Hybrid ARQ schemes for future wireless systems based on MC-CDMA

Johan Roman, Friedbert Berens, Miguel Kirsch, Stephane Tanrikulu
Wireless Systems and Algorithms
STMicroelectronics N.V
39, chemin du champ des filles 1228 Plan-les-Ouates/Geneva, Switzerland
{johan.roman, friedbert.berens, miguel.kirsch, stephane.tanrikulu}@st.com

***Abstract*—The rapid growth of Internet services and increasing interest in portable computing devices will create an even larger demand for high-speed wireless packet based data services in the future. Especially in the downlink, high throughput is needed since the number of downloads of large data files from web sites and servers will increase. These requirements will need to be accommodated by future fully packet based Beyond 3rd Generation (B3G) cellular systems. MC-CDMA, a multicarrier modulation scheme based on code division multiple access (CDMA) is the most promising candidate for this next generation of mobile radio communication for achieving high data rate transmission. In order to successfully standardize a B3G system it needs to be optimized for the use in a TCP/IP based backbone system. This optimization has to be carried out in a joint manner between the physical layer and the higher layers.**

This paper presents as a part of the joint optimization the physical layer implementation and simulation results of different hybrid ARQ schemes for future wireless systems based on MC-CDMA. This work has been carried out within the European IST projects MATRICE and its follow-up 4MORE, dealing respectively with research on MC-CDMA physical layer and higher layers for the use in a future cellular radio system, and research on validation and implementation of a low-power cost-effective SoC solution based on MATRICE inputs. In this paper, the used system parameters represent a simplified version of the MATRICE parameters.

Keywords— MC-CDMA, Chase Combining (CC), Incremental Redundancy (IR), Hybrid Automatic Repeat reQuest (HARQ), Constellation Rearrangement, Turbo Coding.

I. INTRODUCTION

In future wireless systems, packet transmission will be the dominant type of traffic. The backbone will be based on the internet protocol (TCP/IP). Thus efficient packet transmission schemes need to be developed as part of the definition of future air interfaces for beyond 3G mobile radio systems. Due to the demanding characteristics of the wireless transmission channel the simple use of an automatic repeat request (ARQ) protocol to guarantee an error free packet delivery to the application is not sufficient. Hybrid ARQ schemes need to be deployed. This combination of a forward error correction (FEC) system and a simple ARQ scheme leads to the needed robustness against wireless channel impairments.

In the operation of a hybrid ARQ system the physical layer is taking care of the FEC decoding and error detection, and the MAC layer controls the complete process of the ARQ. Thus both entities need to be considered in the investigation of packet transmission schemes using ARQ. The interface between the two layers is of major importance for a proper and optimized operation of the transmission. The overall performance of a packet based wireless system can only be evaluated by a combined simulation of the physical layer and higher layers. This combined simulation is typically performed by passing the physical layer results to the higher layer system simulator as results tables. In the system level simulations the performance of the repeated packets is evaluated based on the packet error behavior of the physical layer without repetition. In this evaluation process only the energy gain is taken into account.

In this publication the effect of repetition protocol regarding the packet error rate has been investigated. The goal is to refine the interface between the physical layer simulations and the system level simulations towards a more realistic view of the hybrid ARQ schemes regarding the combination gains in the ARQ process.

As one of the most promising modulation techniques for the use in B3G systems, MC-CDMA [1] has been used in the downlink direction of the MATRICE airinterface. In MC-CDMA, each user's data-modulated symbol to be transmitted is spread over a number of subcarriers using an orthogonal spreading sequence defined in time or frequency domain.

The rest of the paper is organized as follows. In section II we give an overview of the existing HARQ schemes as a combination of FEC systems and ARQ schemes and present their structure. In section III, we present the system considered based on MC-CDMA and the main parameters of the simulation environment. In section IV, the results of the different Hybrid ARQ schemes implemented are compared together. Finally a conclusion and an outlook is given in section V.

II. HARQ SCHEMES

Although ARQ systems are simple, easy to implement and provide high system reliability, they suffer of a rapid decrease in throughput with increased channel error rates. In fact the increased frequency of retransmission requests has a severe impact on the throughput.

FEC systems, such as systems using turbo codes [2] maintain constant rate (equal to the code rate *R*) regardless of the channel error rates, however, FEC systems have a major drawback. Since the probability of decoding error is usually greater than the probability of an undetected error, such systems are not highly reliable. In order to achieve high system reliability, long powerful codes must be used, which can correct a large number of patterns. The benefits of ARQ systems of obtaining high reliability can be coupled with the advantage of FEC systems to provide constant throughput even with poor channel conditions. Such system, which is a combination of two basic error control schemes FEC and ARQ, is referred to as Hybrid ARQ scheme [3].

A. HARQ type 1

In this scheme, each packet is encoded for both error detection and correction (CRC and FEC).The packet is first encoded for error detection with a cyclic redundancy check (CRC codes). The encoded data is then encoded once again using a FEC code. The receiver discards erroneous packets (when errors remain after FEC decoding), sends a retransmission request to the transmitter and asks for an entirely new retransmission. Retransmissions take place at either the same or lower code rate until the packet is correctly decoded or until a pre-set number of retransmissions have been performed. The data flow graph for HARQ type 1 is presented in Fig. 1. Although this scheme does not require a large buffer at the receiver, it yields a very inefficient method of implementing ARQ. In fact, the main disadvantage with HARQ type 1 is that erroneous packets are always entirely retransmitted, even for channel conditions that wouldn't justify such redundancy.

B. HARQ type 2

In this scheme, each packet is encoded for both error detection and correction (CRC and FEC) like in a simple HARQ 1 scheme. The receiver stores the received symbols of erroneous packets in a buffer in order to reuse them combined with symbols from subsequent retransmissions. Storing the previously received symbols allows the concepts of Incremental Redundancy and Chase Combining to be exploited.

- Incremental Redundancy

With IR, at each retransmission the puncturing pattern after FEC is modified (without changing the number of punctured bits). Thus, a different combination of systematic and parity bits are transmitted. Such procedure gradually increases the receiver coding gain at each retransmission and is particularly suited in terms of throughput adaptation to the channel conditions.

- Chase Combining

The principle of Chase's combining scheme (HARQ type 2 with one redundancy version) [4] is to allow the decoder to combine multiple received copies of the coded packet weighted by their respective SNR prior to decoding. This method provides diversity gain and is very simple to implement. In Chase Combining, the soft-decision data sequence obtained from previously transmitted erroneous packets is stored in a buffer at the receiver side, and it is combined symbol by symbol with the currently retransmitted packet before FEC decoding.

Fig. 2 presents the data flow graph of the HARQ type 2. As can be expected, the throughput of type 2 Hybrid FEC-ARQ is significantly higher than for type 1 Hybrid FEC-

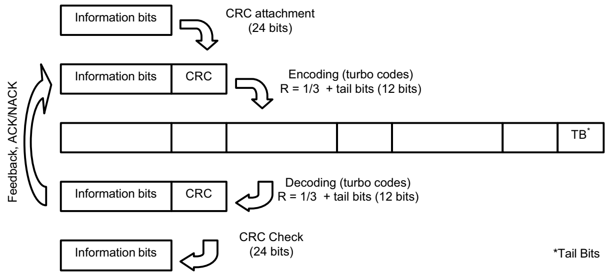

Fig. 1: Data flow graph for HARQ type 1 scheme

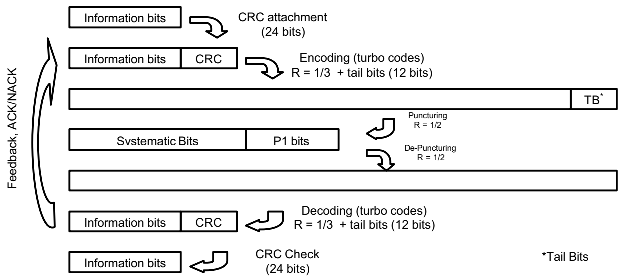

Fig. 2: Data flow graph for HARQ type 2 scheme. In the Incremental Redundancy case, the puncturing pattern changes at each retransmission.

ARQ, especially when multiple copies of the received erroneous packets are combined. In comparison to HARQ type 1, IR and CC data combination schemes respectively achieve additional coding and diversity gains.

III. SYSTEM MODEL AND SIMULATION PARAMETERS

In Fig. 3 the overall simplified MC-CDMA based transmission system for the hybrid ARQ investigations is depicted. At the transmitter, the information sequence is CRC encoded. The resulting sequence is FEC encoded including the needed puncturing. In the simulation chain a UMTS compliant Turbo-Code is used. The encoded sequence is then mapped. The sequence of symbols from the reference user with the HARQ functionality is multiplexed with the sequence of symbols of the interfering users. Thus different load factors can be simulated. The symbol stream is then processed by the MC-CDMA modulator and transmitted over a BRAN-E multipath channel.

In the receiver the signal is processed by a single user MMSE equalizer taking into account ideal channel estimation. The resulting LLR sample sequence is deinterleaved and input to the combining block which performs the depuncturing and combining, and stores the encoded sequence in a buffer. Then, the encoded sequence is sent to the turbo-decoder. Error detection is performed by the CRC check which generates the ACK/NACKs. A request is then sent to the HARQ control block for retransmission in case of error. The CRC Check block inputs the information data sequence to the sink. In the presented simulations no feedback errors are injected.

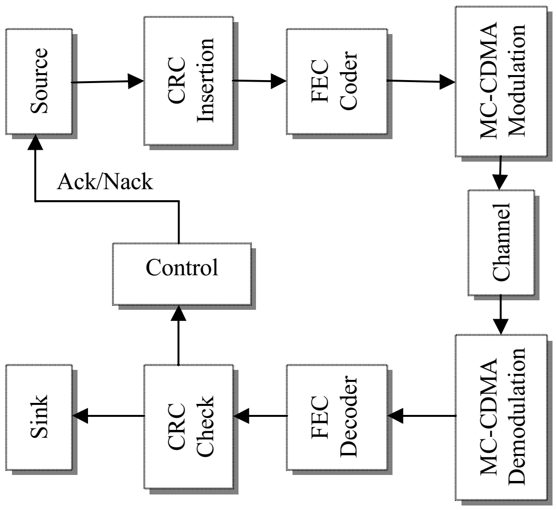

Fig. 3: MC CDMA Chain

The main simulation parameters are shown in Table 1.

Table 1: Simulations parameters

FFT size	1024 points
Frame Size	10ms
Slot size	30 OFDM symbols, 0.667ms
Guard Interval	216 chips
Spreading factor	32
Multipath Channel	BRAN E (multi-path fading channel)
Mobile speed	60km/h
Number of users	32
Number of carriers	1024
Combining type	MMSE
Channel coding/decoding	Turbo code (R=1/3), LogMap decoding (nb of iterations 10)
HARQ packet combining scheme	Type 1; Type 2: Chase Combining/Incremental Redundancy

IV. SIMULATION RESULTS

In the simulation, we evaluate the performance of a Hybrid ARQ scheme in terms of residual BLER and the throughput efficiency. The main parameter of the investigated hybrid ARQ 1 and 2 schemes are given in Table 2 and Table 3.

Table 2: Configuration for HARQ type 1

Constellation mapping	16QAM
Coding rate	1/3
Information block size	1252 bits
Coded block size	3840 bits
CRC length	24 bits
Maximum Throughput per code	1878 kbit/s

A. *HARQ type 1 performance evaluation*

In the MC-CDMA simulation chain, we first evaluate the performance of the functionality of HARQ type 1. At each retransmission we send the whole information sequence after turbo coding ($R = 1/3$). The packet at the output of the FEC coder block is not punctured. Table 2 presents the configuration considered for the simulations for HARQ type 1. Only a 16QAM carrier modulation scheme has been considered as an example. In Fig. 4, the obtained throughput efficiency is plotted as a function of the E_b/N_0. The maximum reachable throughput for one user is 1878kbit/s. The effective coding rates R_{eff} are 1/3, 1/6, 1/9 and 1/12 depending on the number of retransmissions.

Considering the residual BLER presented in Fig. 5, we gain 3.6 dB between the first and the second transmission at 10% residual BLER. Taking into account the energy gain of 3dB the gain due to the repetition diversity is limited to 0.6 dB.

Table 3: Configuration for HARQ Type 2

Constellation	QPSK	16QAM	16QAM	16QAM
Coding rate (R)	½	½	2/3	3/4
Information block size	936	1892	2532	2856
CRC	24	24	24	24
Coded block size	2892	5760	7680	8652
Punctured block size	1920	3840	3840	3840
Maximum Throughput per code in kbit/s	1404	2838	3798	4284

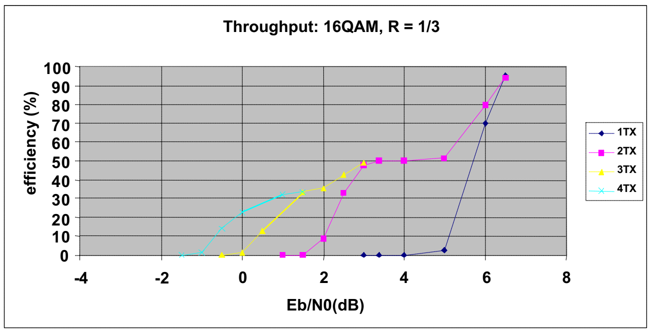

Fig. 4: HARQ type 1 throughput efficiency: maximum throughput per user: 1878kbit/s.

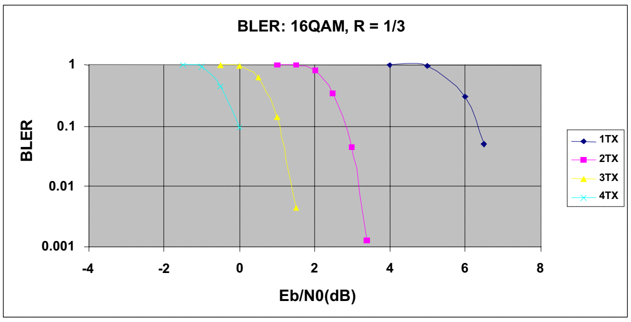

Fig. 5: HARQ type 1 residual BLER.

B. *HARQ type 2 performance evaluation*

In the simulations the two main cases, Chase Combining (CC) and Incremental Redundancy (IR) of HARQ type 2 schemes, are considered. The mother code rate of the turbo coder R_{mother} is equal to 1/3. In order to reach various coding rates from 1/3 to ¾, puncturing of the mother code has been introduced.

CC is applied among the received packets that are identically encoded using the same puncturing pattern for each retransmission and the same coding rate. This leads in the case of a base coding rate of R equal to ¾ to an effective coding rate R_{eff} of ¾, 3/8, 3/12 and 3/16 depending on the number of retransmissions.

IR uses different puncturing patterns, alternatively for each retransmission. Depending on the number of retransmissions and the base coding rate R, the effective coding rates R_{eff} are obtained as previously described in the CC case.

Table 3 presents all four configurations which have been investigated for both CC and IR. In this comparison different carrier modulation schemes and base coding rates have been taken into account. This leads to maximum user data rates between 1404kbit/s and 4284kbt/s.

Generally, CC (diversity combining) is suboptimum with respect to IR (code combining) [3]. Fig. 6, Fig. 7 and Fig. 8 depict this performance difference. In Fig. 6 the residual BLER for the CC and the IR scheme is depicted for a QPSK carrier modulation and a base coding rate R = ½. In Fig. 7 and Fig. 8 a 16QAM carrier modulation is deployed. The base coding rate R in Fig. 7 is equal to ½, whereas in Fig. 8 a based coding rate R = ¾ is used.

For the same effective coding rates, Fig. 6 and Fig. 7, show how higher modulation orders have a large impact on the performance increase of IR over CC.

Keeping the same modulation order (16-QAM), Fig. 7 and Fig. 8 show the increasing gain of IR over CC as the base coding rate gets higher. At 10% residual BLER and a base coding rate R = 1/2, we can see a performance gain of around 2 dB for IR, whereas this can rise to around 4 dB for a base coding rate of R = ¾.

For lower modulation orders and coding rates, as depicted in Fig. 6, the performance difference between IR and CC becomes less significant. Within this operational range only the simplest HARQ schemes should be deployed.

Finally, Fig. 9 depicts the performance in throughput efficiency of CC and IR after the second, third and fourth transmissions in the case of a 16QAM modulation and a base coding rate of R = ¾. The maximum throughput for one user is given by 4284kbits/s. Higher throughputs can be reached by deploying more than one spreading code per user.

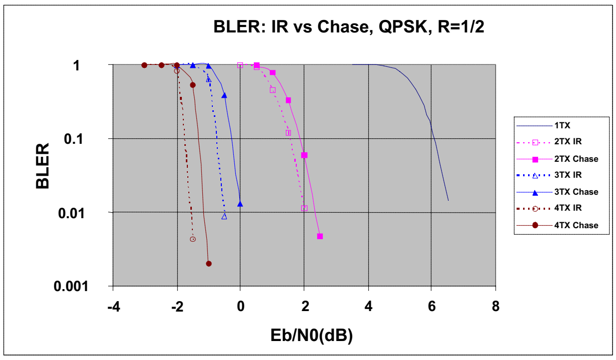

Fig. 6 HARQ type 2 residual BLER: IR vs. CC comparison.

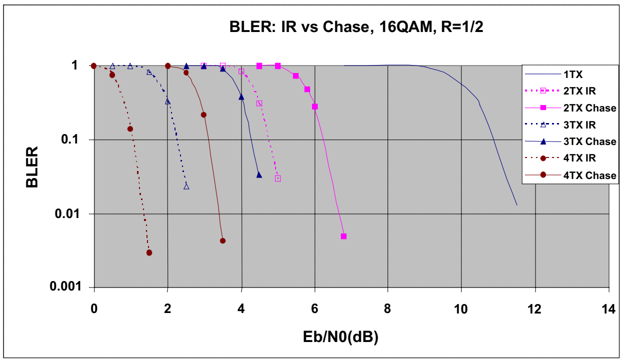

Fig. 7: HARQ type 2 residual BLER: IR vs. CC comparison.

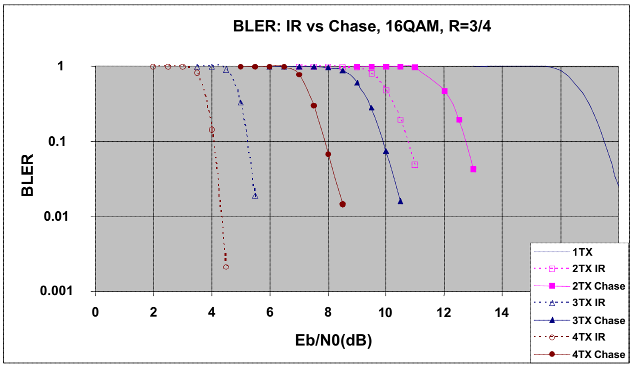

Fig. 8 HARQ type 2 residual BLER: IR vs. CC comparison.

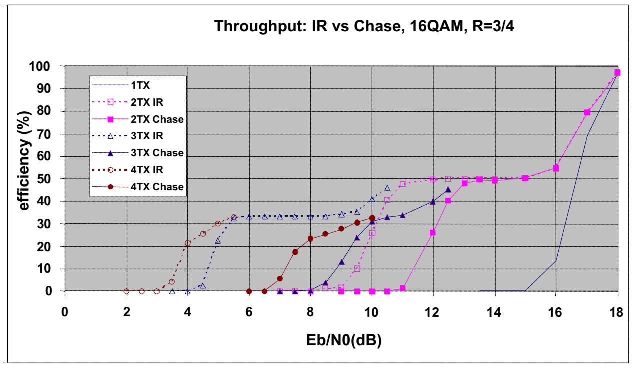

Fig. 9: HARQ type 2 throughput efficiency: IR vs. CC comparison, maximum throughput per user: 4284kbit/s.

C. Simulation results discussion

In terms of complexity, the two HARQ type 2 schemes require larger buffer sizes at the receiver than the HARQ type 1 scheme. Especially for IR the receiver buffer size increases for each retransmission. HARQ type 1 can reach a better residual BLER than without ARQ. For a low E_b/N_0 value the HARQ type 1 scheme can reach better results than the HARQ type 2 schemes for the residual BLER due to the lower reachable effective coding. Due to the granularity of the effective coding rate the HARQ type 1 scheme can not be adapted very well to the different channel conditions and thus leads to a loss in throughput efficiency in the case of higher E_b/N_0 values. Here HARQ type 2 schemes can support a better adaptation of the transmission to the actual channel conditions. Due to the combination of higher diversity and coding gains the IR scheme leads to better overall results than the CC scheme. For channels with different time diversity behavior the comparison between IR and CC would give some different results.

Considering the simulation interface between the physical layer simulations presented here and the system level simulations it has to be noticed that the additional diversity gain needs to be taken into account. Only taking into account the energy gain due to the combination leads to worst case simulations on the system level.

V. CONCLUSION

The MC-CDMA air interface has been designed to meet capacity and data rate requirements of beyond third generation communication services as well as to fulfill the technology gaps for future broadband wireless networks. Cross-layer optimization appears as the key issue in future high data rate packet oriented wireless communication systems, which would enable the reach of quality of service targets required by future wireless applications. In this paper the performance of different hybrid ARQ schemes has been investigated. The results show that in addition to the pure energy gain due to the transmission of additional symbols a diversity gain can be achieved. These diversity gains need to be taken into account in the higher layer simulations in order to obtain realistic throughput results in an overall network simulation. Simple simulator interfaces between the physical layer and the higher layers only take into account the additional energy.

Further investigations are needed in order to improve existing HARQ schemes. Constellation rearrangement [5] is a technique applicable to higher order modulations such as 16 QAM or 64 QAM which can enhance the HARQ performance. The constellation rearrangement method changes the mapping of the bits onto the symbols between successive transmissions. By rearranging the constellations the reliabilities of the various bits are averaged out over several retransmissions, leading to more efficient Turbo channel decoding and a lower packet error probability.

The investigations of the different packet combination schemes need to be refined in order to understand the optimum transmission conditions for the schemes. Especially the mobile speed has a major impact in the comparison process between the IR scheme and CC scheme.

An extension of the presented work towards LDPC codes is planned in the scope of the IST 4MORE project.

VI. ACKNOWLEDGEMENT

This work has been carried out in the framework of the IST projects MATRICE (IST-2001-32620) and 4MORE (IST-2002-507039), partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues from CEA-LETI, France, STMicroelectronics N.V., Switzerland, Nokia GmbH, Germany, Mitsubishi Electric ITE, France, UPM, Spain, FTR&D, France, University of Surrey, UK, INSA-IETR, France and Universidade de Aveiro / Instituto de Telecomunicações, Portugal.

REFERENCES

[1] S. Hare and R.Prasad, "Overview of multicarrier CDMA", IEEE Commun Mag, pp126-144, Dec 1997.

[2] C. Berrou, A. Glavieux, and P. Thitimajshima, "Near Shannon limit error-correcting coding and decoding: Turbo-codes", in Proc. ICC 93, Geneva, Switzerland, May 1993, pp. 1064-1070.

[3] Stephen B.Wicker, Error control systems for Digital Communication and Storage, Prentice Hall, 1995, ch. 15, pp. 393-421.

[4] D.Chase, "Code combining – A maximum likelihood decoding approach for combining an arbitrary number of noisy packets," IEEE Trans. Commun, vol.33, pp.385 – 393, May 1985.

[5] C.Wengerter, A.Von Elbart, E. Seidel, G.Velev and M. P Schmitt, "Advanced hybrid ARQ technique employing a signal constellation rearrangement", in Proc. IEEE VTC'02-fall, Vancouver, Canada, Sept.2002.