Hybrid ARQ Combined With Distributed Packet Space-Time Block Coding for Multicast Power-Line Communications

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***Abstract*—In this paper, hybrid ARQ (HARQ) is realized together with distributed packet space-time block coding in order to provide reliable multicast communications over inhome and inbuilding power-line networks. Two HARQ algorithms are examined and their performance is demonstrated via simulations. The proposed retransmission scheme utilizes information from previous transmissions, since the HARQ algorithms update their parameters according to the experienced transmission conditions. Results show that the combination of a physical-layer technique, such as space-time coding, with data-link layer HARQ provides significant gain regarding throughput and mean delay.**

***Index Terms*—Bus communications, distributed packet space-time block coding (STBC), hybrid ARQ (HARQ), power-line communications.**

I. Introduction

POWER-LINE networks can offer telecommunication services in every location where power wires are installed. However, they present a rather hostile medium for broadband data transmission, since they were originally designed for the distribution of electrical power in the frequency range of 50–60 Hz. Therefore, in order to better control the communication characteristics of power-line grids, and in that way to satisfy the increasing demand for high-data-rate services and quality-of-service (QoS) guarantees, it is not only essential to utilize advanced communication techniques but also to create novel ones.

Error control algorithms have been used to ensure the correct reception of data and 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 [1]. According to ARQ mechanism, a small acknowledgement (ACK) or negative acknowledgement (NACK) packet is sent by the receiver to transmitter, aiming to inform that a correct or erroneous data packet is received, respectively. In case that a NACK or no ACK packet is received, the corresponding data packet should be retransmitted.

HARQ is a combination of FEC and ARQ and is an effective method for reliable communications. The receiver first tries to correct errors but if it cannot correct all errors, it will ask for retransmission. There are two main methods for the implementation of HARQ: retransmissions can either be 1) a simple repeat of the entire coded packet or 2) incremental redundancy, where additional redundant information is transmitted. In conventional HARQ, the retransmitted packets come from the original source while, in generalized HARQ, the retransmitted packets can be sent by relay nodes that overhear the transmission [2].

Traditional multiple-input multiple-output (MIMO) and space-time coding (STC) techniques for wireless communications achieve spatial diversity using multiple transmit and/or receive antennas. Cooperation among users is an alternative way to provide transmit diversity in cases where mobile transmitters cannot support multiple antennas due to size and power limitations. Cooperative diversity allows sharing resources, where every user can serve as an intermediate repeater node (relay), retransmitting data of other users in the network. In general, cooperation methods can be classified into regenerative (decode-and-forward) and nonregenerative (amplify-and-forward) systems.

The idea of merging cooperation diversity with STC resulted in the so-called distributed space-time coding (DSTC) schemes. Opposite of the conventional STC with collocated antennas, DSTC can be implemented when transmitter and relays share their antennas (or their transmission points when wired networks are considered) to create a virtual transmit array. DSTC has also been proposed [3] for multihop transmissions in power-line communication (PLC) networks and it has been used in combination with error-control techniques for wireless cooperative communications [4], [5].

While STC is known as a physical- layer technique that provides diversity and in that way ameliorates system performance, an alternative way to mitigate channel impairments is to rely on ARQ protocols at the data-link layer. Cross-layer design of ARQ packet-data transmissions in MIMO systems employing space-time block coding (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],

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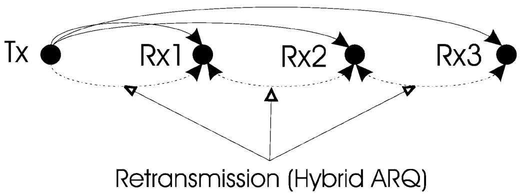

Fig. 1. Transmission scheme.

the impact of MIMO-STBC combined with ARQ on TCP performance is investigated. All of this research involves traditional STBC (i.e., applied on symbols).

In this paper, we introduce packet STBC (PSTBC) which is space-time block coding applied on data packets and not on symbols. A cooperative retransmission scheme is proposed, where generalized HARQ is implemented with the aid of distributed PSTBC. Data signals are sent to the power-line network nodes and each node is assumed to be a potential repeater. Whenever there is a need for retransmission, generalized HARQ retransmissions using distributed PSTBC are made from the nearest nodes that have correctly received the transmitted signal, in order to reduce the distance toward destination as much as possible.

The proposed transmission scheme is shown in Fig. 1.

Based on the work proposed in [9], two HARQ algorithms are presented and examined for multicast communications over power lines. The HARQ algorithms use parameters that dynamically adapt to the conditions experienced in previous transmissions. The principal concept of these algorithms is the introduction of a kind of memory into the system so as to enable an estimation of system's requirements. The proposed cross-layer scheme integrates physical-layer design and link layer HARQ in order to enhance the system performance and to provide reliable communication, reducing the mean service data unit (SDU) delay and increasing system throughput.

The remainder of this paper is structured as follows. In the following section, packet-level FEC and packet-level STBC are described. The two HARQ algorithms under study are analyzed in Section III, while the system structure, including the channel model, network topology, and simulation parameters are depicted in Section IV. In Section V, performance analysis and simulation results are presented, while Section VI concludes this paper.

II. PACKET-LEVEL FEC AND PACKET-LEVEL STBC

A. Packet-Level FEC

Packet-level FEC handles packets as if they were bits, using the same strategy as in traditional FEC. Layered FEC operates independently, aiming at the minimization of required retransmissions by introducing additional information in the transmitted packets. On the other hand, integrated FEC 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 [10].

It is assumed that K information packets are used to produce H redundant packets. Denoting the information packets as $\mathrm{X}_{1\ldots\mathrm{K}}$ and the redundant packets as $\mathrm{Y}_{1\ldots\mathrm{H}}$ then from [11]

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

where $\oplus$ indicates the "exclusive or" operation and "$\ll$" indicates the "left shift" operation.

The $\mathrm{N}=\mathrm{K}+\mathrm{H}$ packets form a transmission group (TG) and are transmitted over the power-line channel. At the receiver, the TG can be decoded if at least any K out of the N packets are received correctly. If not, an NACK, including the TG identifier, is sent to the sender, indicating the erroneous reception. Under HARQ, besides the packet-level FEC that is used for error correction, a cyclic-redundancy-check (CRC) code is calculated for every packet to enable error detection [9].

B. Packet-Level STBC

Based on the same philosophy as packet-level FEC, PSTBC is applied on data packets [protocol data units (PDUs)] and not on symbols. The system encodes m packets X_m that consist of complex or real symbols, creating the transmission matrix G with linear combinations of $\mathrm{X}_1, \mathrm{X}_2, \ldots \mathrm{X}_\mathrm{m}$ and their conjugates.

The general structure of the STBC transmission matrix, employing two transmitting nodes for complex orthogonal design [12] is

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

where the ith row represents the packets transmitted during the ith frame period and the jth column represents the packets transmitted from the jth node. For real constellations, packets in the transmission matrix G consist of real symbols (i.e., the second row of (2) is comprised of real X_i). The process at the receiver is almost identical to the analysis given in [13], with the difference that in [13] x_i represents a symbol, while in the analysis presented here, 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 [14] where a 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, 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 any number of transmit antennas) [12].

III. HARQ ALGORITHMS

A. Algorithm A1

Groups of K PDUs are encoded to $\mathrm{N} = \mathrm{K} + \mathrm{H}$ PDUs at the transmitter, where H are the redundant PDUs. The N PDUs are sent to the multicast users over the power-line network. The K data packets can be recovered by each 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 a receiver is not able to correctly decode the N PDUs, it sends an 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 K original packets are used to generate two (due to the requirements of the STBC implementation) new redundant PDUs (incremental redundancy), which differ from all of the previous ones, and which are sent to the multicast users through the power-line channel. The receivers can now decode $N+2$ PDUs if and only if K of them are correct. The entire procedure continues until all of the receivers can correctly recover the K original PDUs, by decoding the $N+R_{\text{tot}}$ PDUs sent, where R_{tot} is the total redundant PDUs sent for the current TG.

Then, the next TG is sent to the multicast users. If $\min_{i\in N}\{N_{\text{ok}}(i)\} \geqslant K$, where $N_{\text{ok}}(i)$ denotes the number of the correctly received PDUs for the ith user, 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 of the receivers recover the K original packets by decoding the $N+R_{\text{tot}}$ PDUs, R_{tot} is decreased. Otherwise, the transmitter generates two more new redundant PDUs and transmits them to the multicast users until all of the users obtain the K original PDUs. In the latter case, the R_{tot} becomes $R_{\text{tot}} = R_{\text{tot}} + R$, where R is the total number of the additional redundant PDUs regarding this TG.

It should be pointed out that the algorithm 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 to be 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.

B. 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, an NACK message is sent back to the transmitter with the TG identifier. Additionally, each user sends back to the transmitter the minimum number $\mathrm{R_i}$ of the incremental redundant PDUs needed for the decoding of the N PDUs (i.e., $\mathrm{R_i} = \mathrm{K} - \mathrm{N_{ok}(i)}$). The transmitter collects all of the received $\mathrm{R_i}$'s and retransmits $\mathrm{R} = \max\{\mathrm{R_i}\}$ redundant PDUs. If $\{N_{\text{ok}}(i)\} \geqslant K$, then K PDUs can be recovered by the entire group. Otherwise, the algorithm continues until all of the receivers can correctly obtain the K original PDUs.

For the next TG, the sender transmits $\mathrm{N}' = \mathrm{K} + R_{\text{tot}}$, 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 the N' PDUs were enough for a TG and no further retransmission was needed, R_{tot} is decreased; otherwise R_{tot} is computed according to the number of retransmissions required for the current TG. The way R_{tot} is updated is of primary importance, since the algorithm's performance is highly related to this updating mechanism. Thus, the selection of the updating mechanism should target performance optimization.

IV. SYSTEM STRUCTURE

A. Channel Model

In contrast to other communication channels, the power-line channel does not represent an additive white Gaussian noise (AWGN) environment [15]. In the frequency range from some hundreds of kilohertz up to 20 MHz, it is mostly dominated by narrowband interference and impulsive noise. The impulses have durations from some microseconds up to a few milliseconds with random arrival times. The most suitable model for this type of noise is the additive white Class A noise (AWCN).

AWCN is calculated from the combination of AWGN and impulsive noise. The probability density function (pdf) of a Class A noise random (complex) variable x is given by [16]

$$p(x) = \frac{1}{2\pi}\sum_{m=0}^{\infty}\frac{1}{\sigma_m^2}a_m \exp\left(-\frac{|x|^2}{2\sigma_m^2}\right) \tag{3}$$

where $a_m = e^{-A}(A^m/m!), \sigma_m^2 = \sigma^2((m/A)+T)/(1+T)$, σ^2 is the variance of the Class A noise, $T = (\sigma_g^2/\sigma_i^2), \sigma_g^2$ is the variance of the AWGN component, and σ_i^2 is the variance of the impulsive component. The parameter A is called "impulsive index." For small values, for example $\mathrm{A} = 0.1$, the noise is highly impulsive, whereas for $\mathrm{A} \to \infty$, the Class A noise pdf becomes Gaussian.

The samples representing the Class A noise are derived from [17]

$$n = x_G + \sqrt{K_m y} \tag{4}$$

where x_G is a white Gaussian background noise sequence with zero mean and variance $\sigma_G^2, \mathrm{K_m}$ is a statistically independent Poisson distributed random sequence whose pdf is characterized by the parameter A (mean value of Poisson distribution), and y is a white Gaussian sequence with zero mean and variance σ_i^2/A. All random sequences in this model are statistically independent from each other.

The channel transfer function is calculated according to [18], where the two-conductor transmission-line modeling via transmission matrices is used to model the indoor power-line channel. This channel modeling approach is practical and provides improved accuracy, since it takes into account the topology of the link, the particular wiring practices, as well as the cable characteristics.

The electrical components between two nodes X and Y of the power-line network are described by the transmission matrix $\mathrm{T_{XY}}$ [3]

$$T_{XY} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}. \tag{5}$$

It is considered that a source with voltage $\mathrm{V_S}$ and impedance $\mathrm{Z_S}$ is connected to a load with voltage $\mathrm{V_L}$ and impedance $\mathrm{Z_L}$

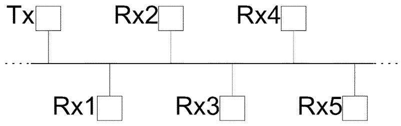

Fig. 2. Network topology.

via a two-port network. The transfer function is expressed as the ratio of the voltage on the load to the source voltage

$$H(f) = \frac{V_L}{V_S} = \frac{Z_L}{AZ_L + B + CZ_SZ_L + DZ_S}. \tag{6}$$

In the case of a uniform two-conductor transmission line, the ABCD coefficients of the corresponding transmission matrix are given as follows [18]:

$$\begin{aligned} A &= D = \cosh(\gamma l) \\ B &= Z_0 \sinh(\gamma l) \\ C &= \frac{1}{Z_0}\sinh(\gamma l) \end{aligned} \tag{7}$$

where γ, l and $\mathrm{Z_0}$ are the propagation constant, the length, and the characteristic impedance of the power-line cable. In order to compute the ABCD coefficients of the transmission matrices, the propagation constant γ and the characteristic impedance $\mathrm{Z_0}$ of the power-line cable have to be computed. γ and $\mathrm{Z_0}$ are frequency dependent and are calculated according to the following equations:

$$\gamma = \sqrt{(R+\omega L)(G+\omega C)} \tag{8}$$

$$Z_0 = \sqrt{\frac{R+\omega L}{G+\omega C}} \tag{9}$$

where R, L, G, and C are the resistance, inductance, conductance, and capacitance of the power-line cable, respectively. In this study, a 1.5-mm^2 copper wire with PVC insulation is considered for the computation of the aforementioned cable parameters.

Moreover, the source and the load impedances are considered to be $\mathrm{Z_S} = \mathrm{Z_L} = 100\ \Omega$, while the network load impedance is assumed to be 10 kΩ. The chain rule [18] allows for the easy calculation of the transfer function for power-line links that consist of several sections with different types of cables and various lengths. In such cases, the overall transmission matrix of the end-to-end link can be computed as the product of the individual transmission matrices of the single network sections.

B. Network Topology

It is assumed that the nodes form a bus topology in an indoor PLC network as shown in Fig. 2, where one node is considered as source node and the rest nodes are possible relay nodes. The number of network nodes can be variable and the distance between them also varies from 10 to 100 m, representing inhome and inbuilding PLC networks. Without loss of generality, it is assumed that the distance between two neighboring nodes is the same.

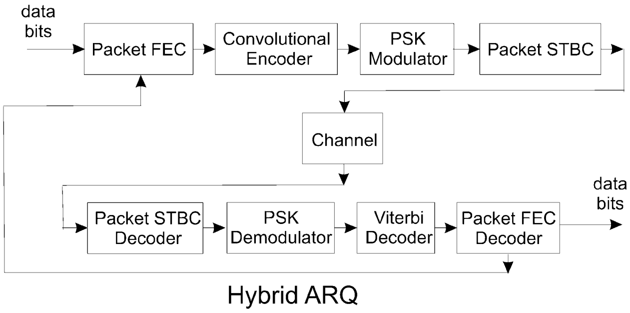

Fig. 3. System structure.

When one or more nodes ask for retransmission, the two nodes that are closer to each asking node and that have correctly received the transmitted signal form a virtual double-node transmitter. Thus, the distributed packet-level STBC with two transmitting nodes and one receiving node (STBC2x1) is implemented. The selection of the closest users for retransmission helps to reduce the amount of retransmissions needed, as it is more probable that fewer errors will occur during data transmission when the distance between transmitters and receivers is as minimum as possible.

C. System Parameters

The data are encoded based on the packet-level FEC as described in Section II. The parameters of the packet level FEC are $\mathrm{K} = 16$ and $\mathrm{N} = 20$. The inner code is convolutional coding (2,l) with generator polynomial [133, 171], while at the receiver's side Viterbi decoding is performed. The modulation scheme under study is binary phase-shift keying (BPSK). The system structure of the simulated system is presented in Fig. 3.

The round trip time (RTT) is assumed to be 80 ms, the data rate is 240 kb/s, the PDU length is 352 b, and the SDU length is 500 B. Moreover, when two nodes implement PSTBC retransmission, the transmit power is considered to be half the transmit power of a single retransmitting node to ensure fair comparison with non-STBC retransmissions. Perfect channel estimation is also assumed at the receivers.

The HARQ algorithms are based on adaptive parameters to transmission conditions, since the mechanism that decides for the number of redundant PDUs is not fixed, rendering the algorithms more flexible and efficient. In this study, it is assumed that the reduction of R_{tot} analyzed in Section III, is performed by the operation $R_{\mathrm{tot}} = R_{\mathrm{tot}}/2$ for the algorithm A1. For the algorithm A2, if the N' PDUs were enough for a TG and no further retransmission was needed, R_{tot} is decreased to the initial value of H in order to prevent R_{tot} from reaching high values and to limit the number of additional redundant packets. In case that only one retransmission was enough, R_{tot} is computed according to $R_{\mathrm{tot}} = R_{\mathrm{tot}}/2$, and if more than one retransmissions were required according to $R_{\mathrm{tot}} = R_{\mathrm{tot}} + (\mathrm{r} - R_{\mathrm{tot}})/2$, where r denotes the total number of redundant PDUs transmitted in the previous TG. In this way, algorithm A2 exploits information from the two previous transmitted TGs.

It should be mentioned here that these updating mechanisms have been chosen after performance optimization and according

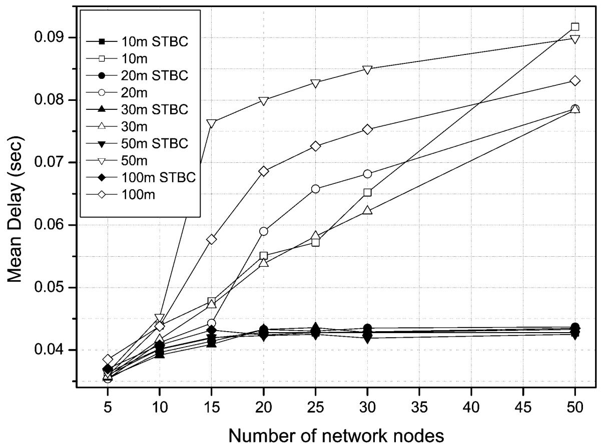

Fig. 4. Mean delay as a function of the number of network nodes for the HARQ algorithm A1.

to the specific characteristics of the system under test. The performance of the algorithms may alter if different updating mechanisms for R_{tot} are employed.

V. Performance Analysis and Simulation Results

In this section, simulation results are presented and discussed. A simulation code was developed in Matlab for the performance evaluation of the proposed scheme. In order to minimize statistical errors and to ensure the validity of the results, the presented figures were obtained by averaging the results of multiple simulation runs.

The system performance is evaluated in terms of throughput and mean delay. Throughput is defined as the number of the original PDUs divided by the total number of PDUs sent. The mean SDU delay 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.

Simulation results for conventional HARQ (i.e., when no distributed PSTBC is employed), are also provided. In that case, when retransmissions are required, the data signal is sent only by the source node while the remaining network nodes are not involved as relays in cooperative retransmission.

Figs. 4 and 5 present the mean delay and throughput, respectively, for the HARQ algorithm A1, as a function of the number of network nodes when the distance between them varies from 10 to 100 m. As it can be seen, distributed PSTBC provides a great advantage for delay and throughput as the number of power-line network nodes (users) increases, since the performance remains almost constant for all network realizations. On the other hand, when there is no cooperation between nodes for the HARQ implementation, it is obvious that the system performance deteriorates dramatically when both the number of users and the distances between them rise. However, the deterioration is not exactly uniform according to the distance increase, since the channel transfer function varies with respect to cable length but not in a linear manner.

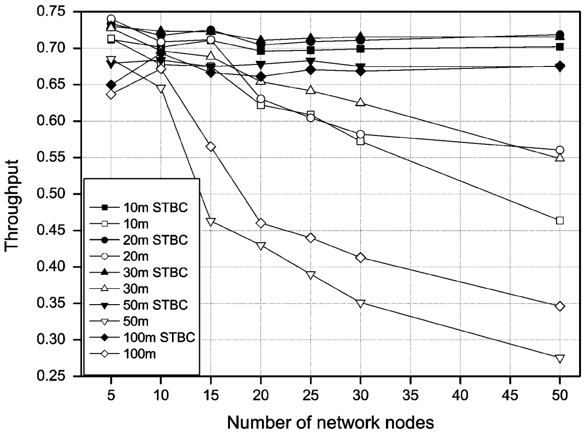

Fig. 5. Mean throughput as a function of the number of network nodes for the HARQ algorithm A1.

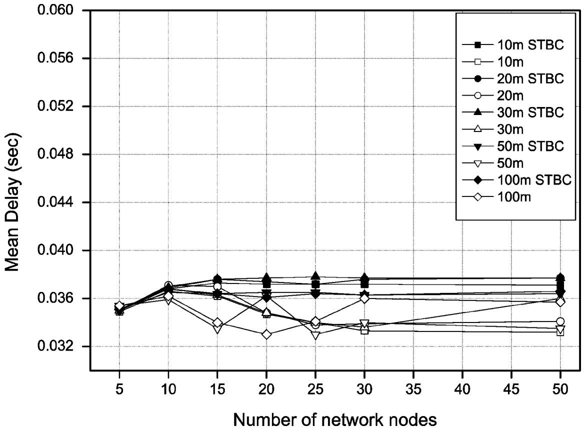

Fig. 6. Mean delay as a function of the number of network nodes for the HARQ algorithm A2.

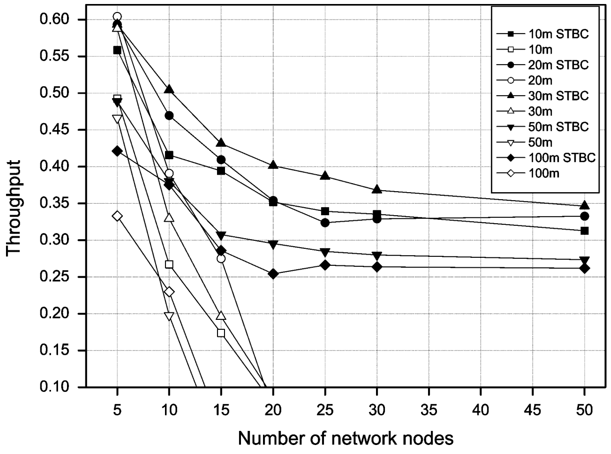

Fig. 7. Mean throughput as a function of the number of network nodes for the HARQ algorithm A2.

Figs. 6 and 7 present the mean delay and throughput, respectively, for the HARQ algorithm A2, as a function of the number of network nodes when the distance between them varies again from 10 to 100 m. It can be observed that the variation of delay is small for both the distributed PSTBC and the non-STBC case and that is close to the statistical error. The distributed PSTBC, when used in combination with HARQ, does not seem to offer clear gain to the system performance even when the number of network nodes increases. On the contrary, the results for throughput demonstrate an evident profit, since the distributed PSTBC technique provides an advantage in comparison with the non-STBC retransmissions where throughput becomes extremely low as the number of users and the distances between them increase. Furthermore, compared with the performance of algorithm A1, the throughput does not remain almost constant but decreases as the network users rise and as longer distances between them are assumed. This decrease, though, is not uniform since throughput is reduced with a slower rate as the number of network nodes grows.

It can be seen that when distributed PSTBC is applied, both HARQ algorithms present similar performance as far as mean delay is concerned. On the contrary, algorithm A1 performs better than algorithm A2 regarding throughput. This is due to the fact that in A2, the total number N of packets that form a TG changes to N' after the first need for retransmission, as described in Section III-B. Consequently, the total number of redundant PDUs is greater in A2 in comparison with A1. Moreover, algorithm A2 uses a different update mechanism for R_{tot}. In case that retransmissions are required in successive TG transmissions, N' is successively increased, resulting in a large amount of redundant PDUs sent in the initial TG transmission.

As a general comment, it should be noted that the proposed HARQ algorithms, combined with distributed PSTBC, can help the system performance to remain stable as the network configuration changes, avoiding rapid fluctuations and unacceptable values of delay and throughput.

VI. CONCLUSION

In this paper, a cooperative retransmission scheme for inhome and inbuilding power-line communications is proposed, where generalized HARQ is realized with the assistance of distributed PSTBC. Two HARQ algorithms with adaptive parameters to transmission conditions are analyzed and their performance regarding throughput and delay is demonstrated via simulations. The principal concept of these algorithms is the introduction of a kind of memory into the FEC mechanism in a way that enables an estimation of the required redundant PDUs. The proposed cross-layer cooperation scheme between physical- and data-link layer offers an important gain for reliable communication services over power lines. Simulation results show that the combination of HARQ with distributed PSTBC provides an important advantage for the system performance, ensuring low mean delay and constant throughput for various indoor PLC network realizations.

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