Performance Evaluation of Modulation and Coding Schemes Proposed for HSDPA in 3.5G UMTS Networks

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Abstract

Upcoming revisions of the UTRA/FDD standard will include adaptive modulation and coding to support data rates up to and exceeding 10 Mbps. This paper shows link performance results for modulation and coding schemes which are currently considered for standardization of high speed downlink packet access (HSDPA). Compared to previous 3GPP contributions, this evaluation considers practical imperfections related to pulse shaping, channel conditions, and channel estimation. Further, the evaluation takes into account the effect of fast hybrid automatic repeat request (F-HARQ) to establish user throughput statistics. Results indicate that near-optimum throughput can be obtained using only 3-4 different modulation and coding schemes.

Keywords

UMTS, UTRA/FDD, HSDPA, MCS, link level evaluation.

1. Introduction

Although implementation work for the present UTRA/FDD specification is still undergoing, efforts are already being made to ensure a continued evolution path of UMTS. One of the near-future targets is to support data rates significantly beyond 2 Mbps and possibly in the vicinity of 10 Mbps on the UTRA/FDD downlink. This is known as *high speed downlink packet access* (HSDPA) and standardization of the feature will be finalized during 2002 [1]. HSDPA uses a special *high speed downlink shared channel* (HS-DSCH) which is similar to the Release'99 *downlink shared channel* (DSCH), but without fast power control. The basic HSDPA packet time, commonly denoted the *transmit time interval* (TTI), is likely to become shorter than the frame time in the final specifications. A TTI of three time slots seems to be a reasonable compromise, although other values and dynamic TTI have also been suggested. To increase peak data rates and cell throughput as well as reduce retransmission delay, several techniques have been proposed for HSDPA including higher order modulation and lower-redundancy coding combined with incremental redundancy. The *modulation and coding scheme* (MCS) may be changed dynamically on a per-TTI basis (*adaptive modulation and coding* (AMC)). Further enhancements to reduce basic link performance requirements include layer-1-based *fast hybrid automatic repeat request* (F-HARQ) and *transmission/reception antenna diversity* (TxD/RxD). Parallel channels are facilitated by multi-code as well as *multiple input multiple output* (MIMO) antenna techniques. Mobility and link performance may be improved using *fast cell selection/switching* (FCS) although the actual value of this feature has not been unanimously proven.

The performance of these individual techniques as well as their combined use must be evaluated to (i) develop efficient *radio resource management* (RRM) algorithms and (ii) reduce the complexity of HSDPA to support good performance while facilitating base station as well as user equipment implementations with reasonable complexity/cost. The true performance of features proposed for HSDPA must be evaluated at both link and network levels with respect to cell throughput, peak data rate, and effective delay. In this paper, we focus on the link level aspects and performance of the MCSs proposed for HSDPA. In the evaluation we will add imperfections related to channel shaping and estimation as well as consider time dispersion and fading. In establishing realistic operating assumptions for our investigation we will consider other techniques as well. Further, the user throughput versus link quality is estimated to evaluate the network value of different MCSs.

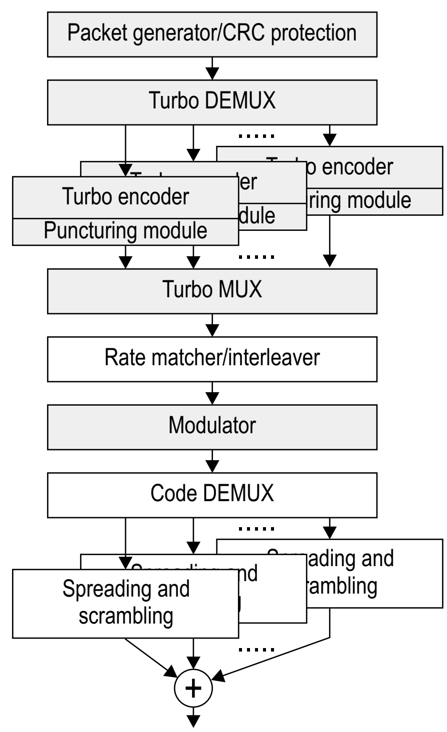

Figure 1: Example generation of HSDPA physical channel.

2. HSDPA Modulation and Coding

An overview of an example HSDPA signal generator is shown in Fig. 1. The basic structure is the same as for DSCH except for certain functionalities which have been added. Compared to the existing UMTS standard, the current HSDPA proposal adds 8PSK, 16QAM, and 64QAM techniques to increase data throughput for favorable channel conditions. Multi-code transmission is obtained by means of a code demultiplexer placed in front of the spreading and scrambling operations. A turbo coding scheme similar to the one already in UTRA/FDD specifications is used for data protection. The enhanced HSDPA scheme is shown in Figs. 2a-c. To support variable rates, and thereby ensure more efficient packet transmission, it has been proposed to add one polynomial per *recursive systematic code* (RSC) [2]. Each RSC encoder is then fundamentally a rate 1/3 encoder with a constraint length of 3. However, the second polynomial specified for HSDPA is not as effective in terms of Hamming distance as the original polynomial and should therefore only be used as a supplement to achieve lower coding rates.

Including the interleaved systematic output symbols, the turbo encoder is fundamentally a rate 1/6 encoder. However, note from Fig. 2a that its performance will not match that of an optimum rate 1/6 encoder since only two RSC encoders and one interleaver are used. The actual implementation is built on top of the existing 3GPP encoder and has been selected as a trade-off between complexity and HSDPA flexibility. The internal interleaver is the same as in the original Release'99 specifications. Since HSDPA facilitates much higher data rates compared to Release'99 UTRA/FDD, the interleaver does not have sufficient memory depth to handle HSDPA packets in a single run-through (limited to 5114 input bits). Hence, the multiplexing/demultiplexing function shown in Fig. 1 is needed in order to fully utilize this turbo coding module with HSDPA. Performance-wise, it is desirable to make these sub-packets as large as possible while facilitating a simple demultiplexing scheme. The dashed data paths in Fig. 2a are only enabled during trellis termination of the code. Tail bits are generated internally in the turbo encoder and follow the definitions in the Release'99 specifications. The systematic output is denoted by x and the parity bits of the two generator polynomials are denoted by z and v respectively. The state transitions as well as the state definitions are shown in Figs. 2b-c.

To adjust the rate, a puncturing scheme composes an output sequence from the parameter set $\{x, z, v, x', z', v'\}$. The puncturing operation is commonly denoted by a 6x6 puncturing matrix where columns denote time (one column per input bit) and rows denote the type of output (in order x, z, v, x', z', v'). As an example, the output sequence

$$\{x_1, z_1, x_2, z_2', x_3, z_3, v_4, z_4', x_5, z_5, x_6, z_6', \ldots\}$$

is represented by the matrix

$$\mathbf{P} = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (1)$$

$$= \{73, 52, 04, 00, 25, 00\}_8 \quad (2)$$

which again corresponds to a rate 6/12=1/2 code. This sequence pattern will then be repeated with a corresponding advancement of the time index.

In the evaluation of these new proposals, we shall consider the subset of modulation and coding schemes listed in Table 1. The first seven schemes are the official candidates for HSDPA. Other schemes have been recently proposed except for QPSK 1/3 which is the existing Release'99 turbo scheme (used as reference for simulations). The puncturing matrices are chosen according to the F-HARQ specification presented in [2] and a

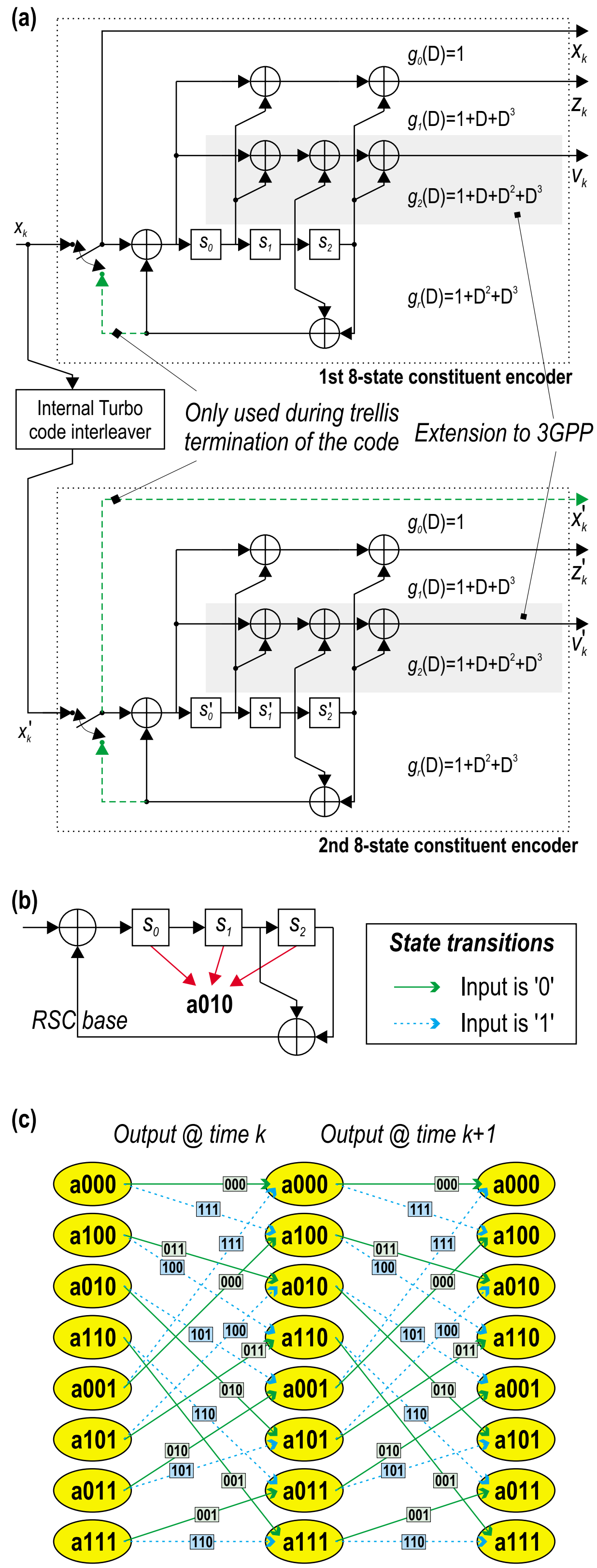

Figure 2: The turbo encoding scheme proposed for HSDPA including (a) overall diagram, (b) overview of one RSC encoder, and (c) state transition diagram with output.

recent proposal [3]. The current working assumption is to use an HSDPA spreading factor of 16. Up to 10 multi-codes are allowed thereby enabling a peak data rate in excess of 10 Mbps.

Table 1: HSDPA MCSs, corresponding puncturing matrix, and available peak data rates per code for spreading factor of 16.

MCS	Peak data rate and $\mathbf{P}$ matrix
QPSK 1/4	0.119 Mbps, $\{77, 77, 52, 00, 77, 25\}_8$
QPSK 1/2	0.237 Mbps, $\{77, 52, 00, 00, 25, 00\}_8$
QPSK 3/4	0.356 Mbps, $\{77, 10, 00, 00, 01, 00\}_8$
8PSK 3/4	0.536 Mbps, $\{77, 77, 52, 00, 77, 25\}_8$
16QAM 1/2	0.477 Mbps, $\{77, 52, 00, 00, 25, 00\}_8$
16QAM 3/4	0.716 Mbps, $\{77, 77, 52, 00, 77, 25\}_8$
64QAM 3/4	1.076 Mbps, $\{77, 77, 52, 00, 77, 25\}_8$
16QAM 5/8	0.595 Mbps, 6×10 matrix [3]
16QAM 9/16	0.531 Mbps, 6×18 matrix [3]
QPSK 1/3	0.158 Mbps, $\{77, 77, 00, 00, 77, 00\}_8$

3. Simulation Assumptions

As consensus has not yet been reached in the HSDPA standardization work groups, there is a vast number of available parameter settings. Hence, it has been necessary to impose some constraints on the simulations. We have attempted to employ simulation assumptions that are regularly found in HSDPA contributions made to 3GPP. The simulation assumptions are summarized in Table 2. We have assumed that 80% of the available Node B power is allocated to HSDPA data users although this would be quite optimistic for today's range of services. However, with an anticipated turn towards more data services it may become more realistic by 2004-2006 when *user equipment* (UE) is expected to support HSDPA. The 80% power allocation has been used in previous simulations presented in 3GPP [3]. We use 10% of the Node B power for common control channels which seems to be a common allocation scheme. Further, 10% of Node B power is allocated for dedicated channel users (16 users with a spreading factor of 128). As seen from Table 2, the simulations are based on the ITU indoor-outdoor[1] channel model which includes four taps, three of which are located within one chip time.

The simulation results are obtained with a full-functionality UTRA/FDD link simulator which supports HS-DSCH in accordance with [1]. Simulation includes pulse shaping filters and channel estimation based on the *common pilot* (CPICH). Only the main channel tap is tracked by the RAKE receiver and the simulation is conducted using 5 times oversampling. The used turbo decoding scheme is based on the soft-input soft-output max-log-MAP algorithm which offers good performance with reasonable decoding complexity [4, 5]. The feedback factor is set to 0.73 and 8 decoding iterations are used. To include the effect of user location in the cell, a geometric factor (G-factor) is defined as the ratio between own-cell received power, I_{or}, and the total received other-cell interference and noise, I_{oc}, experienced at the UE. Thus, $G \doteq I_{or}/I_{oc}$. The other-cell interference and noise are modeled with a single AWGN process and its variance is varied to estimate their effect on the HSDPA *block error rate* (BLER). The G-factor has been adjusted to yield BLER values in the 1-60 percent range. This seems to

[1]Taps at 0 dB (0 μs), -9.7 dB (0.11 μs), -19.2 dB (0.19 μs), and -22.8 dB (0.41 μs).

Table 2: HSDPA simulation assumptions.

Parameter	Setting/Assumption
TTI	Three slots (3×10/15 ms)
Spreading factor	16
Common channels power	10% of Node B power
Dedicated channel power	10% of Node B power
HSDPA power	80% of Node B power
Channel estimation	Perfect timing. Amplitude and phase estimated from common pilot (CPICH)
Channel	ITU indoor-to-outdoor A
Carrier frequency	2 GHz
Chip rate	3.84 Mcps

be the viable range for first time transmission, when F-HARQ operation is considered.

4. Results

Basic link level simulation results for the considered MCSs are shown in Figs. 3-4. Fig. 3 shows the *bit error rate* (BER) performance of the raw modulation schemes without any channel coding. For a single path static AWGN channel, the *signal-to-interference ratio* (SIR) performance difference between 8PSK and 16QAM is approximately 2 dB at a BER level around 1 percent [6]. Between 8PSK and 64QAM, the difference is on the order of 8 dB. As seen from Fig. 3, the QAM schemes suffer more in the time dispersive environment; e.g. by approximately 0.5 dB for 16QAM and significantly more for 64QAM. Although, the other-cell interference is very low, the orthogonality degradation of the transmitted Node B signal is severe enough to limit the obtainable BER for 64QAM. As seen from Fig. 3, the BER curve saturates around 2 percent even though the G-factor becomes very large.

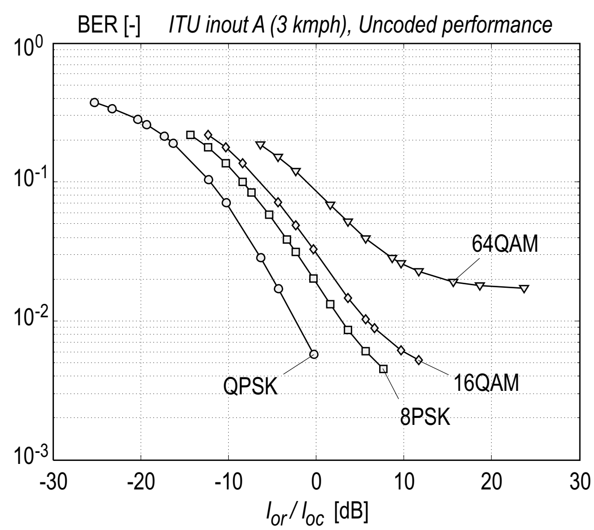

Figure 3: Link performance of higher order modulation schemes without channel coding.

In Fig. 4, the MCS performance including channel coding is considered. For 64QAM, the same effects as noted without coding are visible. Note that rate 3/4 coding only provides limited coding gain. This is seen by comparing rate 1/2 coding using 16QAM with 3/4 coding using 8PSK. Using the results of Fig. 3 as a reference, the coding gain in going from rate 3/4 to rate 1/2 is on the order of 4 dB. Note also that the performance gain of QPSK 1/4 is limited to around 1 dB compared to the reference scheme already contained in Release'99 specifications. This would indicate that only limited gain is obtained by introducing the rate 1/4 scheme. Since the 1/4 coding scheme is the only one to utilize the second RSC polynomial, an alleviation of this scheme would also be advantageous since the original Release'99 encoder could then be used without modification (except for the addition of a more advanced puncturing scheme).

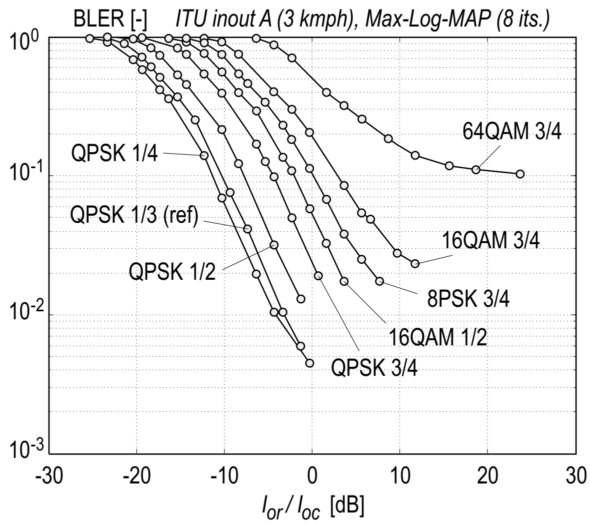

Figure 4: Link performance results of HSDPA MCS set.

From the simulation results of Fig. 4, we may consider the operation range of the MCS selection. At a BLER level around 50 percent, note that the dynamic range of the HSDPA MCS set is on the order of 20 dB (corresponding to pseudo power control). For comparison, the current power control range for DCH is approximately 30 dB. Without 64QAM, the dynamic range remains around 15 dB. The lower-rate QPSK schemes will offer a poor throughput but will effectively increase the coverage of HSDPA operation. To consider the throughput, we define the effective user throughput as simply

$$\Phi(\xi) \quad = \quad (1 - p_{bl}(\xi))D_p, \tag{3}$$

where ξ is the SIR (in this case equal to the dB-sum of I_{or}/I_{oc} and the relative HSDPA power), $p_{bl}(\xi)$ is the BLER corresponding to ξ, and D_p is the maximum data rate per code obtainable with the considered MCS (e.g. 1.076 Mbps for 64QAM 3/4). The user throughput for the seven official MCSs and the maximum obtainable throughput curve are plotted in Fig. 5. It is interesting to note that the 8PSK 3/4 scheme is always lower than the maximum throughput curve which indicates that it will not become active in the case where link adaptation is based solely on the optimization of throughput per individual link.

However, with 8PSK it is possible to alter the power instantaneously since the receiver does not depend on amplitude information. Hence, from a network perspective, it may in fact be better to use 8PSK 3/4 over the 16QAM 1/2 scheme. In terms

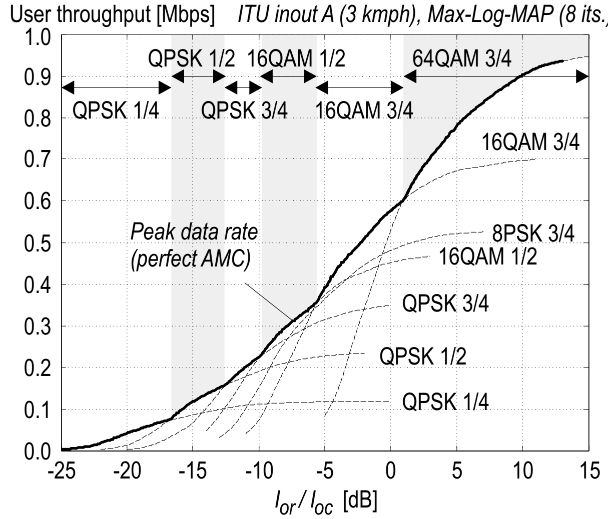

Figure 5: User throughput, Φ, with HSDPA MCS set.

of link performance, however, the 16QAM scheme remains superior for all tested scenarios including varied time dispersion and varied UE velocity (up to 250 kmph).

4.1. MCS Performance with F-HARQ

The use of F-HARQ is commonly viewed as small-scale data rate adaptation. Since F-HARQ has a significant influence on the throughput, it is important that it is considered in conjunction with the basic link simulations. The desired link level performance target depends heavily on the use of HARQ. While robust detection without HARQ requires very low BLERs, the use of retransmissions facilitates very high BLER values, e.g. on the order of 50 percent. The actual operation point depends on the slope of the MCS performance curve and, hence, the HARQ adjustment depends significantly on the operating environment. A typical target is to limit the number of required retransmissions to a maximum of 1-2.

To consider HARQ in a simple way, let us re-define the user throughput. We assume that we are using various forms of retransmission in order to always receive a packet until it is successfully detected (always staying with the same MCS during retransmissions). Thus, we may calculate the effective data throughput for a single user as

$$\Phi(\xi) \quad = \quad \frac{D_p}{1 + \sum_{n=1}^{\infty} n \cdot P(X = n|\xi)}, \tag{4}$$

where X is a random variable denoting the number of required retransmissions before a successful packet reception.

We may consider two basic cases of retransmission. For a simple retransmission scheme where erroneous packets are simply discarded ad retransmitted, we have

$$P(X = n|\xi) \quad = \quad (1 - p_{bl}(\xi))p_{bl}^n(\xi). \tag{5}$$

By inserting this expression into Eq. (4), we arrive at the expression of Eq. (3) as expected.

Second, let us consider a retransmission scheme using soft combining of the received packets. By using soft combining, a continued improvement in SIR is obtained as more packet samples are received. Hence, we may use the following simple model to consider this scheme

$$P(X = n|\xi) \quad = \quad (1 - p_{bl}((n+1)\xi)) \prod_{r=1}^{n} p_{bl}(r\xi), \quad (6)$$

where perfect soft combining is assumed (fully uncorrelated noise and interference). Although this assumption is questionable in practice for lower UE speeds, it allows us to calculate the bounds for F-HARQ.

Using these models and the simulated performance curves established earlier, the throughput has been re-calculated and plotted in Fig. 6. The results of simple retransmission as well as no HARQ have been plotted with a label “No HARQ/HARQ retx”). The use of soft combining (labeled “HARQ scmb”) adds approximately 1-2 dB of SIR gain. Note that the gain of soft combining is best for the lower SIRs for each MCS where the BLER is high. Note that at high G-factor values where 64QAM 3/4 is active, the HARQ soft combining gain is limited since the system is limited by the time dispersion (limited diversity gain available using soft combining).

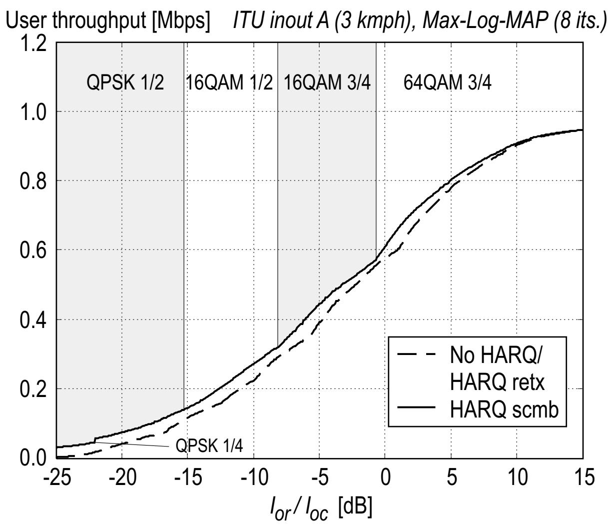

Figure 6: User throughput including the effect of F-HARQ.

It is interesting to note from Fig. 6 which MCSs are active. The use of HARQ does not favor 8PSK 3/4 compared to the non-HARQ case since the slope of the performance curves for 16QAM 1/2 and 8PSK 3/4 are almost the same. Hence, these simulations also indicate that the use of 8PSK is conditioned on a network gain related to its robustness and the possibility of making faster power adjustments. With soft combining, note that the number of active MCSs is reduced to four. At an I_{or}/I_{oc} of -24 dB, the performance of QPSK 1/2 equals the performance of QPSK 1/4. Down to -25 dB, the QPSK 1/4 scheme is only marginally better. In order to determine if QPSK 1/4 is needed, network simulations must be conducted for various scenarios in order to determine the SIR statistics. If HSDPA must operate at SIR levels below -25 dB it may be necessary to include QPSK 1/4, or maybe just the 3GPP QPSK 1/3 scheme, in the final HSDPA selection set.

4.2. Multi-Code Operation Requirements

The selection of most effective MCSs is complicated by the fact that multi-code operation is possible. Hence, the same throughput can be obtained with lower order modulation using more codes or with higher modulation combined with fewer codes. The optimum configuration depends on the channel conditions, transmitter/receiver imperfections and inaccuracies, as well as a possible code-shortage and is therefore a non-trivial task to determine. The link level performance requirements for QPSK 1/4 using 1, 5, and 10 multi-codes are given in Fig. 7. Going to five multi-codes requires an additional 7-8 dB of SIR improvement. That is, up to approximately 1 dB is wasted due to lack of perfect orthogonality in the multi-path environment considered here. For the 10-code case, the loss is up to 2 dB and as seen from Fig. 7 the performance is significantly limited by multipath conditions at better I_{or}/I_{oc}-conditions.

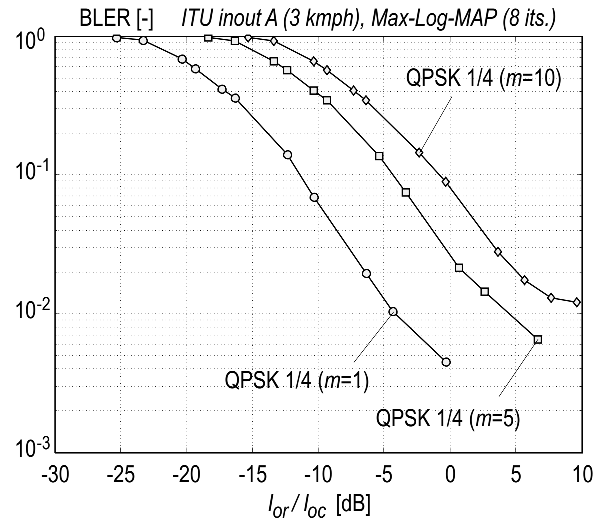

Figure 7: Basic link performance requirements for multi-code operation (m denotes the number of multi-codes).

4.3. Alternative HSDPA MCSs

As was previously established, the performance of rate 3/4 coding is limited. Hence, it is natural to attempt an increased coding rate in conjunction with a higher modulation order to achieve the same data rate or the same performance. Two schemes have been proposed in a recent 3GPP contribution to replace 8PSK 3/4 [3]. The first scheme, 16QAM 5/8, is designed to match the link level performance of 8PSK 3/4 while offering 11% higher data rate. A 6×10 puncturing matrix is required, thereby increasing the complexity of the encoder and decoder. The second scheme, 16QAM 9/16, has been designed to provide the same throughput while having lower link performance requirements. This scheme requires a 9×16 puncturing matrix. In [3], the two schemes have been compared to 8PSK 3/4 using perfect channel estimates and a static AWGN environment. In Fig. 8, the performance of the schemes is evaluated with the simulation assumptions of Table 2.

Note that the general conclusions of [3] also hold in the multi-path case with channel estimation based on CPICH. The link performance of 16QAM 5/8 matches that of 8PSK 3/4 which shows the robustness of the turbo code scheme. The link performance gain obtained with 16QAM 9/16 over 8PSK 3/4 is approximately 0.6-2 dB. Hence, the gain of going from a code rate of 3/4 to 9/16 exceeds the loss of going from 8PSK to 16QAM. However, as it is very questionable from a link perspective that 8PSK should be part of the HSDPA selection set,

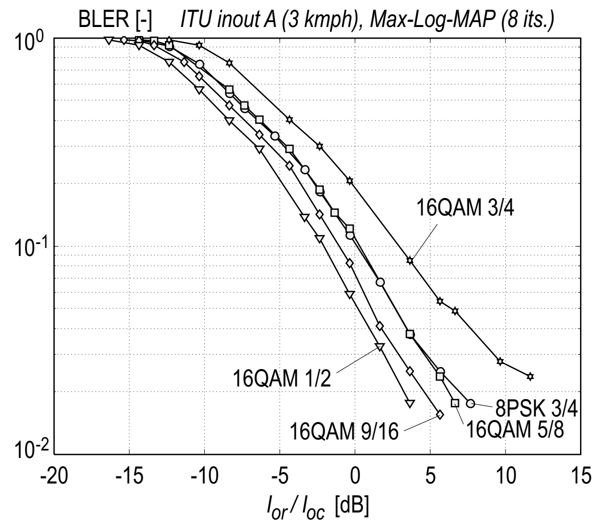

Figure 8: Basic simulation results comparing 9/16 and 5/8 rate 16QAM schemes to 8PSK 3/4.

there seems to be little reason to specify other similar 16QAM schemes that will complicate the puncturing procedure.

5. Conclusions

In this paper, link performance results for various HSDPA modulation and coding schemes have been presented. The basic performance requirements for different data rates have been established, and it has been shown that with 80% Node B power allocated to HSDPA, 10 Mbps can be achieved with a own-cell to other-cell interference ratio better than 10-15 dB. Data rates beyond 2 Mbps are supported for G-factors down to -15 dB showing a good potential for HSDPA.

One of the major tasks of the 3GPP HSDPA work is to select a small and robust MCS set that offers (i) significant link/network gain in HSDPA target scenarios, (ii) reasonable transmitter and receiver complexity, and (iii) small signaling requirements. From a link perspective it seems as if the 8PSK 3/4 scheme can be discarded. However, its robustness and support for fast power variations may be attractive in terms of network performance and efficient RRM. Also, from these considerations it does not seem relevant to introduce new MCSs such as 16QAM 5/8 and 16QAM 9/16 as these do not comprise the same network qualities as 8PSK and cannot out-perform the existing 16QAM 1/2 scheme.

64QAM 3/4 has a large area of operation, but detailed network simulations for desired HSDPA scenarios need be conducted to determine the probability that the required link quality is actually available – also taking antenna diversity schemes into account. Note that the 16QAM 3/4 scheme offers a fair performance even over the range where 64QAM offers the best throughput. 64QAM will have severe implications on transmitter and receiver hardware and it should be given a lot of thought before the inherent complexity is specified as a part of the HSDPA specifications.

The simulations presented here imply that the performance improvement of using QPSK 1/4 is marginal compared to higher-rate QPSK schemes. Alleviating this scheme, removes the need for an additional polynomial in the RSC encoder, thus offering higher backwards-compatibility with the existing 3GPP encoder. This is attractive from a complexity point of view and since the added polynomial offers limited performance gain it also seems reasonable.

Overall, it appears that only 3-4 MCSs are needed to give near-optimum throughput performance when solely considering link level aspects, HARQ with soft combining, and a time dispersive environment. This set is listed in Table 3. The dynamic range for each set is greater than or equal to 7 dB which facilitates robust link adaptation algorithms even when typical SIR estimation errors are considered. By conducting simulations for other environments, it appears that all performance curves move in an absolute sense. Hence, it is assumed that the overall conclusions drawn here apply to a large range of simulation environments.

Table 3: Possible minimum MCS set for HSDPA, peak data rates per code (spreading factor of 16), and operating range.

	MCS	D_p per code	SIR range	
	QPSK 1/2	0.237 Mbps	-25 dB to -16 dB	
	16QAM 1/2	0.477 Mbps	-16 dB to -9 dB	
	16QAM 3/4	0.716 Mbps	-9 dB to -2 dB	
(	64QAM 3/4	1.076 Mbps	-2 dB to 15 dB	)

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