HYBRID ALOHA: A NOVEL MEDIUM ACCESS CONTROL PROTOCOL

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ABSTRACT

In this paper, a novel medium access control (MAC) protocol, name hybrid ALOHA, is proposed to improve the system performance by allowing collision-free channel estimation and simultaneous multiuser data transmission. The idea behind it is to design an MAC protocol that is in favor of the physical (PHY) layer information transmission, and the improved PHY layer, in turn, can improve the MAC performance. Using the general multipacket reception (MPR) model as an interface between the MAC layer and the PHY layer, the hybrid ALOHA protocol is analyzed in terms of throughput, stability, as well as delay behavior. Significant performance improvement is observed in comparison with the traditional ALOHA either with the MPR model or with the collision model.

1. INTRODUCTION

Over the past decades, studies on medium access control (MAC) have largely relied on the "collision" model: a packet is successfully received if and only if there are no concurrent transmissions. Realizing that this idealized binary model fails to reflect all the characteristics of the PHY layer, in [1,2], Ghez, Verdu and Schwartz proposed the multipacket reception (MPR) model, where the reception of packets is characterized by conditional probabilities instead of deterministic failures or successes.

One limitation with the MPR model of Ghez et al. is that it assumes a symmetric model with indistinguishable users. To differentiate users in a multimedia networks where each user may have his own rate, in [3], Naware, Mergen and Tong introduced a more general, asymmetric MPR model as the interfaces between the MAC layer and the PHY layer. Based on the generalized MPR model, their study [3] on the stability and delay of slotted ALOHA leads to an interesting result: ALOHA is optimal as long as the MPR capability at the PHY layer is beyond a critical level.

As is well known, channel state information (CSI) directly influences the quality of the PHY layer and the knowledge on CSI can be exploited to improve network capacity, see [4, 5] for example. The more accurate the CSI estimation is, the more probable the signal can be received successfully, which implies a stronger MPR capability at the PHY layer. In this paper, we examine the effect of the MAC protocol design on the PHY layer performance, and study how the mutual MAC-PHY interaction will influence the overall system capacity. In other words, we aim to design a MAC protocol that is in favor of PHY layer information transmission, and the improved PHY layer, in turn, can improve the MAC performance.

Based on the fact as long as good channel estimation can be achieved, advanced signal processing does allow effective signal separation given that the multiuser interference is limited to a certain degree, we propose a novel random access protocol, named *hybrid ALOHA*, which allows collision-free channel estimation and simultaneous multiuser data transmission. Relying on the general multipacket reception (MPR) model, the hybrid ALOHA protocol is analyzed in terms of throughput, stability, as well as delay behavior. Comparing with the traditional ALOHA, significant performance improvement can be observed due to the improved MPR capability in the hybrid ALOHA.

The rest of the paper is organized as follows. In Section 2 we specify the system model. In Section 3, we propose the hybrid ALOHA protocol and analyze the throughput of the system. In Section 4 we derive the stability region for the two-user case. The delay behavior is studied in Section 5. A practical example is presented in Section 6 and we conclude in Section 7.

2. SYSTEM MODEL

Consider a wireless network with $N \geq 2$ users communicating with a common access point. Each user has a buffer for storing arriving and backlogged packets. The arrival processes are independent from user to user. Packets are of equal size for all users and are composed of two parts: the first part is the *training sequence* for channel estimation, and the second part is the *information data*. The length of the training sequence is typically much smaller than that of the information data. The channel is slotted in time and we assume that during one slot, the user can transmit two parts of the packet separately. The arrivals of the ith ($i \in \{1, 2, \cdots, N\}$) user are independent and identically distributed (i.i.d) from slot to slot, with an average packet arrival rate of λ_i.

For a system involving a set of N users $\mathcal{M} = \{1, 2, \cdots, N\}$, we adopt the asymmetric MPR model in [3] where the multiuser PHY layer is characterized by a set of conditional probabilities. For any subset $\mathcal{S} \subseteq \mathcal{M}$ of users transmitting in a slot, the *marginal* probability of successfully receiving packets from users in $\mathcal{R} \subseteq \mathcal{S}$ given that users in $\mathcal{S}$ transmit is defined as

$$q_{\mathcal{R}|\mathcal{S}} = \sum_{\mathcal{U}:\mathcal{R}\subseteq\mathcal{U}\subseteq\mathcal{S}} q_{\mathcal{U},\mathcal{S}}, \tag{1}$$

where $q_{\mathcal{U},\mathcal{S}}$ is the conditional probability of reception defined as

$$\begin{aligned} q_{\mathcal{U},\mathcal{S}} \;\; = \;\; & Pr\{\text{only packets from users in } \mathcal{U} \text{ are successfully} \\ & \text{received} \mid \text{users in } \mathcal{S} \text{ transmit}\}. \end{aligned} \tag{2}$$

In the two-user case, for example, $\mathcal{M} = \{1, 2\}$. For $i = 1, 2$,

$$\begin{aligned} q_{i,\{i\}} &= Pr\{\text{user i is successful} \mid \text{only user i transmits}\}, \\ q_{\{1,2\},\{1,2\}} &= Pr\{\text{both users are successful} \mid \text{both users transmit}\}, \\ q_{i,\{1,2\}} &= Pr\{\text{user i is successful} \mid \text{both users transmit}\}, \end{aligned} \tag{3}$$

and the marginal probabilities

$$q_{i|\{i\}} = q_{i,\{i\}}, \;\; q_{i|\{1,2\}} = q_{i,\{1,2\}} + q_{\{1,2\},\{1,2\}}. \tag{4}$$

3. THE PROPOSED HYBRID ALOHA PROTOCOL

The proposed hybrid ALOHA protocol is illustrated in Fig. 1 through the two-user case. In the hybrid ALOHA protocol, each slot in the traditional slotted ALOHA is divided into subslots including training sections, data sections and idle sections. Idle sections are inserted so that different users can transmit their training sequences at nonoverlapping subslots, therefore make it possible for collision-free channel estimation. At the same time, multiple users can transmit simultaneously at the data subslot.

In the two-user case, each slot is partitioned into three subslots. The preceding two subslots, each having a length of τ, are the "pilot subslots". When there is a transmission at the slot, the user randomly chooses a pilot subslot to transmit his/her *training sequence*. The selection of the pilot subslot is assumed to be of equal probability. The *information data* is always transmitted in the third subslot called "data subslot". We assume that the length of the data subslot is 1 and that the length τ is much less than 1.

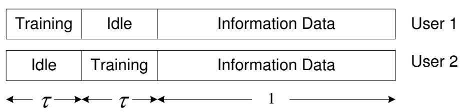


Fig. 1. Illustration of the hybrid ALOHA protocol in the two-user case.

To obtain the quantitative throughput of the hybrid ALOHA, we make the following assumption which is referred to as *Simplistic Assumption*: A collision is considered to have occurred if two users transmit their training sequences at the same pilot subslot. When a collision happens, each influenced user returns to the queue and transmits again at a randomly picked new slot. That is, a transmission is successful as long as collision-free channel estimation is achieved, and it fails otherwise.

Proposition 1 *Based on the Simplistic Assumption, the throughput of the hybrid ALOHA, ν, is given by*

$$\nu = [R^2/2 + R]e^{-R} \text{ (Erlangs)}, \tag{5}$$

where R is the average traffic.

Proof: Please referred to Appendix A in [6].

The throughput in the unit of *packets per unit time* can be expressed as $\nu/(2\tau + 1)$. Fig. 2 presents the throughput comparison of the hybrid ALOHA and the traditional slotted ALOHA in the case when $\tau = 0.1$. It is shown that the proposed scheme has a 46% gain over the traditional ALOHA in throughput.

4. STABILITY REGION FOR $N = 2$

In this section, we analyze the stability region of the hybrid ALOHA for the two-user case, based on the *Simplistic Assumption*. The derivation uses the stochastic *dominance* approach as in [3, 7, 8].

A multidimensional stochastic process, $\mathbf{Q}^t = (Q_1^t, \cdots, Q_N^t)$ is said to be **stable** [3, 8] if for $\mathbf{x} \in \mathbb{N}^N$, $\lim_{t\to\infty} Pr\{\mathbf{Q}^t < \mathbf{x}\} = F(\mathbf{x})$ and $\lim_{\mathbf{x}\to\infty} F(\mathbf{x}) = 1$. For an N-user slotted ALOHA system, the **stability region** ($\mathfrak{S}$) is defined as the set of arrival rate $\lambda = [\lambda_1, \lambda_2, \cdots, \lambda_N]$ for which there exists a transmission probability vector $\mathbf{p} = [p_1, p_2, \cdots, p_N]$ such that the queues in the system are stable. Let $\mathfrak{S}_{H-ALOHA}(\mathbf{p})$ be the stability region

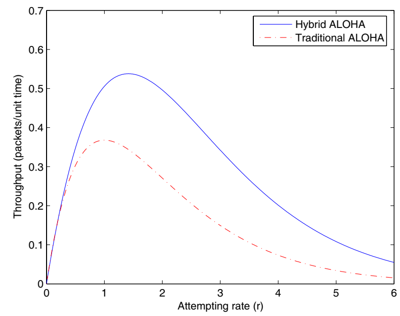


Fig. 2. Throughput comparison between the hybrid ALOHA ($\tau = 0.1$) and the traditional slotted ALOHA.

for a fixed $\mathbf{p}$, then the overall stability region of the proposed H-ALOHA can be characterized as

$$\mathfrak{S}_{H-ALOHA} = \bigcup_{\mathbf{p}\in[0,1]^N} \mathfrak{S}_{H-ALOHA}(\mathbf{p}) \tag{6}$$

Suppose the transmission rates for the two users are λ_1 and λ_2 and their transmission probabilities are p_1 and p_2, respectively, then we have the following result.

Lemma 1 *Under the Simplistic Assumption, for a fixed transmission probability vector $\mathbf{p} = [p_1, p_2]$, the stability region of the hybrid ALOHA $\mathfrak{S}_{H-ALOHA}(\mathbf{p})$ is given by*

$$\lambda_i \le p_i - \frac{p_i \lambda_{\bar{i}}}{2 - p_i}, \text{ for } \lambda_{\bar{i}} \le p_{\bar{i}} - p_i p_{\bar{i}}/2, \tag{7}$$

where $i \in \{1, 2\}$, $\bar{i} = \{1, 2\}\backslash\{i\}$.

Proof: Please referred to Appendix B in [6].

Proposition 2 *Under the Simplistic Assumption, the overall stability region of the hybrid ALOHA coincides with that of the TDMA and is characterized as*

$$\mathfrak{S}_{H-ALOHA} = \{(\lambda_1, \lambda_2) : (\lambda_1, \lambda_2) \ge (0, 0), (\lambda_1, \lambda_2) \text{ lies below the line } \lambda_1 + \lambda_2 = 1,\ 0 \le \lambda_1 \le 1\}. \tag{8}$$

Proof: Please refer to Appendix C in [6].

In Lemma 1, let $\mathbf{p} = [1, 1]$, then it is easy to see that the result coincides with the region given in Proposition 2. This means that the stability region can be achieved if both users transmit whenever they have packets in the buffer, i.e., there is no need of any transmission control.

Fig. 3 illustrates the stability region of the hybrid ALOHA given in Proposition 2 under the *Simplistic Assumption*, which is a triangle region identical to that of the centralized TDMA scheme.

Remark 1 *Beyond the Simplistic Assumption, in the case when the collision of the training sequences does not necessarily lead to reception failure(s), stronger MPR can be achieved. The convexity of the stability region remains and higher transmission rates can be obtained. In this case, the hybrid ALOHA outperforms the TDMA scheme with its stability region containing the triangular region in Fig. 3.*

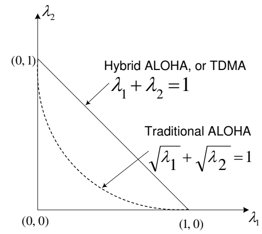


Fig. 3. Stability regions of the traditional ALOHA and that of the hybrid ALOHA under the *Simplistic Assumption*.

For the general reception model, the stability of the slotted ALOHA is derived in [3] using the marginal probabilities of success. Similar derivations can be applied directly to the proposed hybrid ALOHA, resulting in the following result:

Proposition 3 *If $Q_1 = q_{1|\{1\}} - q_{1|\{1,2\}} \geq 0$ and $Q_2 = q_{2|\{2\}} - q_{2|\{1,2\}} \geq 0$, then the stability region of the hybrid ALOHA for the general reception model is given by $\mathcal{R} = \mathcal{R}_1 \cap \mathcal{R}_2$ where*

$$\mathcal{R}_1 = \{(\lambda_1, \lambda_2) : (\lambda_1, \lambda_2) \geq (0,0), (\lambda_1, \lambda_2) \textit{ lies below the curve } \lambda_2 = f(\lambda_1;\ q_{1|\{1\}}, q_{2|\{2\}}, Q_1, Q_2)\} \quad (9)$$

and

$$\mathcal{R}_2 = \{(\lambda_1, \lambda_2) : (\lambda_1, \lambda_2) \geq (0,0), (\lambda_1, \lambda_2) \textit{ lies below the curve } \lambda_1 = f(\lambda_2;\ q_{2|\{2\}}, q_{1|\{1\}}, Q_2, Q_1)\} \quad (10)$$

where,

$$f(\lambda; \alpha, \beta, \gamma, \delta) = \begin{cases} \beta - \frac{\lambda\delta}{\alpha-\gamma}, & \lambda \in \mathcal{I}_1, \\ \frac{(\sqrt{\alpha\beta}-\sqrt{\lambda\delta})^2}{\gamma}, & \lambda \in \mathcal{I}_2. \end{cases} \quad (11)$$

where,

$$\mathcal{I}_1 = [0, \frac{\beta(\alpha-\gamma)^2}{\alpha\delta}], \textit{ and } \mathcal{I}_2 = [\frac{\beta(\alpha-\gamma)^2}{\alpha\delta}, \frac{\alpha\beta}{\delta}]. \quad (12)$$

If either Q_1 or Q_2 equals to zero, then we assume $\frac{1}{0} = \infty$ and the result still holds.

Proof: Please refer to [3].

5. DELAY PERFORMANCE FOR $N = 2$

To characterize delay in ALOHA systems is a nontrivial task. This section contributes to the derivation of the upper and lower bounds for the symmetric two-user system based on the MPR model.

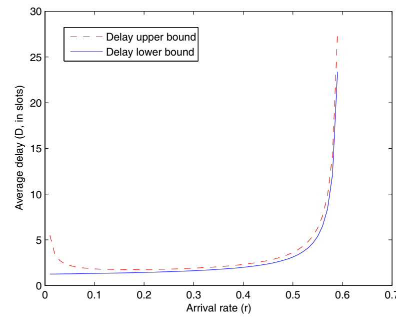
Let r be the arrival rate and p the transmission probability of both users. If we denote $q_{1|\{1\}} = q_{2|\{2\}} = a$, $q_{1,\{1,2\}} = q_{2,\{1,2\}} = b$ and $q_{\{1,2\},\{1,2\}} = c$, the bounds of the average delays for both users are given by the following proposition.

Proposition 4 *If the system is stable, i.e., $r < pa + p^2(b+c-a)$, the average delay D for either user is bounded by*

$$D \geq D_L = \frac{1}{a}[\frac{a(1-r)+p(b+c-a)(1-r/2)}{pa+p^2(b+c-a)-r}], \quad (13)$$

and

$$D \leq D_L + \frac{p^3 c[a-(b+c)]}{2ar[pa+p^2(b+c-a)-r]}. \quad (14)$$



(a) $p = 1,\ a = 0.8,\ b = 0.4,\ c = 0.2.$

Fig. 4. Illustration of the delay bounds.

Proof: Please refer to Appendix D in [6].

As shown in Fig. 4, when the arrival rate r is low (e.g., $r < 0.1$), the given upper bound is quite loose. However, if the MPR capability of the system is strong enough, then for small r's, we can approximate the desired average delay with the lower bound. Intuitively, if the arrival rate r is small and the MPR capability is strong enough to handle all the packets delivery, then the probability that the two queues are empty at the steady sate tends to be 1, i.e., $\lim_{t\to\infty} E(\mathbf{1}[Q_1^t = 0, Q_2^t = 0]) = 1$. In this case, the lower bound becomes the exact average delay (see Appendix D in [6]).

For moderate r, if the MPR capability is relatively strong with $b+c$ being close to a, or the transmission probability p is relatively small, the two bounds are very close to each other. In these cases, the actual delay of the system can be roughly determined by taking the average of the two bounds.

Remark 2 *When the MPR model is reduced to the capture model, the two bounds merge and we obtain the exact delay, which coincides with the result of [3].*

6. A PRACTICAL EXAMPLE

In this section a practical example is provided to illustrate the performance of the proposed protocol.

6.1. System Set-up

Consider a two-user system. Both users communicate with the base station which employs an M-element linear antenna array. The signals of the two users arrive at the array with spatial angles $\theta = [\theta_1, \theta_2]$ with respect to the array normal. The two users access the system based on the hybrid ALOHA and the time slots are assumed to be synchronized. The received signal at the base station $\mathbf{y}$ is given by

$$\mathbf{y} = \mathbf{V}(\theta)\mathbf{H}\mathbf{s} + \mathbf{n}, \quad (15)$$

where $\mathbf{V}(\theta)$ is the array response matrix; $\mathbf{H} = diag[h_1, h_2]$ is the diagonal matrix of channel fading for the two users. For simplicity we assume flat fading with each $h_i (i = 1, 2)$ being a zero mean complex Gaussian random variable normalized to 1, i.e., $E[h_i] = 0$ and $E[|h_i|^2] = 1$; $\mathbf{s} = [s_1, s_2]^T$ is the vector of users' transmitted symbols, s_i takes on the value of ± 1; $\mathbf{n}$ is the additive white Gaussian noise with zero mean and variance $\sigma_n^2 \mathbf{I}_M$, and the noise is assumed to be independent of the information sequences.

We assume the channels are i.i.d from slot to slot yet remain unchanged during one slot. At the base station, the estimate $\hat{h}_i$ of

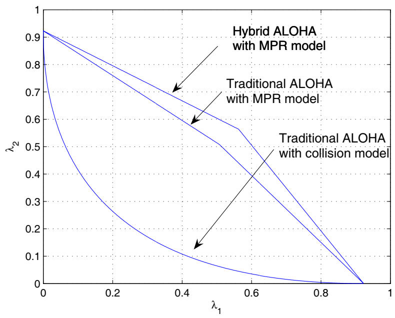


Fig. 5. Comparison of stability regions of different schemes, $SNR = 10dB$, $\beta = 6dB$, $\sigma_{e1}^2 = 0.01$.

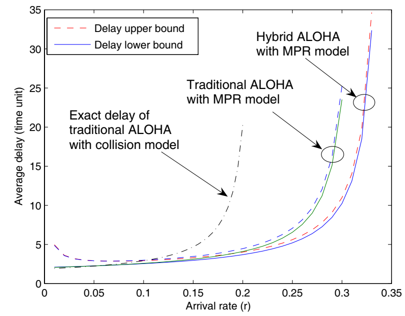


Fig. 6. Comparison of delays of different schemes, $SNR = 10dB$, $\beta = 6dB$, $\sigma_{e1}^2 = 0.01$, $p = 0.6$, $\tau = 0.1$.

h_i is obtained and it is assumed to differ from the actual channel h_i by an independent error Δh_i, where $\Delta h_i \sim \mathcal{N}(0, \sigma_e^2)$. Thus $\hat{h}_i$ is an i.i.d. complex Gaussian random variable with zero mean and variance $\hat{\sigma}^2 = 1 + \sigma_e^2$. The actual channel h_i can be written in terms of $\hat{h}_i$ as [9]

$$h_i = \rho \hat{h}_i + \tilde{h}_i, \quad (16)$$

where $\rho = 1/(1+\sigma_e^2)$, $\tilde{h}_i$ is an i.i.d. complex Gaussian random variable with zero mean and variance $\tilde{\sigma}^2 = \sigma_e^2/(1+\sigma_e^2)$ and $E[\tilde{h}_i \hat{h}_i^*] = 0$.

Considering coherent reception, the signal processing at the receiver produces the output

$$\mathbf{z} = \hat{\mathbf{H}}^* \mathbf{W} \mathbf{y} = \hat{\mathbf{H}}^* \mathbf{W} \mathbf{V}(\theta) \mathbf{H} \mathbf{s} + \hat{\mathbf{H}}^* \mathbf{W} \mathbf{n}, \quad (17)$$

where $*$ denotes complex conjugate, $\hat{\mathbf{H}} = diag[\hat{h_1}, \hat{h_2}]$ contains the estimated channel coefficients for the two users, $\mathbf{W}$ represents the beamforming weight matrix, the ith row of $\mathbf{W}$, $\mathbf{w}_i$, represents the weight vector for the ith user.

If we denote the ith column of $\mathbf{V}(\theta)$ as $\mathbf{v}_i$, (17) can be written as

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} \mathbf{w}_1 \mathbf{v}_1 h_1 \hat{h}_1^* & \mathbf{w}_1 \mathbf{v}_2 h_2 \hat{h}_1^* \\ \mathbf{w}_2 \mathbf{v}_1 h_1 \hat{h}_2^* & \mathbf{w}_2 \mathbf{v}_2 h_2 \hat{h}_2^* \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} \hat{h}_1^* \mathbf{w}_1 \mathbf{n} \\ \hat{h}_2^* \mathbf{w}_2 \mathbf{n} \end{bmatrix}. \quad (18)$$

6.2. Stability Regions and Delays

Under the SINR model, user 1's packet is assumed to be successfully received if $E[SINR|\hat{h}_1] > \beta$, where β is the predetermined threshold required by QoS. Hence when only user 1 transmits,

$$\begin{aligned} q_{1|\{1\}} &= Pr\{\frac{\rho_1^2 |\hat{h_1}|^2}{\tilde{\sigma}_1^2 + \frac{\mathbf{w}_1 \mathbf{w}_1^H}{|\mathbf{w}_1 \mathbf{v}_1|^2} \sigma_n^2} > \beta\} \\ &= exp\{-\beta[\sigma_{e1}^2 + (1+\sigma_{e1}^2) \frac{\mathbf{w}_1 \mathbf{w}_1^H}{|\mathbf{w}_1 \mathbf{v}_1|^2} \sigma_n^2]\}. \quad (19) \end{aligned}$$

where $|\hat{h}_1|^2 \sim exp(1/\hat{\sigma}^2)$, $\rho_1^2 = 1/(1+\sigma_{e1}^2)$, $\tilde{\sigma}_1^2 = \sigma_{e1}^2/(1+\sigma_{e1}^2)$, and σ_{e1}^2 is the variance of the collision-free channel estimation error.

Calculations on other probabilities can be similarly obtained. And we can now portray the stability region and the delay bounds of the proposed protocol. Proposition 3 is used for characterizing the stability regions under the SINR model.

Suppose that at the base station, the linear antenna array has $M = 5$ elements, which are uniformly spaced with a distance of one wavelength. The impinging signals are relatively close with $\theta = [54°, 64°]$. The front-end processing exploits matched filter with the beamforming weight matrix $\mathbf{W} = \mathbf{V}^H(\theta)$. We assume the packets are of small size and can afford only two symbols as the training sequence. Fig. 5 and Fig. 6 show the stability regions and delays for the hybrid ALOHA under these settings, as well as the stability regions and delays of two other schemes. The hybrid ALOHA is shown to have the best performance due to the MPR improvement.

7. CONCLUSIONS

In this paper, we proposed a hybrid ALOHA protocol which allows collision-free channel estimation and simultaneous data transmission. The improvement of the channel estimation increases the MPR capability and significant performance improvement is observed in comparison with the traditional ALOHA. The throughput of the protocol is derived and the stability as well as the delay performances for the $N = 2$ case are analyzed. More general cases for $N > 2$ demand further investigation.

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