Effect of Channel-Quality Indicator Delay on HSDPA Performance

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Abstract- **This paper evaluates the effect of the channel estimation inaccuracy on the performance of an HSDPA system. This study provides some results from system level simulations that have been conducted over a very complete dynamic simulator which models an HSDPA system full compliant with specifications. This emulator allows performing multi-user transmission and link adaptation with a limited modulation and coding scheme (MCS) selection based on the channel quality indicator (CQI) modes. Many factors such as the user equipment (UE) speed, the employed scheduling algorithm or the traffic load have been considered in the assessment. Moreover the intrinsic constraints of a WCDMA system like HSDPA have been also taken into account, i.e. the maximum number of channelization codes and the maximum transmitted power have been modelled jointly with a complete and dynamic interference characterization.**

Keywords- **HSDPA, CQI, Scheduling, Link Adaptation.**

I. Introduction

In order to allow high data rate transmission in Wideband Code Division Multiple Access (WCDMA) third generation mobile networks, High Speed Downlink Packet Access (HSDPA) and its uplink counterpart HSUPA have been recently standardized in 3GPP. HSDPA is already in a very mature state, and first commercial systems are being rolled out in the course of this year. HSDPA achieves high data rates of up to 14 Mbps by means of adaptive modulation and coding, fast scheduling mechanisms (each TTI or Transmission Time Interval of 2 ms) and a powerful Hybrid ARQ mechanism. Link adaptation (LA) is a process of paramount importance to optimise system functioning and therefore user equipment reports channel state either cyclically or in a triggered-based manner by means of the Channel Quality Indicator (CQI).

Several simulation results for HSDPA have been published in conferences and journal papers during last years. A good survey of HSDPA principles and performance simulations can be found in [1]. In [2] a closed formulation was proposed for the calculation of CQI whereas in [3] and [4] different reporting schemes were analyzed evaluating the effect produced by increasing report periods. Several scheduling algorithms have also been evaluated (see e.g. [5]) studying how the algorithm behaves for a constant bit rate traffic pattern.

This paper assesses the intrinsic delay of the Channel Quality Indicator (CQI) reporting process and its effect on the HSDPA system performance. As it is demonstrated in this paper, this delay has a severe impact in the efficiency of the link adaptation process and also affects the performance of the scheduling mechanisms since the upper limit of the resources allocated to each user depends on this report. This paper accomplishes this analysis in a mixed traffic scenario which consists of both best effort (web) and real time traffic (H.263 video telephony). A proper modelling of the HSDPA system constraints is implemented and a complete characterization of interferences is proposed. That is, to the best authors' knowledge, the singularity of this research as compared with for example [6] or [7]. The former considers an ideal traffic source and simplifies the interference variability whereas the latter uses a very simple model of the channel estimation inaccuracy.

The presented results prove that not only the mobile speed determines to what extent the CQI reporting delay has an effect on the system performance but also the scheduling algorithm and the system load among other factors.

This paper is organised as follows. First, the LA mechanism of HSDPA is briefly cleared up highlighting the time elapsed since the user sends its CQI report till the Node-B transmits according to this information. In Section III, all the fast packet scheduling algorithms compared in this paper are described. Next, in Section IV the evaluation environment is presented. Finally, the results of different simulations are presented and discussed and the most important conclusions are summarised.

II. Link adaptation Based on User Reports

In HSDPA the user equipment (UE) is responsible for reporting periodically to the Node-B the downlink channel quality. This channel information is numerically represented by means of the CQI, whose definition is explained in detail in [8]. Numerically CQI extends from 1 to 30, increasing its value when channel quality augments. Each CQI can be translated into a combination of transmission parameters since [8] establishes a relation among each CQI and a concrete value of the transport block size (TBS), number of simultaneous channelisation codes, modulation and code rate. These parameters were specifically chosen to configure a 1dB granularity in the carrier to interference ratio (CIR) among consecutive CQIs for a Block Error Rate (BLER) level of 10%.

As the channel state information is provided by the UE to the Node-B there is a non-negligible delay between channel estimation and the reception of this information in the Node-B. Moreover, some time pass since the Node-B receives the CQI until it uses this information in the LA and scheduling mechanisms. Besides, at least 2 slots more pass until the UE begins to receive the data scheduled in the Node-B due to the constant delay between the HS-SCCH channel which signals the start of data transmission and the HS-PDSCH which handles the data. The whole delay is around 6 ms, that is to say, three TTIs.

All of the previous delays are inherent in the HSDPA functioning and hence are not controllable. This paper deals with the only delay which can be controlled by the system, i.e. the reporting period delay.

In general, the higher the reporting delay is the higher inaccurate the channel estimation is. This inaccuracy depends on how the channel and therefore the CIR level vary in the time domain. This paper assesses the effect of this inaccuracy on the system performance depending on different factors as for example the scheduling algorithm employed.

III. Fast Packet Scheduling

Fast packet scheduling performed in Node B is one of the main features of HSDPA. Its implementation is not specified and investigation in this field can provide a great differentiation among different HSDPA systems.

In each TTI the scheduler makes a decision about to which UEs the Node-B will transmit in the next TTI and the characteristics of this transmission (TBS, number of channelization codes, code rate and power).

The scheduling decision is made taking into account a list of candidate UEs which have data to be delivered in the Node-B buffer. The scheduler can differentiate if these data are new or are waiting for retransmissions, giving a highest priority to retransmissions. A maximum number of code multiplexed users is fixed 'a priori' in the simulations, setting a limit to the number of multiplexed UEs in each TTI.

Category 10 UEs have been considered, which are the most flexible equipments, and only 30 modes of transmission, those corresponding to the 30 modes defined by the CQI table for this category, are employed. In spite of this restriction, the number of modes is enough to correctly consider the flexibility of HSDPA. Moreover, it has been demonstrated that such a resource allocation model can be more robust to the channel estimation inaccuracy than a more flexible one when the channel estimation inaccuracy is within some limits [7].

In this paper two kinds of resource allocating schemes are analyzed. The former does not guarantee any quality of service (QoS) since it employs scheduling algorithms that are not QoS aware. The latter is based on separating different types of services what can preserve real time services from best effort services.

Within the first group some classic scheduling algorithms such as Round Robin, Max-CIR and Proportional Fair are evaluated. Depending on the algorithm, a different prioritising scheme is established among the scheduling candidates. Round Robin scheduler prioritises users with an oldest last serving time, MaxCIR gives priority to the users with the highest last reported CQI (the best channel quality) while Proportional Fair prioritises users with the highest fairness factor (Ff) in the current time interval k defined as:

$$Ff_i(k) = R_i(CQI(k)) / \overline{R_i(k)} \qquad (1)$$

where $R_i(CQI(k))$ is the maximum data rate that UE i can transmit provided the last reported CQI and $\overline{R_i(k)}$ is the mean data rate of the UE i in the time k, which is updated every TTI the UE has data waiting for transmission in the buffer according to the next formula:

$$\overline{R_i(k)} = \left(1 - 1/T\right)\overline{R_i(k-1)} + \left(1/T\right)R_i(k) \qquad (2)$$

where T is the number of TTI considered in the averaging period, $\overline{R_i(k)}$ is the updated mean rate, $\overline{R_i(k-1)}$ is the old mean rate and $R_i(k)$ is the last instantaneous data rate.

Once the candidate list has been ordered the scheduler allocates resources. Generally the retransmissions are first served and afterwards the new transmissions if there are codes and power left. The scheduler processes a lot of information to make a decision as for instance the channel estimation reported by each user, the buffer size, the power available in the Node-B for transmission and, what is more important, the difference between this quantity and what the UE considered in the channel estimation.

Once a user has been served, the process is repeated with the next UE in the prioritised list until there is no more power or codes left. The objective of this scheme is to allocate the minimum power and the most efficient combination of transport block size and code rate to ensure a block error rate (BLER) of around 10% if possible.

All the afore-mentioned scheduling algorithms belong to the first group and provide a more or less good performance when handling best effort traffic but, in order to fulfill the QoS of real time (RT) users, other strategies must be considered. Therefore, another kind of resource allocating schemes is needed. The simplest option is to serve first the RT users and later the best effort traffic. This scheme is able to maintain the QoS for RT users if a call admission control (CAC) mechanism prevents congestion in the cell. This simple differentiation of services provides great results when considering a mixed scenario with RT and best effort users as compared with the case in which there is not differentiation. This aspect is clearly appreciated in the results presented in section V.

IV. Evaluation environment

To conduct this investigation an evolved version of the emulator presented in [9] has been employed, emulating HSDPA packet data transmission.

The simulator models a multi-tier macrocellular architecture with one hexagonal central cell with radius of 2800 or 1000 meters and 3 additional cell tiers. Simulations are only conducted in downlink since HSDPA is specific of this direction. Users are on the move within the cell radius.

The available number of codes has also been carefully taken into account, and the same assumptions as in [10] have been made, assuming a value of 1 for the soft handover overhead. The maximum number of HS-SSCH codes has been set to 4, therefore code multiplexing of 4 users per TTI is allowed.

The HARQ mechanism of HSDPA has been implemented in a very realistic way. A stop and wait (SAW) protocol with 6 parallel processes has been considered in order to control the transmission to each UE.

The available power is modelled assuming a power consumption for the non data channels of HSDPA according to that used in [10]. The total Node-B power is 43 dBm.

Channel modelling comprises path loss, shadowing and also fast fading. Fast fading modelling is quite important when considering technologies, such as HSDPA, that base their radio operation on link adaptation techniques.

Intra-cell interference on a CDMA system is modelled by means of an orthogonality factor, which is usually denoted as α. In absence of multi-path fading, the codes are perfectly orthogonal and therefore $\alpha = 1$. In the worst case $\alpha = 0$, meaning that orthogonality is entirely destroyed. Typical values of α are between 0.4 and 0.9. In this research a value of 0.8 has been chosen. Thus, the HSDPA carrier to interference (*CIR*) level can be expressed as follows:

$$CIR_{HSDPA} = \frac{\dfrac{P_i}{L_P^{ii} \cdot L_S^{ii}} \psi_i}{\dfrac{(P_{Ti} - P) \cdot (1-\alpha)}{L_P^{ii} \cdot L_S^{ii}} \psi_i + \sum_{j \in \Omega} \dfrac{P_{Tj}}{L_P^{ij} \cdot L_S^{ij}} \psi_j + N_0 \cdot W} \quad (3)$$

where P_i is the addition of the power transmitted in all the channels allocated by the reference cell to the user of interest, P_{Ti} is the total power transmitted by the reference cell, Ω is the set of cells interfering the user and P_{Tj} is the total power transmitted by these interferers. In this expression, the parameters P_{Ti} and P_{Tj} also include the base station power reserved for other channels different from the HSDPA High Speed Downlink Shared Channel (HS-DSCH).

The simulation tool models all the interfering paths from each interfering base station to each UE. Other investigations consider a fixed level of interference coming from other cells or a fixed ratio between other cells interference and own cell interference. The more realistic approach implemented in this work allows a more accurate modelling of the interference variability and therefore of the channel quality variability. This accurate modelling is of paramount importance to assess the system performance most of all when radio access technologies based on link adaptation, as for instance HSDPA, are under consideration.

In the simulations presented in this paper several look-up tables (LUT) CIR vs BLER have been employed, one for each CQI value. These LUT are obtained from the European Network of Excellence NEWCOM [11].

In these LUTs it is also included the effect of the HARQ retransmissions with chase combining. In order to decide if a single block is correctly decoded or not the simulator computes the experienced CIR of this block in each slot of a TTI. After completing the transmission of a whole transport block, the three associated CIR values are averaged and a single CIR_{avg} value is obtained, which represents the quality experienced by the transport block. A LUT is employed to map the CIR value in a BLER value and to decide whether a block is correctly received. When a transport block is received in error, it is not discarded but stored in the receiver buffer and combined with retransmissions according to a specific method. The employed simulator uses the Chase Combining (CC) scheme in which retransmitted blocks are identical to that of the first transmission.

In the simulator web traffic has been modelled as a best effort traffic source. The web browsing service has been modelled as in [12]. It follows an ON/OFF pattern and a rate of around 55 kbps per user is expected due to the chosen parameters in [12]averaging over a long period of time.

Real-time services have also been included in the simulations through the emulation of real-time H.263 video transmissions following the model presented in [13].

V. SYSTEM PERFORMANCE

A meticulous simulation study has been carried out to assess the joint effect of CQI delay and processing and scheduling. Moreover different scenarios have been considered varying user speed and traffic patterns. The user speed is 3 km/h for the pedestrian users and 50 km/h for the vehicular users.

A. Performance with Saturated Traffic Sources

Initially, to determine the maximum cell capacity of the HSDPA system, users are simulated considering their traffic sources saturated. Each user has always 80 kbits pending for transmission in the serving Node-B buffer.

Regarding the cell throughput, the MaxCIR algorithm should achieve the highest performance since it allocates more resources to the users with the best channel quality, i.e. users with the highest available data rate. This fact can be observed in Table 1 and Table 2, which show the mean cell throughput for the MaxCIR, RR and PF algorithms. The cell throughput is defined as the total amount of bits correctly received per second in a cell. Both tables summarise the results obtained after 1800 seconds of system emulation with 15 users randomly distributed in the cell. Clearly the MaxCIR algorithm outperforms the other algorithms while the RR scheduler obtains the worst results as expected.

In addition, the relation between the CQI reporting period and the cell throughput is clarified in Table 1. It can be appreciated a reduction in the cell throughput when the reporting period increases. This effect is due to the fact that the CIR level changes dynamically due to the user movement, shadowing and fast fading and additionally due to the non negligible interference variability. Given that the reporting period increment is near milliseconds and the interference variability is highly reduced in a saturated scenario, the fast fading changeability is the most important factor which justifies the reduction in the cell throughput. This difference is higher in the pedestrian scenario than in the vehicular one. For example, the difference in throughput is between 7% and 14% for the pedestrian case and between 0.2% and 3% for the vehicular case. This effect can be explained regarding the channel coherence time. In case of pedestrian users, fast fading is uncorrelated after 32ms whereas for vehicular users this time is reduced down to 2 ms. For this reason, in a vehicular scenario the reporting period increment has not a relevant effect on the system performance since already with 2ms the fast fading is uncorrelated and only the rest of factors, with slower variability, affect the inaccuracy of the channel estimation.

TABLE I. CELL THROUGHPUT IN MBPS FOR 1000M CELL RADIUS

	pedestrian			vehicular		
CQI reporting period (ms)	MCIR	PF	RR	MCIR	PF	RR
2	8.1466	4.6822	4.2911	7.5443	4.7024	4.1867
256	7.6087	4.1181	3.6732	7.5286	4.5412	4.1783

B. Performance with Best Effort traffic.

In the next scenario only web browsing users are considered. The study is focused in the effect of the CQI reporting period depending on the number of users, the scheduling algorithm and the user speed.

Table 2 collects some significant results in terms of the normalized delay experienced in the transmission of each web object when the MaxCIR algorithm is used. The normalized delay is defined as the delay in milliseconds required for transmitting one kbit of information. The mean value and the 95th percentile are shown in the Table. It can be observed that the higher the reporting period the higher the normalized delay, that is to say, the system performance is deteriorated since a higher normalized delay means more time to transmit the same data. Besides, increasing the number of users entails a higher normalized delay what is quite obvious in interference-limited systems as HSDPA. Moreover, these results reinforce the idea stated before, that is, in case of a vehicular scenario the degradation experienced with increasing reporting periods is greater when the interference variability is higher, i.e. when more users are active in the cell.

The Table 3 compares the performance of the three scheduling algorithms with a fixed number of users. The MaxCIR algorithm provides the best results in the pedestrian scenario. PF improves the RR performance since its functioning is channel state aware and hence it can take advantage of the good channel estimation. In spite of the greater fairness of PF as compared with MaxCIR, in this scenario with 30 users it is not enough to improve the MaxCIR performance in terms of delay. On the other hand, in the vehicular scenario all the algorithms suffer degradation in their performance, more pronounced in the case of the MaxCIR algorithm since this algorithm is totally channel state dependant and in the vehicular environment the channel estimation present lower accuracy. Again the degradation with increasing reporting periods is lower in the vehicular scenario for all the algorithms.

C. Performance with RT traffic.

To measure the level of QoS for the H.263 users, the user satisfaction concept (US) is introduced representing the percentage of H.263 frames transmitted before the next video frame is generated. The scenario for RT traffic considers a fixed number of 8 H.263 users transmitting at 64 kbps and moving in a cell with a radius of 2800m. Figure 1 shows the results after 2 hours of simulation for RR and MCIR algorithms. The set of simulated CQI reporting periods is 2, 8, 16, 32 and 64 ms.

From the results it can be concluded that the MaxCIR algorithm outperforms the functioning of the RR for the simulated environment in both the pedestrian and the vehicular scenarios. It is worth noting that the user satisfaction decreases as the reporting period increases but in a different way depending on the mobility. In the pedestrian scenario the slope is more pronounced than in the vehicular scenario.

TABLE II. NORMALIZED DELAY FOR MAXCIR ALGORITHM

N. of Users	CQI reporting period (ms)	pedestrian MCIR		vehicular MCIR	
		mean	95%	mean	95%
20	2	11.13	23.01	10.30	41.85
	16	13.56	26.83	11.10	44.16
	64	15.53	31.27	11.60	49.61
30	2	15.84	29.36	15.60	70.34
	16	17.63	34.22	15.47	71.15
	64	20.07	39.00	17.85	84.50
50	2	27.53	45.16	24.35	126.90
	16	28.86	48.97	28.10	144.40
	64	30.24	51.02	30.62	156.45

TABLE III. 95TH PERCENTILE OF THE NORMALIZED DELAY

		pedestrian			vehicular		
N. of Users	CQI reporting period (ms)	MCIR	PF	RR	MCIR	PF	RR
30	2	29.36	32.99	36.55	70.34	51.90	44.89
	16	34.22	34.52	42.43	71.15	52.03	45.92
	64	39.00	45.12	49.22	84.50	52.98	48.32

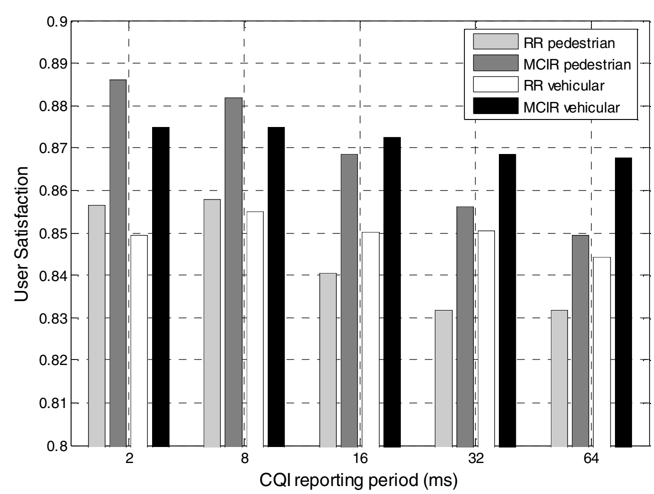

Figure 1. User satisfaction vs CQI reporting period with 8 H.263 users at 64 kbps for RR and MaxCIR algorithms

TABLE IV. USER SATISFACTION WITHOUT SERVICE DIFFERENTIATION

	MCIR		PF		RR	
CQI reporting period (ms)	H263	WWW	H263	WWW	H263	WWW
2	0.8247	0.9715	0.8155	0.9623	0.7847	0.9540
16	0.7965	0.9693	0.7789	0.9648	0.7521	0.9512
32	0.7885	0.9654	0.7705	0.9559	0.7367	0.9513
64	0.7762	0.9672	0.7296	0.9488	0.7325	0.9434

TABLE V. USER SATISFACTION WITH SERVICE DIFFERENTIATION

	MCIR		PF		RR	
CQI reporting period (ms)	H263	WWW	H263	WWW	H263	WWW
2	0.8741	0.9305	0.8624	0.9040	0.8464	0.8969
16	0.8749	0.9221	0.8614	0.9070	0.8423	0.8774
32	0.8570	0.9124	0.8604	0.9035	0.8320	0.8801
64	0.8636	0.9033	0.8579	0.8932	0.8211	0.8682

C. Performance in a mixed traffic scenario

Finally a mixed traffic scenario is considered with 8 H.263 users and 8 web users. Only pedestrian users are considered. The cell radius is again 2800 meters.

The user satisfaction in WWW is defined as the percentage of web pages transmitted in less than 4 seconds. Tables 4 and 5 collect the user satisfaction experimented by the H263 users and the web users in the simulated scenarios. From these results it can be concluded that the MaxCIR algorithm presents the best performance and RR shows again the worst functioning. The PF represents an intermediate point between these two algorithms since it allocates resources in a more intelligent way as compared with RR but does not take the best advantage from good channel conditions as MaxCIR does.

In the differentiation of services there is a transfer in the user satisfaction from the less priority service to the more priority service. By means of this differentiation it is possible to obtain better results in terms of H263 user satisfaction at the expense of a poorer WWW user satisfaction. The results show clearly that the service differentiation becomes a good option to maintain the H263 QoS. An improvement between 5 and 10 percentage points in the H.263 user satisfaction is observed. It is worth noting that the H263 user satisfaction is in this scenario worse than the observed in Fig. 1 since in this case some additional interference is produced in the system due to the transmission of web users.

VI. CONCLUSIONS

In this paper it has been evaluated the effect of the channel estimation inaccuracy on the performance of an HSDPA system. As explained, this inaccuracy is due to the delays in the acquisition and processing of the CQI reports. Generally if the reporting period of the CQI increases the system performance becomes worse. However, it has been demonstrated that this degradation depends on the speed of UE and in some situations on the load or on the resource allocating scheme. There is a trade off between the performance improvement produced by frequently reported CQIs and the degradation in uplink interference produced by these reports. Therefore, it is possible to optimise the CQI reporting period to reduce the number of CQI transmissions while maintaining the users QoS and the overall system performance.

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REFERENCES

[1] H.Holma and A.Toskala, HSDPA/HSUPA for UMTS. John Wiley and Sons, Ltd, 2006.

[2] F. Brouwer et alt., “Usage of Link-Level Performance Indicators for HSDPA Network-Level Simulations in E-UMTS”, in Proc. IEEE ISSSTA, Aug. 2004.

[3] Soo-Yong Jeon; Dong-Ho Cho, “Channel Adaptive CQI Reporting Schemes for HSDPA Systems”, IEEE Communications Letters, Vol.10, Issue 6, pp 459-461, Jun. 2006.

[4] Soo-Yong Jeon; Dong-Ho Cho, “An Enhanced Channel-Quality Indication (CQI) Reporting Scheme for HSDPA Systems”, IEEE Communications Letters, Vol. 9, Issue 5, pp 432-434, May. 2005.

[5] P.J.A. Gutiérrez, “Packet Scheduling and Quality of Service in HSDPA”, Ph.D.dissertation, Aalborg University, Oct. 2003.

[6] T. Kolding. Link and system performance aspects of proportional fair scheduling in WCDMA/HSDPA. IEEE Proc. VTC 2003 vol 3, pp 1717--1722, October 2003.

[7] M. Döttling, A. Seeger, M. Sikora, “Impact of Imperfect Channel Quality Feedback and User Terminal Capabilities on Throughput of HSDPA”. COST 273, Barcelona, Spain, January 2003.

[8] 3GPP, Physical layer procedures (FDD), 3GPP TS25.214 V7.1.0.

[9] J. Gozalvez y J. Dunlop, "System Performance and Adaptive Configuration of Link Adaptation Techniques in Packet-Switched Cellular Radio Networks", Computer Networks Journal (Elsevier), pp 404-426, 2006.

[10] W. Bang, K.I. Pedersen, T.E. Kolding, P.E. Mogensen, “Performance of VoIP on HSDPA”, IEEE Proc. VTC, Stockholm, June 2005.

[11] NEWCOM Project FP6-IST-507325-2002. Available at http://newcom.ismb.it.

[12] P. Barford and M. Crovella, “Generating representative web workloads for network and server performance evaluation”, Joint International Conference on Measurement and Modeling of Computer Systems, June 1998.

[13] O. Lázaro, D. Girma and J. Dunlop, “H.263 video traffic modelling for low bit rate wireless communications”, IEEE PIMRC, pp. 2124-2128, September 2004.