A Deep Pipelined VLSI Architecture For High Throughput HSDPA Wireless Standard

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Abstract: High Speed Packet data Access (HSPA) has been an upgrade to WCDMA networks (both FDD, and TDD) used to increase packet data performance. The HSDPA concept has been designed to increase packet data throughput by means of fast physical layer (L1) retransmission and transmission combining as well as fast link adaptation controlled by the Node B (Base transceiver Station (BTS). We investigate single user throughput optimization in High Speed Downlink Packet Access (HSDPA). Specifically, we propose offline and online optimization algorithms which adjust the Channel Quality Indicator (CQI) used by the network for scheduling of data transmission. In the offline algorithm, a given target block error rate (BLER) is achieved by adjusting CQI based on ACK/NAK history. This algorithm could be used not only to optimize throughput but also to enable fair resource allocation among multiple users in HSDPA. In the online algorithm, the CQI offset is adapted using an estimated short term throughput gradient without the need for a target BLER. An adaptive step size mechanism is proposed to track temporal variation of the environment. Convergence behaviour of both algorithms is analyzed. The convergence analysis is confirmed by our simulations. Simulation results also yield valuable insights on the value of optimal BLER target. Both offline and online algorithms are shown to yield up to 25% of throughput improvement over the conventional approach of targeting 15% BLER.

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1. Introduction

The success of 3rd generation wireless cellular networks is mainly based on efficient provisioning of the expected wide variety of services requiring different Quality of Service with respect to data rate, delay and error rate. In order to improve support for high data rate packet switched services, 3GPP has developed an evolution of UMTS based on WCDMA known as high Speed Downlink Packet Access (HSDPA) [1]. HSDPA targets increased capacity, reduced round trip delay, and higher peak downlink (Dl) data rates. In HSDPA, the user equipment (UE) (also known as mobile station) monitors the quality of the downlink wireless channel and periodically reports this information to the base station (referred to here as NodeB) on the uplink. This feedback, called Channel Quality Indicator (CQI), is an indication of the highest data rate that the UE can reliably receive in the existing conditions on the downlink wireless channel. The frequency of reporting CQI is configured by the network, and is typically set to once every few milliseconds. Using the channel quality reports, the NodeB accordingly schedules data on the High Speed Physical Downlink Shared Channel (HS-PDSCH). The NodeB's selection of the transport block size (number of information bits per packet), number of channelization codes, modulation and resource allocation choices such as HS-PDSCH transmit power allocation are guided by the NodeB's interpretation of the reported CQI.

CQI reports are intended to accurately reflect the HSPDSCH performance that the UE can support in the existing wireless channel conditions. It is recommended in [2] that, in static channel conditions, the UE reports CQI such that it achieves a block error rate (BLER) close to 10% when scheduled data corresponds to the median reported CQI reported CQI. In practice, the accuracy of CQI reports in reflecting HS-PDSCH performance is influenced by the wireless channel conditions such as the speed of the mobile user and the dispersive nature of the channel. Achieving a certain target BLER at a given scheduled data rate requires different average HS-DSCH SNR under different channel conditions. Also, the NodeB often uses different transport block sizes, number of codes and modulation, collectively referred to as the transport format resource combination (TFRC), to achieve similar data rates. The exact choice of TFRC that the NodeB uses affects the required HS-PDSCH SNR to achieve a certain target BLER. This variability's may cause the actual BLER to deviate from the 10% target. Moreover, the 10% target BLER may not yield maximum throughput under all conditions of the wireless channel.

The cell throughput optimization in HSDPA can be considered as a two part problem [3]: one is code and power allocation across users, and the other is link throughput optimization for each user for a given resource allocation. In other words, one is the multi-user scheduling problem while the other is per-user link throughput optimization problem. An example of multi-user scheduling study can be found in the HSDPA throughput analysis with proportional fair scheduler in [4]. An instance of link throughput study can be found in [5], where throughput of HSDPA using the linear minimum mean square error (LMMSE) receiver is analyzed. In this paper, we focus on the second part of the problem, which deals with the maximization of link throughput for a single user. The results readily extend to a multi-user system, with one instantiation of the algorithm running for each user. Furthermore, the offline algorithm will be able to compensate for differences in accuracy of CQI reporting among multiple users. Since multiuser scheduler typically takes CQI as one of the inputs, this in turn improves the accuracy of the scheduler.

For link throughput optimization, existing literature typically focus on good receiver techniques [5]. In this study, we instead propose optimization algorithms that adjust the CQI by applying an additional offset. There are two flavors of algorithms proposed: the offline algorithm and the online algorithm. The offline algorithm achieves a given target BLER using the stochastic gradient descent method. It adjusts the CQI offset adaptively based on the short term BLER obtained from the ACK/NACK history. By searching through different target BLERs, we can find the throughput optimal BLER offline. The proposed algorithm can be implemented at the UE as well as at the Node B. When applied at the Node B, in addition to achieving the target BLER, it can also save transmit power. We further conduct convergence analysis. In the literature, stochastic approximation (SA) algorithms regularly use a decreasing step size [6] which is not practical for mobile communication. With a constant step size, which is the case with our proposed algorithm, the ordinary differential equation analysis in the literature can only show convergence to a neighborhood of the optimal solution but not the optimal value itself. In this paper, we show the exact convergence of the offline algorithm with a constant step size. The technique used can be applied to the analysis of other stochastic optimization techniques. In the online algorithm, we use a variation of the Kiefer-Wolfowitz algorithm [8] in SA. It does not need a target BLER as input. The CQI offset is adapted gradually using an estimated short term throughput gradient. Unlike [8], the step size in the proposed algorithm does not decrease to zero.

In addition, an adaptive step size mechanism is proposed to track temporal variation of the environment. With a constant stepsize, we show that the proposed online algorithm converges to a small neighborhood of the optimal solution. Our simulation results show that the proposed offline algorithm can achieve the given target BLER with good accuracy. Both throughput optimization algorithms are shown to improve the throughput by up to 25% in simulation over the conventional approach of targeting 10% BLER. The throughput optimal BLER is calculated for standard 3GPP channel path profiles. In general, the throughput optimal BLER is not always 10% and depends on the fading channel. For additive white Gaussian noise (AWGN) channels, it is about 10%, as is implied in [9]. Considering that the UE implementation in the simulation closely mirrors commercially shipping devices and already includes several receiver optimizations, the additional gain obtained through the algorithm is indicative of potential HSDPA throughput enhancement realizable in practice.

2. Related work

Literature survey is the most important step in software development process. Before developing the tool it is necessary to determine the time factor and strength. Once these things are satisfied, then next steps is to determine which operating system and language can be used for developing the tool. Before developing the tool we have to analysis the Networking: In the world of computers, networking is the practice of linking two or more computing devices together for the purpose of sharing data. Networks are built with a mix of computer hardware and computer software. Networks consist of the computers, wiring, and other devices, such as hubs, switches and routers that make up the network infrastructure. Some devices, such as network interface cards, serve as the computer's connection to the network. Devices such as switches and routers provide traffic- control strategies for the network. All sorts of different technologies can actually be employed to move data from one place to another, including wires, radio waves, and even microwave technology.

Asynchronous Transfer Mode:

Asynchronous Transfer Mode (ATM) is a switching technique for telecommunication networks. It uses asynchronous time-division multiplexing and encodes data into small, fixed-sized cells. This differs from other protocols such as the Internet Protocol Suite or Ethernet that use variable sized packets or frames. ATM has similarity with both circuit and packet switched networking. This makes it a good choice for a network that must handle both traditional high-throughput data traffic, and real-time, low-latency content such as voice and video. ATM uses a connection-oriented model in which a virtual circuit must be established between two endpoints before the actual data exchange begins. Network topology-Common layouts A network topology is the layout of the interconnections of the nodes of a computer network. Common layouts are:

- A bus network: all nodes are connected to a common medium along this medium. This was the layout used in the original Ethernet, called 10BASE5 and 10BASE2.
- A star network: all nodes are connected to a special central node. This is the typical layout found in a Wireless LAN, where each wireless client connects to the central Wireless access point.
- A ring network: each node is connected to its left and right neighbor node, such that all nodes are connected and that each node can reach each other node by traversing nodes left- or rightwards. The Fiber Distributed Data Interface (FDDI) made use of such a topology.

3. CQI Table and Throughput Expression in HSDPA

In HSDPA systems, an UE reports CQI to the Node B once every several milliseconds. 3GPP standards define CQI to be an integer with value between 0 and 30 (0 means no transmission can be received reliably). In other words the channel quality is quantized into 30 possible levels, ignoring the trivial value of 0. Each increment of CQI represents one dB increase in channel quality. For a given resource allocation, i.e., amount of power and number of codes available, each CQI level has a corresponding maximum TFRC that the UE can decode reliably. When the 30 values of CQI are listed sideby-side with corresponding TFRC's a CQI table is formed. Because higher values of CQI represent better channel quality, the transport block sizes in the table are typically monotonically increasing. Examples of CQI tables can be found in [2]. In practice, the Node B signals to the UE a reference resource allocation based on which UE generates CQI reports. At the time of scheduling, Node B interprets the received CQI taking into account the difference between the actual resource available and the signaled reference. In addition, Node B can manipulate received CQI in order to improve performance. Examples of such operation include filtering for the purpose of reducing noise or predicting future variation. After such manipulation the interpreted CQI can no longer take integer values. This means in practice the CQI table used by the Node B may be more than 30 entries, providing finer granularity for transmission decisions. In this paper, we assume the Node B conducts link transmission following an M-entry CQI table with 1 dB spacing. In this study, we consider throughput optimization algorithms that adjust the CQI by applying an additional offset to the existing CQI report such that the scheduled TFRC of Node B may be changed through this offset, which in turns changes the achievable throughput. The proposed algorithms can be easily extended to cases where the CQI table has finer granularity, or where Node B applies compensation for the difference between signaled resource allocation and what is indeed available. Throughput of a user in HSDPA is the rate of transfer of information bits over the wireless channel in units of bits per sub-frame.

4. Offline Throughput Optimization

A. Algorithm

The average first BLER function is a monotonic function in the CQI offset Δ is shown. Therefore, there is a unique first BLER that corresponds to the CQI offset. We thus propose an adaptive algorithm to achieve a given target first BLER. The optimal throughput can be found by searching through the target first BLER offline. The algorithm compares the current short term BLER with the target BLER and updates the CQI offset according to

$$\Delta_{n+1} = \left[\Delta_n - \alpha\left(\hat{b}_n(\Delta_n) - b^*\right)\right]^{\mathcal{U}}.$$

where Δn is the CQI offset at the n-th iteration, $bn(\Delta n)$ is the short term BLER at the n-th iteration, and $\mathcal{U}$ denotes the mapping onto the set $\mathcal{U}$ to limit the range of CQI offset, i.e.,$[x]\mathcal{U}$ = argmin $y \in \mathcal{U}$ $|x-y|$. In the simulation, we choose $\mathcal{U} = [-2, 2]$. Though the mapping $[.]\mathcal{U}$ is unnecessary to achieve convergence, we use it to avoid undesired large CQI offsets. The short term average first BLER (Δ) is estimated using the ACK/NACK history of the first transmission within a sliding window of size w. Let tn be the starting sub-frame of the n-th window for CQI offset update with $t1 = 1$, and (t) and Y (t) denote the status of the first transmission ACK and NACK in sub-frame t, respectively, where $X(t) = 1$ if a first transmission ACK is received and $X(t) = 0$ otherwise, and $Y(t) = 1$ if a first transmission NACK is received and $Y(t) = 0$ otherwise 1. After choosing tn, $tn+1$ is chosen such that the number of first time transmissions between tn and $tn+1$ is w,i.e., $\Sigma tn+1-1$ $t=tn$ $(X(t) + Y(t)) = w$. The short term first time BLER is then estimated by

$$\hat{b}_n(\Delta) = \frac{\sum_{t=t_n}^{t_{n+1}-1} Y(t)}{w}.$$

As the status of ACK/NACK is available at both Node B and UE, the CQI update algorithm can be implemented at both sides. At the UE, since unquantized (or raw) CQI is available, we can add Δn to the raw CQI, CQI raw directly, The reported CQI is the quantization of Δn+CQI raw. At Node B, only reported quantized CQI from UE is available. After obtaining CQI offset Δn, it performs quantization (Δn+CQI reported) and transmits the TBS corresponding to the CQI after quantization, where CQI is the reported from UE and $Q(.)$ is the CQI quantization function which maps its input to an integer between 1 and M. To get a fine control of the BLER and throughput and to achieve the target BLER even at high SNR, we can also change the power of the HS-PDSCH channel by using the residual CQI, i.e., the HS-PDSCH channel power is reduced by (Δ+CQI reported) − Q(Δ+CQI reported)

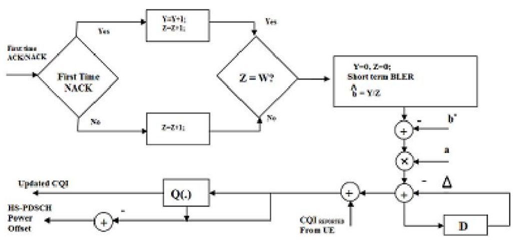

Fig 1: Offline algorithm to achieve the target BLER

By using the UE algorithm, in high geometry, CQI raw may be greater than M, where geometry G is defined as $G = Ior\ Ioc{+}N$ with Ior the signal power from Node B in the target cell, Ioc the signal power received from adjacent cells, and N the thermal noise power. Because the maximum CQI is M, UE should report M even though the current channel condition can support a data rate (TBS) higher than that corresponding to CQI= M. In this case, we cannot achieve the target first BLER no matter what CQI offset is applied because $bcq(g) < b$, $\forall cqi \in \{1, .,M\}$ and $b(\Delta)$ in (7) is less than b for all Δ. Similarly, when CQI raw is less than 1, we cannot achieve the target first BLER either because $bcq(g) > b^*$, $\forall cqi \in \{1, . . .,M\}$. This problem can be resolved by using the Node B algorithm. By applying the Node B algorithm, when Δ+CQI reported $>M$, the HS-PDSCH power is reduced such that there exists a cqi with $bcq(g) > b^*$ because $bcqi(g)$ decreases as power reduces for any cqi. Thus, the target BLER can still be achieved. This algorithm also leads to power saving at Node B. From the system point of view, this means that Node B can support more users and the overall system's performance is improved.

Fig. 1 describes the Node B algorithm. The algorithm constitutes two parts: short term BLER estimation, CQI and HS-PDSCH channel power offset generation. With both UE and Node B algorithms, for each target first BLER b, we can find the corresponding CQI offset and the achievable throughput. The optimal throughput can be found by searching through the target first BLER offline.

B. Monotonicity of the Average First BLER

To get the algorithm, we need to show that the first BLER is a monotonic function in the CQI offset Δ. The average first BLER can be written as

$$b(\Delta) = \sum_{cqi=1}^{M} p_{cqi}(\Delta) b_{cqi}(g).$$

Taking the derivative of (Δ) with respect to Δ and taking into account the expression of $pcqi(\Delta)$, we obtain

$$\frac{db(\Delta)}{d\Delta} = \sum_{cqi=2}^{M} f(cqi - 0.5 - \Delta, m(g)) \left(b_{cqi}(g) - b_{cqi-1}(g)\right).$$

As stated before, higher CQI maps to high TBS. Typically, $bcq(g) > bcqi{-}1(g)$, $db(\Delta)\ d\Delta > 0$ and $b(\Delta)$ is a strictly increasing function in Δ. Thus, in this case, given throughput optimal CQI offset Δ^*, there exists a unique BLER b^* such that $(\Delta^*) = b^*$. This result also holds in fading channels as $d(\Delta)\ d\Delta > 0$ holds for each g, which indicates that $db(\Delta)\ /\ d\Delta > 0$ after averaging over all fading states. As (Δ) is monotone, there is a one-to-one correspondence between BLER and CQI offset. Therefore, finding the throughput optimal BLER is equivalent to finding the optimal CQI offset.

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5. Online Throughput Optimization

In this section, we develop an online throughput optimization algorithm, which does not need to specify a target BLER. The online algorithm works for any CQI table and any SNR.

A. Algorithm

To maximize the average throughput $T(\Delta)$, we consider using the gradient descent method to find the maximum throughput and its corresponding CQI offset. In this section, we assume that $0 < m \leq -T''(\Delta) \leq M$, i.e., $T(\Delta)$ is a concave function with bounded curvature. We assume that g is fixed until the algorithm converges. Let Δn be the CQI offset at the n-th iteration and let $d(\Delta)\ d\Delta$ be the derivative of $T(\Delta)$ with respect to Δ. By using the gradient descent method, the CQI offset update is given by

$$\Delta_{n+1} = \Delta_n + \alpha' \frac{dT(\Delta_n)}{d\Delta}$$

Where $\alpha' > 0$ is a stepsize, a larger stepsize α' may make the algorithm converges faster but with a larger oscillation. There is a tradeoff between convergence and oscillation. There are several difficulties using the gradient descent method (15) directly.

1 Even though the expression of the average throughput is given, the evaluation of the throughput requires the knowledge of SNR, the distribution of CQI, and the BLER curve for each TFRC, which are hard to obtain online. Hence, it is hard to evaluate the partial derivative $d(\Delta n)\ d\Delta$ directly.

2 One way to solve the first problem is to replace the partial derivative by a finite difference.

$$\Delta_{n+1} = \Delta_n + \alpha' \frac{T(\Delta_n + \epsilon) - T(\Delta_n)}{\epsilon}$$

Where ϵ is a small number. However, this method needs exact knowledge of $(\Delta n{+}\epsilon)$. In practical systems, it is hard to obtain the precise average throughput at a given CQI offset. Due to the above two reasons, we would like an algorithm that can update CQI offset without the knowledge of both the exact derivative and the average throughput function. We propose to replacing ˆ (Δn) is an estimate of $T(\Delta n)$. We use a window based algorithm to estimate the short term average throughput similar to that in short term BLER estimation in the offline algorithm. Let TBS(t) be the TBS transmitted in sub-frame t and $R(t)$ and $F(t)$ denote the status of the ACK/NACK, where $R(t) = 1$ if an ACK is received and $R(t) = 0$ otherwise (including discontinuous transmission (DTX) sub-frames), and $F(t) = 1$ if an ACK or NACK is received and $F(t) = 0$ otherwise, e.g., an DTX sub-frame. Suppose that the CQI offset Δ is updated every w sub-frames and the average throughput (Δn) is computed using the past w received sub-frames. At the beginning of the n-th iteration, we compute ˆ (Δn) via

$$\hat{T}(\Delta_n) = \frac{\sum_{t=(n-1)w+1}^{nw} R(t)\mathrm{TBS}(t)}{\sum_{t=(n-1)w+1}^{nw} F(t)}$$

The numerator can be estimated using a counter to count the accumulated acknowledged TBS, and the denominator can be estimated using a counter to count the number of DTX sub frames received so far. We can compute $(\Delta n + \epsilon)$ using the same way. To prevent throughput degradation, we may set the sign of ϵ to be the direction of the gradient $T'(\Delta n{-}1)$.

We need to compute the second order derivative ˆ T (Δn), which is approximated by

$$\Delta_{n+1} = \left[\Delta_n + \left[\frac{\alpha}{T_n}\frac{\hat{T}(\Delta_n+\epsilon) - \hat{T}(\Delta_n)}{\epsilon}\right]^{S}\right]^{\mathcal{V}},$$

Where $k < n$ is the first integer such that $\Delta n - \Delta k > \epsilon n$. The above equations constitute the online throughput maximization algorithm.

6. Loss characteristics

CQI reports are intended to accurately reflect the HS-PDSCH performance that the UE can support in the existing wireless channel conditions. It is recommended in that, in static channel conditions, the UE report CQI such that it achieves a block error rate (BLER) close to 10% when scheduled data corresponding to the median reported CQI. In practice, the accuracy of CQI reports in reflecting HS-PDSCH performance is influenced by the wireless channel conditions.

The input design is the link between the information system and the user. It comprises the developing specification and procedures for data preparation and those steps are necessary to put transaction data in to a usable form for processing can be achieved by inspecting the computer to read data from a written or printed document or it can occur by having people keying the data directly into the system. The design of input focuses on controlling the amount of input required, controlling the errors, avoiding delay, avoiding extra steps and keeping the process simple.

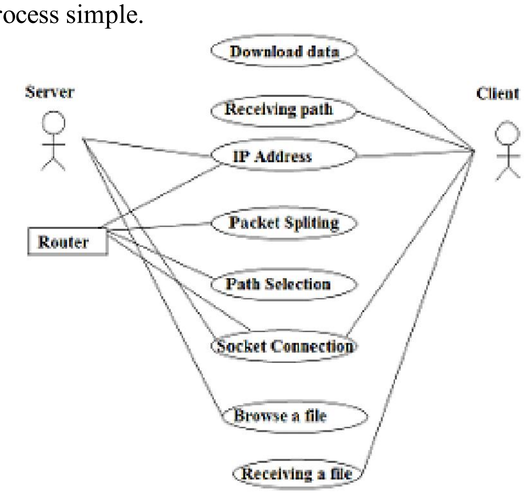

Fig 2: Use case diagram

7. Simulation results

We evaluate the performance of the proposed throughput optimization algorithms using a HSDPA simulator. Communication link of a single user is simulated. The CQI mapping table for UE category 10 specified in [2] is used in all tests. The parameter, geometry G, is used in the simulations. From the simulations, we find that for the offline algorithm the constraint set $\mathcal{U} = [-2, 2]$ that limits the CQI offset between -2 and 2 gives good performance, while choices of $\mathcal{S} = [-0.1, 0.1]$ and $\mathcal{V} = [-2, 2]$ for the online algorithm give good results. The offline algorithm depends on two parameters: window size w and stepsize α. For a fixed window size w, the larger the α, the larger the deviation of the CQI offset, the lower the throughput, and the faster the convergence. We find that in the online algorithm case the window size should be chosen to be small to track the channel variation when channel varies fast. Table I compares the BLER achieved using the proposed offline algorithm in different channels with target BLER value of 15%. We can see that the target BLER is achieved with high accuracy. Target value of 15% is used as an example and we have similar results for many other values of BLER target. The plotted first BLER is averaged from the beginning of the simulation. As we can see, the algorithm converges to the target BLER about 1000 sub-frames, which is equal to about 2 seconds of transmission. Fig. 3 shows the power offset histogram when the target BLER is 10% in AWGN channel at 10 dB geometry using. Due to quantization, the power offset can be negative.

As references we also show the convergence curve of gradient descent method when $\mathcal{T}(\Delta)$ is computed. And we observe that the online algorithm converges to a small neighborhood of the maximum throughput after about 2000 sub-frames. From this observation the throughput gain of the online algorithm is 12.48% in this case compared with the case where there is no optimization. Offline algorithm simulation that sweeps through different BLER targets show that the target BLER of 10% is not always optimal. The throughput optimal BLER depends on the channel profile. In Table II, we see that the throughput optimal BLER varies from 10% to 90% for different channel profiles. At 10 dB geometry, the throughput optimal BLER is 15% in AWGN and PA3, 20% in PB3, and 90% in VA30 and VA120. Through in our simulation.

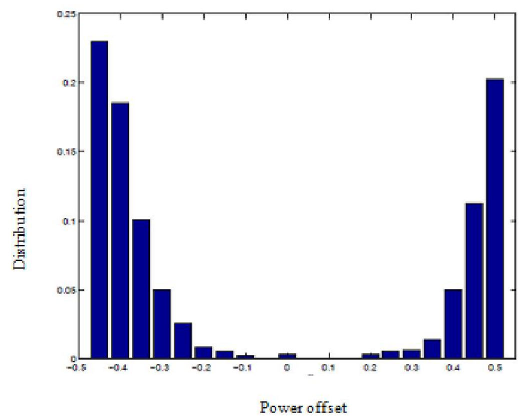

Fig 3: Power offset distribution of the offline Node B algorithm

Table 1: Achieved First BLER Using the Offline Algorithm

Geometry (db)	AWGN	PA3	PB3	VA30	VA120
0	15.11%	15.04%	15.02%	15.13%	15.10%
5	15.12%	15.03%	15.02%	15.09%	15.09%
10	15.05%	15.03%	15.02%	15.11%	15.05%
15	15.08%	15.02%	15.01%	15.12%	15.07%

Fig 2: Gain in Throughput At The Optimal BLER Relative To That At The 10% BLER In Different Channels

Channel type	Offline (Target BLER)			Online (w=10)	Online (w=20)
AWGN	0.5330% (5%)	0% (10%)	-1.9719% (15%)	2.0880%	1.9761%
PA3	7.2154% (15%)	8.2116% (20%)	7.2362% (25%)	8.7254%	9.0086%
VA120	17.845% (50%)	20.100% (70%)	24.198% (90%)	17.983%	16.231%

We have observed that these optimal BLER levels vary little with Geometry and are largely dependent on the fading channel, especially the speed of fading. The optimal target BLER is higher in high speed fading channels due to the following reason. In HSDPA system, there is a delay of about 7 ms or more between the time when CQI is measured, and the time the earliest corresponding packet is transmitted from the Node B. In fast fading conditions, this can be comparable or greater than the channel coherence time. In that case, the instantaneous variation of CQI relative to mean is uncorrelated between the time of measurement and the time of application.

The optimal link transmission strategy, as it turns out, is to be aggressive in the sense that to schedule higher TFRC than what stale CQI reports indicate, and to let highly effective hybrid automatic repeat request (HARQ) take care of retransmission. During our simulations, we have observed that even at 90% BLER on first transmission, almost all failed packets are recovered with a single HARQ retransmission. In static and slower fading, the up-and- downs of CQI are much more meaningful and it's better for link transmission to aim for lower targets. In high speed fading channels, the throughput at the optimal BLER is about 25% higher than the throughput at 10% BLER. In field logs we have collected and reviewed, we believe many commercial networks design for a target BLER of about 10% even in high speed fading conditions. The insight derived here means that up to 25% gain can be achieved if these low complexity techniques are deployed in practical systems. The network should base its choice of target BLER on channel variations.

8. Conclusion

We have investigated throughput optimization in HSDPA using two adaptive outer loop algorithms. Both of them adjust the CQI offset to maximize the throughput. The offline algorithm used an adaptive algorithm to achieve a given target BLER using the stochastic gradient descent method based on the history of ACK/NACK. By searching through different target BLERs, the throughput optimal BLER can be found offline. The online algorithm used a variation of the Kiefer-Wolfowitz algorithm without specifying a target BLER. An adaptive step size mechanism was also proposed to make the algorithm robust to non-stationary condition. We have shown the convergence of both algorithms with a constant step size. Simulation results show that the proposed algorithms can achieve up to 45% throughput improvement over that with 10% target BLER. Interplay between the algorithms proposed here and other system level optimizations.

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