Overview of ARQ and HARQ in Beyond 3G Systems

Antonio Maria Cipriano, Paul Gagneur
Waveform Design Team
Thales Communications France
160, Boulevard de Valmy, 92704 Colombes, France
{antonio.cipriano,paul.gagneur}@fr.thalesgroup.com

Guillaume Vivier, Serdar Sezginer
Sequans Commmunications
Bâtiment CitiCenter, 19, Le Parvis de la Défense
92 073 Paris La Défense Cedex
{gvivier, serdar}@sequans.com

***Abstract*—In this paper, we present a review of automatic repeat request (ARQ) and hybrid ARQ (HARQ) mechanisms implemented or proposed in beyond 3rd generation (B3G) wireless systems based on OFDMA. In particular, we will focus on part of the IEEE 802.16 standard family (IEEE 802.16-2005, IEEE 802.16m) and on 3GPP Long Term Evolution (LTE). In the second part of this overview, some performance curves show how HARQ can help in reducing performance degradation in mobility context.**

ARQ; HARQ; WIMAX; LTE; LTE-A; IEEE 802.16

I. INTRODUCTION

A traditional way to obtain reliability in wireless and wired communications is repetition. Automatic Repeat reQuest (ARQ) retransmits a packet when the previous attempt was unsuccessful [11]. In wireless transmissions, the conditions of reception can vary faster than in a wired context because of the presence of fading due to mobility and interference. Protection is mainly given by forward error coding (FEC), thanks to additional coded bits in the packet. However, for providing the same quality as in wired systems, FEC overhead could lead to very inefficient transmission. As a result, hybrid schemes combining FEC and ARQ, called Hybrid ARQ (HARQ), have been defined (see [12, 13]).

Hybrid ARQ is defined as the joint use of ARQ and forward error coding (FEC) at the transmitter and/or receiver. Several ways of combining retransmission and channel error coding exist. In Chase Combining, the same coded packet is retransmitted while the receiver combines several copies to improve the quality of the decoding [13]. Incremental redundancy schemes consist to encode the first transmission with a high rate code (and thus low overhead but low protection) while the following transmissions consist of additional redundancy in order to decrease the code rate seen by the receiver [14], [15].

HARQ has now become a fundamental tool of modern cellular wireless communications. However, the various standards 802.16e and evolutions, or 3GPP based ones, do not consider HARQ in the same way. In Section II, this paper provides a quick survey of the use of HARQ in LTE and WIMAX based standards. Section III provides an example of exploitation of HARQ in a mobility context. First we present the simulation set-up, which is inspired to IEEE 802.16m. Then, we consider a non-adaptive HARQ strategy based on low-density parity-check (LDPC) codes with a standard low-complexity receiver and we show the beneficial effect of HARQ in recovering part of the performance degradation.

II. RETRANSMISSION PROTOCOLS IN 3G AND B3G SYSTEMS

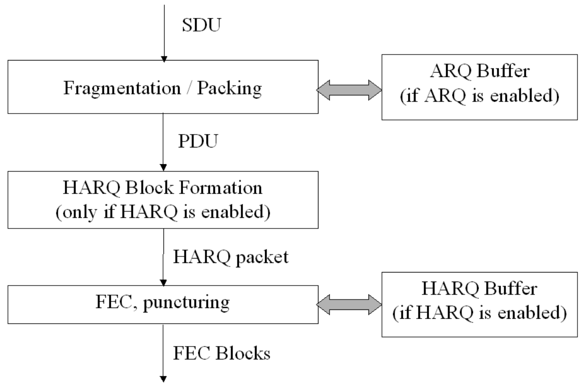

Figure 1. ARQ and HARQ functional structure at the transmitter.

Both WIMAX and LTE, as well as their respective evolutions, have the same functional architecture in the user data plane, as far as the management of HARQ and ARQ is concerned. Fig. 1 illustrates this common functional architecture at the transmitter side. Data packets entering into the fragmentation/packing function are called MAC Service Data Units (SDUs) in IEEE 802.16 and Radio Link Control (RLC) SDUs in 3GPP LTE. Here, when talking of both standard families, we will use the generic terms of SDUs and Payload Data Units (PDUs). SDUs are first segmented and/or packed and can be protected by a first ARQ protocol. The output PDUs can be arranged in HARQ packets, managed by HARQ processes, which maintain HARQ buffers.

ARQ is a standard way to increase the reliability of a given link (in this case a wireless one) by asking the repetition of lost PDUs, i.e. PDUs incorrectly delivered by HARQ or by traditional FEC. ARQ is usually suited to error-sensitive and delay-tolerant services and it can be in charge also of ordering of the received PDUs (HARQ may change the order with respect to the transmitted sequence).

In all systems considered here, HARQ is implemented with multiple parallel Stop-And-Wait (SAW) channels (in IEEE

The authors acknowledge the support of the European Commission through the FP7 project 215167 WiMAGIC, www.wimagic.eu.

802.16) or processes (in 3GPP LTE). The SAW protocol is probably the most simple retransmission protocol and it needs just a 1 bit ACK/NACK message as a feedback. It introduces a higher latency with respect to more elaborated protocols like Selective Repeat (SR) [11]. However, the fact of having parallel HARQ processes, the fast operation due to implementation in the base station, a tunable expiration timer, a tunable maximum number of retransmissions, and, finally, a careful design of the PHY frame allow a good control of the overall HARQ latency.

In the following we will give more details on the implementations of the retransmission protocols in different systems.

A. IEEE 802.16-2005

IEEE 802.16-2005 [1] defines the notion of transport connection. A transport connection carries the data traffic of a given service flow with an assigned Quality of Service (QoS) between MAC peers in one direction. A terminal can have multiple active transport connections. ARQ implementation is mandatory, and it can be enabled or not on a per-connection basis.

When ARQ is activated, MAC SDUs are divided into ARQ blocks with fixed size, negotiated at the connection establishment. Each ARQ block is identified by a block serial number (BSN), which is used at the receiver for ordering. MAC SDUs can be fragmented but the fragments boundaries must coincide with ARQ block boundaries. Error detection capabilities are implemented via a 32-bit cyclic redundancy check (CRC). ARQ is based on sliding window approach where the transmitter can transmit up to a negotiated number of ARQ blocks without receiving an ACK. The transmitter resends the ARQ blocks which are not acknowledged (i.e. it receives a NACK) and it moves the sliding window boundary when ACKs are received.

When ARQ is not enabled, MAC SDU fragments can in any case be reordered thanks to the fragment sequence number (FSN), which allows to recreate the original payload. The MAC can in this way be aware of a fragment loss: in this case all subsequent fragments are discarded until the start of a new MAC SDU or a new un-fragmented MAC SDU is detected. ARQ can be enabled on top of HARQ.

In the IEEE 802.16-2005 standard, HARQ is optional and it may be implemented only for the OFDMA-PHY layer. For mobile stations (MS), HARQ is implemented on a connection basis. A HARQ packet is formed by the concatenation of one or more MAC PDUs which are padded to reach a given size. After this operation, a cyclic redundancy check (CRC) of 16 bits is appended. If the packet size is greater than 4800 bits, then it is split into two or more FEC blocks which are finally encoded.

Two HARQ strategies are allowed: Incremental Redundancy (IR) and Chase Combining (CC). For IR, only 4 different redundancy versions can be used in the standard, and they can be repeated a generic number of time in an arbitrary order. HARQ is adaptive in the sense that modulation, redundancy version (RV), i.e. the coded bits to be sent, and transmit resource allocation can be changed at each retransmission, in order to exploit (when possible) the variations of the channel.

HARQ is asynchronous in both DL and UL, meaning that the timing of a retransmission is flexible, while the ACK/NACK signaling is a synchronous process both for UL and DL. For DL HARQ, a fast feedback ACK/NACK channel in UL is designed. For UL HARQ a one-bit ACK/NACK mechanism is implemented in the signalization part of the DL frame. The maximum number of retransmissions varies; the default value is set to four. Each connection supports multiple HARQ channels. They are distinguished using an HARQ channel identifier (ACID). The number of HARQ channels per terminal depends on its capability, but the maximum number is 16. Each HARQ channel is managed separately.

HARQ is affected by ordering issues. If an HARQ-enabled connection is not ARQ-enabled, the standard defines a MAC PDU serial number mechanism which can be exploited to recover the ordering at MAC PDU level.

Convolutional turbo codes (CTC) and convolutional codes are mandatory in IEEE 802.16-2005. Low-density parity-check (LDPC) codes are defined and optional. Even if different frames are defined in the standard, both in time and frequency division duplexing (TDD and FDD), mobile WIMAX implementation is TDD with frame length of 5 ms.

B. IEEE 802.16m

Task group m (TGm) in IEEE 802.16 is in charge of defining an advanced air interface, compliant with IMT-Advanced requirements. The standard is not yet finalized. Hence, the material presented here comes from two documents: the amendment working document (AWD) [2], and the system description document (SDD) [3] and it is subject to possible changes. IEEE 802.16-2005 is no longer an active standard, and it is currently replaced by the IEEE 802.16-2009 standard [4], coming from the integration of the outcomes of TGf and TGg. Some features described for IEEE 802.16m below, like persistent scheduling and HARQ, have been already integrated the in IEEE 802.16-2009, at least in part.

Like in IEEE 802.16-2005, in IEEE 802.16m, ARQ and HARQ can be enabled on a per connection basis. The ARQ state machine is similar to IEEE 802.16-2005: each ARQ-enabled connection has an independent ARQ state machine. In IEEE 802.16m, one MAC PDU contains one ARQ block (data coming only from 1 connection) or more ARQ blocks (data coming from multiple connections). The number of ARQ blocks in a MAC PDU coincides with the number of connections in the MAC PDU. Moreover, ARQ retransmissions may be refragmented in ARQ sub-blocks. ARQ feedback supports cumulative or selective ACK, and the transmitter can ask the receiver for a status report, in order to know the status of the receiver.

In IEEE 802.16m, a new PHY frame has been introduced in order to lower the latency introduced by HARQ. One superframe of 20 ms is divided in 4 frames of 5 ms. For channel bandwidth of 5, 10, or 20 MHz, each 5 ms radio frame consists of 8 subframes for guard intervals equal to 1/8 and

1/16 or 7 subframes for guard interval of ¼. This is the basic frame structure which is applied to all duplexing schemes (FDD, half-duplex FDD and TDD with two switching points as in IEEE 802.16-2005). In order to lower the latency, a data burst can occupy just one subframe, corresponding to the default Time Transmission Interval (TTI), even if longer TTIs are allowed. As an example, subframes length for 5, 10, or 20 MHz, FDD, and guard interval 1/8 is equal to 0.617 ms.

IR strategy in IEEE 802.16m is mandatory and includes CC as a special case. CC is implemented as in IEEE 802.16-2005. In DL, HARQ is adaptive and asynchronous. However, in UL, HARQ is synchronous, adaptive or fixed (default mode) depending on signalling. When fixed IR in UL is used, subpackets shall be transmitted in a fix sequential order. Another novelty in 16m is that constellation rearrangement is supported in two versions, i.e. the bits are differently mapped to complex symbols in order to guarantee an equal level of protection (in 16- and 64-QAM certain bits are more protected than others) [10]. Bits or symbols of retransmissions can be sent in different order over the subcarriers, for exploiting frequency diversity, or over the antennas, if MIMO is used, for exploiting spatial diversity.

IEEE 802.16m also introduces individual and composite persistent scheduling (like 3GPP LTE), for services like Voice over IP, and group allocation. With persistent scheduling, HARQ in DL is asynchronous (hence non-persistent), while in UL it is synchronous. For group allocation, HARQ retransmissions are allocated individually in an asynchronous way in DL, and individually and synchronously in UL.

As in IEEE 802.16-2005, the only mandatory channel code defined in IEEE 802.16m for FEC block encoding is CTC while tail-biting convolutional coding is used for encoding control channels.

C. 3GPP Long Term Evolution (Release 8)

IEEE 802.16m, LTE and LTE-Advanced (LTE-A) benefit from cross-fertilization: innovations from one standard benefited to the other one. Therefore, there are not so much differences between the two systems.

In LTE, HARQ reordering is done in the Radio Link Control (RLC) layer: independently if it operates in unacknowledged mode (without ARQ) or in acknowledged mode (with active ARQ). ARQ is structured in a flexible way, as in IEEE 802.16m: possibility of retransmission re-fragmentation and polling with status reports.

HARQ, in both UL and DL, is organized in multiple parallel SAW process, whose maximum number is 8. As in IEEE 802.16m, HARQ in DL is asynchronous and adaptive, while in UL it is synchronous and adaptive or non-adaptive. However, the PHY layer is different since, both LTE and 16m uses OFDMA in DL, but LTE implements single-carrier FDMA in UL, while 16m is built on top of OFDMA also in UL. As in IEEE 802.16m, IR and CC are both supported. For IR, 4 different redundancy versions can be signaled, and they are built thanks the so called circular buffer (LTE implementation of the rate matching block). LTE uses convolutional codes and convolutional turbo codes.

D. 3GPP Long Term Evolution - Advanced

HARQ in LTE-A is very similar to HARQ in LTE. Only small adaptations have been done to cope with the change in the supported bandwidth since LTE-A is supposed to support bandwidth up to 100MHz. Typically for this case, one can think of dealing with 5 more HARQ process, each of them working on a 20 MHz part of the total available bandwidth.

III. HARQ SIMULATIONS

While the previous review dealt also with ARQ, here we focus on results about HARQ. In particular we are interested in assessing non-adaptive HARQ performance at vehicular speeds.

A. Metrics

HARQ performance can be measured under different angles: residual bit error rate (BER) or FEC block error rate (BLER), throughput, throughput efficiency, delay. Many different definitions of throughput and delay are given in the literature.

Here, we will use the following definition of throughput (or transmission) efficiency T_{eff}, measured in bit/s/Hz

$$T_{eff} = \frac{\text{n° of correct rx information bits}}{\text{n° of complex symbols used for their tx}} \quad (1)$$

When Chase Combining is used in non-adaptive protocol, then the throughput efficiency can be written as follows:

$$T_{eff} = \frac{MCS_{eff}}{N_T^{avg}} G(BLER_r) \quad \text{[bit/s/Hz]} \quad (2)$$

where N_T^{avg} is the average number of HARQ transmissions needed for a burst to be successfully decoded (including the first transmission). The efficiency of the used modulation and coding scheme (MCS) is denoted by MCS_{eff} and is computed as:

$$MCS_{eff} = \frac{M_{eff} R}{N_{rep}} \quad \text{[bit/s/Hz]} \quad (3)$$

where M_{eff} is the modulation efficiency (M_{eff} = 2 for QPSK, 4 for 16-QAM, 6 for 64-QAM); R is the coding rate (1/2, 2/3, 3/4 or 5/6); N_{rep} is the number of repetitions used (1, 2, 4 or 6). The function $G(BLER_r)$ in (2) is usually equal to (1 – $BLER_r$), where $BLER_r$ is the residual FEC block error rate (BLER) after HARQ. However, here we will use also a gating function: when the error probability is greater than a target residual BLER, where the throughput is assumed to be 0:

$$G(BLER_r) = \begin{cases} 1 - BLER_r, & BLER_r \leq \text{Target BLER} \\ 0 & , \; BLER_r > \text{Target BLER} \end{cases} \quad (4)$$

This gating function allows to take into account the target BLER of QoS classes. By means of this, the impact of HARQ throughput over specific QoS classes in terms of throughput is shown in a more apparent way.

B. Simulation scenarios

Irregular low-density parity-check (LDPC) codes are considered. They are built by using the progressive edge growth (PEG) algorithm described in [7], have a mother code rate of 1/2 and their degree distribution is p(2) = 0.826586, p(9) = 0.173414. The proposed irregular LDPC codes have slightly better performance than IEEE 802.16e LDPC in AWGN channel [8]. However, the structure of LDPC built with PEG does not allow for parallelization and complexity reduction as for IEEE 802.16e LDPC codes.

HARQ protocol is non-adaptive CC or IR. We will consider random puncturing for each retransmission. For IR, the first transmission and the retransmissions have different sizes in coded bits, respectively N_1 and N_2 (see Tab. I). When all the coded bits have been sent, if a new transmission is scheduled, the HARQ IR protocol starts resending previously sent coded bits. At the receiver side, the Log-Likelihood Ratios (LLRs) of the repeated bits at the output of the soft demodulation block are added. This approach is applied also for CC, even if suboptimal, in order to lower complexity at the receiver [9].

TABLE I. MCS USED IN THE SIMULATIONS AND THEIR STRATEGY.

MCS	1^{st} tx rate	Modulation	MCS_{eff}	Strategy	K	N_1	N_2
MCS 1	1/2	QPSK	1	CC5	480	960	960
MCS 2	3/4	QPSK	1.5	IR5	480	640	320
MCS 3	1/2	16 QAM	2	CC5	480	960	960
MCS 4	3/4	16 QAM	3	IR5	480	640	320
MCS 5	5/6	64 QAM	5	IR5	480	576	192

Tab. I presents the investigated MCSs where K represents the number of information bits per FEC block and the number at the end of the strategy, e.g. CC5, indicates the maximum number of transmissions including the first one.

We use the IEEE 802.16m frame structure with 6 OFDM symbols [3]. Main OFDM parameters are reported in Table II. A FEC block is contained inside one subframe which is the basic TTI. We will use instantaneous and perfect ACK/NACK, since here our interest is in measuring the impact of speed at the receiver side and not in the robustness of ACK/NACK message. If a retransmission occurs, it is accommodated in the subframe following the previous transmission. Even if unrealistic, this choice does not affect the value of throughput efficiency, which is not adapted to measure time delays, but rather efficiency losses due to retransmissions.

What we are interested in here is the impact of a varying channel at the receiver side. For each subframe, the channel taps corresponding to the very beginning of the subframe are perfectly known at the receiver. This channel state information is acquired by the receiver and used for the whole duration of the subframe: we suppose that there is no algorithm tracking the variation of the channel but just a simple channel estimation algorithm which uses the pilots of the subframe and give a constant estimate for each subcarrier for the whole subframe. The channel estimate is used for zero forcing (ZF) equalization and for estimating the noise variance which is fed to the soft demodulator. At each new subframe the receiver estimates again the channel, as described before, and uses it for detection and decoding. However, in a mobility context, the channel seen by the packet (in our simulator) changes on a sample by sample basis and introduces performance degradations due to inter carrier interference (ICI).

TABLE II. MAIN OFDM PARAMETERS.

Parameter	Value
FFT size	512
Number of OFDM symbols per frame	6
Number of used subcarriers per subframe	80
Subcarrier allocation	pseudo-random
Length of the CP	64 samples
Carrier frequency	2,5 GHz
Sampling frequency	5,6 MHz
Subcarrier spacing	10,9375 kHz

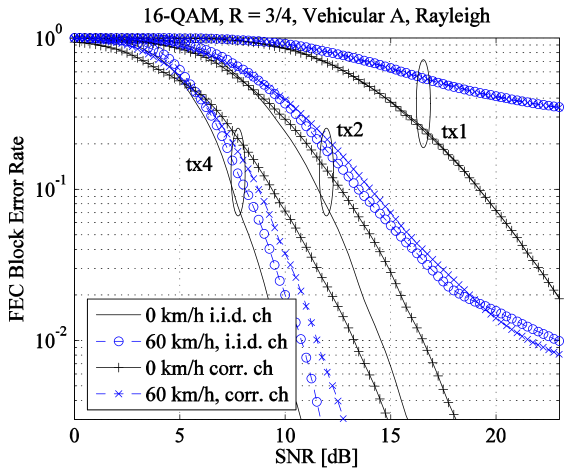

Figure 2. BLER performance for 16-QAM rate 3/4 in Vehicular A channel.

C. Simulation results

In Fig. 2, we report FEC BLER curves for MCS 4 from Tab. I over a Vehicular-A channel [16]. Tx1, tx2 and tx 4 in the figure refer to the BLER curves respectively at transmission 1 (no HARQ), 2 and 4 of the IR protocol. We considered either correlated channel realizations inside a HARQ process (curves with crosses), or i.i.d. channel realizations between different retransmissions of the same HARQ process (curves without marks). The channel seen by each transmission evolves with time if speed is non-zero. In the presence of mobility, an error floor in the BLER is present due to the suboptimal receiver which is not able to cope with the introduced ICI. At vehicular speeds, HARQ contributes to lower the BLER error floor and is able to exploit the time diversity of the channel (coherence time of about 7,5 ms). For instance, BLER performance at transmission 4 is better for 60 km/h than for zero speed, when the channel is correlated inside an HARQ process. With i.i.d. channel, the best case is always the one with zero speed (no interference due to mobility).

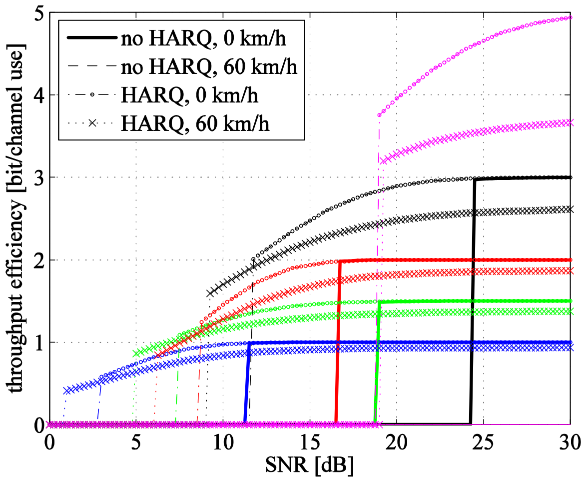

Figure 3. Gated throughput at target BLER = 0.01 for HARQ and no HARQ in Vehicular A channel correlated inside an HARQ process.

In Fig. 3, the gated throughput efficiency defined in (1) and (4) is shown for a Vehicular A channel, with channel realizations correlated inside a HARQ process. We consider MCSs in Tab. I. Two cases of gated throughput are studied for each MCS: with HARQ and without HARQ, the goal being to quantify the gain provided by HARQ in terms of minimum SNR required to achieve target QoS. We notice that the gated throughput efficiency without HARQ at 60 km/h is always zero in the considered SNR interval, even for the most robust MCS; hence no curve is shown in the figure in this case. This is due to the fact that, even for MCS 1, the BLER floor is already higher than 0.01 at 60 km/h. Hence, the loss with respect to static conditions is important: no service with target BLER of 0.01 or smaller can be delivered. Moreover, we see that the MCS 2 (QPSK with rate ¾, green solid curve) at first transmission is not interesting, since it works worse than MCS 3 (red solid curve). Gated throughput efficiency without HARQ for MCS 5 does not fall into the SNR range of the figure.

At 60 km/h HARQ increases or maintains the performance at 0 km/h in terms of limit SNR, which is defined as the SNR for which the gated throughput efficiency falls to zero. Of course, this increased robustness, which may be seen as increased coverage, is achieved at the cost of throughput degradation. Finally, notice that traditional (non-gated) throughput efficiency curves continues for each MCS at lower SNRs than the corresponding limit SNR (not shown in the figure). In those SNR regions, however, the target BLER is not achieved.

Fig. 4 summarizes the results for Vehicular A channel with channel correlated inside a HARQ process. The behavior of the minimum guaranteed gated throughput efficiency with respect to speed with and without HARQ is presented. The minimum guaranteed gated throughput efficiency is the point of the gated throughput curve (at target BLER = 0.01) corresponding to the limit SNR (below this limit the gated throughput is zero). Without HARQ (1st transmission), the minimum gated throughputs are zero at 60 km/h for all MCS (hence, the points are not shown in the figure), while at 0 km/h they aregreater than zero and represented by the markers with the label “tx1”. For MCS 5, the “tx1” point is outside the figure range. Fig. 4 summarizes the effects of speed on HARQ performance. The increased robustness in static conditions, as well as the degradation in throughput efficiency, can be appreciated in the figure. For example, for MCS 3 (diamonds) at 0 km/h a gain of 8 dB in the limit SNR is achieved with a throughput degradation of about 37%. At 60 km/h, the gain with respect to the case without HARQ is substantial, because the minimum gated throughput efficiency was zero without HARQ. If we compare with respect to HARQ at 0 km/h, an additional gain of 3 dB is achieved for the limit SNR, with a global degradation of 60% of the throughput. The big degradation at 120 km/h for MCS 1 can be explained by the fact that each FEC block of MCS 1 occupies 6 OFDM symbols, while MCS 2 and 3 retransmissions occupy respectively 2 and 3 OFDM symbols (see N_1 and N_2 values in Tab. I, which should be divided by the modulation order and number of occupied subcarrier given in Table II). Hence, MCS 1 is the MCS which experiences the highest channel variability, since its FEC blocks are sent over a longer time.

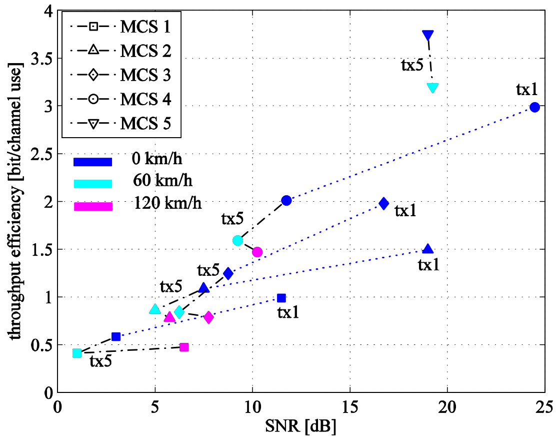

Figure 4. Minimum gated throughput at target BLER = 0.01 and the corresponding limit SNR with and without HARQ for Vehicular A channel correlated inside a HARQ process. The case withouth HARQ is indicated by the label “tx1”.

Finally, Fig. 5 summarizes the results for Vehicular A channel with i.i.d. channel realizations between subframes. The behavior of the minimum guaranteed gated throughput efficiency with respect to speed and the number of transmissions is presented. In Fig. 5 we have presented results only for MCS 1, 4 and 5 for seak of readability. For each speed (marked with a different color) and for each MCS, the trade off between degradation of the minimum gated throughput efficiency and the improvement in the limit SNR is presented. For example, we can see that for using MCS 4 at 60 km/h, a maximum number of transmissions equal to 2 is sufficient for having a non-zero gated throughput, while we need 4 transmissions at 120 km/h. On the other hand, for MCS 5 there is no possible operation with target BLER equal to 0.01 at 120 km/h. The fact that MCS 1 can not be operated at 120 km/h with 4 maximum transmissions, differently to MCS 4 which is less robust, is due to the fact that the FEC blocks of MCS 1 span more OFDMA symbols than the ones of MCS 4 and hence suffer from higher degradation especially at high speed.

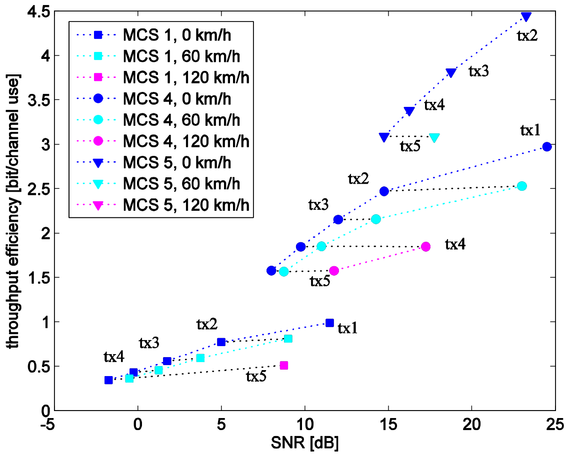

Figure 5. Minimum gated throughput at target BLER = 0.01 and the corresponding limit SNR as a function of the number of maximum transmissions for Vehicular A channel with i.i.d. channel realizations, for MCS 1, 4 and 5.

Finally, also the effect of the channel correlation can be appreciated when comparing Fig.5 to Fig. 4. With i.i.d. channels, the minimum throughput efficiency points as a function of the speed approximatively align on a horizontal line for a given MCS and maximum number of transmissions (black dotted lines). This means that the distribution of the retransmissions is substantially the same for those points, at the considered target BLER. Channel correlation introduces different distributions of retransmission probabilities as a function of the speed for a given MCS and fixed maximum number of transmissions at the given target BLER. This is reflected in a decrease of the minimum guaranteed throughput efficiency.

IV. CONCLUSIONS

In this overview paper we have presented the principal features of the ARQ and HARQ implementation of current B3G wireless standard based on OFDMA, namely IEEE 802.16-2005/2009, IEEE 802.16m, 3GPP LTE/LTE-A. All these standards share the main structure in the assignment of the functional roles of ARQ and HARQ. Concerning HARQ, the main differences are on the type of adopted protocol (synchronous/asynchronous, adaptive/non-adaptive) and in which direction they are used (UL/DL). Substantial alignment exist between IEEE 802.16m and 3GPP LTE.

In the second part of the paper we present the results of non-adaptive HARQ IR and CC based on LDPC codes at vehicular speed. We focus our presentation on the gated throughput efficiency metric, which integrates also the target BLER of the Quality of Service classes. With respect to this metric we show that HARQ, thanks to its well known capability of recovering the time diversity of the channel, is able to achieve non-zero gated throughput efficiencies for vehicular speeds. In this context, the improvement with respect to the case without HARQ is substantial.

REFERENCES

[1] IEEE Std 802.16e-2005 and IEEE Std 802.16-2004/Cor 1-2005, "*IEEE Standard for Local and metropolitan area networks: Part 16: Air Interface for Fixed Broadband Access Systems; Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1*," 28 February 2005.

[2] IEEE 802.16 TGm, "*Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems;*" IEEE 802.16m-09/0010r1a (working document), June 2009.

[3] IEEE 802.16 TGm, "IEEE 802.16m System Description Document," IEEE 802.16m-08/003r3, September 2009.

[4] IEEE Std 802.16-2009, "*IEEE Standard for Local and metropolitan area networks: Part 16: Air Interface for Broadband Wireless Access Systems*," 29 May 2009.

[5] 3GPP Description document, "Overview of 3GPP Release 8 V0.1.0 (2010-04)". Available at http://www.3gpp.org/Release-8

[6] *LTE – The UMTS Long Term Evolution: From Theory to Practice*, Editors: S. Sesia, I. Toufik and M. Baker, John Wiley & Sons, 2009.

[7] X.-Y. Hu, E. Eleftheriou, and D. M. Arnold, "Regular and Irregular Progressive Edge-Growth Tanner Graphs," *IEEE Trans. on Information Theory*, vol 51, n. 1, pp 386-398, January 2005.

[8] EC FP7 WiMAGIC project D5.3, "MAC and Higher Layers Techniques And Cross-Layer Optimization for WiMAGIC - III", September 2009.

[9] J. Lee, H.-L. Lou, D. Toumpakaris, E. W. Jang and J. M. Cioffi, "Transceiver Design for MIMO Wireless Systems Incorporating Hybrid ARQ", IEEE Commun. Magazine, pp. 32-40, January 2009.

[10] S. Bliudze, N. Billy, and D. Krob, "On optimal hybrid ARQ control schemes for HSDPA with 16QAM," in Proc. of IEEE International Conference on Wireless And Mobile Computing, Networking And Communications (WiMob'2005), vol. 1, August 2005, pp. 121–127.

[11] S. Lin, D. J. Costello, and M. J. Miller, "Authomatic-Repeat-Request Error-Control Schemes," *IEEE Commun. Mag.*, vol. 22, no. 12, pp. 5–17, December 1984.

[12] S. B. Wicker, "Adaptive rate error control through the use of diversity combining and majority-logic decoding in a hybrid-ARQ protocol," *IEEE Trans. Commun.*, vol. 38, no. 3, pp. 263–266, March 1990.

[13] D. Chase, "Code Combining – A maximum-likelihood decoding approach for combining an arbitrary number of noisy packets," *IEEE Trans. Commun.*, vol. com-33, no. 5, pp. 385–393, May 1985.

[14] S. Sesia, G. Caire, and G. Vivier, "Incremental redundancy hybrid arq schemes based on lowdensity parity check codes," *IEEE Trans. Commun.*, vol. 52, no. 8, pp. 1311–1321, August 2004.

[15] J.-F. Cheng, "Coding performance of Hybrid ARQ Schemes", *IEEE Trans. Commun.*, vol. 54, no. 6, pp. 1017–1029, June 2006.

[16] IEEE 802.16 TGm, "802.16m Evaluation Methodology", IEEE 802.16m-008/004r5, January 2009.