Hindawi Publishing Corporation
Research Letters in Communications
Volume 2008, Article ID 982805, 5 pages
doi:10.1155/2008/982805

Research Letter

Reducing CQI Signalling Overhead in HSPA

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Received 27 January 2008; Accepted 17 March 2008

Recommended by Ibrahim Develi

The efficiency of adaptive modulation and coding (AMC) procedure in high speed Downlink packet access (HSDPA) depends on the frequency of the channel quality information (CQI) reports transmitted by the UE to Node B. The more frequent the reports are the more accurate the link adaptation procedure is. On the other hand, the frequent CQI reports increase uplink interference, reducing thus the signal reception quality at the uplink. In this study, we propose an improved CQI reporting scheme which aims to reduce the required CQI signaling by exploiting a CQI prediction method based on a finite-state Markov chain (FSMC) model of the wireless channel. The simulation results show that under a high downlink traffic load, the proposed scheme has a near-to-optimum performance while produces less interference compared to the respective periodic CQI scheme.

1. Introduction

High-speed packet access (HSPA) aims to advance the performance of the existing UMTS networks by improving the level of quality of service (QoS) and increasing the supported peak data rates at both the forward and the reverse link. HSPA consists of the HSDPA and high-speed uplink packet access (HSUPA) standards.

AMC procedure of HSDPA makes possible the adaptation of the employed transport format and resource combination (TFRC) to the wireless channel variations as well as to the varying rate requirements of the UE. However, as the rate of the wireless channel variation increases, more frequent CQI reports by the UE to Node B are needed in order to have an efficient AMC. On the other hand, as the number of CQI reports increases, uplink interference also increases, thus reducing uplink reception quality. The authors of [1–3] propose a number of CQI schemes which aim to keep high the efficiency of AMC while at the same time reduce the required CQI information. In this paper, we propose a new CQI reporting scheme which reduces the required CQI signaling by exploiting a CQI prediction method based on an FSMC model of the wireless channel.

The remainder of the paper is organized as follows: in Section 2, we describe the CQI reporting procedure as it is determined by 3GPP specifications and subsequently we discuss the CQI interference problem at the uplink. The proposed prediction-based CQI reporting scheme (P-CQI) is presented in Section 3. The employed packet scheduler is illustrated in Section 4. Finally, in Section 5, we present and discuss the simulation results, while Section 6 concludes our paper.

2. System Concepts and Problem Statement

2.1. System Concepts

The HSDPA operation utilizes a number of new channels [4].

The user data are transmitted through the high-speed Downlink shared channel (HS-DSCH) while the associated signaling is transmitted through the high-speed shared control channel (HS-SCCH) at the forward link and at the high-speed dedicated physical control channel (HS-DPCCH) in the uplink.

The feedback information from the terminal to the base station, carried on the HS-DPCCH, is essential for the HSDPA operation as it makes possible the use of adaptive modulation and coding. The HS-DPCCH frame consists of three slots and has duration of 2 milliseconds. The first slot is used by the hybrid automatic repeat request (HARQ) process, while the other two slots are used for the transmission

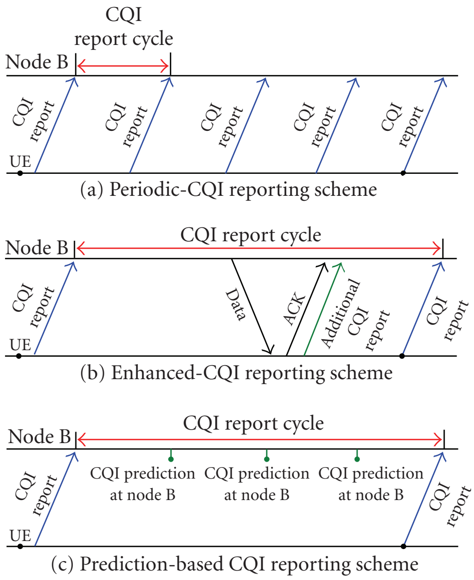

Figure 1: CQI reporting schemes.

of CQI. CQI is not a direct signal-to-interference and noise ratio (SINR) measurement but instead it is an integer index to the TFRC which the UE requests from the packet scheduler located at Node B [5].

Given a typical target error rate of 10%, the requested TFRC corresponds to the maximum transport block size which has a minimum of 90% probability to be transmitted correctly. Two successive CQI values correspond approximately to a step of 1 dB at the SINR of the HS-DSCH [4, 5].

At Release 5, 3GPP [6] proposes a periodic-CQI feedback scheme which, as illustrated at Figure 1(a), has a report cycle of r_c. The possible values of r_c are 0, 1, 5, 10, 20, 40, 80 sub-frames or correspondingly 0, 2, 10, 20, 40, 80, 160 milliseconds. The enhanced-CQI reporting (E-CQI) scheme described at release 6 [7] extends Release 5 specifications by introducing additional CQI reports during periods of downlink activity. As shown in Figure 1(b), the additional CQI reports are transmitted with every packet acknowledgment (ACK) (and/or Non-ACK). The aim of the "enhanced-CQI reporting" is to use longer report cycles compared to the periodic-CQI scheme and increase the number of the CQI reports when it is needed (i.e., when the downlink activity increases).

2.2. Problem Statement

It is obvious that the shorter the report cycle is, the more advantageous for the AMC procedure of HSDPA it is, as it provides better adaptation to the variations of the wireless channel. However, at the same time, the frequent CQI signaling increases uplink interference and thus decreases the average UE throughput as well as the achievable energy-per-bit to noise E_b/I_0 ratio at the reverse link. The "enhanced-CQI reporting" scheme of [7] is a step towards the right direction, however, it will still perform as a periodic scheme

Table 1: E_b/I_0 gain versus increasing ratio of CQI predictions.

Ratio of predicted CQI reports/total CQI reports	1/2	2/3	3/4	4/5
E_b/I_0 Gain (dB)	1,48	2,23	2,67	2,98

in the case of CBR services such as VoIP or even during the bursty periods of VBR services such as FTP.

In this paper, we propose an improved CQI reporting scheme which aims to reduce the required CQI signaling even when the downlink data activity is high by employing a CQI prediction method. According to this scheme, Node B predicts all the intermediary CQI reports between two subsequent CQI reports by utilizing an FSMC model of the wireless channel. Thus, as shown in Figure 1(c), in our proposed mechanism, a number of CQI reports can be predicted instead of transmitted.

The proposed prediction-based CQI reporting scheme (P-CQI) is based on the optimum periodic-CQI feedback scheme [6] which has the minimum reporting cycle of 2 milliseconds. Therefore, every 2 milliseconds, a CQI report is either transmitted by the UE or predicted at Node B. By increasing the number of intermediary CQI predictions, the actual reporting cycle is increased and consequently CQI transmissions are decreased. Thus, by employing P-CQI, a significant interference reduction in the uplink can be achieved.

Adopting the simplified interference analysis presented at [8], we can measure the benefit of using P-CQI or any other report scheme which omit the same percentage of CQI reports. Considering a fixed number $M_u = 30$ of users in the cell, we calculate an approximate estimation of the signal reception quality gain at Node B. Table 1 shows how the gain of the E_b/I_0 ratio increases, as the ratio of predicted CQI reports to the total number of CQI reports increases. The periodic-CQI scheme with a reporting cycle of 2 milliseconds is used as a reference base.

As we can see in Table 1, the uplink reception quality improves as the number of CQI predictions increases. Although a high ratio of CQI predictions may be impractical in a real system, as prediction accuracy decreases when the number of predicted samples is increased, we can conclude from Table 1 that even by predicting, and thus avoiding, the transmission of just one every two CQI reports, we can achieve a significant gain of approximately 1.5 dB.

3. Prediction-Based CQI Scheme

The CQI reports indicate the requested transport format by the UE and thus they reflect the current channel conditions. Therefore, they can be interpreted to SINR measurements. The obtained SINR values are then used by the P-CQI scheme to predict, through an FSMC model, the next state of the wireless channel and therefore the next CQI. Consequently, we can predict the next CQI at Node B reducing thus the number of the needed CQI reports.

3.1. Defining the FSMC Model of the Wireless Channel Conditions

Let ψ_i be a random variable denoting the value of the received SINR_i of user i in a Rayleigh multipath fading environment, which is proportional to the square of the signal envelop. The probability density function of ψ_i can be expressed [9] as $p(\psi_i) = (1/\psi_0)e^{-\psi_i/\psi_0}$, $\psi_i \geq 0$, where $\psi_0 = E\{\psi_i\}$ is the mean value of SINR, which can estimated by averaging the SINR of all M_u active users in the cell as $\psi_0 = \sum_{j\in M_u}\psi_j/M_u$. According to the FSMC model, $K+1$ increasing SINR values $\Psi_0 = 0 < \Psi_1 < \Psi_2 < \cdots < \Psi_K = \infty$ define K states that describe the channel condition as follows: the wireless channel of user connection i is considered to be in state S_k if the measured ψ_i lies in the interval $\{\Psi_k, \Psi_{k+1}\}$.

Assuming that the channel fades slowly with respect to the CQI feedback report cycle and the Doppler shift f_d in the carrier frequency f_c is $f_d = \nu f_c/c$, then, following the equal probability method, the steady-state probability of state k is [10]

$$\pi_k = \int_{\Psi_K}^{\Psi_{K+1}} p(\psi)\,d\psi = e^{-\Psi_k/\psi_0} - e^{-\Psi_{k+1}/\psi_0}. \tag{1}$$

Then the transition probabilities at the FSMC model can be approximated by the following equation:

$$\begin{aligned} p_{k,k+1} &\cong \frac{1}{\pi_k} f_d T_s \sqrt{\frac{2\pi\,\Psi_{k+1}}{\psi_0}}\, e^{-\Psi_{k+1}/\psi_0}, \\ p_{k,k-1} &\cong \frac{1}{\pi_k} f_d T_s \sqrt{\frac{2\pi\,\Psi_k}{\psi_0}}\, e^{-\Psi_k/\psi_0}, \\ p_{k,k} &= 1 - (p_{k,k+1} + p_{k,k-1}), \end{aligned} \tag{2}$$

where T_s is the HSDPA subframe duration (2 milliseconds). We also assume that the channel remains in one state at each HSDPA subframe and that the transition probability between nonadjacent states is very small. Therefore, we can assume that transitions happen at the end of the HSDPA subframe and occur only between adjacent states.

3.2. Prediction of the Next CQI

The CQI prediction is based on the constructed FSMC wireless channel model. Given the current state of the channel which is computed by a CQI report, the next state m is the one in which the Markov chain will transit to with the highest state transition probability $p_{m,k} = \max(p_{k,k}, p_{k,k+1}, p_{k,k-1})$.

More future states may be predicted in the same manner using the same calculated transition probabilities. The SINR value is then translated at Node B to the respective CQI value (i.e., TFRC). The state transition probabilities are updated periodically based on the real SINR levels received from the mobiles each time the real CQI measurements are collected. The steps involved in the prediction procedure are illustrated in Figure 2.

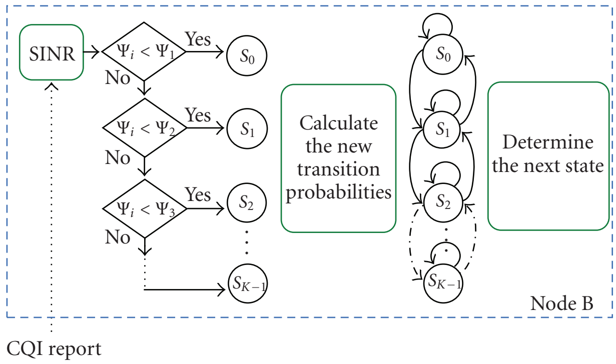

Figure 2: CQI prediction method.

4. Node B Packet Scheduling

For the packet scheduling, we employ the scheduler presented at [11] and adapt it to HSDPA. Thus, the scheduling period T_s is decreased to 2 milliseconds while multicode operation and AMC are employed.

4.1. Priority Sorting

According to this scheme, a priority P_i that can be calculated by the following equation is assigned to the traffic flow of user i:

$$P_i = \frac{T_{Q,i}(nT_s)}{T_{\text{th},i}} \times (1 - P_{e,i}) \quad i \in M_u, n = 0, 1, 2, \ldots, \tag{3}$$

where $T_{Q,i}$ is the delay of the head of line (HOL) packet in the queue during the nth scheduling period, $T_{\text{th},i}$ is the delay threshold of packets for the specific service, and $P_{e,i}$ is the bit-error probability during the next frame determined by the state of the wireless channel which is predicted by the FSMC model of the channel. If k is the predicted next state of the wireless channel of user i, $P_{e,i}$ is given by [10]

$$P_{e,i} = \frac{1}{\pi_k}\int_{\Psi_k}^{\Psi_{k+1}} p_{\text{em}}(\psi)\cdot p(\psi)d\psi, \tag{4}$$

where $p_{\text{em}}(\psi)$ denotes the error probability for a specific modulation scheme.

In HSDPA, the transmitted signal is modulated with either QPSK or 16QAM. The $p_{\text{em}}(\psi)$ for the QPSK and 16QAM is given, respectively, by the following equation [12]:

$$\begin{aligned} p_{\text{em}}^{\text{QPSK}}(\psi) &= \frac{1}{2}\operatorname{erf}c(\sqrt{\psi}), \\ p_{\text{em}}^{\text{16QAM}}(\psi) &= \frac{3}{8}\operatorname{erf}c\left(\sqrt{\frac{2}{5}\psi}\right) - \frac{9}{64}\operatorname{erf}c^2\left(\sqrt{\frac{2}{5}\psi}\right). \end{aligned} \tag{5}$$

4.2. Rate Allocation

The flows are sorted in decreasing order of their priorities and the scheduler assigns, to the highest priority connection, the maximum TFRC for the current subframe according to

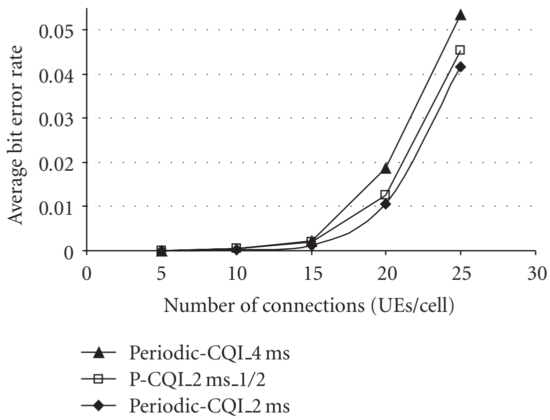

Figure 3: Average bit-error rate under periodic-CQI and P-CQI.

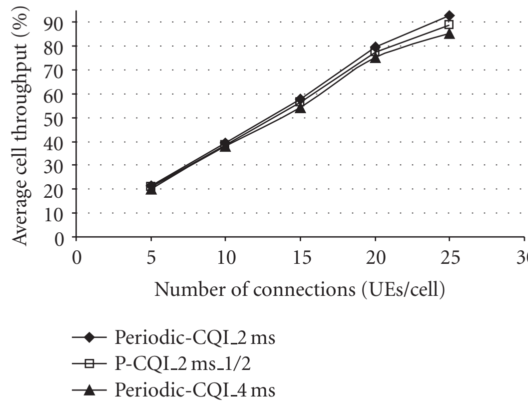

Figure 5: Average cell throughput under periodic-CQI and P-CQI.

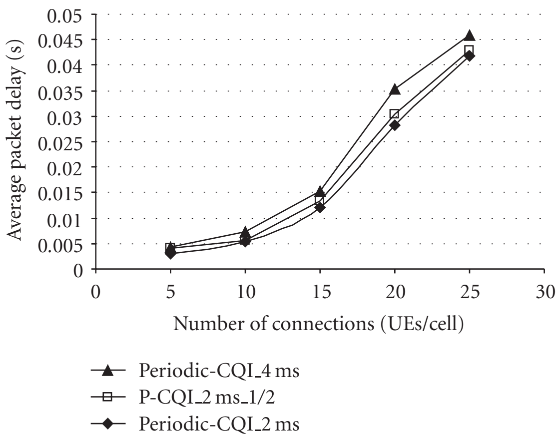

Figure 4: Average packet delay under periodic-CQI and P-CQI.

the requested (or predicted) CQI and the available HSDPA capacity. The rate allocation procedure continues with the next connection in the sorted list until either (a) all the connections of the list are examined and all their respective queued packets are scheduled for transmission during the next subframe, or (b) all the available capacity has been allocated.

5. Performance Evaluation

The performance of the proposed P-CQI reporting scheme is evaluated via event-driven simulation. We consider a cell with a radius of 1 km. Node B is located at the centre of the cell. The session arrival process is modelled by a Poisson distribution, while the session duration is exponentially distributed with equal mean. The traffic load increases by increasing the number of users in the cell. At the downlink, the user's data are transmitted through HSDPA while on the uplink the HS-DPCCH is employed for the transmission of the signaling data.

For each connection the traffic is assumed to arrive according to an "ON-OFF" model during the duration of the session. As long as the connection is in the "OFF" state, it has no arrivals. While in the "ON" state, a batch of N packets arrives per timeslot. N is uniformly distributed between N_L and N_H, where $N_L, N_H \in R^+$. A packet is defined as the amount of bits that can be received during one timeslot at the lowest available rate R. The probability P_{ON} of being in the ON state, as well as the N_L, N_H are predefined for each connection.

The initial location of each UE is randomly distributed in the cell, the directions of movement of the users are uniformly distributed, while their velocity is also uniformly distributed in a [0,3] km/h interval. The macrocell propagation model proposed in [13] is adopted for calculating the path loss at distance d_i (km) from Node B. Therefore, the attenuation L_p of the transmitted signal for a Node B antenna height of 15 meter and a 2 GHz carrier frequency is defined as $L_p(d_i) = 128.1 + 37.6 \log(d_i)$ [dB]. The modeling of the wireless channel is performed through a four-state FSMC [10] which provides the required accuracy without adding excessive complexity. The equal probability method (EPM) [10, 14] is used to determine the steady-state probabilities and by this means the transition probabilities. The CQI signaling delay is not taken into account as it is expected to affect the performance of all the evaluated CQI schemes in a similar manner and thus does not alter our comparison.

5.1. Effect of the CQI Reporting Scheme in AMC

If the CQI information is not accurate, the AMC operation of HS-DSCH cannot be efficient. As a consequence, this affects various metrics, such as bit-error rate (BER), packet delay and throughput. In the following, we evaluate the proposed P-CQI scheme by measuring the effect of prediction on the above metrics.

Considering the worst case, where E-CQI performs as the periodic-CQI due to high downlink activity, we assume services with P_{ON} equal to 1 while $N_L = 4$, $N_H = 6$ and the delay threshold Dth is set to 100 milliseconds. Furthermore, given that the optimum performance of AMC is achieved when the CQI reporting is as frequent as possible, we use the periodic-CQI feedback scheme with a report cycle of 2 milliseconds as a reference. The evaluated P-CQI scheme has a report cycle of 2 milliseconds with a CQI prediction ratio of 1/2 (P-CQI_2ms1/2). Hence, one every two CQI reports is predicted and the required CQI signaling is reduced by half corresponding to an actual report cycle of 4 milliseconds. The periodic-CQI feedback scheme with a report cycle of 4 milliseconds, which causes the same uplink interference as P-CQI_2ms1/2, is also evaluated for comparison.

As we can see in Figure 3, the average BER for the periodic-CQI_4ms is significantly higher than that of P-CQI at medium-to-high traffic loads. On the other hand, the performance of P-CQI is close to the optimum performance of the periodic-CQI_2ms at all traffic loads. The difference between P-CQI and periodic-CQI_2ms is due to the fact that the CQI prediction procedure cannot always be accurate. Therefore, P-CQI can achieve performance comparable to the performance of the optimum periodic-CQI_2ms while produces as low interference as the periodic-CQI_4ms.

This conclusion can also be verified by Figures 4 and 5 where the average packet delay and the average cell throughput, as a percentage of the total capacity, are shown, respectively. While both metrics increase as the traffic load increases, we can see that again the performance of P-CQI is very close to the optimum performance while at the same time outperforms periodic-CQI_4ms especially at medium to high traffic loads.

6. Conclusions

In this paper, we propose a prediction-based CQI reporting scheme (P-CQI). P-CQI has better performance compared with a periodic-CQI scheme which causes the same uplink interference. Due to the prediction of a number of CQI reports, the P-CQI scheme reduces significantly the required CQI signaling while at the same time has a performance near to optimum. As a consequence, the reception quality at the uplink is increased. The only induced cost by the use of P-CQI is an insignificant increase of the complexity at Node B because Node B has to calculate a number of CQI reports instead of receiving them from the UE.

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The goal of this special issue is to solicit high-quality unpublished research papers on design, evaluation, and performance analysis of femtocell networks. Suitable topics include but are not limited to the following:

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The recent advances in embedded software/hardware design have enabled large-scale and cost-effective deployment of Wireless Sensor Networks (WSNs). Such a network consists of many small sensor nodes with sensing, control, data processing, communications, and networking capabilities. The wireless sensor networks have a broad spectrum applications ranging from wild life monitoring and battlefield surveillance to border control and disaster relief, and have attracted significant interests from both academy and industry.

A wireless sensor node generally has limited storage and computation capabilities, as well as severely constrained power supplies, and the networks often operate in harsh unattended environments. Successful design and deployment of wireless sensor networks thus call for technology advances and integrations in diverse fields including embedded hardware manufacturing and signal processing as well as wireless communications and networking across all layers. We have seen the initial and incremental deployment of real sensor networks in the past decade, for example, the ZebraNet for wildlife tracking, the CitySense for weather and air pollutants reporting, and the Sensormap portal for generic monitoring services, to name but a few; yet the full potentials of such networks in the real world remain to be explored and demonstrated, which involves numerous practical challenges in diverse aspects.

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