Multi-Carrier HSPA Evolution

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Abstract—**The HSPA Evolution will during the next decade be a key radio access technology for a cost-effective provisioning of mobile broadband services. In addition to the continuous improvements of WCDMA/HSPA in terms of spectral efficiency and latency, "multi-carrier operation" (or "carrier aggregation") for individual connections is now introduced. This paper presents the evolution of Multi-Carrier HSPA, discusses implications on network architecture & user equipment, and evaluates the achievable system performance (with focus on downlink). It is concluded that Multi-Carrier HSPA can be implemented at a low incremental cost; both in the radio access network, which already supports multiple carriers, and in terminals (due to synergies with LTE). Numerical results further show that achievable data rates of a Multi-Carrier HSPA system increase proportional to the number of carriers; in terms of peak physical layer data rates as well as (for bursty packet data) average user throughput. Thus, Multi-Carrier HSPA will be an attractive means for operators to provide higher data rates and decrease the production cost of mobile broadband access.**

Keywords-3G; WCDMA; HSDPA; HSUPA; EUL; HSPA; Multi-Carrier; Dual-Carrier; Dual-Cell; Multi-band; Dual-band; Inter-band; HSPA Evolution; Carrier aggregation; Mobile broadband

I. Introduction

Mobile broadband is expected to contribute substantially to a continued spreading of Internet access; either as complement to, or substitute for, wireline broadband access. Similar to the formidable success of mobile telephony, it is envisaged that the 3rd Generation Partnership Project (3GPP) family of standards will contribute substantially to a high penetration of mobile broadband globally. While GSM/GPRS/EDGE has been the most successful system for mobile telephony and rudimentary data access, and LTE is an attractive technology in the longer term, High Speed Packet Access (HSPA) – including High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA; also known as Enhanced Uplink, or EUL) – will in many markets be the primary mobile broadband technology for the next decade.

After its launch in 2005/2006, HSPA is today (2009) a global success with commercial deployments in more than 100 countries [1]. The number of HSPA subscriptions exceeds 80 millions and show an accelerated growth, which will lead to greater economies of scale and thereby increased affordability of mobile broadband services for different markets, customer segments, and applications. In order to provide new and enhanced wireless access infrastructure at a low incremental cost, it is vital for network providers to whenever possible exploit existing infrastructure – including, for example, base station sites and equipment. At the same time, a smooth migration towards higher rates and new services require support for legacy terminals and services. Hence, it is plausible that an evolution of HSPA will in the foreseeable future be a key for cost effective provisioning of mobile broadband access.

Included in 3GPP Releases 7 and 8, the HSPA Evolution introduces several new features that enable [2][3]:

- higher data rates,
- lower latency,
- increased capacity,
- better support for VoIP, and
- improved support for multicast services.

In addition, multi-carrier operation, which is the focus of this paper, is introduced. More specifically, Dual-Carrier HSDPA operation (also known as Dual-Cell HSDPA or DC-HSDPA) with downlink transmission on two adjacent 5 MHz carriers is included in 3GPP Release 8 [3], and an evolution to more than two downlink carriers as well as uplink multi-carrier operation will be included in future releases. Notice that we, for general discussions, will refer to a Multi-Carrier HSPA (MC-HSPA) system, which corresponds to simultaneous transmission for a given terminal (user equipment) on more than 1 carrier in downlink and/or uplink.

Most previous work on multi-carrier CDMA systems are related to the physical layer modulation schemes. Similar to OFDM, the problem of inter-symbol interference caused by time-dispersive channels is combated by the use of many orthogonal waveforms; each having a small bandwidth relative to the total system bandwidth. In this paper though, Multi-Carrier HSPA instead refers to an aggregation of WCDMA/HSPA 5 MHz carriers. By aggregating radio resources of multiple carriers, peak data rates and capacity (supported traffic load for a given quality of service level) can be increased substantially. A similar approach has been proposed for LTE Advanced [4], with an aggregation of (up to) 20 MHz wide carriers, and for the cdma2000 EV-DO system an aggregation of several 1.25 MHz carriers was introduced [5]. This paper, instead, discusses the system design and evaluates the performance benefits of a Multi-Carrier HSPA system, with emphasis on the downlink.

The rest of this paper is organized as follows. Section II describes and motivates the key steps in the evolution of Multi-Carrier HSPA. In section III the Multi-Carrier HSPA network architecture and terminal design issues are discussed. Performance benefits are covered in section IV, focusing on the downlink and the paper is concluded in section V.

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II. EVOLUTION OF MULTI-CARRIER HSPA

The evolution of Multi-Carrier HSPA beyond the features defined in the 3GPP Release 8 standard is continuing with current focus on 3GPP Release 9. A number of extensions of DC-HSDPA are therefore under discussion in 3GPP.

A. Multi-Carrier HSDPA

The system performance as well as the achievable data rates scale with the number of aggregated 5 MHz downlink carriers (see further section IV). Therefore, 3GPP discusses to extend the concept of Dual-Carrier HSDPA to Multi-Carrier HSDPA, which (as a first step) would support multi-carrier operation on 3 or 4 carriers simultaneously.

Assuming the support of MIMO and 64QAM, Multi-Carrier HSDPA can achieve downlink data rates of up to 84, 126, or 168 Mbps – assuming 2,3,4 x 5 MHz are employed, respectively.

B. Dual-Band HSDPA

A pre-requisite for a mobile operator deploying Multi-Carrier HSDPA is the availability of sufficient spectrum. Not all mobile operators have access to more than 5 or 10 MHz of spectrum in a single operating band. Dual-Band HSDPA will hence be a key feature for operators to aggregate multiple 5 MHz spectrum blocks from two different bands; for example, combining 5 MHz blocks from the 900 MHz and 2100 MHz bands for operation of a Multi-Carrier HSDPA system.

As a side effect, because Dual-Band HSDPA capable devices are able to receive and monitor two bands simultaneously, such operations would facilitate improved mobility (inter-frequency handover) mechanisms and load balancing of users in different frequency bands. Such functionality would especially be useful in range (noise) limited scenarios (that is, it would in particular aid uplink transmission for users at the cell edge).

C. Dual-Carrier HSUPA

Aside from higher downlink data rates, improved uplink data rates (throughout the coverage area) will be a key for operators to meet end user expectations of future mobile broadband services [4]. This is motivated by increased downlink traffic volumes and data rates, requiring high uplink user throughput for feedback signaling (e.g, TCP), and by various new applications that increase uplink traffic volumes.

3GPP therefore considers introducing Dual-Carrier HSUPA operation on two adjacent 5 MHz uplink carriers; supporting not only uplink data rates up to 23 Mbps, but also the possibility for a more dynamic scheduling in the frequency domain (in order to maximize capacity and cell edge rates).

III. MULTI-CARRIER HSPA SYSTEM DESIGN

In this section we briefly describe the impact of Multi-Carrier HSPA on radio access network architecture & protocols and the user equipment. Focus is on Dual-Carrier HSDPA, standardized in 3GPP Release 8, but the concept is readily extendable to uplink and beyond two carriers in downlink.

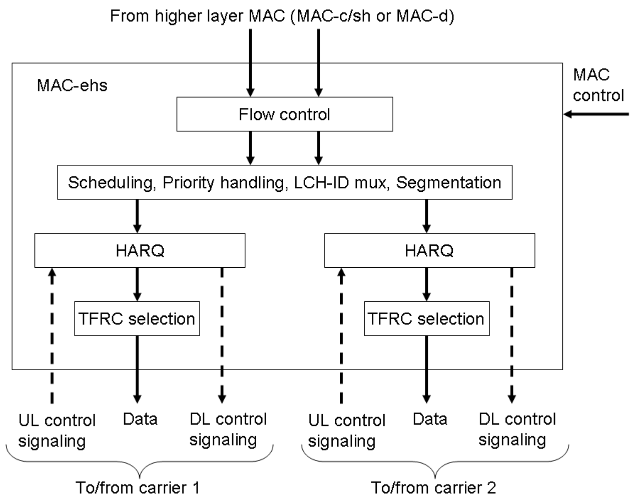

Figure 1. UTRAN side of MAC architecture for Dual-Carrier HSDPA.

A. Network Architecture and Protocol Impact

If both the network and the user equipment are capable of Dual-Carrier HSDPA operation, the network will be able to configure the user equipment not only with a (primary) serving cell but also with a secondary serving cell originating from the same base station but on an adjacent carrier frequency.

From the point of view of the user equipment, only the primary serving cell has a corresponding uplink channel, and non-HSDPA-related information such as the synchronization channel (SCH) and transmit power control (TPC) commands are always mapped to the primary serving cell, never to the secondary serving cell. However, from a network point of view, a particular cell can be the primary serving cell for some users and the secondary serving cell for others. Furthermore, legacy single carrier users can be supported in any cell.

The user data processing – including channel coding, interleaving, modulation and hybrid ARQ retransmission protocol, as well as the corresponding signaling of related physical layer control information to the user equipment – are performed independently for each one of the two serving cells, meaning that the user can be scheduled independently in the two serving cells. For each serving cell, one hybrid ARQ acknowledgement and one downlink channel quality indicator are fed back by the user equipment to the base station. The UTRAN side of the MAC architecture [6] is illustrated (somewhat simplified) in figure 1.

Taking into account that many base stations already support multiple carrier frequencies (although for Single-Carrier HSPA operation) the complexity increase due to the introduction of Multi-Carrier HSPA operation may very well be quite modest on the network side. One part that nevertheless needs to be upgraded is the scheduler, which now needs to be able to schedule data transmissions for a single user over more than one carrier. There may also be a potential for enhancements and optimizations of mobility (handover) measurements and procedures.

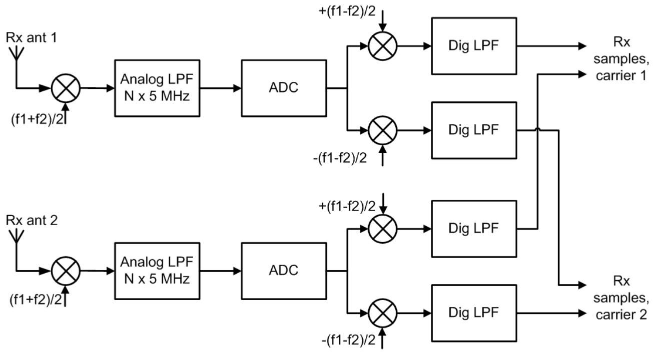

Figure 2. A possible receiver architecture for Multi-Carrier HSDPA on adjacent carriers, as in Dual-Carrier HSDPA in 3GPP Rel 8 (assuming $N = 2$ carriers). Notice that the analog architecture may be reused for operation in LTE systems.

B. *Cost Effective Terminal Implementation*

When introducing new features to existing standards, it is highly important that these can be implemented in cost-effective ways for them to be successfully employed. This is especially true for equipment that is subject to large-scale production, such as mobile broadband devices. A lower implementation cost increases the likelihood that the feature is included in more products, which in turn makes it more attractive than less cost-effective technologies offering similar performance.

1) Terminal architecture

Several architectural options exist for the implementation of Multi-Carrier HSPA devices. Depending on the deployment scenario – considering for example spectrum allocation of the carriers of interest – different architectures will be more or less viable. As an example, the Dual-Carrier HSDPA feature in 3GPP Release 8 applies only to adjacent carriers within the same band. As illustrated in figure 2, adjacent carriers enables the use of a (per antenna branch) single RF chain in the receiver, operating at 10 MHz bandwidth, instead of a more expensive solution with two RF chains, each one operating at 5 MHz bandwidth. In scenarios with disjoint spectrum allocation, on the other hand, multiple RF chains will typically be the desired architecture. This is especially true if the carriers reside in different frequency bands.

Because the UE may have to operate either in single-carrier or multi-carrier mode, the analog receive filters need either be tunable, or implemented as separate fixed filters with different bandwidths. The situation is similar to an LTE receiver, which has to be able to operate in different system bandwidths, from 1.4 MHz up to 20 MHz. Thus, in a dual-mode HSPA + LTE capable device, it is feasible to use the same RF architecture for both radio access standards.

2) Synergies between LTE and Multi-Carrier HSPA terminals

LTE is currently being standardized in 3GPP, with the possibility to provide data rates exceeding 100 Mbps over up to 20 MHz bandwidth. It is expected that there will be a demand for multi-standard devices involving both HSPA and LTE.

Given the 20 MHz RF front-end, and the high data-rate capabilities in a LTE terminal, the incremental cost of a joint Multi-Carrier HSPA implementation with adjacent carriers within 20 MHz can be considered relatively low. In particular if similar requirements on the transmitter and receiver characteristics in terms of, for example, linearity and error vector magnitude (EVM) are employed in both standards.

In conclusion, it is highly feasible to implement a Multi-Carrier HSPA terminal and, because synergies with LTE terminal implementation can be exploited, it will be a cost-effective evolution path for HSPA towards higher rates.

IV. MULTI-CARRIER HSDPA PERFORMANCE

The conventional approach for operators to increase capacity and/or user data rates in a HSPA system is to deploy more carriers. While this approach scales the supported traffic volumes linearly with the number of carriers (subject to quality of service constraints; for example, "95% of the users should experience some minimum average throughput during busy hour"), the end user throughput is not increased accordingly. The fundamental problem is that, for single-carrier operations, all resources can not be exploited for individual connections. Hence, there might be unused resources (within a sector; constituted of cells on different carrier frequencies having similar coverage area) even though a user has data to transmit.

The introduction of multi-carrier operation opens up the possibility to exploit an increased system bandwidth for individual connections, which increases system capacity and the end-user experience. In particular, assuming N carriers, the N-fold increase of system bandwidth directly translates to an N-fold improvement of the peak data rate of the system. In fact, given that the transmission power is scaled accordingly – such that the power spectral density is maintained – users served by the multi-carrier system will experience an N times higher data rate on the physical layer throughout the network. In addition, channel aware scheduling can now operate also in the frequency dimension, and the opportunity to balance the load of the carriers *per subframe* (2 ms) is introduced.

In addition to increased physical layer data rates the average user throughput will, due to increased resource utilization, be significantly increased. While, in the case of multiple single carriers each user can only be served on one carrier at a time, the multi-carrier system enables simultaneous transmission on N carriers to a single user. For bursty packet data traffic, this property will as shown below translate into an N-fold gain in average throughput experienced per user (compared to single-carrier HSDPA operation exploiting the same number of carriers). An intuitive interpretation of this system property would be that a faster file download time for a given user will make the system well prepared to serve the next user that desires service; a time-dynamical effect that is further motivated next using a simple queuing system model.

A. *Analytical Results*

As a first assessment of the gain of Multi-Carrier HSDPA we will model each cell as a separate queuing system. Furthermore, let us assume we have an M/M/1 queuing system, where packets arrive according to a Poisson process with arrival intensity λ and an exponentially distributed per packet service rate with mean μ (which is independent of the number of users currently being served). The average time to transmit a packet, excluding waiting time, equals $1/\mu$ and the average time T spent in the system including waiting time for a packet is given by $T = 1/[\mu(1-\rho)]$, where $\rho=\lambda/\mu$ is the traffic intensity (offered load).

If we now assume N servers are available (notice that a server corresponds to a *carrier* in an HSDPA system), the mean offered load per server equals ρ/N and hence the average service time for a single server system composed of N servers equals $1/[\mu(1-\rho/N)]$. If, however, a packet can exploit all N servers in parallel, the average per packet service rate equals $N\mu$ and consequently $T = 1/[N\mu(1-\rho/N)]$. Thus, the average service time is for the "multi-server" system decreased by a factor of N (which equals the increased packet, or user, throughput). In fact, we will in the following numerical examples see that the same gain and underlying reasoning are applicable also for multi-cell scenarios.

B. Numerical Results

The performance of Multi-Carrier HSDPA has been evaluated by means of time-dynamical multi-cell system simulations in a scenario representing a dense urban network deployment. The following network configurations are compared:

1. Single-Carrier HSDPA system composed of 1,2, 3, and 4 carrier frequencies (1-4 x 5 MHz)
2. Multi-Carrier HSDPA system composed of 2, 3, and 4 carrier frequencies (MC 2-4 x 5 MHz)

For a fair comparison in terms of available system resources – including, for example, backhaul transmission, spectrum bandwidth, baseband processing, and radio frequency hardware – system configurations having the same bandwidth should be compared. For example, a Multi-Carrier HSDPA system with 2 carriers should be compared with a (Single-Carrier) HSDPA system composed of 2 carriers.

1) System Model and Simulation Assumptions

Key radio environment related parameters are summarized in table I. A simplified time-dynamical traffic model is applied. Users arrive to the system according to Poisson process and their positions are random according to a uniform distribution. An arriving user immediately initiates a download of a file and when the file download is completed the user disconnects. Hence, in this model, the observed per packet throughput is equal to the user throughput.

Assuming files having a fixed size f [bits] and a file arrival intensity λ [files/second/sector], the offered load per sector (average sector throughput) equals λf [Mbit/s/sector], and the experienced per packet (user) throughput equals f/t (where t is the time spent in the system for a packet of size f, including queuing and transmission time).

For the Multi-Carrier HSDPA system all users connect to all carriers and the scheduling functionality (located in the base station, or NodeB) will in a joint fashion schedule transmissions for all users on all available carriers (according to a "proportional fair" scheduling mechanism). For the single-carrier system, instead, each user will select on which carrier to connect randomly with equal probability. The scheduling is for the single-carrier system performed in a disjoint fashion per carrier.

TABLE I. RADIO NETWORK PARAMETER ASSUMPTIONS.

Parameter	Value
Number of 3-sector sites	19
File arrival process	Poisson process
File size	500 kB
Type of UE Receiver	Type 3 (GRAKE2)
Maximum L1 data rate (per carrier)	14.4 Mbps
Log normal fading - Standard deviation - Inter-NodeB correlation - Correlation Distance	 8 dB 0.5 50 m
NodeB Tx power	20 W/5MHz
Control channel over head	28 %
Indoor penetration loss	10 dB
Fraction of indoor users	100%
Path loss at 1m	15.3 dB
Path loss attenuation factor	3.76
Fading characteristics	Pedestrian A
Carrier frequency	2 GHz

2) Simulation Results

In figure 3 the average user throughput is plotted as a function of offered load (average sector throughput). The performance is depicted for different number of carriers for single-carrier HSDPA and Multi-Carrier HSDPA systems, respectively. Up to the points where systems become severely congested (and user throughput approaches 0 Mbps), the Multi-Carrier HSDPA system configurations with N carriers bring the expected N-fold gain in average user throughput as compared to the single carrier HSDPA system with an equal number of carriers. In practice though, the performance for a saturated system is less interesting because networks are typically dimensioned so that average system utilization (fractional load; which corresponds to ρ in the analysis in section IV.A) is well below 100% – even during busy hour. And, for all stable traffic conditions (that is, fractional load less than 100%), Multi-Carrier HSDPA will reduce the probability for a buildup of users in a sector, which translates into a higher average user throughput.

The gain can also be expressed in terms of supported offered load for a given quality of service level. From this point of view, the gain of Multi-Carrier HSDPA is a decreasing function of fractional load. However, we believe that from an end-user experience point of view, the gain seen in user throughput at given offered load should in the context of mobile broadband access services be the most important to consider when assessing the gain of Multi-Carrier HSDPA.

Moreover, it is interesting to note that Multi-Carrier HSDPA will increase the user throughput by a factor N throughout the system coverage area; that is, even at the cell edge. This fact is illustrated in figure 4, which shows the CDF of user throughput for a system composed of 2 carriers and an offered load of 6.4 Mbit/s/sector. For instance, in this example, the 5-percentile user throughput is increased by 100% (from 300 kbit/s to 600 kbit/s).

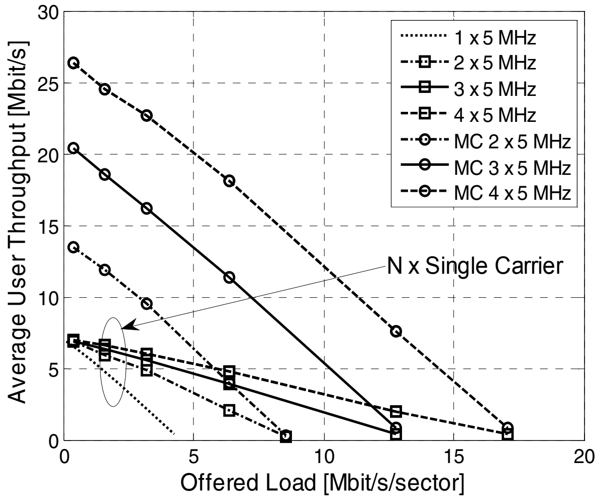

Figure 3. Average user throughput [Mbit/s] as a function of offered load [Mbit/s/sector] for a Single-Carrier HSDPA system (1-4 x 5 MHz carriers) and a Multi-Carrier HSDPA system (2-4 x 5 MHz carriers), respectively.

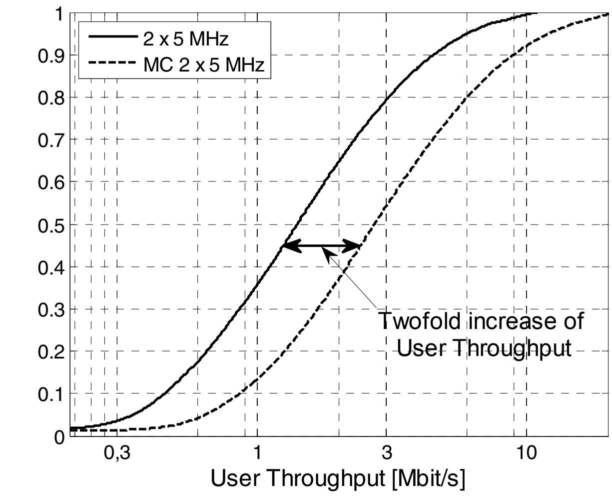

Figure 4. Empirical Cumulative Distribution Function (CDF) of user throughput [Mbit/s] for a Single-Carrier HSDPA system (2 x 5 MHz) and Multi-Carrier HSDPA system (2 x 5 MHz), respectively. The offered load equals 6.4 Mbit/s/sector.

V. CONCLUSIONS

The evolution of WCDMA/HSPA towards higher rates has in this paper been discussed with emphasis on the possibility to use multiple carriers simultaneously for individual users; so called multi-carrier operation, or Multi-Carrier HSPA. Focusing on the downlink, the impact on network architecture and possibilities to reuse LTE terminal implementation for Multi-Carrier HSPA was discussed. Moreover, numerical results show that, compared to single-carrier operation, an *N*-fold gain can be expected for a Multi-Carrier HSDPA system composed of *N* carriers. For example, the gain of Dual-Carrier HSDPA equals 100%, and so forth. It is also notable that, contrary to several other enhancements proposed for cellular systems, the gain is *N*-fold for all users in the coverage area. Thus, thanks to large synergies with existing radio access network architecture, protocols, and terminal platforms, Multi-Carrier HSPA will be a cost-effective way for operators to provide higher bit rates for mobile broadband services.

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