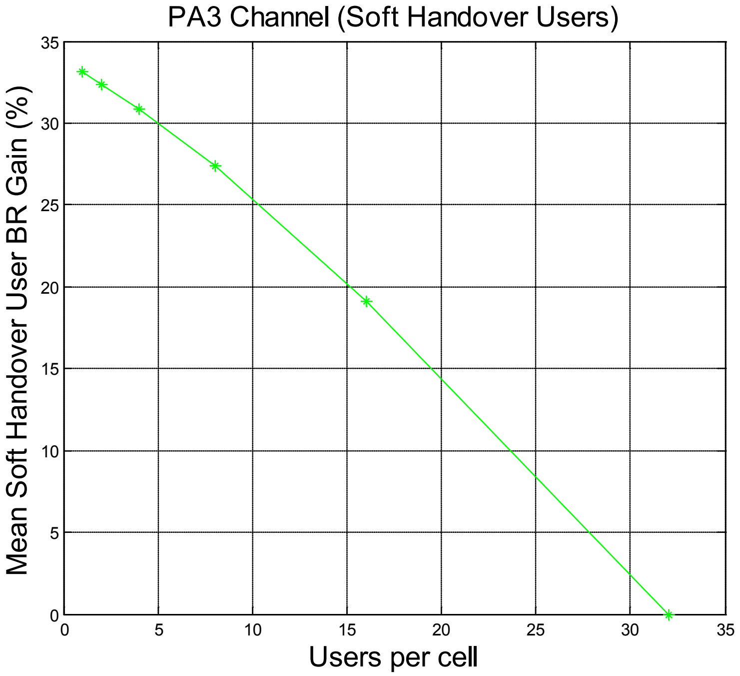


Figure 16: Gain in Mean burst rate for Soft handover users Vs Users/Cell (PA3)

In these simulations, the schedulers are operated independently and legacy (non SF-DC) users given absolute priority over SF-DC capable UEs. Co-ordination between schedulers has been suggested in [10] as a means for further fine-tuning of the data offload enabled by SF-DC capable UEs.

In addition to the UE needing to provide feedback to both participating NodeBs to enable SF-DC, type 3i receivers will likely be needed in the UEs to suppress interference due to simultaneous transmissions from these NodeBs. From the network perspective, it is also important to ensure that problems with out-of-order delivery of RLC PDUs are minimized, if not eliminated, via appropriate flow control to the Node Bs as well as tracking and closing gaps in RLC PDU reception. [11] evaluates SF-DC performance with realistic modeling of RLC and Flow Control showing that SF-DC gains are maintained in practical realizations.

SFN-based Schemes

These schemes, focused mainly on the intra-NodeB case, attempt to provide the coherent combining gain of SFN transmissions to softer-handoff users. SFN transmissions are enabled by replacing the cell specific cover with a common scrambling code and transmitting the same spread modulation symbols on the HS-PDSCH from two collocated cells.

Figure 17 [12] shows the performance gain from SFN transmission applied to two collocated cells assume type 3 receivers. One UE corresponds to 200kbps offered load per cell. Higher gains are possible with enhanced type 3i receivers that suppress interference.

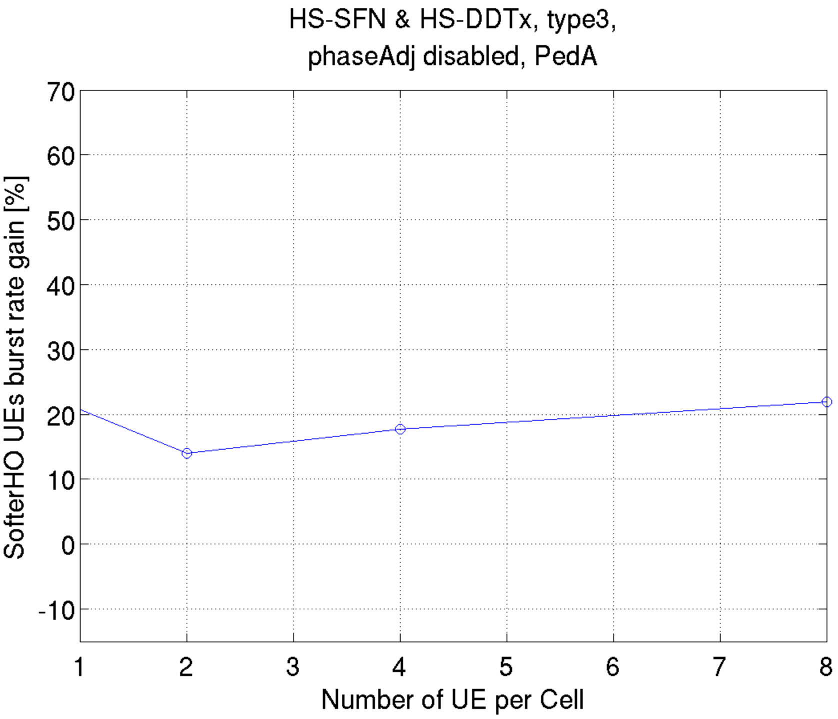


Figure 17: HS-SFN gain for softer HO UEs over single cell operation at various load points with Type 3 and Type 3i receivers, (PedA channel)

The main requirement on the UE for HS-SFN support is to provide channel quality feedback corresponding to both SFN and non-SFN operation.

3.1.3 DOWNLINK 4-BRANCH MIMO

The introduction of 2x2 MIMO in HSDPA Rel-7 described in subsection 2.1.1 increased the downlink peak rates significantly. It also provided higher user bit rates throughout the cell, as well as increased capacity. Recent additions to the standard have also demonstrated how MIMO can be efficiently introduced into the networks without affecting performance of legacy users. In LTE, the MIMO functionality is much more extensive than in HSPA. Already in LTE Rel-8, 4x4 MIMO was introduced, and the development is very much still ongoing.

Also, to support the uplink data rates it is becoming increasingly common for mobile operators to equip base stations with additional receive antennas. In situations where four receive antennas have been installed in the node B, it is of course desirable to use all the antennas also for the downlink transmissions.

Therefore, it is now natural to further consider utilizing the spatial dimension to improve HSPA performance. With the introduction of 4x4 MIMO in HSDPA, the peak rate that can be supported on 5 MHz would double compared to the 2x2 MIMO case, reaching 84Mbps in only 5 MHz. In addition to doubling the peak data rate the possibility of transmitting from four antennas will also increase the coverage for rank-1 and rank-2 transmissions. Thus, 4-branch MIMO transmission schemes are an attractive way to increase the cell and cell-edge user data rates.

System simulations have been run to demonstrate the potential performance of 4x4 MIMO, as compared to 2x2 MIMO, 2x4 MIMO and 4x2 MIMO. The results are depicted in Figure 18, where average user throughput is plotted as a function of average cell throughput as the load increases from 0.1 users/cell to 2 users/cell.

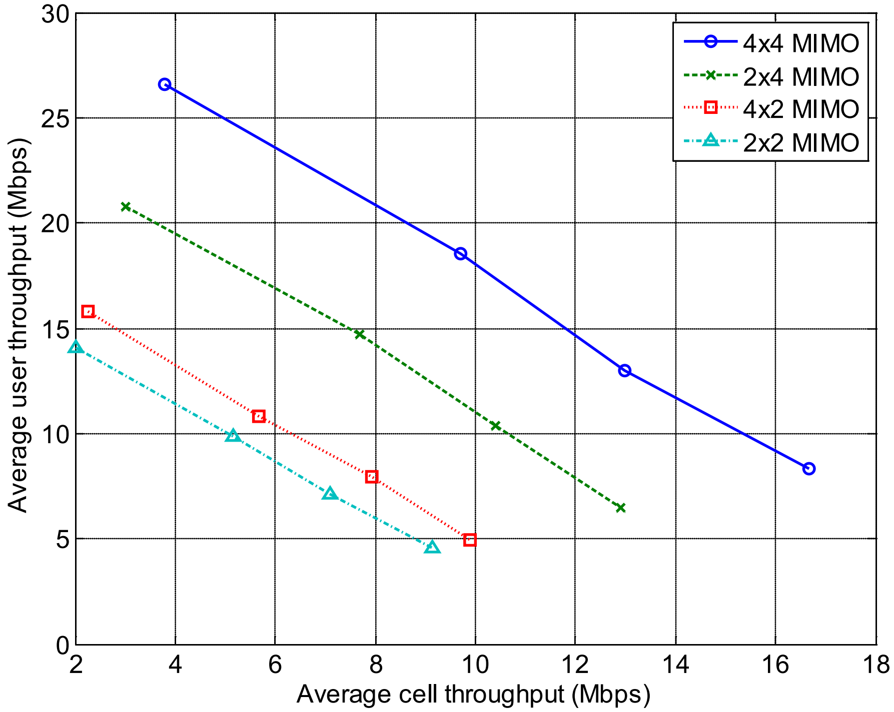


Figure 18: Average user throughput as a function of the sector throughput for different antenna configurations at the transmitter and receiver

When implementing 4-branch MIMO in the standard, a lot of LTE concepts and solutions can be reused. For instance, the reasoning around the codeword-to-layer mapping may apply to HSDPA, as would the choice of pre-coders.

One aspect that needs to be considered from the start is the performance of legacy users. Initial deployments of 4-branch MIMO should not affect performance of pre-Rel-11 UEs. For instance, the pilot schemes must be designed so that the interference on legacy users is minimized.

3.2 NEW REL-11 FEATURES SPECIFIC TO UPLINK

3.2.1 UPLINK CLOSED LOOP TRANSMIT DIVERSITY

The introduction of 2x2 MIMO in HSDPA Rel-7 described in subsection 2.1.1 increased the downlink peak rates significantly, and as noted, LTE Rel-8 already supported downlink 2x2 and 4x4 MIMO configurations. As the devices are expected to carry more than one antenna due to receive diversity and DL MIMO support, it becomes increasingly interesting to start using those antennas for uplink transmission as well. As it happens, in LTE, the MIMO functionality was extended to uplink in 3GPP Rel-10 with the support of both 2 and 4 transmit antenna configurations. In addition the 64QAM modulation included in Rel-7 as described in subsection 2.1.3 has demonstrated its usefulness in the field, and already the LTE Rel-8 had the support for uplink 64QAM modulation.

3GPP Rel-11 started to develop uplink multi-antenna transmission for HSUPA having a focus in both transmit diversity (also called Rank 1 MIMO or single stream MIMO) for coverage as well as MIMO for data rates, as well as started considering the uplink 64QAM modulation for additional uplink data rate gains. The 3GPP specification work for uplink transmit diversity was initiated in December 2010, at the same time with the uplink MIMO feasibility study [20, 21]. In completion of the the uplink MIMO study, the findings were captured in a 3GPP Technical Report [24] and the subsequent proposal for 3GPP work item for uplink MIMO with 64QAM was submitted to RAN#53 in September 2011 [23], but the specification work was not started at that time due to work load reasons. The specification work for the uplink closed loop transmit diversity is expected to be completed in March 2012.

The uplink transmit diversity and uplink MIMO use the same basic transmission principle in the uplink as is used in the downlink ‘single stream MIMO’ and 2x2 MIMO described in subsections 2.3.3 and 2.1.1 respectively. One significant difference does exist between the uplink and downlink multi-antenna transmitter structures. Unlike in downlink, where each transmit antenna has a separate, non-precoded pilot channel, the uplink sends the ‘primary’ pilot on the DPCCH channel with the same precoding vector as the Tx diversity data. The secondary pilot (S-DPCCH) is sent using an orthogonal precoding vector, which also in MIMO case is used to transmit the secondary stream.

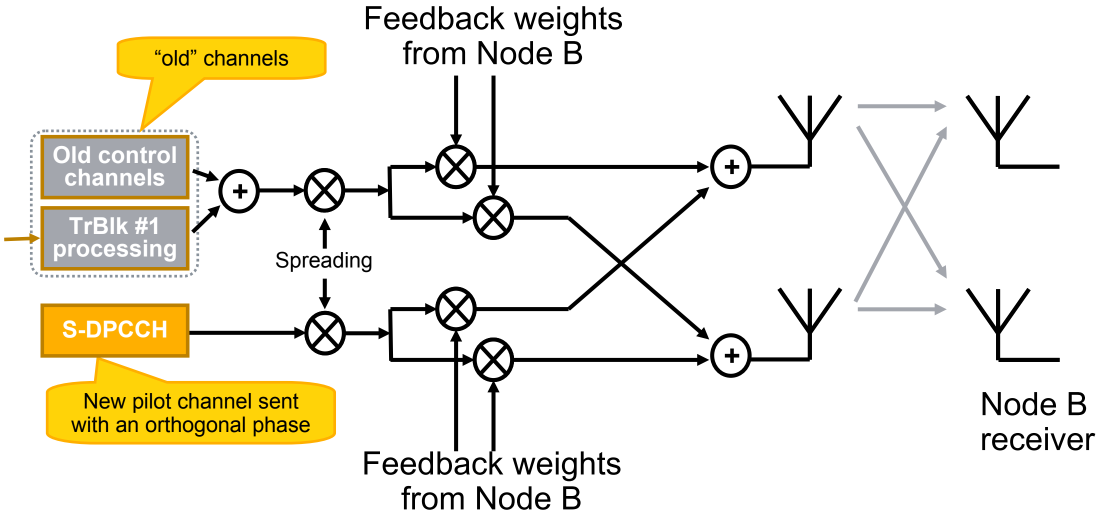


Figure 19: The UE transmitter structure used in uplink closed loop transmit diversity transmission mode

The practical benefit of precoding the 'old' DPCCH pilot and other control channels with the same precoding vector as the data is that it is possible for the Node B to receive the data block with the same receiver that is used for single antenna transmission. This property is especially useful in uplink soft handover, where the serving link controls the uplink precoding vector and optimizes the UE transmission towards itself, and the other links, unaware of changes in the precoding, or possibly even of the UE being configured in uplink transmit diversity mode, are still able to receive the uplink transmission.

The uplink closed loop transmit diversity (or beamforming) offers a reduced transmit power need in the uplink for a given data rate, which manifests itself as better uplink coverage and reduced intercell interference, which helps improving the uplink capacity. The 3GPP specification work for the uplink closed loop transmit diversity is expected to be completed in March 2012.

3.3 NON LINK-SPECIFIC REL-11 IMPROVEMENTS

3.3.1 CELL_FACH STATE RELATED IMPROVEMENTS

Even with the improvements introduced in Rel-7 and Rel-8, the massive increase in smart phone traffic results in large challenges for the RRC state machine. The traffic patterns from smart phones are difficult to predict, their nature is bursty and irregularly spread over relatively long intervals of time compared with the classical interactive traffic. This behavior has a strong impact on the UE state switching and therefore challenges the established models of resource allocation dimensioning, users handling and quality of service provision. As discussed in section 2.1.2, frequent state changes are associated with a significant amount of signaling overhead. The optimal approach would be a scheme where the smart phones can be kept as long as possible in the same state. The state should serve efficiently the non-critical bursty traffic keeping a low consumption of network and battery resources and only be switched to other states whenever peak data rates are required or total inactivity is detected reducing also the amount of signaling traffic.

Currently, none of the RRC states has all the needed properties to handle all these aspects. All the states but CELL_FACH and CELL_DCH are limited or disabled in terms of transmission and reception of data. Introducing changes in their behavior in this respect would more or less change their definitions, requiring a massive standardization effort.

The high resource and power consumption in CELL_DCH state experienced by the terminal and the network rules out the deployment of this state to handle the smart phone traffic, even when the introduction of CPC has significantly reduced the battery consumption on the terminal. Regarding the CELL_FACH state, the release 7 and 8 enhancements have improved the latency and provide smoother and faster states transition for mobile broadband capable terminals. The fundamentals of this state make it very attractive for handling the smart phone traffic. With the introduction of further improvements to provide better control of the network resources, increase the downlink spectrum efficiency and decrease the terminal power consumption and finally to reduce even further the transmission latency in the state, it becomes possible to keep smart phone terminals in CELL_FACH for a quite long time. The frequent packets can be transmitted efficiently without having to transit to CELL_DCH.

To improve the CELL_FACH state to make it suitable for the majority of the smartphone traffic, the following enhancements should be introduced:

- Stand-alone HS-DPCCH without ongoing E-DCH transmission
- Support of concurrent deployment of 2ms and 10ms TTI in a cell
- Per-HARQ-process grants for 2ms TTI and TTI alignment between CELL_DCH and CELL_FACH UEs
- Fallback to Rel-'99 PRACH
- Reduction in timing of the initial access in the physical random access procedure
- UE battery life improvements and signaling reduction

With the introduction of EUL in CELL_FACH in Rel-8, HS-DPCCH can be transmitted in CELL_FACH whenever E-DCH is transmitted. However, to improve downlink transmission, it should be possible to transmit HS-DPCCH even when there is no transmission of uplink data. This will enable transmission of CQI and HARQ ACK/NACK in CELL_FACH without necessarily setting up E-DCH. Such fast feedback has been the key to the dramatic improvements in spectral efficiency already achieved for UEs in CELL_DCH, and will boost the performance of DL transmissions in CELL_FACH to similar levels as in CELL_DCH. Still, the highest user bit rates will be supported only in CELL_DCH, using features like MIMO.

One limitation of the E-DCH in CELL_FACH standardized in Rel-8 is the lack of support for concurrent use of 2 ms and 10 ms TTI. This means that in most cells for coverage reasons, application of E-DCH in CELL_FACH requires that 10 ms TTI is used, preventing that users in the cell benefit from the shorter latency of the 2ms TTI. Therefore, concurrent support for both TTI lengths should be introduced for E-DCH in CELL_FACH, so that only the users in bad coverage situations need to use the 10 ms TTI, while the majority use 2 ms TTI with the associated advantages.

When E-DCH is used in CELL_DCH, one valuable option is the possibility to use *per-HARQ* grants to EUL 2 ms users. A grant is then valid only in a subset of the HARQ processes, making it possible to introduce uplink TDM. This possibility should be introduced also in CELL_FACH to improve the control of the radio interface and the handling of small packets. To reap the full benefits of 2ms TTI, TTI alignment between UEs in CELL_DCH and CELL_FACH should also be supported. Furthermore, although E-DCH should be the preferred option to carry uplink traffic in CELL_FACH, the handling of really small packets is handled more efficiently by the Rel-'99 PRACH. Such a fallback option should also be introduced in the standard.

As previously mentioned, the UE battery consumption in CELL_FACH is still too high. Therefore, more aggressive DRX schemes must be introduced to make it possible for the UEs to remain in CELL_FACH for longer periods of time. Since downlink transmissions can only be initiated when the UE receiver is switched on, the introduction of longer DRX cycles comes at the price of increasing latency for network-originating transmissions. Hence, to counter-act the effects of the longer DRX cycles, it may be required that additional latency enhancements are introduced.

The improvements to the CELL_FACH state mentioned above are all part of a Rel-11 work item.

4 CONCLUSION

The explosive growth of wireless data usage is driving the continuing evolution of today's mobile broadband networks and HSPA has provided a foundation for high speed data connectivity with 412 commercial networks in 157 countries and over 756 million subscribers worldwide. As new extremely powerful and capable user-devices and useful mobile applications penetrate the markets, operators find the need to upgrade their wireless networks to meet their customer's insatiable demand for high-speed mobile data. Initially, HSPA technologies defined in Rel-5 (HSDPA) and Rel-6 (HSUPA) have supported the growing data capacity demands but continuing technological evolutions towards HSPA+ and beyond are still necessary, and are proceeding at a fast pace.

The Rel-7 standards defined by 3GPP introduced major HSPA+ enhancements which increased peak-data throughput such as Multiple Input Multiple Output (MIMO) antenna schemes and High Order Modulation (HOM) techniques. Other features such as Continuous Packet Connectivity (CPC) and Enhanced CELL_FACH State were also introduced in Rel-7 to improve the connected-user experience. These enhancements were well accepted by operators and their customers. Globally, as of October 2011, there are 165 commercial HSPA+ networks in 82 countries, and it is expected that the majority of all HSPA carriers will someday upgrade to HSPA+.

Evolving HSPA+ standards continued to boost the peak-data rate in Rel-8 to a potential 42Mbps by combining 64QAM and 2x2 MIMO, and also to introduce Dual Carrier operation and further improvements to the User Equipment state transitions and battery life.

Beyond Rel-8, the peak-data rate is improved once again by combining existing features in Rel-9. In this case, Dual Carrier HSDPA is combined with 2x2 MIMO and 64QAM, resulting in a theoretical peak data rate of 84Mbps.

Rel-10 standardized enhancements increase the multi-carrier capabilities to utilize up to 20MHz over two frequency bands by introducing the Four Carrier HSPDA feature, again doubling the potential peak-data rate to 168 Mbps. Another Rel-10 feature worth noting is adding support for MIMO operation with non-MIMO coexistence in HSDPA, minimizing the potential negative performance impact of the introduction of MIMO in the network on legacy non-MIMO UEs.

3GPP work-items are currently underway for Rel-11. Some of the key Rel-11 HSPA+ features are expected to be downlink enhancements to support 8-carrier HSDPA, 4-branch MIMO and multi-point transmission, and uplink enhancements to support dual antenna beamforming and MIMO.

Another interesting and exciting future technical concept which will be considered in Rel-12+ is the possibility of multi-band, multi-carrier aggregation utilizing HSPA and LTE technologies. This would allow further integration of HSPA and LTE technologies for operators that have deployed both technologies.

Looking at the progression of HSPA+ capabilities with an eye on the increasing potential peak-data rate, it is clear the potential of this technology is still exceptionally strong and will provide operators with the capabilities and enhancements required to meet the exploding data usage demands of their customers.

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ANNEX: FEATURES NOT INCLUDED IN REL-11

Some study items that were originally considered for inclusion in this paper were removed from the 3GPP Rel-11 prioritization work to limit the number of work items to a level manageable by the standards groups. This resulted with a standards group decision in September 2011 to postpone the feature proposals. Uplink MIMO with UL 64 QAM was postponed for 3 months and HSPA+LTE Carrier Aggregation was postponed for 6 months. These study items, which we describe below, can be resubmitted for consideration in a future 3GPP release.

4.1 UPLINK MIMO AND 64QAM FOR UPLINK

The introduction of 2x2 MIMO in HSDPA Rel-7 described in subsection 2.1.1 increased the downlink peak rates significantly, and as noted, LTE Rel-8 already supported downlink 2x2 and 4x4 MIMO configurations. As the devices are expected to carry more than one antenna due to receive diversity and DL MIMO support, it becomes increasingly interesting to start using those antennas for uplink transmission as well. As it happens, in LTE, the MIMO functionality was extended to uplink in 3GPP Rel-10 with the support of both 2 and 4 transmit antenna configurations. In addition the 64QAM modulation included in Rel-7 as described in subsection 2.1.3 has demonstrated its usefulness in the field, and already the LTE Rel-8 had the support for uplink 64QAM modulation.

3GPP Rel-11 started to develop uplink multi-antenna transmission for HSUPA having a focus in both transmit diversity (also called Rank 1 MIMO or Single stream MIMO described in section 3.2.1) for coverage as well as MIMO for data rates, as well as started considering the uplink 64QAM modulation for additional uplink data rate gains. The 3GPP specification work for uplink transmit diversity was initiated in December 2010, at the same time with the uplink MIMO performance studies [20, 21]. The uplink MIMO study findings were captured in a 3GPP Technical Report [24] and the subsequent proposal for 3GPP work item for uplink MIMO with 64QAM was submitted to RAN#53 in September 2011 [23], but the specification work was not started at that time due to work load reasons.

Table 1: Uplink peak rates in different BW, modulation and MIMO combinations

	No MIMO		**MIMO**	
	16QAM	**64QAM**	**16QAM**	**64QAM**
Single carrier	12 Mbps	18 Mbps	24 Mbps	36 Mbps
Dual carrier	24 Mbps	36 Mbps	48 Mbps	72 Mbps

The uplink MIMO offers a 100% increase in data rates, which takes HSUPA peak data rate to 24 Mbps in a single carrier or 48 Mbps in dual carrier configuration with 16QAM modulation.

The uplink 64QAM offers a 50% increase in data rates, which in a single carrier configuration gives peak data rates of 17.3 Mbps without MIMO and 36 Mbps with MIMO. In dual carrier configurations the non-MIMO peak rate reaches 36 Mbps, and the MIMO peak rate to 72 Mbps.

The uplink transmit diversity and uplink MIMO use the same basic transmission principle in the uplink as is used in the downlink 'single stream MIMO' and 2x2 MIMO described in subsections 2.3.3 and 2.1.1 respectively. One significant difference does exist between the uplink and downlink multi-antenna transmitter structures. Unlike in downlink, where each transmit antenna has a separate, non-precoded pilot channel, the uplink sends the 'primary' pilot on the DPCCH channel with the same precoding vector as the Tx diversity data. The secondary pilot (S-DPCCH) is sent using an orthogonal precoding vector, which also in MIMO case is used to transmit the secondary stream.

The uplink closed loop transmit diversity transmission structure described in section 3.2.1 acts as a basic foundation for building the uplink MIMO transmission structure, so that when the MIMO configured link cannot sustain a rank 2 (dual-stream) transmission, the operation would fall back to uplink transmit diversity model. Three different MIMO rank 2 transmission options have been considered, and a structure compatible with option II is show in Figure 20.

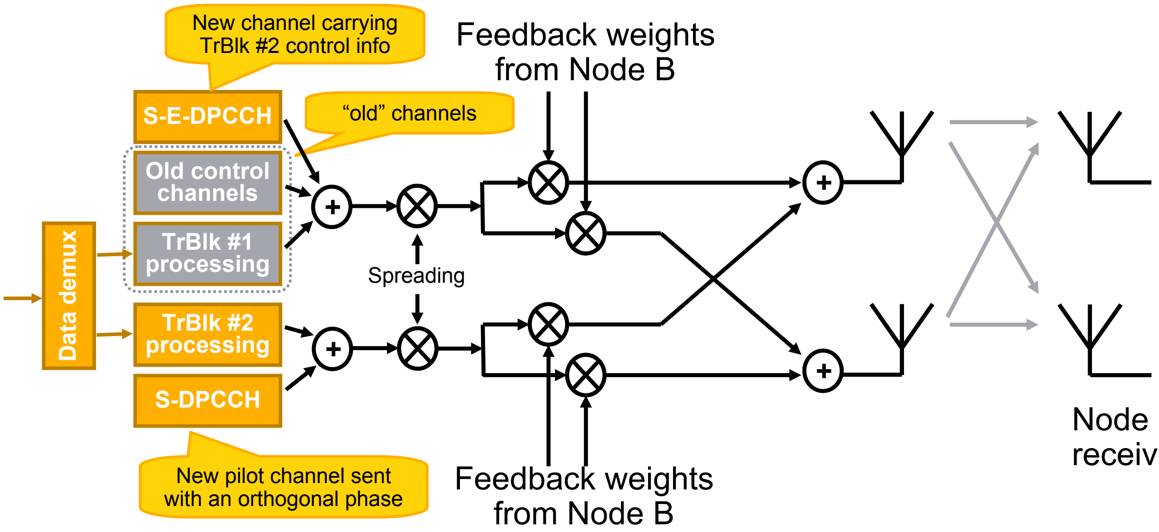

Figure 20: A possible uplink MIMO UE transmitter structure. Depicted structure is compatible with MIMO option II. Location and need of S-E-DPCCH is an open issue

MIMO Option I – single TB rank-2 transmission. The main advantage of this architecture is low control signalling overhead: it is sufficient to indicate a single E-TFC and, possibly, the transmission rank in uplink, whilst the only additionally required signaling in DL is possibly the transmission rank. In addition, the number of HARQ processes does not increase for rank-2, compared to rank-1 transmission. This leads to not needing a second E-DPCCH channel in uplink or additional HARQ feedback in downlink for rank-2 transmissions. The disadvantage of Option I is a poor channel adaptation ability in the case of a significant imbalance between the MIMO spatial streams.

MIMO Option II – dual TB rank-2 transmission, independently over the spatial streams. The advantage of this architecture is the flexibility to independently assign a different E-TFC to each spatial stream, i.e. to make an adaptation of data rate on each stream in order to maximize the throughput, at the cost of the overhead to signal the scheduling and HARQ-related information associated with each stream in UL (second E-DPCCH channel) and the ACK/NACK and E-TFC selection information for each stream in DL.

MIMO Option III – dual TB rank-2 transmission, TBs interleaved between the two spatial channels. This can be viewed as a hybrid between options I and II above. Due to the interleaving, each transport block is transmitted over the same channel conditions, corresponding to an average over the two spatial streams. This can be expected to negatively affect the performance when comparing to option II, as the ability to adapt to channel conditions is similar to that of Option I. In terms of signaling, the HARQ overhead is the same as in the case of Option II. The amount of scheduling information for Option III lies between that of Option I at the minimum and Option II at the maximum. One advantage of option III as compared to option II is that there is no need to introduce an additional loop controlling the second stream for achieving a targeted BLER.

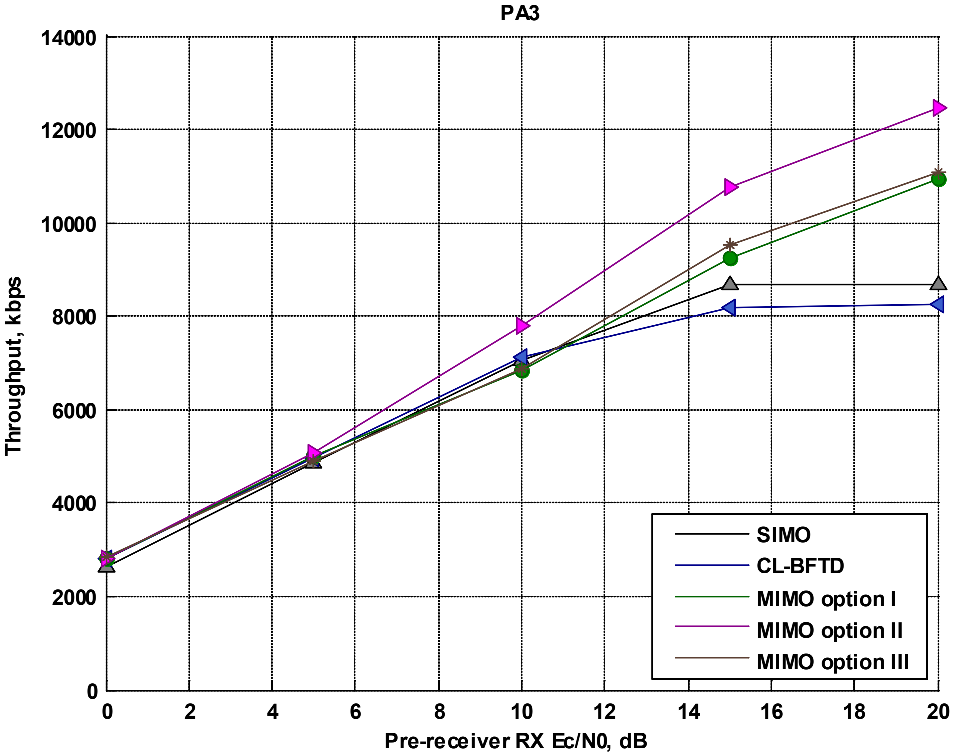

Figure 21: Link throughputs of different transmission modes, PedA 3 km/h, 2x2 (1x2) antenna configuration [19]

Figures 21 and 22 show the link performance of the two-transmit antenna uplink Closed Loop Beam forming Transmit Diversity (CL- BFTD) and MIMO against regular single transmit antenna multiple receive antenna diversity using 2 and 4 NodeB receive antennae respectively. The small loss observed for the CL-BFTD over normal single antenna transmission with close to peak data rates is due to the fact that the receiver sensitivity is slightly degraded due to the added inter-stream interference from the S-DPCCH causing some sensitivity loss. This receiver sensitivity loss with very high data rates is more than offset in the system level due to lower transmit power needed for a particular data rate.

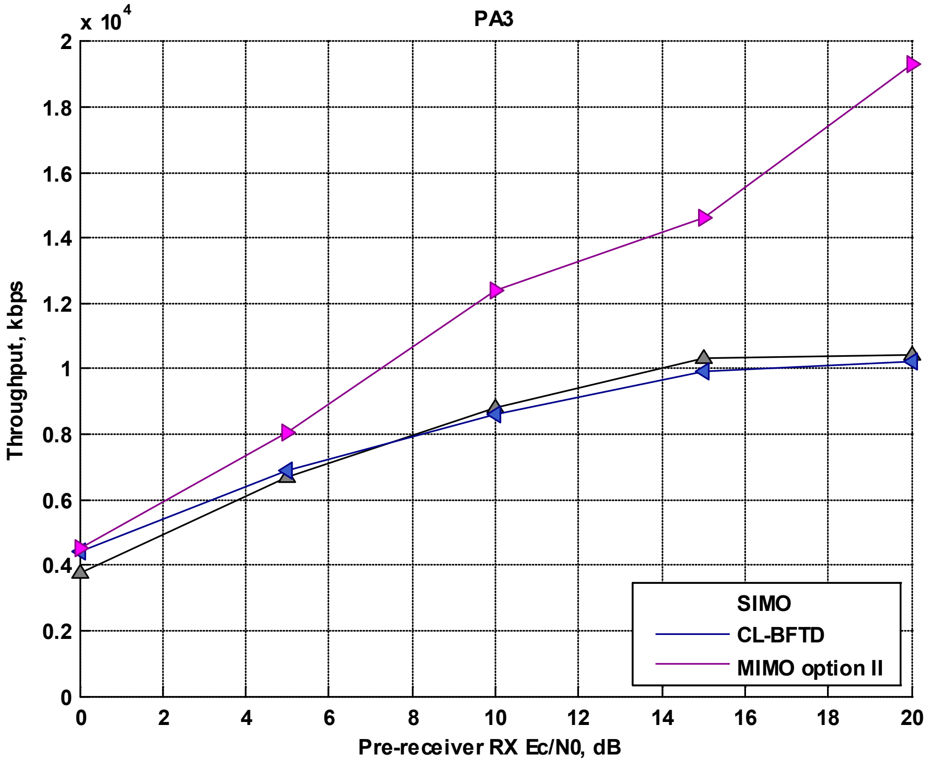

Figure 22: Link throughputs of different transmission modes, PedA 3 km/h, 2x4 (1x4) antenna configuration [19]

4.2 HSPA+LTE CARRIER AGGREGATION

As discussed in this paper, the HSDPA bandwidth has evolved from the original 5 MHz through phased introduction of multicarrier support to the standards. The Rel-8 introduced 10 MHz support through aggregating two adjacent carrier frequencies in a Dual Cell HSDPA, and is extending the support to up to 40 MHz (8 carriers) in 3GPP Rel-11. On a parallel track the 3GPP standards have introduced the carrier aggregation feature to LTE in Rel-10. The LTE carrier aggregation feature is in principle is capable of bonding up to 5 carriers, each up to 20 MHz, although the Rel-10 defines band combinations scenarios only for aggregation of two LTE carriers.

A natural evolution from HSDPA multicarrier, LTE carrier aggregation and handovers between the two radios would appear to be to extend the carrier aggregation to support aggregating carriers operating on different radio technologies. The evolution has been depicted in Figure 23.

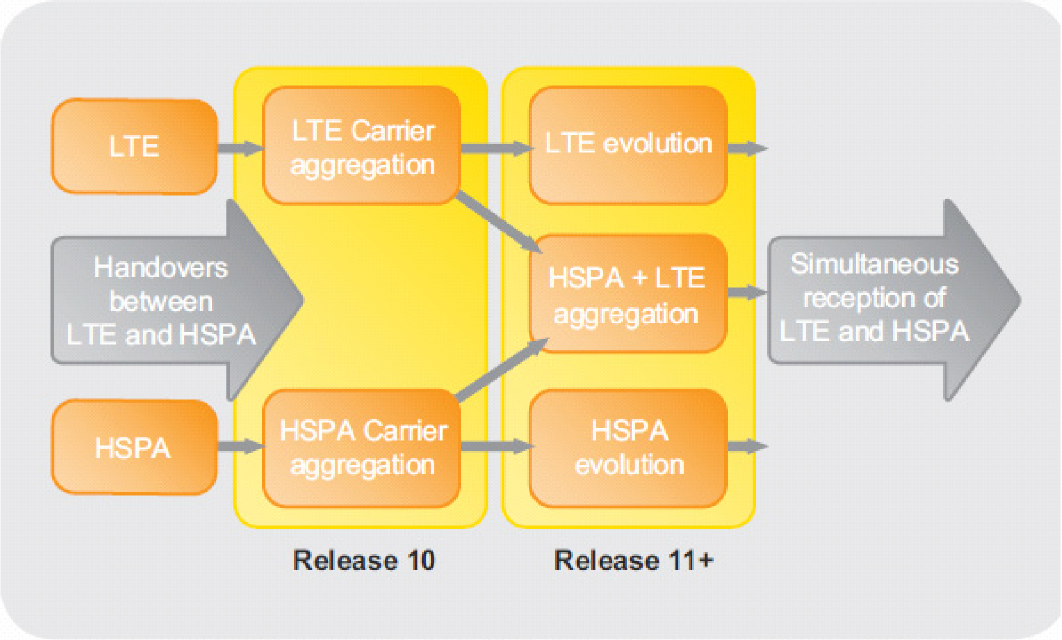

Figure 23: Potential 3GPP evolution of LTE and HSPA radio interworking from inter-RAT handovers to simultaneous reception through aggregation

The basic motivation for aggregating the two radios is very much deployment and spectrum situation dependent. A HSPA network operator considering in deploying to move to LTE, but lacking abundant spectrum is forced to consider the bandwidths in which the LTE networks can be initially deployed, as well as the current and future bandwidth needs of the already deployed HSPA network needs to carefully weigh how much spectrum to allocate to each of the radios to be able to provide sufficient service experience on them both.

For example, an operator with 15 MHz available for both LTE and HSDPA would be able offer aggregated peak rate of the two systems instead of being limited to what 15 MHz can deliver on each of the two systems alone. When considering the HSDPA peak data rate of 42 Mbps per carrier with 2x2 MIMO, then the peak data rate offered with aggregated HSDPA + LTE solution with 15 MHz +15 MHz spectrum would be over 230 Mbps (again assuming 2x2 MIMO on all carriers), a clear step from the 110 Mbps available with the 15 MHz LTE or 126 Mbps with 15 MHz HSDPA. Of course comparable peak data rates can be achieved with 30 MHz HSDPA or 30 MHz LTE (252 or 220 Mbps respectively, again assuming 2x2 MIMO), however in many cases it is not really an option to just deploy either HSPA or LTE, but both need to coexist in parallel.

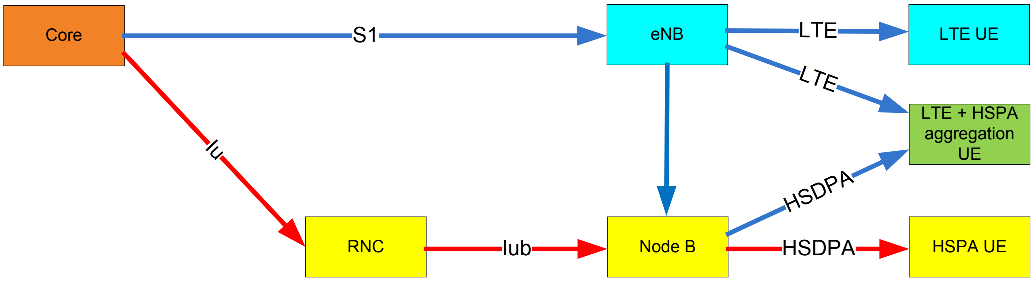

Figure 24: A possible architecture for HSPA+LTE aggregation

Figure 24 depicts a possible architecture of a network capable of HSPA+LTE aggregation and simultaneously serving LTE UEs and HSPA UEs together with the UEs capable of simultaneous reception of the two radios.

A practical deployment benefit with HSPA+LTE carrier aggregation can be obtained in an environment where the operator deploys multi-radio base stations capable to both HSPA and LTE, and similarly multimode devices are, as expected, commonplace. This leads to the fact that there is no need for additional hardware in either the network or in the device to be able to support the aggregation. The same hardware in the device just needs to be designed so that it is capable of operating with both receivers at the same time, and this is already needed in limited occasions when the device is doing mobility related measurements towards the other radio technology than it is already connected to. A multi-radio base station is by definition anyway required to be able to operate on both radio systems simultaneously, so aggregating the two radios towards a single user can be seen to be more close to be a configuration question than a new base station type.

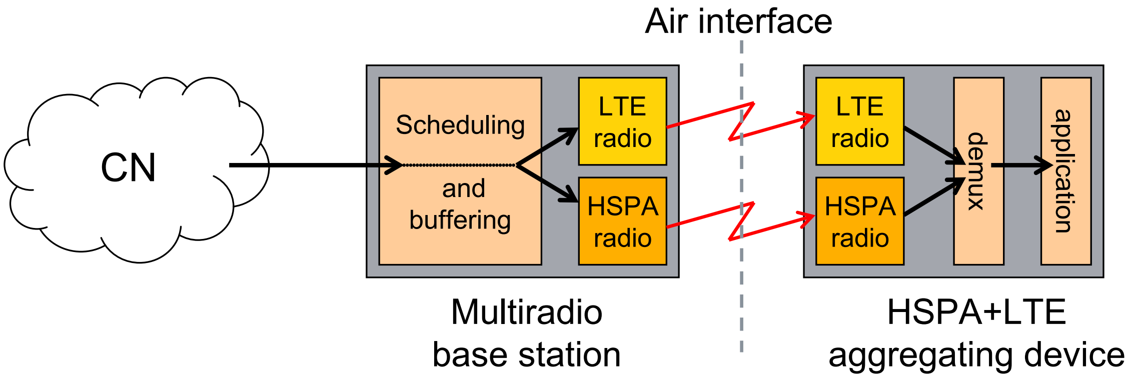

Figure 25: A HSPA + LTE aggregation data flow through a Multi-Radio base station

7 GLOSSARY

3GPP	3rd Generation Partnership Project
4G	4th Generation
16QAM	(4bits per symbol) Quadrature Amplitude Modulation
64QAM	(6bits per symbol) Quadrature Amplitude Modulation
ACK	ACKnowledgement
BLER	Block Error Rate
CDM	Code Division Multiplexing
CL-BFTD	Closed Loop Beamforming Transmit Diversity
CN	Core Network
CPC	Continuous Packet Connectivity
CPICH	Common Pilot CHannel
CQI	Channel Quality Information
CS	Circuit Switched
D-TxAA	Double Transmit Adaptive Array
DCH	Dedicated Channel
DL	Down Link
DRX	Discontinuous Reception
DTX	Discontinuous Transmission
EDGE	Enhanced Data rates for GSM Evolution
eNodeB	evolved NodeB
eUTRAN	evolved UTRAN (also known as LTE)
FACH	Forward Access Channel
FDD	Frequency Division Duplexing
HOM	Higher Order Modulation
HARQ	Hybrid Automatic Repeat request
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSPA+	Evolved HSPA
LTE	Long Term Evolution
Mbps	Mega bits per second
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Squared Error
NACK	Negative ACKnowledgement
PARC	Per Antenna Rate Control
PCH	Paging Channel
PDU	Protocol Data Unit
QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RLC	Radio Link Control
RRC	Radio Resource Control
Rx	Receive
SF-DC	Single Frequency Dual Carrier

SFN	Single Frequency Network
SINR	Signal to Interference and Noise Ratio
SDMA	Space Division Multiple Access
STTD	Space Time Transmit Diversity
TDD	Time Division Duplexing
TTI	Transmit Time Interval
Tx	Transmit
UE	User Equipment
UL	Up Link
UTRA	Universal Terrestrial Radio Access
VAM	Virtual Antenna Matrix
VoIP	Voice over Internet Protocol

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The mission of 4G Americas is to promote, facilitate and advocate for the deployment and adoption of the 3GPP family of technologies throughout the Americas. 4G Americas' Board of Governor members include Alcatel-Lucent, América Móvil, AT&T, Cable & Wireless, CommScope, Ericsson, Gemalto, HP, Huawei, Nokia Siemens Networks, Openwave, Powerwave, Qualcomm, Research In Motion (RIM), Rogers, T-Mobile USA and Telefónica.

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