System Performance of Inter-NodeB MF-HSDPA with Enhancements to Backhaul Flow/Congestion Control

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Abstract— **In this paper, we study the feature of Multi-Flow HSDPA (MF-HSDPA), which allows simultaneous transmission of separate data packets from two or more serving cells (across different sectors or NodeBs) to a User Equipment (UE). This new feature brings challenges for system design, especially for the Inter-NodeB case, in which the serving cells reside in different NodeBs. To address these challenges, we propose enhancements to the Radio Link Control (RLC) layer and backhaul flow control/congestion control. Simulation results show significant performance gain can be achieved by the MF-HSDPA feature. The gain is more promising when the backhaul is congested, because Inter-NodeB MF-HSDPA offers "backhaul diversity" by utilizing two backhaul links to serve a MF UE.**

I. INTRODUCTION

HSDPA is the most popular packet-switched air-interface for 3rd Generation (3G) cellular systems. Over the last few years, a number of advanced features, such as Higher Order Modulation, Multiple Input Multiple Output (MIMO), Dual Cell/Carrier-HSDPA (DC-HSDPA) and Multi-Carrier HSDPA (MC-HSDPA), have been added to the HSDPA specifications. These enhanced features offer improvements in data rates, user experience, and system capacity.

Recently, a new enhancement, called Multi-Flow HSDPA (MF-HSDPA), is being discussed in the HSPA specifications. MF-HSDPA further improves user experience and throughput of cell-edge users by allowing multiple cells (across different sectors or NodeBs) to transmit separate data packets to a single user in soft or softer handover [1][2].

In the proposed MF-HSDPA feature, the data can be aggregated from multiple cells residing either in the same NodeB (Intra-NodeB MF-HSDPA) or in different NodeBs (Inter-NodeB MF-HSDPA). For Intra-NodeB aggregation, the protocol architecture is the same as that of aggregation in MC-HSDPA, where a single MAC (Media Access Control) entity handles multiple HARQ (Hybrid-Automatic Repeat reQuest) entities, each mapped to a cell. A single data stream is split at the MAC layer at the NodeB, and transmitted over multiple serving cells. At the receiver side, a single MAC entity merges the data received from all the serving cells and passes the data to the upper layer in-order. For Inter-NodeB aggregation, on the other hand, data is sent to the UE through two NodeBs, each having its own MAC-ehs entity (MAC-ehs is the MAC entity in NodeB and UE supporting HS transmission). This requires the data to be split at a higher layer (i.e., RLC or higher), as shown in Figure 1.

The Inter-NodeB data aggregation brings new challenges to the design of the Iub flow control. Specifically, for Inter-NodeB MF, data at the Radio Network Controller (RNC) is forwarded to each NodeB in batches. The size of the batches is determined by the flow control request made by the respective NodeB. As a consequence, the RLC Protocol Data Units (PDUs) may not arrive at the RLC receiver in UE in the same order as they are transmitted. Even if the channel conditions in the two cells are identical and error-free, the RLC PDUs received across the two serving cells may be out-of-order due to the batched nature of the Iub flow control. This may lead to holes in the RLC sequence number space at the UE receiver.

To avoid excessive RLC retransmissions, the RLC layer must be able to distinguish holes caused by skew from those caused by over-the-air losses. This requires *RLC enhancements* either on the RNC side or on the UE side.

To reduce the out-of-order delivery seen at the RLC receiver, the size of batches of packets sent from the RNC to the NodeB should be made as small as possible. This requires certain *enhancements to the Iub flow control algorithm*. In this paper, we present these enhancements to address the challenges raised by Inter-NodeB MF-HSDPA.

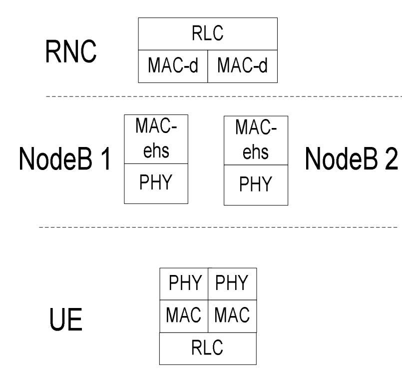

Figure 1: Protocol stack for Inter-NodeB aggregation

Moreover, the Iub link has limited bandwidth and may be congested when the flow control request from the NodeB is larger than its bandwidth. For Inter-NodeB MF, congestion on one Iub link may lead to unbalanced data splitting between the two serving NodeBs. This can exacerbate the issue of out-of-order RLC PDUs seen at the RLC receiver. To address this, we propose an Iub congestion control algorithm and study the system performance of Inter-NodeB MF-HSDPA under a limited bandwidth Iub link.

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The rest of this paper is organized as follows: enhancements to the RLC layer are described in Section II. Section III, discusses enhanced Iub flow control/congestion control schemes required for Inter-NodeB MF-HSDPA. In Section IV, simulation results are provided to show the benefits of MF-HSDPA with limited backhaul. The paper is concluded in Section V.

II. RLC ENHANCEMENTS

In this section, we present an RNC-based RLC enhancement scheme [4]. In this scheme, the RNC is required to remember the cell which a RLC PDU is sent to. With this knowledge, when the RNC receives a Status PDU from the UE, it can infer the Last RLC Sequence Number (LSN) that has been successfully received on each cell. When the RLC transmitter in the RNC finds a RLC SN gap reported by the UE, in contrast to a legacy RLC transmitter in which all SNs in the gap will be retransmitted immediately, here the RLC transmitter has two options:

- If the SN in the gap is smaller than the LSN on the cell where the PDU in the gap was sent, the gap is a genuine loss and the RLC transmitter will retransmit the PDU.
- Otherwise, this gap is considered due to skew:
  - If the gap is not part of any existing gap, a timer called RetransmissionDelayTimer is started for this gap. Else, if the gap is an old one or part of an old one, it will inherit the RetransmissionDelayTimer value of the old gap.
  - For gaps that have RetransmissionDelayTimer running, they are handled as follows:
    - If the gap is filled before the RetransmissionDelayTimer timer expires, the UE stops the timer.
    - If the gap is not filled when the timer expires, the RLC transmitter at the RNC will retransmit the unacknowledged PDUs in the gap.
    - If before the timer expires, the gap becomes smaller than the LSN on the cell it is sent (this can happen since the LSN keeps increasing with new received Status PDU), the gap is considered as a genuine loss and will be retransmitted immediately. The RetransmissionDelayTimer is stopped.

III. ENHANCEMENTS TO IUB FLOW CONTROL AND CONGESTION CONTROL

To reduce the out-of-order delivery of RLC PDUs seen at the RLC receiver, a short queue at each NodeB is desirable. At the same time, frequent buffer under-runs should be avoided to fully utilize the physical layer resource. Thus, the flow control algorithm should ensure that the amount of data each NodeB requests from the RNC matches the UE throughput on this NodeB. This will also maintain a tight range on the queueing delay at each NodeB such that the delay differential seen by PDUs served by the two NodeBs is optimized.

Along with flow control, Iub congestion control also plays a key role in regulating the queueing delay at each NodeB: in cases where the Iub capacity is the bottleneck, the flow control requests should be scaled to match the Iub capacity.

In this section, we present an enhanced flow/congestion control algorithm. Due to space limitations, we only present a high-level description of the flow/congestion control algorithm. Details of the algorithm can be found in [5] [6].

For ease of discussion, we distinguish the UEs in a cell as:

1. Primary UEs: Legacy UEs or MF UEs who have this cell as their primary serving cell
2. Secondary UEs: MF UEs who have this cell as their secondary serving cell.

A. Assumptions on Iub

We assume that all cells at a NodeB share the Iub capacity. However, Iub capacity is not shared between different NodeBs. We also assume the Iub capacity is fixed and known to the NodeB, but not known to the RNC [7].

B. Flow Control Request

The flow control request is generated on a per flow basis (note that one UE may have multiple flows). For each flow, the NodeB periodically requests data from the RNC. (Across flows, the requests can be generated at different time.) The amount of data requested tries to maintain a stable target queueing delay at the NodeB. As shown in [5], one possible approach to computing the amount of data to be requested at the NodeB for flow i, denoted by R_i, is

$$R_i = \max(Q_{target} - Q_{NB}, 0),$$

where Q_{NB} is the current NodeB queue length, and Q_{target} is target NodeB queue length which is given by

$$Q_{target} = Th_{est}\left[T_{max} - \frac{(Th_{est} - Th_{min})(T_{max} - T_{min})}{Th_{max} - Th_{min}}\right]$$

where Th_{est} is the average throughput of flow i over this NodeB; T_{max}, T_{min}, Th_{max} and Th_{min} are the upper and lower bounds of the target queueing delay and average throughput respectively. The intuition is that the target queueing delay is a linear decreasing function of Th_{est}. When Th_{est} reaches Th_{max}, the target queueing delay reaches T_{min}. When Th_{est} is at Th_{min}, the target queueing delay equals $T_{max.}$ When Th_{est} is in between, the target queueing delay is a linear decreasing function of Th_{est}, as shown in Figure 2.

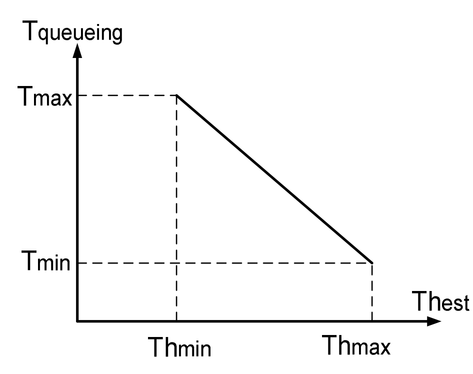

Figure 2: Target queueing delay as a function of Th_{est}

In cases where the amount of data requested by the NodeB is larger than the Iub link capacity, to avoid unnecessary Iub link congestion, the NodeB scales the requests on a per flow basis to keep the total requests across UEs within the Iub capacity. Moreover, the NodeB needs to prioritize primary UEs over secondary UEs to minimize possible impact of MF UEs on the performance of primary UEs. To fulfill these purposes, NodeB calculates the total requests from all the flows and scales the requests in accordance with the Iub capacity and a two-tier prioritization scheme. Specifically, let C denote the Iub capacity. For each flow *i* for primary UEs, if

$$\sum_i R_i \geq C$$

then R_i is scaled as

$$R_i \leftarrow C R_i / \sum_j R_j$$

otherwise, the remaining capacity is distributed among the flows for secondary UEs, in proportion to their requests.

C. Response of RNC to the Flow Control Request

The Flow Control request is sent by the NodeB to the RNC during the Flow Control period. In Figure 3, this period is shown as X ms. However, to avoid building large queues at the NodeB, the RNC can send smaller amounts of data (than requested by Flow Control) more frequently than the Flow Control period. As an example, if the Flow Control request is for D bytes, the RNC can send (D*Y/X) bytes every Y ms, for a total of D bytes over X ms.

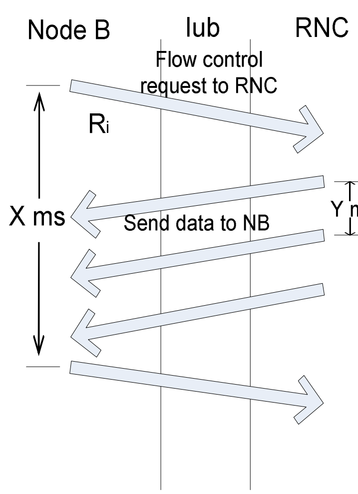

Figure 3: Sketch of Iub flow control algorithm

If the amount of data at the RNC is less than the total amount of data requested by NodeBs, the RNC would send data to each NodeB in proportion to its request.

The RNC adds a Delay Reference Time (DRT) field in the header of each data frame sent to the NodeB to enable congestion detection at the NodeB.

D. Congestion Detection at NodeB

The NodeB detects Iub congestion based on the measured downlink Iub delay. The Iub delay is computed as the difference between the time the data frame is received by NodeB and the DRT value in the frame.

During each flow control cycle, a counter of congested packets is maintained. If the downlink Iub delay is larger than a threshold, $T_{thresh,delay}$, for an incoming packet, the counter of congested packets is incremented by one. At the end of each flow control period, if the counter of congested packets is higher than a threshold, C_{thresh}, congestion is declared for this flow.

It is worth noting that in the steady state without flows arriving, there should be no congestion on the Iub due to the scaling mechanism mentioned in Section II.B. However, when a new flow arrives and the NodeB generates the first Flow Control request for this flow, congestion could happen since the Flow Control requests of all the existing users have not been updated accordingly.

E. Congestion Reaction by the NodeB

When congestion is detected, the flow control request for the congested flow is scaled down by the NodeB; the scaling recovers gradually once the congestion is over.

Specifically, the request for flow *i*, R_i, after the scaling in Section II.B, is further scaled as:

$$R_i = v_i * R_i$$

where $v_i = 0.5$, if congestion is detected for flow *i*; otherwise, $v_i = \min[(v_i + 0.1), 1]$. In other words, when the flow is in congestion, its request is reduced to half; otherwise, the scaling factor gradually increases to 1.

IV. SIMULATION RESULTS

In this section, we present simulation results showing performance gains of the MF-HSDPA feature assuming finite Iub capacity, which exercises both flow and congestion control algorithms. We also simulate cases where an MF-HSDPA UE and a legacy UE are present at the same time, and share air-interface resources as well as limited Iub capacity. Our aim is to evaluate how the performance seen by each type of UE is impacted by the presence of the other.

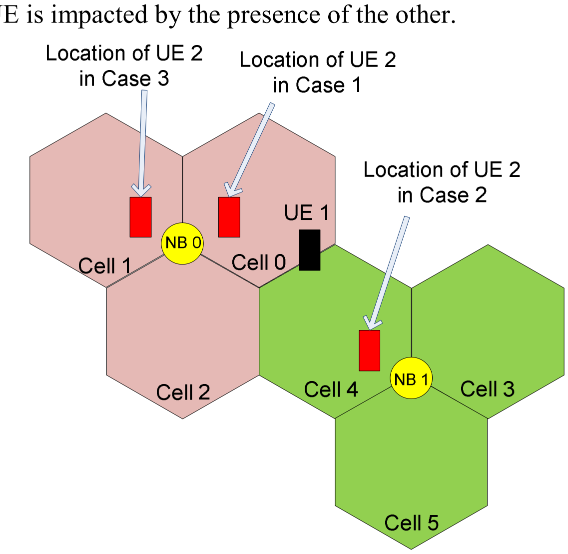

Figure 4: Network layout

A. Simulation setup

The following scenarios were chosen for our simulations: there are two UEs in the network, as shown in Figure 4:

- UE 1 is either an Inter-NodeB MF UE or a legacy UE. It is at 0dB geometry, and downloads a large file using TCP. Note that we use TCP as the transport protocol since UDP can hide some of the effects of the interaction. As an example, if the MF-HSDPA sees larger out-of-order delivery at the RLC receiver due to the interaction, TCP may react by timing out, while UDP will not show such impacts.
    - When UE 1 is a legacy UE, cell 0 is its serving cell.
    - When UE 1 is an Inter-NodeB MF UE, cell 0 is its primary serving cell and cell 4 is its secondary serving cell. These two serving cells are equally strong.
- UE 2 is a legacy UE. It has a bursty downlink traffic source with burst size 1Mb and inter-burst arrival time of 1 second. In different simulation runs, UE 2 is located in different cells, but always at 15dB geometry. Choosing a high geometry allows its air-interface capacity to be larger than the Iub link capacity. Thus, whenever it has traffic, it congests the Iub link. Moreover, the traffic of UE 2 is modeled as UDP to maximize the impact from burst arrival and departure. In the simulations, we choose three different locations for UE 2:
    - Case 1: UE 2 has cell 0 as its serving cell. In this case, UE 2 is in the primary serving cell of UE 1, and shares both scheduler and Iub link with UE 1.
    - Case 2: UE 2 has cell 4 as its serving cell. In this case, UE 2 is in the secondary serving cell of UE 1, and shares both scheduler and Iub link with UE 1 when UE 1 is in MF mode.
    - Case 3: UE 2 has cell 1 as its serving cell. In this case, UE 2 only shares Iub link with UE 1.

Based on our two-UE layout, only the Iub link capacity for NodeB 0 (Cells 0, 1, and 2) and NodeB 1 (Cells 3, 4, and 5) need to be specified. We consider four combinations of the Iub capacities:

1. NodeB 0: 6Mbps, NodeB 1: 6Mbps;
2. NodeB 0: 6Mbps, NodeB 1: 2Mbps;
3. NodeB 0: 2Mbps, NodeB 1: 2Mbps;
4. NodeB 0: 2Mbps, NodeB 1: 6Mbps.

These Iub capacities are chosen to exercise different behaviors. With the 6Mbps Iub link, the air-interface is the bottleneck for UE 1; whereas with the 2Mbps Iub link, the Iub link is the bottleneck for UE 1. For UE 2, the Iub link is always the bottleneck.

We follow the NodeB centric soft prioritization used in [3]. In particular, the scheduler provides a relatively higher priority for the primary traffic. The details of the scheduler are discussed in [3][5].

The rest of the simulation assumptions, summarized in Table 1, follow the methodology used by 3GPP in standardization studies for WCDMA/HSPA [8].

Table 1: Simulation Assumptions

Parameters	Comments
Cell Layout	Hexagonal grid, 19 NodeBs, 3 sectors per NodeB with wrap-around
Inter-site distance	1000 m
Carrier Frequency	2000 MHz
Path Loss	L=128.1 + 37.6$\log_{10}$(R), R in kilometers
Log Normal Fading	Standard Deviation : 8dB Inter-NodeB Correlation:0.5 Intra-NodeB Correlation: 1.0
Channel Model	Pedestrian A at 3km/h
Soft Handover Parameters	R_{1a} (reporting range constant) = 6 dB, R_{1b} (reporting range constant) = 6 dB
UE capabilities	All UEs are capable of 15 SF 16 codes and 64QAM for each cell. All UEs are MF-HSDPA capable with Type 3i receiver.
DL Scheduling	NodeB centric soft prioritization (detailed description can be found in [3])
RLC Layer Parameters	RLC PDU size is fixed as 300 bytes Timer_Status_Prohibit is 100ms

B. Simulation results: UE 1 only

Table 2 shows the TCP throughput and throughput gain for the case where only UE 1 is present. It is worth noting that with a single UE in the network, Iub link can be the bottleneck, but Iub congestion does not happen, as the flow control request is scaled in accordance with the Iub link capacity as described in Section II.B. From the table, we observe that MF-HSDPA achieves significant throughput gain over legacy operation in all the cases. More interestingly, in the Iub limited case, the throughput is determined largely by the Iub link capacity, and MF UE shows ~100% gain over the legacy UE. This is because Inter-NodeB MF offers a new dimension of diversity by utilizing two Iub links to serve one MF UE. This new diversity can be seen as “Iub diversity”.

Table 2: TCP Throughput Gain for UE 1 Only Case

	Iub Link Capacity (Mbps)		TCP Throughput (Mbps)		Throughput Gain (%)
	Primary Cell	Secondary Cell	MF Mode	Legacy Mode	
Air-interface limited	6	6	6.7	4.4	52.3
Imbalanced Iubs	6	2	5.3		20.5
Iub limited	2	2	3.8	1.9	100
Imbalanced Iubs	2	6	5.3		179

C. *Simulation results: UE 1 and UE 2*

In Table 3, we show the TCP throughput and throughput gain for UE 1 when we have both UE 1 and UE 2 in the network. From the table, we see that substantial gain from MF-HSDPA is observed in all the cases. In particular, in Cases 1 and 3, where the Iub link can be highly congested on the primary serving cell of UE 1, Inter-NodeB MF provides backhaul diversity and shows significant throughput gain over the legacy case. We also looked at the performance of the legacy UE: across all the cases, we did not see any significant difference in the legacy UE's performance, when UE1 is either in legacy mode or MF mode.

Table 4 shows the RLC retransmission rate due to RetransmissionDelayTimer expiration. It can be seen that Iub congestion has little impact on RLC retransmission rate.

V. CONCLUSIONS

In this paper, we discussed new challenges for system design in Inter-NodeB MF-HSDPA and proposed enhancements to Iub flow/congestion control to address these challenges. We then studied the performance of Inter-NodeB MF-HSDPA with these enhancements under limited backhaul bandwidth.

Simulation results showed that MF-HSDPA UEs see significant throughput gains. More interestingly, a congested Iub often increased the gain from Inter-NodeB MF due to "backhaul diversity". Moreover, the impact to legacy UEs due to MF-capable UEs was seen to be insignificant in all the simulated scenarios.

REFERENCES

[1] 3GPP document RP-111375, "HSDPA multiflow data transmission", Qualcomm Inc, Orange, Nokia Siemens Networks, Ericsson, ST-Ericsson, T-Mobile USA, Alcatel-Lucent, Huawei, 2011

[2] Danlu Zhang, Pavan Kumar Vitthaladevuni, Jilei Hou and Bibhu Mohanty, "Performance Gains of Single-Frequency Dual-Cell HSDPA", GLOBECOM 2011.

[3] W. Ge, R. Kapoor, D. Zhang, S. Sambhwani, and M. Scipione, "System Performance of Inter-NodeB MF-HSDPA with RLC and MAC Enhancements" IEEE ICC 2012.

[4] 3GPP document R1-110126, "DL Scheduling and Flow Control assumption for Inter-NodeB aggregation", Qualcomm Incorporated, 2010.

[5] 3GPP document R2-114477, "System Performance Evaluation of SF-DC Inter NodeB Aggregation in Assuming Realistic RLC and Flow Control", Qualcomm Incorporated, 2011.

[6] 3GPP document R2-114479, "TCP Performance Evaluation of SF-DC Inter NodeB Aggregation Assuming Realistic RLC, Flow Control and Iub Congestions Control", Qualcomm Inc., 2011

[7] S. Nadas, S. Racz, Z. Nagy, and S. Molnar, "Providing congestion control in the Iub Transport Network for HSDPA" IEEE Globecom 2007.

[8] 3GPP document R1-110563, "Simulation Framework for System Evaluation of Multi- Point HSDPA", Qualcomm, Ericsson, ST-Ericsson, Nokia Siemens Networks, Nokia, Huawei, HiSilicon, ZTE, 2011.

Table 3: TCP Throughput and Throughput Gain for UE 1

Iub Link Capacity (Mbps)		Case 1: UE 2 is in cell 0 (Primary serving cell of UE 1)			Case 2: UE 2 is in cell 4 (Secondary serving cell of UE 1)			Case 3: UE 2 is in cell 1 (Share Iub link with UE 1)		
Pri	Sec	Throughput in MF mode (Mbps)	Throughput in Legacy mode (Mbps)	Gain (%)	Throughput in MF mode (Mbps)	Throughput in Legacy mode (Mbps)	Gain (%)	Throughput in MF mode (Mbps)	Throughput in Legacy mode (Mbps)	Gain (%)
6	6	6.3	3.6	75	6.1	4.1	48.8	6.3	3.6	75.0
6	2	5.0		38.9	4.5		9.8	5.2		44.4
2	2	3.0	1.1	173	2.7	1.9	42.1	3.0	1.1	173
2	6	4.8		336	4.8		153	4.8		336

Table 4: RLC Retransmission Rate due to RetransmissionDelayTimer Expiration for UE 1

Iub Link Capacity (Mbps)		RLC Retransmission Rate due to expiration of RetransmissionDelayTimer (%)		
Primay cell	Secondary cell	Case 1: UE 2 is in cell 0	Case 2: UE 2 is in cell 4	Case 3: UE 2 is in cell 1
6	6	0.005	0.1	0
6	2	0.2	0.4	0.08
2	2	0	0	0
2	6	0.1	0.2	0.09