A Cross Layer Design of Packet Level STBC Combined with Hybrid ARQ Algorithms for Multicast Communications in UMTS Networks

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Abstract: - In this paper, a cross layer design of the combination of packet level Space-Time Block Coding (STBC) with adaptive Hybrid Automatic Repeat reQuest (HARQ) algorithms for efficient and reliable multicast transmission in UMTS networks is proposed. The aim of this paper is to provide a packet-data transmission scheme in Multiple-Input Multiple-Output (MIMO) systems employing orthogonal STBC over Rayleigh fading channels. This work integrates physical layer design and Radio Link Control (RLC) layer HARQ, in an attempt to enhance the system performance in terms of delay and throughput. The proposed scheme exploits the fact that the diversity order is increased. It combines temporal and spatial diversity in order to provide less attenuated replicas of the transmitted signal to the receiver and thus to mitigate the destructive effects of attenuation. Further, it exploits the channel autocorrelation in order to dynamically estimate the multicast users' channel conditions and thus reduce the mean Service Data Unit (SDU) delay and increase the average SDU throughput. As stated in the results section, the proposed scheme outperforms other stand-alone HARQ algorithms presented in the literature so far, for multicast systems in both metrics examined, i.e., mean SDU delay and average SDU throughput.

Key-Words: - MIMO, Cross layer design, Packet STBC, Packet FEC, Hybrid ARQ algorithms, Multicast communications, UMTS

1 Introduction

One of the scopes of the research efforts around the world, in the area of wireless networks, has always been the efficient usage of network resources. The significance of this scope becomes higher and higher, taking into account that wireless networks have grown up very quickly and are now a part of everyday life. The development of Universal Mobile Telecommunications System (UMTS) promises high communications bandwidth to end users, while supporting a great variety of new services. A popular subclass of these new services involves multicast communications instead of the existing unicast ones. However, multicasting raises the issue of efficient exploitation of network resources. In this framework, the 3rd Generation Partnership Project (3GPP) has been working on an overall multicast scheme that covers almost all network layers, called Multimedia Broadcast/Multicast Service (MBMS) [1].

This paper is focused on the UMTS Radio Link Control (RLC) layer existing in the Radio Network Controller (RNC) and in the user equipment (UE). The RLC, as a link layer mechanism, aims at ensuring the reliable transmission and reception of packets between the RNC and the UE. Only the downlink part is considered, since it is most unlikely that a multicast user will transmit data onto the uplink. On account of the wireless medium that introduces a significant amount of errors, error control techniques have been used to ensure the correct reception of transmitted packets.

Error control algorithms can be classified into three general categories: Forward Error Correction (FEC), Automatic Repeat reQuest (ARQ) and Hybrid ARQ (HARQ). FEC techniques use different error correction codes to produce redundant information that is transmitted along with the original information in order to enable the correct reception of the latter. Moreover, according to the ARQ mechanism, the reverse link is used by the receiver to transmit back to the sender a small ACKnowledgement / Negative ACKnowledgement (ACK/NACK) packet, which informs the sender that a correct/erroneous data packet was received,

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respectively. If the sender receives a NACK (or if it does not receive an ACK) packet the corresponding data packet is retransmitted. HARQ combines the merits of both previous two categories; FEC is used along with ARQ techniques in order to enhance system performance and save valuable network resources. Layered FEC operates independently, aiming at the minimization of required retransmissions by introducing additional information in the transmitted packets. Integrated FEC, on the other hand, combines FEC and ARQ in a single layer, where information packets are used to produce parity packets, similarly to traditional coding. In this case, FEC aims at the reduction of packet loss probability, thus decreasing the number of required retransmissions [2].

In most scattering environments, antenna diversity is a practical and convenient method aiming at ameliorating the detrimental effects of multipath fading. Space-time coding implements the idea of using multiple transmitting and multiple receiving antennas by linearly combining the transmitted signal at the transmitter, while the inverse process takes place at the receiver. A simple transmit diversity scheme for two transmitting antennas was first introduced by Alamouti in [3] and generalized to an arbitrary number of antennas as Space-Time Block Coding (STBC) by Tarokh *et al.* in [4]. Extensive research has been devoted to STBC in the literature [5], where the coding technique is ordinarily performed on symbols.

Cross-layer design of ARQ packet-data transmissions in Multiple-Input Multiple-Output (MIMO) systems employing STBC has barely been examined in the literature. In [6] an adaptive modulation scheme combined with link layer Truncated ARQ (T-ARQ) employing STBC over Nakagami fading channels is investigated. A Selective-Repeat ARQ (SR-ARQ) scheme combined with orthogonal STBC in Nakagami Markovian channels is analyzed in [7], while in [8] the impact of MIMO-STBC combined with ARQ on TCP performance is investigated. All this research involves traditional STBC, i.e., applied on symbols.

In this paper, the work done in [9] is being enriched. Based on the same philosophy as in packet level FEC, STBC is applied on data packets (Protocol Data Units – PDUs) and not on symbols. The STBC technique is combined with two HARQ algorithms for reliable multicast communications in the UMTS RLC layer, which have been proposed in [10]. The proposed scheme exploits the fact that the diversity order is increased. It combines temporal and spatial diversity in order to provide less attenuated replicas of the transmitted signal to the receiver and thus mitigate the destructive effects of attenuation. In addition, the proposed scheme takes advantage of the channel autocorrelation in order to dynamically estimate the multicast users' channel conditions and thus reduce the mean Service Data Unit (SDU) delay and increase the SDU throughput. The aim of this work is to integrate physical layer design and RLC layer HARQ over Rayleigh fading channels, in an attempt to improve the system performance in terms of delay and throughput.

The remainder of this paper is structured as follows. Packet level FEC is described in the following section, while in section 3 the packet level STBC is examined. In section 4 the HARQ algorithms under study are reviewed. The system structure and the simulation model are delineated in section 5. The performance evaluation of the system and simulation results are presented in section 6, while concluding remarks are drawn in section 7.

2 Packet Level FEC

In traditional block codes [11], a group of bits is used in order to produce redundant bits. Then, all the bits are transmitted over the channel and the reverse procedure at the receiver's side finally provides the original information bits. The more redundant bits are used, the more errors can be recovered at the receiver.

In point-to-multipoint communication networks, the FEC technique is desirable as a complement to ARQ [2]. In [12] Reed-Solomon erasure correction code is examined at the packet level, while in [13] and [14] the general concept of packet level FEC is described. Using the same strategy as in traditional FEC, packet level FEC handles packets as if they were bits. To better explain the procedure, assume that K information packets are used to produce H redundant packets. If the information packets are denoted as $X_{1..K}$ and the redundant packets as $Y_{1..H}$, then from [13]:

$$Y_j = \underset{i=1..K}{\oplus}(X_i \ll (i^{j-1}-1))\ ^{1}. \qquad (1)$$

The $N=K+H$ packets (which form a Transmission Group – TG) are transmitted over the Common Channel (CCH). At the receiver, the TG can be decoded if at least any K out of the N packets are received correctly. If not, a NACK is sent back to the sender, indicating the erroneous reception of the TG by including the TG identifier in its fields.

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[1] $\oplus$ indicates the "*exclusive or*" operation and $\ll$ indicates the "*left shift*" operation.

Thus, under HARQ, besides the packet level FEC which is used for error correction, a Cyclic Redundancy Check (CRC) code is calculated for every packet and included into the packet field, in order to detect errors [14].

3 Packet Level STBC

A STBC system with N_T transmitting and N_R receiving antennas is considered, hereafter referred to as STBC $N_T \times N_R$. The system encodes a block of m PDUs, which are consisted of complex or real symbols. The PDUs $\{X_i\}_{i=1}^{m}$ are encoded by a STBC, creating the orthogonal transmission matrix G, with linear combinations of X_1, X_2,..., X_m and their conjugates.

The general structure of the transmission matrix, employing two transmitting antennas for complex orthogonal design [15], is

$$G_c^2 = \begin{pmatrix} X_1 & X_2 \\ -X_2^* & X_1^* \end{pmatrix} \qquad (2)$$

where the i^{th} row represents the PDUs transmitted during the i^{th} frame period and the j^{th} column the PDUs transmitted from the j^{th} antenna. For real constellations, the transmission matrix G consists of real symbols inside a PDU, i.e., the second row in (2) is comprised of real X_i's.

At the receiver, the process is almost identical to the analysis given in [3-5,16], with the difference that in these analyses x_i is supposed to be a symbol, whereas in the approach presented in this paper X_i is supposed to be a PDU.

Generally, the code rate is defined as $R = m/p$, since p frame periods are used to transmit m PDUs, as in [16] where traditional STBC is considered. It should be mentioned, that STBC achieves the maximum possible transmission rate for any number of transmitting antennas when using any arbitrary real constellation (e.g. M-PAM). On the other hand, for an arbitrary complex constellation (e.g. M-PSK and M-QAM), full-rate exists only for two transmitting antennas, while for other cases R is below unity (3/4 for three and for four transmitting antennas and 1/2 for all the other transmitting antenna schemes, i.e., $N_T \geq 5$) [15].

4 Hybrid ARQ Algorithm

In this section, two HARQ algorithms for multicast streaming, proposed in [10], are reviewed, which constitute an improvement on the algorithms proposed in [17] (also investigated in [18]).

4.1 Algorithm A1

At the sender's side, groups of K PDUs are encoded to $N = K + H$ PDUs, where H are the redundant PDUs, as explained in section 2. The N PDUs are sent to the multicast users over the CCH. The K data packets can be recovered by each multicast user if and only if the number of erroneous PDUs received in a TG is less than or equal to H. In the case that at least one receiver is not able to correctly decode the N PDUs, it sends a NACK message back to the transmitter, including the identifier for the TG that it could not decode correctly.

If at least one receiver requires retransmission, the sender uses the K original packets to generate one new redundant PDU (incremental redundancy), which differs from all the previous ones, and sends it again to all the multicast users through the CCH channel. The receivers can now decode $N + 1$ PDUs if and only if K of them are correct. The entire procedure continues until all the receivers can correctly recover the K original PDUs, by decoding the $N{+}R_{tot}$ PDUs sent, where R_{tot} is the total number of retransmissions.

Then, the next TG is sent to the multicast users. If $\min_{i\in N}\{N_{ok}(i)\} \geq K$ (with $N_{ok}(i)$ denoting the number of the correctly received PDUs for user i) the original K PDUs can be obtained and the TG is correctly received. Otherwise, the transmitter sends R_{tot} redundant PDUs generated from the K original PDUs, where R_{tot} is the total number of the redundant PDUs of the last TG transmission that needed a retransmission. If all the receivers recover the K original packets by decoding the $N + R_{tot}$ PDUs, R_{tot} is decreased. Otherwise, the transmitter generates one more new redundant PDU and transmits it to the multicast users until all the users obtain the K original PDUs. In the latter case, the R_{tot} becomes $R_{tot} = R_{tot} + R$, where R is the number of the additional retransmissions of one PDU each time, regarding this TG.

To better explain the algorithm, it should be emphasized that it exploits the information from the previous transmitted TG, in order to make an estimation of the channel conditions, based on the fact that the channel does not change too fast and the expected overall error rate will be very close to the one experienced previously. Thus, the expected number of redundant PDUs is considered equal to the total number of redundant PDUs needed in the previous TG. Additionally, the algorithm adapts itself to the dynamics of the channel conditions and increases or decreases the number of retransmissions in the following TG transmissions according to the experienced conditions.

4.2 Algorithm A2

As in the previous scheme, N PDUs are sent to the multicast users at the beginning. If at least one user cannot recover the K original PDUs, he sends a NACK message back to the transmitter with the TG identifier. Additionally, each user $i \in \Omega$ (where Ω is the set of multicast users in a cell) sends back to the transmitter the minimum number R_i of the incremental redundant PDUs needed for the decoding of the N PDUs, i.e. $R_i = K - N_{ok}(i)$. The transmitter collects all the received R_i's and retransmits $R = \max_{i \in \Omega}\{R_i\}$ redundant PDUs. If $N_{ok}(i) \geq K \ \ \forall i \in \Omega$, then the K PDUs can be recovered by the entire multicast group. Otherwise, if $N_{ok}(i) < K$ the algorithm continues until all the receivers can correctly obtain the K original PDUs.

For the next TG, though, the sender transmits $N' = K + R_{tot}$, instead of N, where R_{tot} is the total number of redundant PDUs required in the previous TG transmission. In this way, the algorithm dynamically adjusts to the system's requirements. There is also a mechanism that updates R_{tot}; if for a TG, the N' PDUs were enough and no further retransmission was required, the R_{tot} is decreased. In case that additional retransmissions were required, then R_{tot} is increased. The way R_{tot} is updated is of primary importance, since its performance is highly related to the mechanism of updating and can vary from minimum delay with low throughput to high delay with high throughput.

5 System Structure and Analysis

The general layout of the simulated system can be seen in Fig.1. The data is first encoded based on the packet level FEC, as described in section 2. The inner code is convolutional coding (2,1) with generator polynomial [133,171], while at the receiver's side Viterbi decoding is performed. The modulation scheme under study is the commonly used Binary Phase Shift Keying (BPSK).

The noise characterizing the channel is AWGN. The channel gain from the i^{th} (i = 1, 2,..., N_T) transmitting to the j^{th} (j = 1, 2,..., N_R) receiving antenna is denoted as $h_{i,j}$ and is modeled as a complex random variable (RV) with its phase uniformly distributed within $[0, 2\pi)$, whereas its envelope $c_{i,j} = \|h_{i,j}\|$ is distributed according to the well-known Rayleigh distribution family. The STBC systems examined here are the STBC 2×1 and the STBC 2×2. Thus, the channel matrix H is defined as

$$H \triangleq \begin{bmatrix} h_{1,1} & h_{2,1} \\ h_{1,2} & h_{2,2} \end{bmatrix}. \qquad (3)$$

The entries of H are assumed to be uncorrelated, but not necessarily identically distributed, with arbitrary values for the fading severity parameters. The channel considered is a quasi-static flat fading channel, so that the path gains are constant over a period of two transmitting PDUs and vary

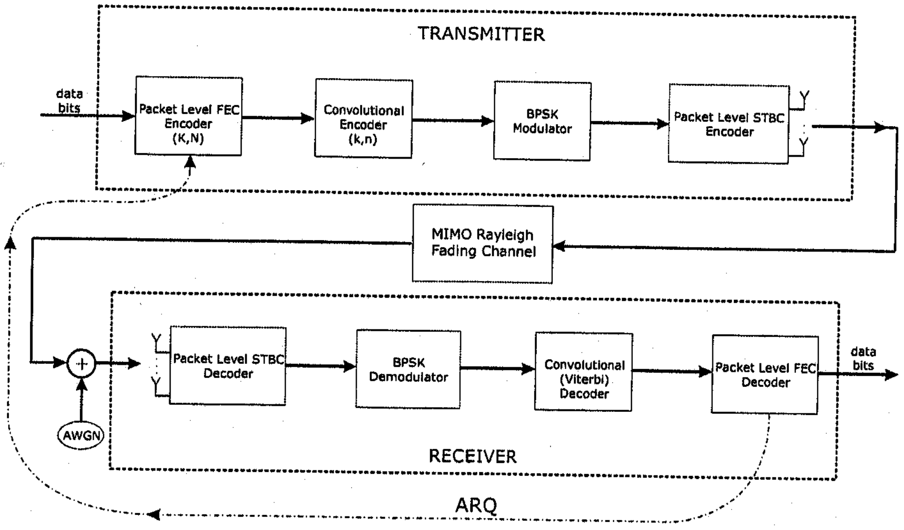

Fig.1. System Structure

independently from one frame to another. Furthermore, it should be mentioned that perfect channel estimation is assumed at the receiver.

It should be noted at this point that the channel characteristics are independent of each user of the multicast group. The parameters of the packet level FEC are $K = 15$ and $N = 20$. A RLC round trip time (RTT) of 80ms, a link layer logical bit rate of 240kbps, a PDU length of 352 bits and a SDU packet length of 500 bytes are considered [17].

As concluded from section 4, the HARQ algorithms are based on variable parameters; the mechanism that decides on the number of additional PDUs is not fixed, rendering the algorithms more flexible. For the computer simulations the following parameters has been chosen. In A1, the reduction of R_{tot} analyzed in subsection 4.1 is performed by the operation $R_{tot} = R_{tot} - 2$. In A2, R_{tot} is increased and decreased, as explained in subsection 4.2, according to $R_{tot} = R_{tot} + (r - R_{tot})/2$ and $R_{tot} = R_{tot} - 2$, respectively, where r is the total number of redundant PDUs transmitted in the previous TG. These parameters are not the same as the ones chosen in [10], but they are chosen after optimizing the algorithm for the case that packet level STBC is employed, in order to achieve a good trade-off between delay and throughput. However, the performance of the algorithms may alter if other mechanisms are employed.

In the following section, simulation results for the plain ARQ mechanism are also presented discussing the benefit that packet level STBC can offer to such a system.

6 Results and Discussion

For the performance evaluation of the proposed system, a computer simulation was developed in Matlab. The figures presented below were obtained by averaging the results of multiple simulation runs in order to minimize the statistical errors and to assure the validity of the results.

In this work, two metrics were evaluated to assess the efficiency of the scheme described in the previous section. The first one is the mean SDU delay, which is defined as the time elapsed from the transmission of the first PDU (belonging to the first TG of an SDU) until the reception of the last PDU related to the corresponding SDU, from all the users, with no further retransmissions needed, averaged over the total number of SDUs sent. The second one is throughput, which is considered as the number of the original PDUs divided by the total number of PDUs sent.

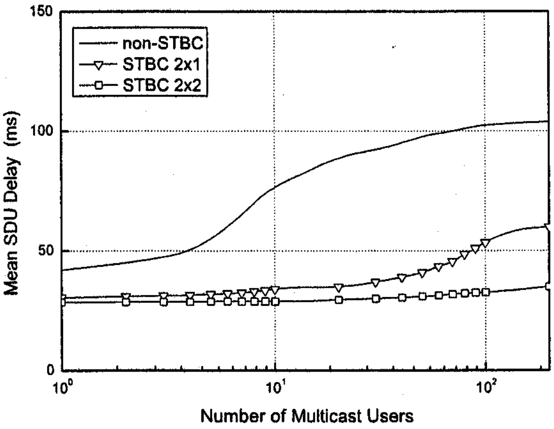

Fig.2. Mean SDU delivery delay time as a function of the number of multicast users for the HARQ algorithm A1

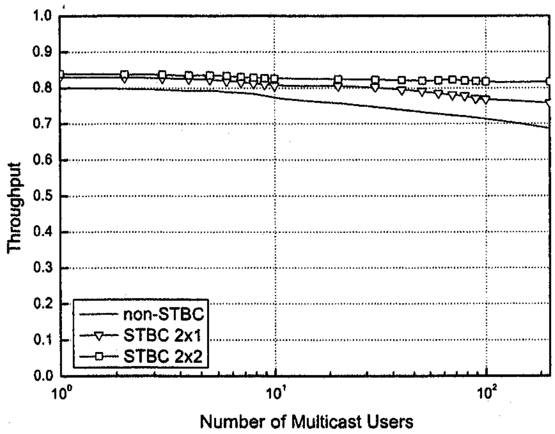

Fig.3. Mean throughput as a function of the number of multicast users for the HARQ algorithm A1.

In all the presented figures, the solid line corresponds to the results when no STBC is applied, the line with triangular symbols stands for the results of the STBC 2×1 system and with the line with rectangular symbols the results of the STBC 2×2 system are denoted.

In Fig.2 the mean SDU delay is presented, when the HARQ algorithm A1 is applied. It can be noticed that packet level STBC 2×1 outperforms the system without STBC. In the case that STBC2×2 is applied, the curve of the mean SDU delay is even below the curve of STBC 2×1, as expected.

Average throughput is depicted in Fig.3, when the same HARQ algorithm is applied to the system. As in the mean SDU delay curves, the average throughput is improved with the implementation of packet level STBC. When the number of transmitting/receiving antennas is increased, the curve tends to show an almost constant performance, no matter of the number of multicast users.

The performance of the HARQ algorithm A2 is presented in figures 4 and 5. Comparing figures 2 and 4, it can be observed that algorithm A2 performs better than A1 when no STBC is applied to the system in terms of average delay, about the same when STBC 2×1 is applied, but much worse when the system uses STBC 2×2. This happens partially due to the update mechanism chosen for algorithm A2, which uses a bigger step when it increases the number of the redundant PDUs, while A1 uses a smaller step. Regarding the improvement that STBC can offer to the system employing algorithm A2 when average delay is concerned, it can be seen that STBC 2×1 provides a significant gain to the system's performance, while in the case that STBC 2×2 is applied the curve is very close to the STBC 2×1 one. Yet, the improvement that STBC technique offers to A2 is not as great as in the case that A1 is employed.

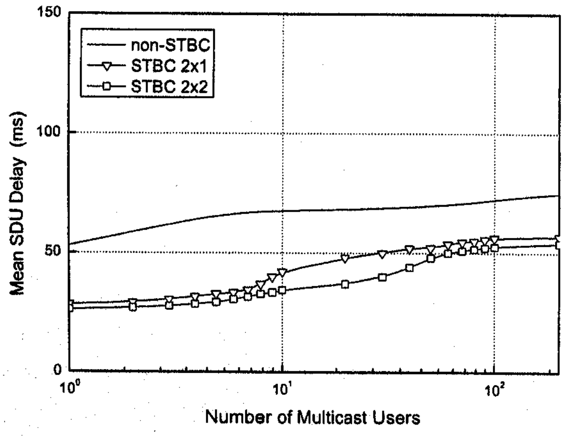

Fig.4. Mean SDU delivery delay time as a function of the number of multicast users for the HARQ algorithm A2.

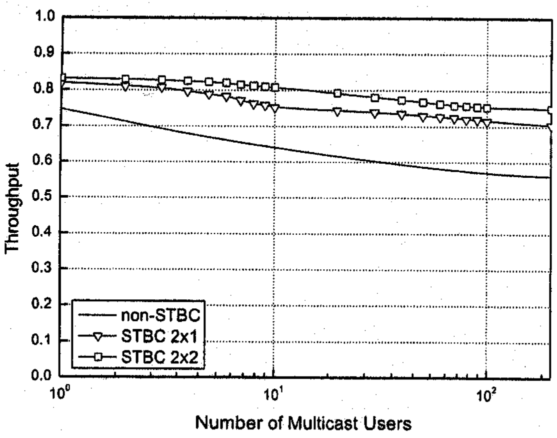

Fig.5. Mean throughput as a function of the number of multicast users for the HARQ algorithm A2.

In Fig.5 the average throughput is examined, when HARQ algorithm A2 is applied. The results are deteriorated compared to the ones depicted from algorithm A1. Though, the gain that the STBC application can offer, is clear both in the case of a STBC 2×1 and STBC 2×2 system.

Results for the plain ARQ mechanism are presented in figures 6 and 7 as a reference for comparison with the HARQ algorithms. Here the amelioration in the performance is not as great as in the case that the HARQ algorithms are applied. Nevertheless, it is obvious that the application of STBC to the multicast system is quite beneficial.

As a general comment, it should be mentioned the difference between the results derived here (regarding the non-STBC system) and the ones presented in [10]; this happens firstly because the HARQ algorithms are based on a different mechanism chosen to increase or reduce the R_{tot} parameter of the algorithms, and secondly because in this work the simulation model is more realistic

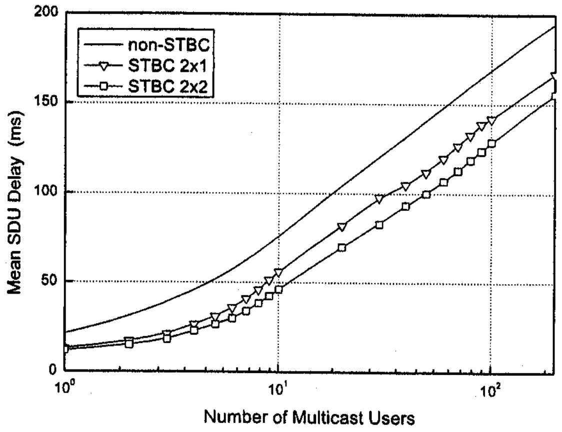

Fig.6. Mean SDU delivery delay time as a function of the number of multicast users for plain ARQ mechanism.

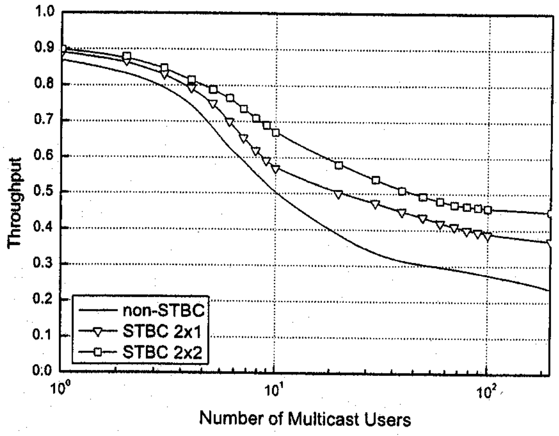

Fig.7. Mean throughput as a function of the number of multicast users for plain ARQ mechanism.

on account of the application of bit-level communications.

From all the presented figures, and taking into account the performance regarding both the mean SDU delay and the average throughput, it is evident that STBC is profitable in both the examined metrics. With respect to complexity, packet level STBC is faster implemented compared to the ordinary STBC, since the application is applied to a number of symbols each time, and not on a symbol-by-symbol basis.

Furthermore, a comparison among the work presented here and work from the literature regarding multicast systems in UMTS networks, shows that the performance of the packet level STBC technique combined with HARQ algorithms is superior to other stand-alone (without the application of STBC) HARQ algorithms proposed so far, in regard to both metrics examined, i.e., mean SDU delay and average SDU throughput. The results of the proposed scheme presented in this paper outperforms not only the A4 and A5 HARQ algorithms proposed in [10], as discussed above, but also A1, A2 and A3 HARQ schemes proposed in [17] and [18].

7 Conclusion

In this paper, the application of packet level STBC combined with two adaptive HARQ algorithms for efficient and reliable multicast communications in UMTS networks was proposed. The main idea behind the proposed scheme is that packet level STBC is based on traditional STBC, where packets of symbols are used instead of symbols. A cross-layer design of packet-data transmissions in MIMO systems over Rayleigh fading channels was provided. The proposal attains interesting results and outperforms other stand-alone HARQ algorithms for multicast systems proposed in the literature so far, in both metrics examined, i.e., mean SDU delay and average SDU throughput.

In the future, it is intended to examine the performance of packet level STBC, applying other modulation schemes and generalize packet level STBC to an arbitrary number of antennas, in order to validate the efficiency of the proposal. It is also intended to make theoretical analysis of both delay and throughput performance.

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