A Multiaccess Protocol assisted by Retransmission Diversity and Multipacket Reception

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***Abstract*— In this paper we propose a new multiaccess protocol that combines the concept of splitting tree algorithms for collision resolution with two of the most relevant cross-layer technologies for random access: retransmission diversity (e.g., NDMA-Network Diversity Multiple Access) and multipacket reception (MPR). The proposed protocol is shown to outperform all the existing algorithms based on either NDMA or MPR. Additionally, the protocol formulation provides an important generalization of the model used for the analysis of solutions in these three fields. Unlike conventional NDMA protocols, in which all the colliding users are requested to immediately retransmit in the next time-slot, our proposed algorithm calculates the optimum set of users allowed to retransmit at each one of the following time-slots. The optimization is based on the previous collected transmissions and on the MPR and source separation (SS) probabilities, thus maximizing throughput and minimizing access-delay. Two possible suboptimal algorithms with simplified feedback assumption and hence suitable for distributed resolution are further derived from the original algorithm: an enhanced version of NDMA assisted by MPR and a fair splitting tree algorithm assisted by MPR and SS. The capacity/stability region of the protocol for several system configurations with two active users is employed to assess the benefits of the proposed algorithms.**

***Index Terms*— Cross-layer design, random access, network diversity, multipacket reception, splitting tree algorithms.**

I. INTRODUCTION

Cross-layer design has become a hot topic among the communication network design community. One of the areas where cross-layer design is playing a particular important role is in the joint design of the MAC (medium access control) and the PHY (physical) layers for wireless mobile communications [1].

The first wireless random access protocols such as ALOHA were designed considering that the collision of two or more packets yielded the loss of any useful information (collision-model) [2]. This assumption, for wireless channels, is both optimistic and pessimistic at the same time. Optimistic because it ignores wireless channel impairments such as multipath fading, attenuation, noise, etc; and, pessimistic because there are some cases in which a packet collision does not necessarily mean the destruction of all the information. For example, the capture effect allows a packet to be correctly decoded when its power is high enough with respect to the combined power from all the other colliding users. Furthermore, recent advances in signal processing have sparkled technologies that allow the deployment of multipacket reception (MPR) systems using for example multiple receiving antennas and source separation (SS). Therefore the analysis of modern multiaccess protocols requires other considerations different to the conventional collision-model [3].

A. The first cross-layer solutions

Motivated by the lack of an appropriate model for the analysis of the effects of wireless channels in the performance of multiaccess protocols, researchers started to propose the first combined models. Examples of this are the hybrid systems that incorporate into the Slotted-ALOHA (S-ALOHA) collision model capture probabilities calculated with different channel statistics (e.g. [4], [5] and [6]). These works represented the first cross-layer design attempts for random access.

B. The S-ALOHA protocol with MPR

Although the aforementioned works were the first that can be considered as cross-layer solutions, they still relied upon a collision model coupled to a particular PHY layer feature. The first formulation that attempted a complete modeling of wireless channels impairments was the work in [7]. The authors proposed a stochastic MPR matrix for symmetrical systems and derived the maximum stable throughput (MST) of an S-ALOHA protocol considering an infinite user population model.

Nevertheless, the MPR model introduced in [7] still lacked an important feature of wireless networks: asynchronous reception. To compensate this, Naware et al. have proposed in [8] a conditional reception probability approach for a finite-user S-ALOHA protocol. They have derived the exact stability region for the case of two-users and have provided sufficient conditions for the case of more than two users. They have also found that S-ALOHA without transmission control is optimum when the MPR parameters lie within a critical region that makes the stability characteristic to be convex. The model proposed in this paper is an extension to the model used in [8], but this time including SS probabilities that exploit a set of collected transmissions and retransmissions.

It is worth mentioning the recent work in [9], where the authors have proved that the stability region and the optimum capacity region of random access protocols with MPR are identical for the case of two users. The same conjecture appears to hold also for the case of more than two users. However, this demonstration remains as an open problem today.

C. The NDMA protocols

The MPR capabilities studied for the S-ALOHA protocol were implemented or obtained only across the spatial or code dimensions. The recently proposed Network Diversity Multiple Access (NDMA) [10] protocol is perhaps the first one using SS across the time dimension. In these NDMA protocols the collided packets are not discarded as in conventional approaches, but instead they are stored in the BS memory for further processing. The system calculates the collision multiplicity and requests the appropriate number of retransmissions from the involved users. The system then exploits the stored collided packets to recover the initial packets using SS tools. The model used for the analysis of the NDMA protocols consists of a collision-model with probabilities of detection and false alarm which are used to evaluate the separation capabilities of the system. As explained later in this section, in this paper we use a model that improves and generalizes this previous formulation of the NDMA protocols.

D. Tree algorithms assisted by signal processing

Inspired by NDMA, a new protocol called SICTA (Successive Interference Cancellation Tree Algorithm) has also been proposed in [11]. This protocol combines the properties of a standard tree algorithm with a successive interference cancellation (SIC) operation that also exploits the stored collided packets. This procedure reduces the number of necessary steps for collision resolution reaching an impressive MST of 0.693 packets/time-slot [11].

The SICTA algorithm has only been analyzed using a collision-model adapted to the possible SIC operations. As a unification of the SICTA and NDMA protocols, we have proposed in [12] a contention binary tree algorithm that is assisted by SS and SIC. The protocol reaches MST values higher than SICTA at the expense of additional signal processing complexity for SS. We also demonstrated that NDMA is a particular case of this tree algorithm with perfect separation capabilities and splitting probability equal to one. The tree algorithm and particularly the splitting mechanism were used to reduce the maximum number of colliding users, thereby reducing the required SS complexity. The protocol presented here further generalizes the concept of splitting transmissions in order to adapt the system to the SS and MPR capabilities.

E. The proposed solution

In this paper we propose a generalization of the previously discussed cross-layer technologies. Our algorithm exploits the principles of user splitting of tree algorithms in order to improve the SS and MPR probabilities. We have focused first in proposing a system that is not limited in feedback resources and then in deriving particular solutions in which such feedback is limited. Based on this we have obtained a multiaccess algorithm that exploits the set of previous transmitting users and the MPR and SS probabilities in order to calculate the optimum set of users allowed to retransmit in the following time-slot, thus maximizing throughput and reducing access-delay. The model used in our analysis is based on the conditional reception probability approach originally employed in the analysis of the S-ALOHA protocol with MPR in [8].

The algorithm is able to reduce to any of the previous solutions under different SS and MPR conditions. For example, the algorithm can reduce to the conventional NDMA, to the S-ALOHA with and without MPR, to the standard tree algorithm (STA), to TDMA (time-division multiple access) or to SICTA. Furthermore, two new suboptimum systems have been derived from our general formulation. These two suboptimum algorithms require a less complex feedback, which makes them suitable for distributed resolution.

The first suboptimal algorithm is an improved version of NDMA with MPR. The difference from the conventional NDMA is that our system attempts the recovery of the packets after each received retransmission using MPR. If the system recovers the packets successfully (i.e. all the packets from all the users are correctly decoded) then it stops requesting further retransmissions; and if not, the system continues with the normal NDMA operation. The feedback required for this system is the same as in the conventional NDMA, which consists of a simple flag indicating whether a retransmission is required from all the involved users or not.

The second suboptimal solution is a fair splitting algorithm in which the users that were not successfully decoded in the current time-slot split into two groups with equal probability $p_s = 0.5$. One of those groups retransmit in the following time-slot thus reducing the number of colliding users. The procedure is repeated until all the packets are recovered or until another mechanism stops it. The algorithm can be useful for systems in which the SS and feedback resources are limited. Details are given in the following sections.

F. Paper structure

The structure of this paper is as follows. Section II formulates the protocol rules and states the main system assumptions. Section III presents the throughput analysis. Section IV presents the optimization of the protocol with respect to the probabilities of transmission. Finally, Section V shows some analytical results for the capacity/stability region of the systems.

II. System Model

In this section we proceed to describe the rules for the operation of the multiaccess protocol. We consider a slotted multiaccess network with a central controller or base station (BS) and J possible active users. Whenever user j has a packet to transmit, it does so with probability p_j. The packet arrival rate for user j is denoted by λ_j packets/time-slot. If two or more users collide in a particular time-slot, the BS attempts the decoding of the colliding packets using signal processing operations for MPR. The BS has perfect knowledge of the set of transmitting users, denoted by the variable $\mathcal{T}(1)$, where the 1 stands for the first time-slot of the collision resolution period or epoch-slot (in practice the set of transmitting users can be estimated using orthogonal training sequences multiplexed in each packet as in [10]). If the decoding process is not successful (i.e., the decoded information does not satisfy a prescribed quality of service) then the BS proceeds to calculate an optimum set of users allowed to retransmit in the second time-slot, denoted by $\mathcal{T}(2)$. The BS uses the new collided packet to attempt the decoding of the original packets using SS with the current and previous collided packets. If the decoding of the packets is not successful then the process is repeated.

In order to optimize system delay we consider that the number of requested retransmissions is upper limited to a maximum of K retransmissions, where K is the collision multiplicity. The length of an epoch is denoted by the random variable l.

The reception model to be used is based on a conditional reception probability approach that was first introduced by Naware et al. in [8] for the analysis of the S-ALOHA protocol with MPR. They defined the marginal probabilities of reception for user j conditional on the transmission from a set of active users, denoted by $\mathcal{T}$. As an extension of this definition, we define the following probabilities that evaluate the SS and MPR capabilities of the system using retransmission diversity:

$$q_{j|\mathcal{T}(1),\ldots,\mathcal{T}(n)} = \sum_{\mathcal{R}:j\in\mathcal{R}\subseteq\mathcal{T}(1)} q_{\mathcal{R};\mathcal{T}(1),\ldots,\mathcal{T}(n)}, \tag{1}$$

where $q_{\mathcal{R};\mathcal{T}(1),\ldots,\mathcal{T}(n)}$ is the probability of decoding packets only from the set of users $\mathcal{R}$ conditional on the succession of transmitting user sets $\mathcal{T}(1),\ldots,\mathcal{T}(n)$. The term $\mathcal{T}(n)$ denotes the set of transmitting users in the n-th time-slot of an epoch-slot. Having defined the conditional reception probabilities we now analyze the performance of the protocol by means of the throughput expressions.

III. Performance analysis

For the analysis of the system we define the packet throughput of user j as the ratio of the probability of successful transmission from user j, denoted by $p_{suc,j}$, to the average length of an epoch or collision resolution period ($E[l]$):

$$T_j = \frac{p_{suc,j}}{E[l]}. \tag{2}$$

A successful transmission means the decoded packet is above certain quality of service level. The term $p_{suc,j}$ can be calculated as:

$$p_{suc,j} = \sum \Pr\{\mathcal{T}(1),\ldots,\mathcal{T}(n)\} q_{j|\mathcal{T}(1),\ldots,\mathcal{T}(n)}, \tag{3}$$

where the summation is taken over all the possible epoch lengths and all possible realizations of such epoch. The term $\Pr\{\mathcal{T}(1),\ldots,\mathcal{T}(n)\}$ denotes the probability for a particular realization of an epoch with n time-slots. We can also express $E[l]$ in eq.(2) by averaging over the probability mass function that defines the length of a resolution period as follows:

$$E[l] = \sum_{\mathcal{T}(1)\neq\emptyset} n\Pr\{\mathcal{T}(1),\ldots,\mathcal{T}(n)\} + \Pr\{\mathcal{T}(1)=\emptyset\}, \quad (4)$$

where $\Pr\{\mathcal{T}(1)=\emptyset\}$ is the probability that no user transmits. The probability mass function for the length of an epoch slot can be easily derived using the following expression which is valid for $K>1$:

$$\Pr\{l=n|\mathcal{T}(1),\ldots,\mathcal{T}(n-1)\} = \sum_{\mathcal{T}(n)}\Pr\{\mathcal{T}(n)\}\times \begin{cases} (1-\prod_{j\in\mathcal{T}(1)} q_{j|\mathcal{T}(1),\ldots,\mathcal{T}(n-1)})\times & \\ \prod_{j\in\mathcal{T}(1)} q_{j|\mathcal{T}(1),\ldots,\mathcal{T}(n)} & 1<n<K, \\ 1-\prod_{j\in\mathcal{T}(1)} q_{j|\mathcal{T}(1),\ldots,\mathcal{T}(n-1)} & n=K, \\ 0 & \text{otherwise}, \end{cases} \quad (5)$$

where $\Pr\{l=n|\mathcal{T}(1),\ldots,\mathcal{T}(n-1)\}$ denotes the probability for the length of an epoch being n time-slots conditional of the realization of the $n-1$ previous time-slots. Eq.(5) means that the probability for the length of an epoch being n time-slots is given by the probability that the collision is not resolved in the previous $n-1$ slots and that all the packets can be decoded in the current time-slot. If the collision is not resolved after the (n-1)-th received retransmissions the system proceeds to calculate an optimum set of transmitting users at time-slot n as follows:

$$\mathcal{T}(n) = \arg\max_{\mathcal{R}} \sum_{j\in\mathcal{T}(1)} q_{j|\mathcal{T}(1),\ldots,\mathcal{T}(n-1),\mathcal{R}}, \quad \mathcal{R}\subset\mathcal{T}(1),$$

which optimizes the total throughput. Note that other objective functions can also be used in this equation. In practice, estimates of the MPR and SS probabilities can be obtained through adaptive channel estimation or using channel state information.

IV. Protocol optimization

In this section we proceed to optimize the system expressions with respect to the probabilities of transmission. The optimum transmission probabilities can be obtained by solving the following Jacobian determinant [13]:

$$\left|\left\{\frac{\partial T_j}{\partial p_k}\right\}\right| = 0. \quad (6)$$

For simplicity, let us solve this problem for a system with two users, where we have $T_1 = \frac{p_{suc,1}}{E[l]}$ and $T_2 = \frac{p_{suc,2}}{E[l]}$. For the K-fold collision the derivation of a closed-form expression for the optimum probabilities of transmissions is an open problem due to the complicated MPR interactions. In order to obtain an expression for $p_{suc,1}$ and $p_{suc,2}$ from the general expression in eq.(3) and for $E[l]$ from eq.(4), we need to obtain first the probability mass function for the length of an epoch using eq.(5) and analyzing all the possible combinations of transmitting users. The case when only one of the users transmits, i.e. $\mathcal{T}(1)=\{1\}$ or $\mathcal{T}(1)=\{2\}$, can be easily solved as the epoch consists of only one time-slot. In the case when $\mathcal{T}(1)=\{1,2\}$ we assume a system scenario where $q_{1|\{1,2\},\{1\}}+q_{2|\{1,2\},\{1\}} > q_{1|\{1,2\},\{2\}}+q_{2|\{1,2\},\{2\}} > q_{1|\{1,2\},\{1,2\}}q_{2|\{1,2\},\{1,2\}}$, thus leading the proposed scheme to ask always user 1 for retransmission in the following time-slot. Therefore eq.(5) becomes:

$$\Pr(l=n|\{1,2\}) = \begin{cases} q_{1|\{1,2\}}q_{2|\{1,2\}}, & n=1. \\ 1-q_{1|\{1,2\}}q_{2|\{1,2\}}, & n=2. \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

From these results, it is possible to derive the expression for $p_{suc,1}$ from eq.(3) as follows:

$$p_{suc,1} = p_1\bar{p}_2 q_{1|\{1\}} + p_1p_2[q^2_{1|\{1,2\}}q_{2|\{1,2\}} + (1-q_{1|\{1,2\}}q_{2|\{1,2\}})(q_{1|\{1,2\}}+q_{1|\{1,2\},\{1,2\}})]$$

where $\bar{p}_j = 1-p_j$. This last expression can be further simplified to:

$$p_{suc,1} = p_1(q_{1|\{1\}} - p_2Q_1),$$

where $Q_1 = q_{1|\{1\}} - q_{1|\{1,2\}} - q_{1|\{1,2\},\{1\}}(1-q_{1|\{1,2\}}q_{2|\{1,2\}},)$. Similar expressions can be worked out for $p_{suc,2}$ and Q_2. Now, if we consider that $\Pr\{\mathcal{T}(1)=\emptyset\} = \bar{p}_1\bar{p}_2$ then $E[l]$ can be obtained from eq.(4) as follows:

$$E[l] = p_1\bar{p}_2 + p_2\bar{p}_1 + p_1p_2[q_{1|\{1,2\}}q_{2|\{1,2\}} + 2(1-q_{1|\{1,2\}}q_{2|\{1,2\}})] + \bar{p}_1\bar{p}_2 = 1 + p_1p_2(1-q_{1|\{1,2\}}q_{2|\{1,2\}}).$$

Using these expressions and after some algebraic manipulations exploiting the properties of determinants, we can express the elements of the Jacobian determinant as follows:

$$\frac{\partial T_1}{\partial p_1} = q_{1|\{1\}} - p_2Q_1, \quad \frac{\partial T_1}{\partial p_2} = q_{1|\{1\}} + p_2Q_1 - q_{1|\{1\}}E[l].$$

Similar expressions can be obtained for user 2. If we explicitly calculate the Jacobian determinant then eq.(6) reduces to the following useful expression for the optimum set of transmission probabilities:

$$\frac{p_2Q_1}{q_{1|\{1\}}} + \frac{p_1Q_2}{q_{2|\{2\}}} = 2 - E[l]. \quad (8)$$

Finally note that by substituting in the previous expressions $E[l]=1$ with $q_{j|\{1,2\},\{1,2\}}=0$, the solution can be proved to be equivalent to the result presented for the S-ALOHA protocol with MPR in [8].

A. NDMA assisted by MPR

The previously proposed system requires a complex feedback in order to inform each colliding user when to retransmit within an epoch slot. A simplification of this scheme can be obtained if we assume that, upon a collision, all the users are requested to retransmit using a simple flag that indicates such procedure (i.e. a conventional NDMA retransmission scheme). For a two-user system, the expressions that describe this protocol are identical to the ones presented in Section IV, except for the values for the Q_j's which are given by:

$$Q_1 = q_{1|\{1\}} - q_{1|\{1,2\}} - q_{1|\{1,2\},\{1,2\}}(1-q_{1|\{1,2\}}q_{2|\{1,2\}}.)$$

The same procedure can be followed for user 2. The conventional NDMA without MPR can be obtained from the protocol expressions by just substituting the product term $q_{1|\{1,2\}}q_{2|\{1,2\}}=0$.

B. Fair splitting tree algorithm

The second suboptimum solution consists of a modified tree algorithm assisted by MPR and SS. Unlike our original algorithm which calculates the optimum set of users allowed to retransmit, in this solution, upon the request for retransmission, the colliding users split into two groups with probability $p_s=0.5$, one of which retransmits in the following time-slot. This results in the following system parameters for our two-user case:

$$Q_1 = q_{1|\{1\}} - q_{1|\{1,2\}} - X_1(1-q_{1|\{1,2\}}q_{2|\{1,2\}}),$$

where $X_1 = 0.25(q_{1|\{1,2\},\{1,2\}} + q_{1|\{1,2\},\{2\}} + q_{1|\{1,2\},\{1\}})$ denotes the possible splitting scenarios of the tree algorithm and the probabilities of successful decoding. Similar expression can be worked out for user 2. Details of the derivation have been omitted due to lack of space.

V. Analytic results

Having obtained the main system equations, we now provide some analytical results by plotting the stability/capacity region for a system with two users. We use the parametric equations given by $\lambda_j = T_j$ and the formula for the optimum transmission probability in eq.(8), which describes the envelope of the capacity region.

Fig. 1 shows the stability/capacity region for the proposed algorithms with the following MPR and SS parameters $q_{1|\{1\}} = 0.9$, $q_{2|\{2\}} = 0.9$, $q_{1|\{1,2\}} = q_{2|\{1,2\}} = 0.3$, $q_{1|\{1,2\},\{1,2\}} = q_{2|\{1,2\},\{1,2\}} = 0.6$, $q_{1|\{1,2\},\{2\}} = 0.88$, $q_{2|\{1,2\},\{2\}} = 0.91$, $q_{1|\{1,2\},\{1\}} = 0.7$ and $q_{2|\{1,2\},\{2\}} = 0.5$. We have plotted the results for the proposed system (tagged Adaptive), for the NDMA protocol with the optimum retransmission diversity scheme (tagged NDMA2) , for the conventional NDMA (tagged NDMA1), for the tree algorithm and for the S-ALOHA protocol with MPR. With the particular MPR configuration given the proposed system greatly improves the performance of the other schemes, being S-ALOHA the one with the worst performance. The conventional NDMA has a slightly better performance due to the fact that the SS probabilities are also slightly higher than the MPR probabilities. The tree algorithm provides a considerable better performance than S-ALOHA and the conventional NDMA due to the fact that the splitting mechanism helps in reducing the collision size and thus increasing the decoding probability. Finally NDMA with the optimum retransmission diversity and the proposed algorithm show the best performance.

Let us now analyze a different system configuration. Fig. 2 shows the stability/capacity region for the analyzed algorithms with the following parameters $q_{1|\{1\}} = 0.8$, $q_{2|\{2\}} = 0.6$ $q_{1|\{1,2\}} = q_{2|\{1,2\}} = 0.5$, $q_{1|\{1,2\},\{1,2\}} = 0.75$, $q_{2|\{1,2\},\{1,2\}} = 0.55$, $q_{1|\{1,2\},\{1\}} = 0.8$, $q_{2|\{1,2\},\{1\}} = 0.6$, and $q_{1|\{1,2\},\{1\}} = 0.5$, $q_{2|\{1,2\},\{1\}} = 0.7$. In this example we have stronger MPR capabilities, which makes the S-ALOHA protocol outperforms the conventional NDMA and the tree algorithm. The NDMA with the optimum retransmission is better than S-ALOHA and closer now to the proposed adaptive scheme. On the limit when the SS probabilities are perfect, NDMA equals our proposed scheme.

VI. Conclusions

In this paper we have proposed a new random access protocol that outperforms any previous algorithm assisted by MPR or SS. The algorithm combines the properties of splitting transmission, MPR and network retransmission diversity, which are currently important topics in the MAC/PHY cross-layer design literature. Unlike the S-ALOHA protocol with MPR, our algorithm uses SS assisted by retransmission diversity as the conventional NDMA protocols; and, unlike the NDMA protocols, in which all the colliding users are requested for retransmission, our algorithm exploits the information about the colliding users, the MPR and the SS probabilities to calculate the optimum set of users allowed to retransmit in the following time slot. This operation fully exploits the capacity of the multiaccess channel.

We also proposed two suboptimal solutions derived from the original algorithm which are less demanding in feedback resources, hence being suitable for distributed implementation. Based on this, an interesting future research topic is the derivation of suboptimal solutions that can be adapted to different system constraints.

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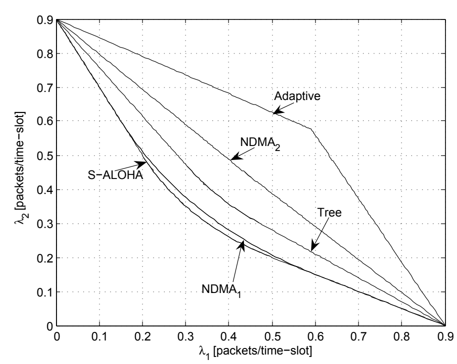

Fig. 1. Comparison between the stability regions of the proposed random access protocol, the conventional NDMA protocol, NDMA with the optimum retransmission scheme and S-ALOHA with MPR (Low MPR probabilities).

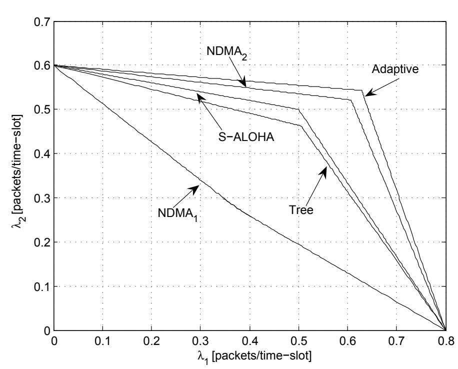

Fig. 2. Comparison between the stability regions of the proposed random access protocol, the conventional NDMA protocol, NDMA with the optimum retransmission scheme and S-ALOHA with MPR (High MPR probabilities).