

Multilevel Type-II HARQ with Adaptive Modulation Control

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Abstract—The cross-layer design is a promising strategy to maximize the spectral efficiency in communication systems. In this paper we focus on packet-oriented systems and we propose to combine adaptive modulation and coding (AMC) at physical layer and hybrid automatic repeat request (ARQ) at the data link layer. In the proposed multilevel hybrid ARQ (M-HARQ) strategy, the transmitted symbols are decomposed into a set of parallel sub-channels with an independent ARQ protocol over each sub-stream. It follows a layered structure where each sub-channel can be decoded only once the lower sub-channels have been resolved, thus sub-channels are sequentially detected. The number of parallel streams is adaptively arranged according to the channel state information (CSI). Considerable throughput gain is achieved using the same encoder/decoder structure for all the sub-channels. Moreover, M-HARQ permits an adaptive and flexible implementation even when CSI is not available. The drawback is an increase in the decoding delay, which might be tolerable in some applications.

I. INTRODUCTION

Wireless communication systems are required to support high-rate services under demanding Quality of Service (QoS) requirements. In a limited resource system, the performance is often degraded by the fluctuation of the wireless channel due to fading and interference. Throughput can be enhanced by adaptive modulation and coding (AMC) strategy that adjusts the physical layer parameters to the instantaneous channel quality.

Adaptation usually guarantees prescribed bit error rate (BER) constraints. If these requirements are demanding, large code protection and small size constellations are made necessary at the cost of throughput reduction. A possible solution relies on the hybrid automatic repeat request (HARQ) protocol at the data link layer, which requests the retransmission when decoding fails in frame recover. Since retransmission is activate only when necessary and reduced code protection can be used, HARQ improves the throughput with respect to using only forward error correction (FEC).

Based on how retransmission is managed, HARQ schemes are basically grouped into three different kinds. The simplest approach is based on the retransmission of the same coded frame till detection succeeds. The efficiency of such scheme is improved by the second kind of HARQ, called packet combining or Type-I HARQ [1], in which the receiver combines together all the past failed transmissions of the same frame before decoding. More efficient approach, called code combining (CC) [2] or Type-II HARQ, introduces memory not only at the receiver but also at the transmitter. At each ARQ request the transmitter sends only incremental parity bits.

AMC and HARQ are well known resource allocation techniques and they have been recently incorporated into 3rd generation cellular high-speed packet data communication systems (i.e., HSDPA [3]). Although they have been initially proposed as independent schemes and they are advocated to separated lay-

ers, recent works have pointed out that a cross-layer design can enhance the spectral efficiency of packets transmission over fading channel. Ref. [4] properly combines AMC and truncated HARQ scheme to maximize the throughput under prescribed maximum delay constraint. Ref [5] enhances the same framework to MIMO systems employing space-time block coding (STBC). Analytical optimization is made possible by using the simple but spectral inefficient pure HARQ protocol. In [6] the MIMO channel is decomposed into parallel sub-streams and the sub-streams are encoded by using a set of Trellis Coded Modulations (TCMs) and Type-I HARQ scheme. Since TCMs require a limited set of encoders, low complexity is needed. Nevertheless TCM codes prevent using efficient code combining scheme (without an increase in the receiver complexity) and hence they are usually proposed with the pure HARQ or the packet combining scheme [1][6]. Efficiency of Type-II HARQ is combined with AMC in [7][8]. In these references a convolutional encoder is employed at the transmitter and packets are transmitted by means of Gray mapping over adaptive multilevel constellations.

In this paper we propose the multilevel HARQ strategy (M-HARQ), which is a novel framework for joint management of Type-II HARQ at the data link layer and adaptive modulation scheme at the physical layer. The main idea is that each symbols selected from a 2^N mapping constellation is equivalent to the superposition of N binary digits transmitted over N parallel channels. Using a trellis code set-partitioning (as in TCM), at physical layer each binary digit is associated to a different level and therefore offers a different protection against noise impairments. At the data link layer an independent Type-II HARQ protocol is employed for each level, so that the HARQ automatically selects the needed redundancy. Decoding of each level is possible only once all the lower levels have been resolved, thus an ad-hoc scheduling strategy is needed. When decoding of the previous lower level fails and incremental redundancy is requested, transmission is filled by scheduling a new packet. When HARQ on the previous lower level succeeds, all the undetected packets are decoded and retransmissions are requested if needed.

In order to meet prescribed requirements on the packet detection latency, the constellation size, that corresponds to the number of levels N , is adaptively selected according to the channel state information (CSI). Alternatively, a blind adaptation technique is proposed in case of no CSI at the transmitter.

This paper is organized as follows. Sect. II reviews the Type-II HARQ scheme for coding adaptation. In Sect. III we introduce adaptive modulation system and develop the proposed M-HARQ. The achieved spectral efficiency is illustrated in Sect. IV for perfect channel state information (CSI). In Sect. V we proposed a blind adaptive implementation for M-HARQ in case of unknown channel. Finally Sect. VI draws some concluding remarks.

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II. TYPE-II HARQ SCHEME

Type-II HARQ scheme, as proposed by Hagenauer [2], is the most efficient ARQ strategy and it is based on the concept of adaptive error correction. The frame transmission starts at a very high-rate code, obtained by periodically puncturing a lower rate code, called parent code. A CRC code enables error detection at the receiver. If detection is unsuccessful, the retransmission will incrementally contain the punctured bits, called incremental redundancy, until decoding succeeds. The receiver appends these newly received bits to the saved frame, thus enhancing the error correction capability. Compared to pure HARQ and packet combining, this scheme avoids the retransmission of the whole frame and automatically adjusts the coding rate to the need of the wireless link.

Although Type-II HARQ can also be implemented by block-codes and turbo-codes [9], we deal here with punctured convolutional codes. The basic procedure for constructing an higher rate punctured code from a rate $r = \frac{1}{n}$ code can be described as encoding by the parent code followed by a puncturing device. This deletes the encoded output symbols using an $n \times p$ perforation matrix containing binary elements, where p is the puncturing period. For example the rate $3/4$ code can be generated from the rate $r = 1/2$ parent code using perforation matrix (for $p = 3$).

$$\mathbf{A}_{\frac{3}{4}} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \end{bmatrix}, \quad (1)$$

where 0 implies puncturing. In Type-II HARQ the concept of punctured convolutional codes is modified for the generation of a family of codes by adding a rate compatibility restriction to the puncturing period. The restriction implies that the lower rate codes use the same coded bits as the higher rate codes plus some parity additional bit(s). A family of rate compatible convolutional codes (RCPC) can be obtained by using a set of puncturing matrices, in which the lower code rate places an additional one where zeros appears in the puncturing matrix of the previous higher code, for example from (1)

$$\mathbf{A}_{\frac{3}{8}} = \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}, \mathbf{A}_{\frac{1}{2}} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}. \quad (2)$$

The puncturing period p determines the range of codes rates

$$R_k = \frac{1}{1 + \frac{k}{p}}, \text{ with } k \geq 0. \quad (3)$$

Large puncturing period corresponds to thin granularity in coding rate adaptation, thus few bits of redundancy are transmitted for each HARQ retransmission. This strategy leads to an high number of retransmissions and a large amount of overhead, thus for practical applications a reasonable number of the retransmissions must be selected.

For any code $\frac{k}{n}$, the bit error probability (BER) can be upper bounded as

$$BER(\gamma) \leq \frac{1}{k} \sum_{d=d_f}^{\infty} a_d PEP(d, \gamma), \quad (4)$$

where d_f is the Hamming distance and a_d is the number of incorrect path at distance d . $PEP(d, \gamma)$ stands for the pairwise probability for the error event at distance d with the SNR

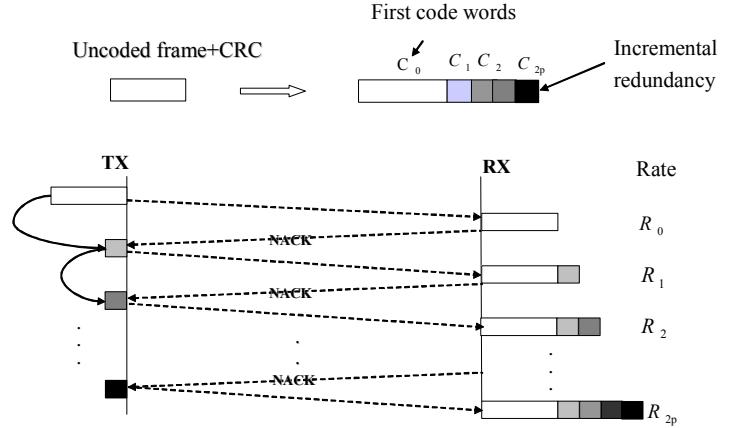


Fig. 1. Type II-HARQ scheme.

$\gamma = \frac{E_s}{N_0}$, where E_s is the symbol energy at the receiver and N_0 is the noise spectral density. Optimum codes should maximize d_f and minimize terms a_d as low BER leads to a low number of retransmission requests and a corresponding throughput enhancement. Hagenauer [2] describes a search algorithm for deriving a efficient RCPC codes (for different p) and also discusses their application to Type-II HARQ. Svensson et al. [10] construct the family of optimal RCPC according to the Optimal Distance Spectrum (ODS) criteria.

In this paper we deal with the parent code $r = 1/3$ with generator polynomials (13, 15, 17) in octal form and constraint length $K = 4$. Two different puncturing period ($p = 1$ and $p = 4$) will be considered according with the code granularity supported by the system. Optimum puncturing patterns are derived from the ODS criteria (see [10]) except for rate $R_0 = 1$ that is selected by simulations. In order to clarify the notation used in the next Section, Fig. 1 illustrates the management of the incremental redundancy packets in HARQ scheme. We denote as C_k the packet that contains the bits of the code at rate R_k not included in the code words of the higher rate codes. First transmission is depicted as C_0 and corresponds to rate $R_0 = 1$. When frame decoding fails, redundancy packets C_1, \dots, C_{2p} are sequentially sent to the receivers at each retransmission request, thus the coding rate sequentially decreases (from R_1 to R_{2p}) as in (3). After the transmission of sub-block C_{2p} , the parent code rate r is achieved. If errors are still detected, retransmission starts again from the first sub-block C_0 . Thus the codes at rate lower than the parent code (R_k for $k > 2p$) are obtained by simple repetition scheme. Notice that the incremental redundancy words C_k , for $k > 1$, contain the same number of bits, while code word C_0 is p times longer.

III. MULTILEVEL HARQ (M-HARQ)

A. Review of existing methods

Type-II HARQ protocol has been widely studied in literature for BPSK modulation systems in a low SNR regime. Nevertheless wireless channel fluctuations and the demand for high data rates make it necessary the employment of spectrally efficient schemes as in AMC strategy.

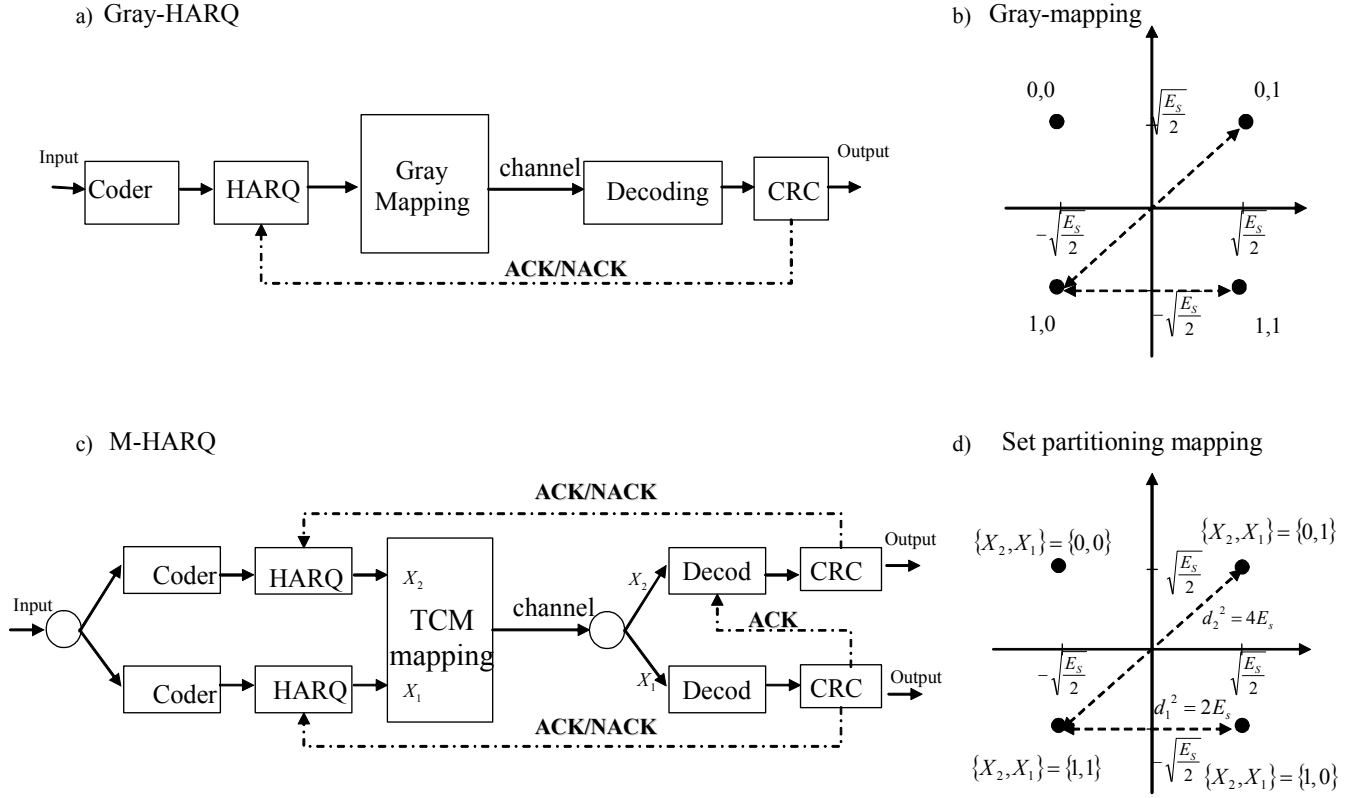


Fig. 2. Block-diagram for Gray-HARQ (a) and M-HARQ for $N=2$ (c). Gray mapping and set partitioning mapping are in (b) and (d) respectively.

A simple scheme toward the combination of AMC and HARQ is by using a set of TCMS, which are spectral efficient signaling techniques that permit to adapt the bit rate to the channel (assumed known) by adding uncoded bits to the modulation scheme. The error correction capability can be further improved by using multi-dimensional coding [6] (MTCMs). Nevertheless TCMS and MTCMs are usually employed in conjunction with Type-I HARQ, while combining with more efficient Type-II HARQ requires some developments. Although TCM based on punctured convolutional codes have been investigated, no strategy has been proposed for redundancy bits transmission and combining.

A possible solution that combines Type-II HARQ scheme and multilevel modulation has been proposed in [7]. The block-diagram of this strategy is shown in Fig.3 (a), while part (b) of the same figure contains the Gray mapping for QPSK signalling constellation with symbol energy E_s . The packets are encoded by the parent code and subsequently punctured according to the optimum ODS pattern. Then the code words are bit-interleaved and sequentially transmitted using Gray mapping over variable signalling constellation till packet detection succeeds. Although this technique, here referred to as Gray-HARQ, exploits the efficiency of the Type-II HARQ, Gray mapping offers reduced protection (in term of Euclidian distance) against noise impairments. The performance of Viterbi decoding (4) for an arbitrary code can be approximated asymptotically (at large SNR) by the $PEP(d_f, \gamma)$ of the error events at the minimum distance. Under assumption of ideal interleaver, each error event corresponds to a single bit in error for each transmitted symbols. Since Gray

mapping offers Euclidian distance $d = \sqrt{2E_s}$ for each bit in error, the PEP for any code with Hamming distance d_f results

$$PEP(d_f, \gamma) = Q(\sqrt{\gamma \cdot d_f}), \quad (5)$$

where $Q(x)$ stands for the error-function.

B. M-HARQ method

We here introduce a novel strategy, referred to as M-HARQ technique, that permits an efficient coupling of Type-II HARQ and AMC. Each transmitted symbol Y is constructed by a set of binary digits $\{X_N, X_{N-1}, \dots, X_1\}$. When using the trellis code subset mapping (as in TCM), each binary digit has a different Euclidian distance. Specifically, the most significant bit (MSB) X_N is protected by high Euclidian distance, while the least significant bit (LSB) X_1 by minimum mapping distance. These sets of binary digits can be regarded as a set of parallel sub-channels and thus M-HARQ employs an independent Type-II HARQ protocol on each sub-channel (up to N parallel ARQ protocols).

For sake of simplicity the M-HARQ scheme is proposed here for Q-PSK signalling constellation ($N = 2$), extension to larger modulation is straightforward. Fig. 3 (c) depicts the block-diagram of the M-HARQ strategy. At the transmitter the data packets are arranged into two separated sub-channels. Each sub-channel is independently encoded using the same parent code $r = \frac{1}{n}$. Higher code rates and the incremental redundancy code words are obtained by puncturing the parent code according to the ODS pattern. The two sub-streams are mapped respectively

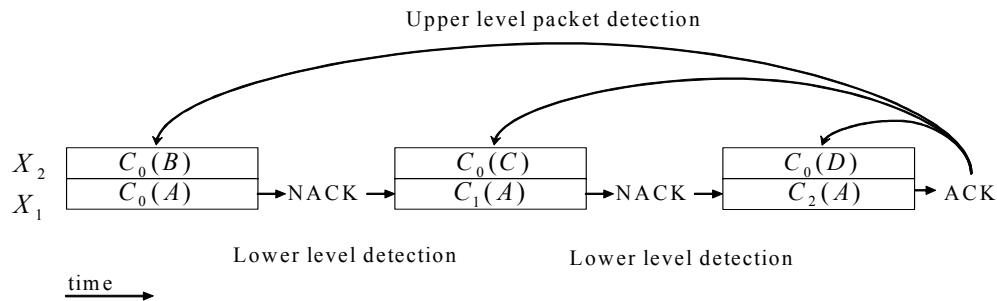


Fig. 3. Packet scheduling in M-HARQ procedure.

over bits X_1 and X_2 , corresponding to the set partitioning mapping of Q-PSK modulation, as depicted in part (d) of Fig. 3. At the receiver the sub-streams are sequentially decoded. Specifically, the receiver first decodes the packet sent over level X_1 . If CRC module detects an error, a retransmission request is fed back to the corresponding HARQ module. Packets transmitted over level X_2 can not be decoded now, thus the receiver stores the received data stream and the transmission over MSB is filled by scheduling a new packet. Differently, when detection succeeds, the bits transmitted over level X_1 can be perfectly restored. This makes feasible the decoding of the packets previously transmitted over the MSB X_2 , that are still undetected.

According to Fig. 3 (d) decoding of LSB X_1 achieves the same performance as for Gray-HARQ (5). Differently, the MSBs are protected by the Euclidian distance $d = \sqrt{4E_s}$, once LSBs are known. Thus PEP for level X_2 reads

$$PEP(d_f, \gamma) = Q(\sqrt{2\gamma \cdot d_f}), \quad (6)$$

with a gain of 3 dB in SNR with respect to (5). The gain further increases with the size of the modulation (or equivalently the number of sub-channels).

So far we have shown that the parallel encoding makes higher levels work more efficiently by avoiding retransmission of all the symbol levels whenever lower levels fail. The strategy permits the employment of the code combining, that automatically select the code error protection to the need of each specific level so that the parity digits are sent only if necessary.

C. Packets scheduling

It is crucial to notice that bits transmitted on level X_2 are decoded by assuming that the bits on lower level X_1 are perfectly known. This assumption holds true for the particular design of M-HARQ scheme explained in Sect. (III-B). We remark that the key point is that ARQ protocol guarantees packet detection after that the needed retransmissions have been sent. When HARQ protocol on low level succeeds, bits X_1 are perfectly restored and receiver can decode the packets transmitted on sub-channel X_2 . In order to provide a deeper insight in M-HARQ strategy, the Fig.3 illustrates the M-HARQ procedure for puncturing period $p = 1$ (equal length code words). At the beginning of transmission the words C_0 corresponding to two independent information packets, referred to as A and B are simultaneously transmitted over the two parallel levels corresponding to bits X_1 and X_2 of QPSK modulation (Fig.3 (d)). The receiver stores the data

stream and soft decodes the lower-level packet A . If error is detected (as happens in figure), retransmission request (NACK in figure) is fed back and the incremental redundancy code words $C_1(A)$ for packet A is sent at the first level. Simultaneously the second level can not decode packet B and the transmitter schedules the transmission of the code word $C_0(C)$ corresponding to a new independent information packet C . This procedure is repeated till detection of packet A succeeds (in figure after two 2 retransmissions). Then, the knowledge of the digits transmitted at the first level is exploited to resolve the packets sent over the upper level and packets B, C and D in figure can be decoded. In case of error in one or more packets, incremental redundancy C_1 for packets B, C or D will be sent during the successive transmissions. Thus the transmitter has to keep memory of all packets sent till they are perfectly recovered and the receiver has to keep memory of the received data stream Y to decode all levels.

D. Adaptive modulation

When higher rate modulation is employed ($N > 2$), each level can be decoded once all the lower levels have been detected. An excessive number of levels can cause the low levels to require a large redundancy. Since decoding of the upper levels must wait for all the lower levels retransmissions, this strategy leads to a large delay between packets scheduling and detection and to the need of large buffers to store the unresolved data stream. In order to guarantee practical QoS requirements, we adaptively select the constellation size in order to constrain the average packet detection latency L defined as the average time between the first packet transmission and the packet detection to be lower than a prescribed threshold L_{th} .

We consider $Q = 160$ data bits in a packet, where each packet contains 12 CRC bits to enable error detection. Fig. 4 shows the throughput (i.e., the fraction of bit/s/Hz successfully detected) versus the SNR achieved by M-HARQ when employing M-PSK modulation with $M \in \{2, 4, 8, 16, 32\}$, while fig. 5 shows the normalized average packet detection latency, that is defined as

$$\bar{L} = \frac{L}{Q \cdot T}, \quad (7)$$

where T is the transmission symbol time. We set the boundary (or the switching threshold) for each modulation format to be the minimum SNR required to guarantee $L \leq L_{th}$ with $L_{th} = 4 \cdot Q \cdot T$. As a result the employment of large signalling constellations reduces to high SNR region.

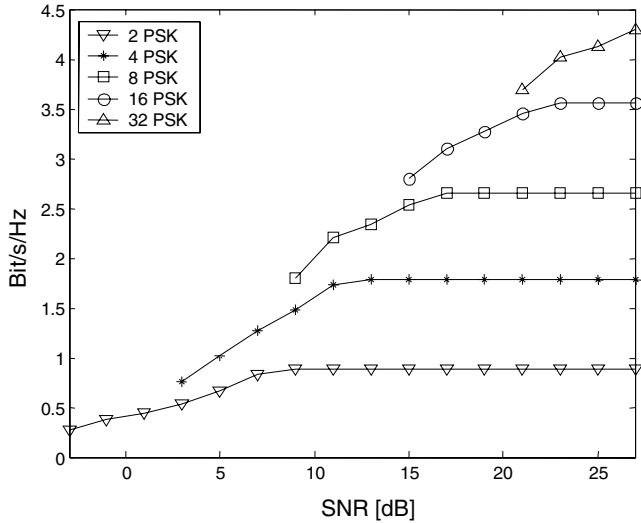


Fig. 4. Achieved throughput (a) versus SNR for M-HARQ technique (2-4-8-16-32 PSK modulation and $Q = 160$).

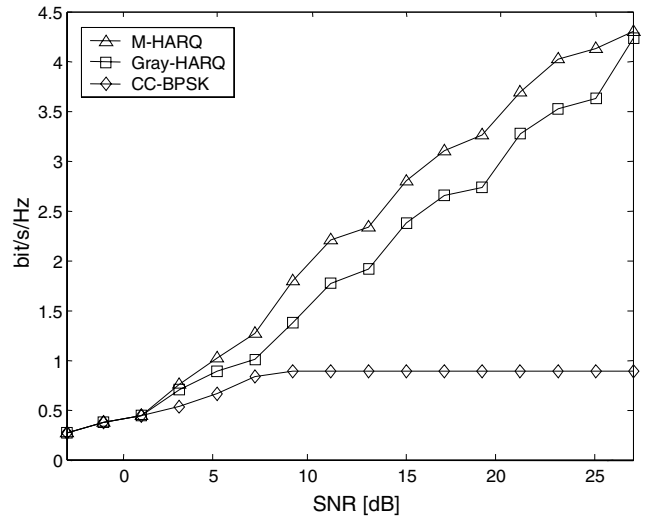


Fig. 6. Maximum achievable throughput versus SNR for M-HARQ, Gray-HARQ and Code Combining over BPSK modulation ($p = 1$).

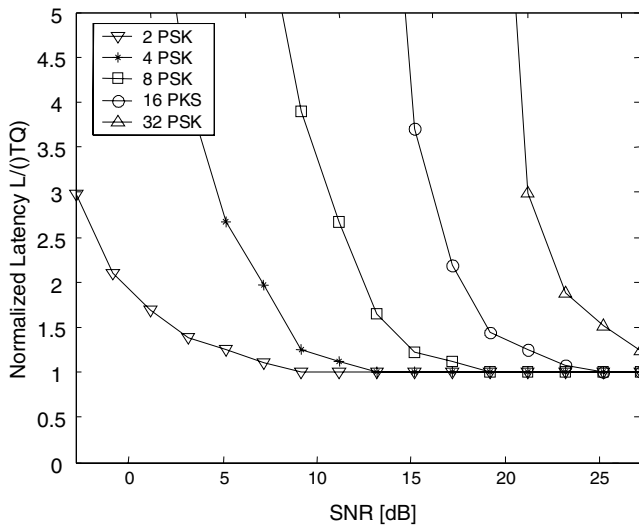


Fig. 5. Normalized average packet detection latency \bar{L} versus SNR for M-HARQ technique (2-4-8-16-32 PSK modulation and $Q = 160$).

IV. PERFORMANCE COMPARISON

In slow-fading environment, the channel variability over the packet transmission and the corresponding retransmissions is negligible, provided that frame length has been properly selected. Under assumption of perfect CSI at the transmitter, the channel can be regarded as an equivalent AWGN over the packet transmission time-scale. Therefore we compare here performance of different strategies over AWGN channel model. Fig. 6 compares the performance of the M-HARQ with the aforementioned Gray-HARQ and the conventional code combining over binary modulation (referred to as CC-BPSK) scheme. Frame structure, modulation range and puncturing period ($p = 1$) are the same as in Fig. 4. In Gray-HARQ technique, AMC maximizes the throughput according to the SNR, while in M-HARQ the selection of the modulation size is constrained by the average detection latency $L_{th} = 4 \cdot Q \cdot T$. At high SNR the maximum rate is limited by the 32-PSK constellation, that guarantees a nominal rate (without CRC) up to 5 bit/s/Hz. At low SNR M-HARQ

($\gamma < 2 \div 3$ dB), Gray-HARQ and CC-BPSK techniques reduce to the same performance (for BPSK). We notice that CC-BPSK strategy is efficient only in low SNR regime, whereas the M-HARQ technique outperforms Gray-HARQ by approx. 2 dB in SNR.

The efficiency of the code combining-based strategy can be further improved by selecting a thinner granularity in code adaptation. In Fig. 7 the puncturing period of code combining is selected as $p = 4$. This strategy leads to a slight increase in the complexity of M-HARQ packets scheduling as first code word C_0 is p times longer than other incremental redundancy code words. Performance of M-HARQ (for $P = 4$) and Gray-HARQ is compared with MTCM Type-I HARQ. We consider both two-dimensional (2-dim) and four dimensional (4-dim) trellis codes. For 4-dimensional MTCM we employ the set of trellis codes with constraint length $K = 4$ (chosen here for the sake of a fair comparison) suggested in [6], which offers a bit rate granularity of 1/2 bit and maximum throughput (without CRC) of 4.5 bits/s/Hz. For TCM we refer to the set in [11], that reaches 4 bits/s/Hz at high SNR.

We notice that M-HARQ permits a considerable throughput gain even when compared with MTCM using 4-dimensional mapping. Even if 4-dimensional mapping could further improve the M-HARQ schemes performance (not shown here), we believe that the throughput improvement would not be justified by the corresponding detection delay.

V. NO-CSI AT THE TRANSMITTER

In this section we assume that the feedback channel is employed only for retransmission requests but no-CSI is provided to the transmitter. As a consequence standard AMC is infeasible and alternative schemes (blind techniques) should be used. Falahati and Svensson [8] propose a blind version for the Gray-HARQ, in which the modulation size is gradually changed from a large constellation to smaller constellations whenever more incremental redundancy is required. Following this idea we show that the proposed M-HARQ scheme offers an efficient and flexible adaptive implementation provided that the channel fad-

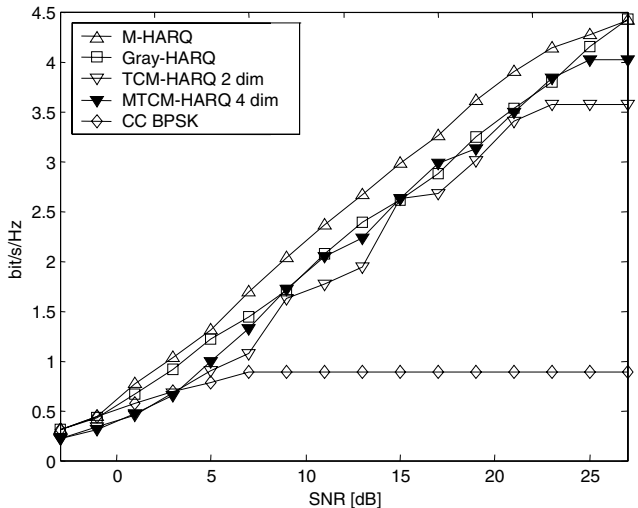


Fig. 7. Maximum achievable throughput for M-HARQ, Gray-HARQ, Code Combining BPSK ($p = 4$) and MTCM-HARQ protocol.

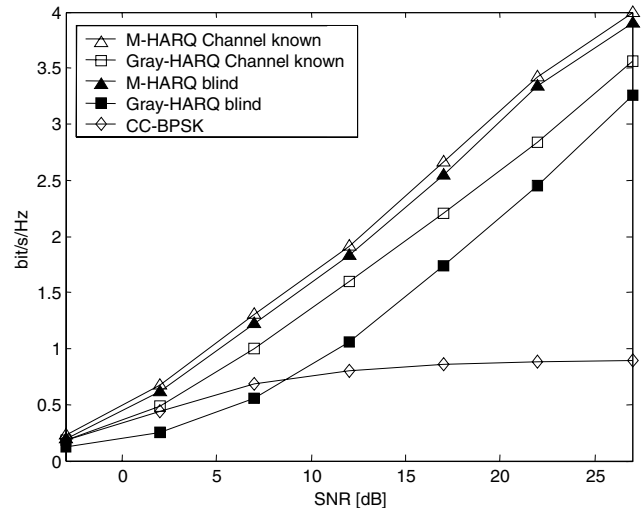


Fig. 8. Performance comparison between Gray-HARQ, M-HARQ and CC-BPSK for channel known and unknown (blind) at the transmitter.

ing is not so fast. We change the constellation size controlling the redundancy requested by the lowest level. If the transmission on the lowest level requires no incremental redundancy, the number of levels is increased. If the transmission requires a number of retransmission over a fixed threshold, the signalling constellation (and the number of levels) is automatically scaled down after the detection of the current packet. In other words the system is used to transmit over a set of parallel channels, whose number varies according to the channel conditions.

Fig. 8 shows the performance results for Gray-HARQ and M-HARQ for known and unknown channel (referred to as blind in figure) at the transmitter and puncturing period $p = 4$. M-HARQ scales the constellation size when errors are detected up to a redundancy rate equal or lower to $R = 1/2$. To provide a fair comparison Gray-HARQ reduces the modulation according to the required code protection as follows

$$\begin{matrix} 32\text{-PSK} & 16\text{-PSK} & 8\text{-PSK} & 4\text{-PSK} & 2\text{-PSK} \\ R \leq R_0 & R \leq R_3 & R \leq R_7 & R \leq R_{11} & R \geq R_{12} \end{matrix}$$

The figure also depicts the performance of CC-BPSK. A frequency flat Rayleigh fading channel $h_t \sim CN(0, 1)$ is considered here, temporal autocorrelation $\rho(k) = E[h_t h_{t+k}^*]$ depends on the Doppler frequency (f_D) normalized to the sampling frequency (f_c) according to the Jakes function $\rho(k) = J_0(2\pi k f_D / f_c)$. We here consider a Doppler frequency $f_D = 15\text{Hz}$ corresponding to a velocity of 18 Km/h at 900 MHz . It can be noticed that M-HARQ with unknown channel performs closely to the M-HARQ for perfect CSI and considerably outperforms the Gray-HARQ both with known (empty markers) and unknown (filled markers) channel.

VI. CONCLUSION

This paper has proposed an efficient combination of HARQ and AMC here referred to as Multilevel HARQ (M-HARQ). The idea is based on the iterative partitioning of the signalling constellation into subsets that permits to design a set of parallel channels with different protection to the noise impairments. Distinct Type-II HARQ protocols are employed over these parallel levels. The Type-II HARQ automatically adapts the code

rate to the need of each specific layer, thus permitting an efficient coding rate adaptation. Cross-layer design permits to adaptively select the number of parallel HARQ protocols (or equivalently the modulation size) according to the fading conditions. Simulation results show that M-HARQ provides a considerable throughput enhancement with respect to existing techniques. Since multiple modulation levels are sequentially decoded, this coding strategy leads to an increase in the packet detection time, thus it is well suited to delay tolerant applications.

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