Smart Antennas, Dumb Scheduling for Medium Access Control

Vidyut Naware and Lang Tong[1]
School of Electrical and Computer Engineering,
Cornell University,
Ithaca, NY 14853.
Email : ltong@ece.cornell.edu

Abstract — **We consider the problem of stability of slotted ALOHA for a system consisting of N users communicating with a common receiver, which employs spatial diversity to receive multiple transmissions simultaneously. We introduce a general packet reception model to incorporate multiple packet receptions since the collision channel model is no longer valid in such a scenario. We characterize the stability region of slotted ALOHA for the two user case explicitly. We find that the relaxation of the collision channel model introduces a distinct change in the structure of the stability region. We show that the stability region undergoes a *phase transition* from a concave region to a convex region bounded by lines. We show that after this phase transition slotted ALOHA is optimal in the sense that slotted ALOHA can stabilize any rates that can be stabilized by any MAC protocol. Not only that, we find that after the phase transition, the best strategy is for both users to transmit with probability one which is an extreme case of slotted ALOHA with retransmission probability one. This significant finding suggests that if the physical layer is even *reasonably* good there is no need for sophisticated Medium Access Control protocols.**

I. Introduction

The recent surge of interest in multiple antenna wireless systems has once again brought into focus the ability of the physical layer to utilize spatial diversity for increasing capacity. Most of the effort in utilizing the spatial diversity at the Media Access Control (MAC) layer has been directed either towards modifying existing protocols like ALOHA, CSMA etc. [14] -[19] or design of new MAC protocols to exploit directional antennas and smart adaptive antenna arrays [20]-[24]. In systems with spatial diversity, the main issues that need to be addressed are the design of multiple antenna receiver at the physical layer and keeping buffers of packets on the transmitter side under control at the MAC layer. Smart antennas provide spatial diversity by employing sophisticated signal processing techniques and thus allowing the possibility of receiving packets from many users *simultaneously.* To date, the issues of multiple antenna receiver design and buffer stability have been looked at almost in isolation. Our main goal in this paper is to look at the aforementioned problems jointly *i.e.*, to see how signal processing techniques like beamforming affect buffer stability. In particular, we restrict ourselves to slotted ALOHA as the MAC layer protocol and examine the effect of Multipacket receptions on buffer stability.

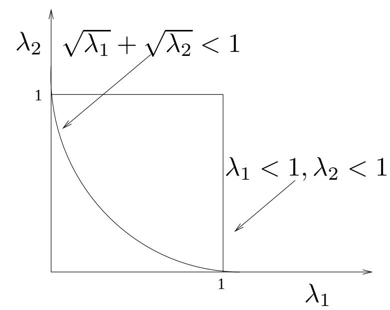

Figure 1: Two user stability region of slotted ALOHA for the Collision Channel and Orthogonal Channels

In Figure 1, we show the regions of buffer stability *i.e.*, the rate pairs for which queues are stable for slotted ALOHA with the collision channel and with perfectly orthogonal channels (no interference) for $N = 2$ users. For orthogonal channels we have a unit square, whereas for the collision channel we have a complex form. Our motivation was to look at the behavior of the stability region when the diversity we have lies in between these two extreme cases. We find that the stability region makes a smooth phase transition from concavity to convexity as we move from one extreme to another. In other words, as we allow multipacket receptions to become more likely there comes a point at which the stability region becomes convex. We also find that the stability region is bounded by lines as soon as it becomes convex.

More surprisingly, we find that after this phase transition slotted ALOHA is *optimal* in the sense that slotted ALOHA can stabilize any rates that can be stabilized by any MAC protocol. This means that there is no need for any sophisticated MAC protocols once we have a critical level of spatial diversity —the simple slotted ALOHA will do. But perhaps the most striking finding of this correspondence is that when slotted ALOHA is optimal, the best strategy for both users is to transmit with retransmission probability one. In other words, the critical phase transition is the point where the need for a MAC layer disappears—users should transmit if they have packets. From Figure 1, it is obvious that when spatial diversity can provide orthogonal channels then the users should transmit whenever they have packets. But the surprising finding is that the need for a MAC protocol disappears well before we have an ideal physical layer. In fact, we show that in Figure 1 if the physical layer is strong enough to sustain a sum rate $(\lambda_1 + \lambda_2)$ greater than one with slotted ALOHA, then we don't need a MAC layer. Thus, there is a large class of rates which can be stabilized with a very simple MAC protocol *viz.,*

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slotted ALOHA with retransmission probability one.

In [7], the problem of scheduling transmissions for the downlink of a multiple antenna cellular system is considered. Viswanath *et al.* show that from an information theoretic point of view, a good strategy for the base station is to employ "dumb" antennas (in the sense of not doing any signal processing other than that in a single antenna system) and implement "smart" scheduling (in the sense of scheduling users who have the best channel at that time). Thus, they show that more resources should be allocated to scheduling than to the physical layer for the downlink. Our problem is in some sense the dual of the downlink problem. Since, we wish to address source burstiness, we choose the framework of random access and consider the uplink of a multiple antenna cellular system. In contrast to [7], our results show the trade-off involved in allocation of resources to the MAC and the PHY layer. We show that if we allocate sufficient resources (sophisticated signal processing by smart antennas) to the physical layer then "dumb" scheduling (transmit if you have packets) is optimal.

In [11]-[13], a packet radio system is analyzed in which a multiple beam adaptive array is used at the base station to separate users signals. In this system, the adaptive array uses a different set of weights for every user in the system to nullify interference from other users to maximize the SINR. The authors characterize the performance of slotted ALOHA for such a system in terms of the throughput, assuming the users have single packet buffers. In [6], Ghez *et al.* consider the stability of ALOHA for an infinite user slotted channel with multipacket reception (MPR) capability. In such a channel, the number of packets successfully received in a slot is a random variable which depends only on the number of attempted transmissions in that slot. Thus, this model can capture the event of simultaneous packet successes although it is not sufficient to capture asymmetry among users since all users are treated equal by the model, which need not be true for a multiple antenna wireless system.

Tsybakov and Mikhailov [1] initiated the study of the slotted ALOHA system in terms of the stability of queues at each of the terminals in the system. By stability we mean that all queues are finite with probability one. In such a buffered system, stability is not easy to establish because of the stochastic interdependence among the queues. Nonetheless, Tsybakov and Mikhailov found sufficient conditions for stability of the queues in the system using the principle of stochastic dominance. For the symmetric case (*viz.* equal arrival rates for all terminals), they found the maximum stable throughtput. They also found the stability region for the two-user case explicitly. Rao and Ephremides [2] explicitly used the principle of stochastic dominance to find inner bounds to the stability region for the $N > 2$ case. Szpankowski [3] found necessary and sufficient conditions for the stability of queues in a slotted ALOHA system for a fixed retransmission probability vector for the $N > 2$ case. Recently, Luo and Ephremides [4] introduced the concept of instability ranks in queues to obtain tight inner and outer bounds on the stability region for the $N > 2$ case. However, to date there is no closed form characterization of the stability region for the $N > 2$ case. The point to note is that the above results were derived assuming the collision channel model for packet success—an assumption that we relax.

II. System Model

The system consists of N users, each having an infinite buffer for storing arriving and backlogged packets, communicating with a common receiver. The receiver has multiple antennas used to implement beamforming for receiving multiple packets simultaneously. The channel is slotted in time and a slot duration equals the packet transmission time. Packets are assumed to be of equal length for all the users. The arrivals at the ith queue ($i \in \{1, 2, \ldots, N\}$) are independant and identically distributed Bernoulli random variables from slot to slot with mean λ_i. Arrival processes are assumed to be independant from user to user. If the ith users' buffer is nonempty, he transmits a packet with probability p_i in a slot.

Now we define a very general packet reception model to capture the event of multipacket reception. Suppose that the set $\mathcal{S} \subseteq \{1, 2, \ldots, N\}$ of users transmit in a slot, then we define for $i \in \mathcal{S}$,

$$q_{i|\mathcal{S}} = \Pr\{i\text{th users' packet is successfully received} \mid \mathcal{S} \text{ transmits}\} \quad (1)$$

We assume that user i's packet is successfully received independantly from slot to slot. We further assume that the receiver gives an instantaneous feedback of all the packets that were successful in a slot at the end of the slot to all the users. The users remove successful packets from their buffers while unsuccessful packets are retained in the buffers. It should be clear that the conditional probabilities $q_{i|\mathcal{S}}$ are a function of the receiver front-end which will be employed by the receiver to "separate" users' signals. Before we proceed to derive some of the results of the next section, a few definitions are in order. We use the definition of stability used by Loynes [5].

Definition: A multidimensional stochastic process, $\mathbf{Q}^t = (Q_1^t, \ldots, Q_N^t)$ is *stable* if for $\mathbf{x} \in \mathbb{N}^N$ the following holds

$$\lim_{t\to\infty} \Pr\{\mathbf{Q}^t < \mathbf{x}\} = F(\mathbf{x}) \text{ and } \lim_{\mathbf{x}\to\infty} F(\mathbf{x}) = 1. \quad (2)$$

If a weaker condition holds *viz.*,

$$\lim_{\mathbf{x}\to\infty} \liminf_{t\to\infty} \Pr\{\mathbf{Q}^t < \mathbf{x}\} = 1 \quad (3)$$

then the process is called substable. Further, the process is said to be unstable if it is not substable.

It can be easily shown that stability implies substability. For the slotted ALOHA system we described in Section II, the stochastic process under consideration is the queue length at the N buffers. Thus, Q_i^t represents the queue length at ith buffer at time t. Because of the special arrival and departure statistics in this system, the N dimensional queue evolution is an aperiodic and irreducible Markov chain. The notion of stability in this system is then equivalent to the positive recurrence of the Markov chain. Intuitively this means that the buffers in the system are not growing to infinity.

Definition: For an N user slotted ALOHA buffer system, the stability region is defined as the set of arrival rates $\boldsymbol{\lambda} = [\lambda_1, \lambda_2, \ldots, \lambda_N]$ for which there exists a retransmission probability vector $\mathbf{p} = [p_1, p_2, \ldots, p_N]$ such that the buffers in the system are stable. The stability region clearly depends on the underlying packet reception model.

III. Stability region for the two user case

Since the stability region for the collision channel is unknown for the $N > 2$ case, we first find the stability region for the

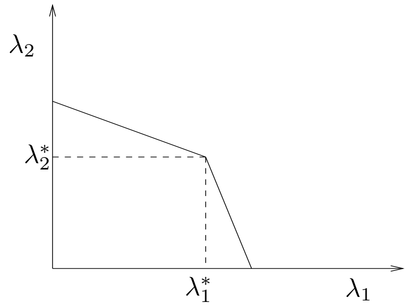

Figure 2: Stability region for a fixed retransmission probability vector $[p_1, p_2]$

$N = 2$ case for the general reception model given by (1). For notational convenience, we define the probabilities of packet success in the two user case as

$$q_i^{(1)} = \Pr\{\text{user } i \text{ is successful} \mid \text{only user } i \text{ transmits}\}$$
$$q_i^{(2)} = \Pr\{\textit{only} \text{ user } i \text{ is successful} \mid \text{both users transmit}\}$$
$$q^{(2)} = \Pr\{\text{both users are successful} \mid \text{both users transmit}\}$$

Further, we define $Q_1 \triangleq q_1^{(1)} - q_1^{(2)} - q^{(2)}$ and $Q_2 \triangleq q_2^{(1)} - q_2^{(2)} - q^{(2)}$. Thus, Q_1 and Q_2 denote the difference between the (conditional) probability of success in the absence of interference and the (conditional) probability of success in the presence of interference for the users. Note that the above probabilities can capture not only all possible packet reception events but also correlations among those events and user asymmetry. To find the stability region, we first need to find the stability region of the system for a *fixed* retransmission probability vector $\mathbf{p}(= [p_1, p_2])$. The following lemma gives us exactly that.

Lemma 1 *If $Q_1 \geq 0$ and $Q_2 \geq 0$, the stability region of slotted ALOHA for the general packet reception model for a given $[p_1, p_2]$ is given by*

$$\lambda_1 < p_1 q_1^{(1)} - \frac{p_1 p_2 \lambda_2 Q_1}{\lambda_2^*}, \ \textit{for } \lambda_2 < \lambda_2^* \tag{4}$$

and

$$\lambda_2 < p_2 q_2^{(1)} - \frac{p_1 p_2 \lambda_1 Q_2}{\lambda_1^*}, \ \textit{for } \lambda_1 < \lambda_1^* \tag{5}$$

where,

$$\lambda_1^* = p_1 q_1^{(1)} - p_1 p_2 Q_1 \ \textit{and } \lambda_2^* = p_2 q_2^{(1)} - p_1 p_2 Q_2$$

Proof: We use the idea of stochastic dominance and use an argument similar to that by Rao and Ephremides [2]. □

Figure 2 shows us the stability region as given by Lemma 1. The conditions $Q_1 \geq 0$ and $Q_2 \geq 0$ are needed for the stochastic dominance of the associated dominant systems. In fact, these conditions are equivalent to the probability of success of any user in the presence of interference (from the other user) be no greater than the probability of success in the absence of interference—a reasonable and practical assumption.

We now give a key result of this paper in the form of this theorem.

Theorem 1 *If $Q_1 \geq 0$ and $Q_2 \geq 0$, then the stability region of slotted ALOHA for the general reception model is given by $\mathcal{R}_1 \cap \mathcal{R}_2$ where*

$$\mathcal{R}_1 \triangleq \{(\lambda_1, \lambda_2) : (\lambda_1, \lambda_2) \geq (0,0), \ (\lambda_1, \lambda_2) \textit{ lies below the curve } \lambda_2 = f(\lambda_1, q_1^{(1)}, q_2^{(1)}, Q_1, Q_2)\} \tag{6}$$

and

$$\mathcal{R}_2 \triangleq \{(\lambda_1, \lambda_2) : (\lambda_1, \lambda_2) \geq (0,0), \ (\lambda_1, \lambda_2) \textit{ lies below the curve } \lambda_1 = f(\lambda_2, q_2^{(1)}, q_1^{(1)}, Q_2, Q_1)\} \tag{7}$$

where

$$f(\lambda, \alpha, \beta, \gamma, \delta) = \begin{cases} \beta - \frac{\lambda\delta}{\alpha-\gamma}, & \lambda \in \mathcal{I}_1 \\ \frac{(\sqrt{\alpha\beta} - \sqrt{\lambda\delta})^2}{\gamma}, & \lambda \in \mathcal{I}_2 \end{cases} \tag{8}$$

where

$$\mathcal{I}_1 = [0, \frac{\beta(\alpha-\gamma)^2}{\alpha\delta}] \textit{ and } \mathcal{I}_2 = (\frac{\beta(\alpha-\gamma)^2}{\alpha\delta}, \frac{\alpha\beta}{\delta}]. \tag{9}$$

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

Proof: We use Lemma 1. Since we know the stability region for a fixed retransmission probability vector $\mathbf{p}$, we need to find the union of all the stability regions as the parameter $\mathbf{p}$ varies over $[0,1]^2$. One way of doing this is to setup a corresponding constrained optimization problem *i.e.* for a fixed λ_1, maximize λ_2 as $\mathbf{p}$ varies over $[0,1]^2$, where λ_1 and λ_2 are related by (4) and (5). This is the method which we used in our proof [9]. □

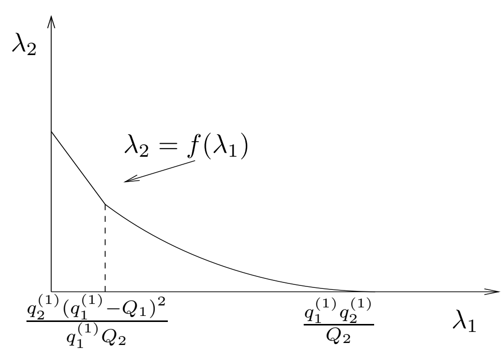

Figure 3: The appearance of $f(\lambda_1)$ as a function of λ_1.

We note a few interesting things about the stability region. First, the function f characterizing the stability region in (8) is linear for some part of the domain and is strictly convex in the remainder of its domain as illustrated in Figure 3. The stability region for the two user collision channel can be found as a special case of our model with $q_1^{(1)} = 1$, $q_2^{(1)} = 1$, $q_1^{(2)} = 0$, $q_2^{(2)} = 0$ and $q^{(2)} = 0$ and is bounded by the curve $\sqrt{\lambda_1} + \sqrt{\lambda_2} = 1$, which is strictly convex everywhere. In fact, it is easy to see from Figure 3 that the interval where f is linear has non-zero Lebesgue measure as soon as there is a nonzero probability of success in the presence of interference *i.e.* $q_1^{(1)} - Q_1 > 0$. Thus, there is a characteristic *change* in the structure of the stability region as soon as we have multi-packet reception. Second, we see that there is a symmetry in the way in the two regions $\mathcal{R}_1$ and $\mathcal{R}_2$ are defined in terms of the function f. Third, the stability region is entirely characterized by $q_1^{(1)}$, $q_2^{(1)}$, Q_1 and Q_2. In turn, Q_1 and Q_2 depend only on the *marginal* probabilities of success in the presence and absence of interference, which is not surprising since the two users are not collaborating their packet transmissions.

Further, we observe the following three important properties of the stability region:

Property 1 (P1): Assume that $q_1^{(1)} > 0$, $q_2^{(1)} > 0$, $q_1^{(1)} - Q_1 > 0$ and $q_2^{(1)} - Q_2 > 0$ *i.e.* non-zero probability of success in the presence and absence of interference. Then, the stability region is bounded by lines iff

$$\frac{Q_1}{q_1^{(1)}} + \frac{Q_2}{q_2^{(1)}} \leq 1 \tag{10}$$

Property 2 (P2): Assume that $q_1^{(1)} > 0$, $q_2^{(1)} > 0$, $q_1^{(1)} - Q_1 > 0$ and $q_2^{(1)} - Q_2 > 0$. Then, the stability region is bounded by lines iff the stability region is convex.

Property 3 (P3): If the stability region is not bounded by lines, then the strictly convex parts of f which bound the regions $\mathcal{R}_1$ and $\mathcal{R}_2$ coincide on the boundary of the stability region.

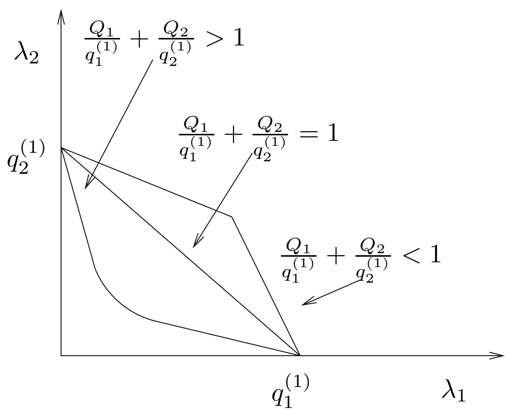

Figure 4: The shape of the stability region for different $\mathbf{q}$ vectors with $q_1^{(1)}$ and $q_2^{(1)}$ fixed.

Figure 4 shows the stability regions characterized by the $\mathbf{q}$ vector based on the above properties. P1 has a nice interpretation; there is a critical point for the $\mathbf{q}$ vector at which the behavior of the stability region makes a phase transition from a very simple form (bounded by lines) to a much more complex form. Further, this critical point depends only on the sum of the ratios of probability of success of users in the presence of interference to that in the absence of interference. P2 tells us that the two simple properties (convexity and being bounded by lines) of a region are equivalent for the stability region. The condition of the stability region being bounded by lines and being convex corresponds to a regime in which when one user increases his rate, the other users' maximum supportable rate decreases only linearly, and that too at a rate which is low till a certain point and then suddenly increases. Another interpretation is that when the stability region is convex then higher sum rates can be achieved. In addition, when the stability region is convex we know that if two rate pairs are stable then any rate pair lying on the line segment joining those two rate pairs is also stable. This is an important point because the stability region for the two user collision channel is not convex. When equality holds in equation (10), the stability region is a triangle as shown in Figure 4. All the rate pairs in this region can be stabilized by TDMA schemes (in a collision channel). Thus, the condition $\frac{Q_1}{q_1^{(1)}} + \frac{Q_2}{q_2^{(1)}} < 1$ gives us the regime in which a distributed strategy like slotted ALOHA can do better than a centralized TDMA scheme. P3 also has an interesting interpretation; it tells us that if the stability region has a complex form then there are certain regions where the behavior of the channel is similar to a collision channel. This is also the regime in which the stability region is not convex. In this regime, when one user increases his rate the other user has to reduce his rate drastically for stability.

IV. Optimality of slotted Aloha

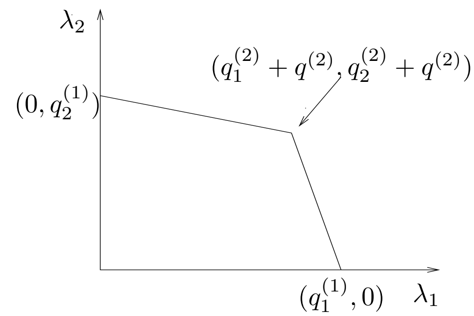

Figure 5: Stability region when it is convex.

In fact a closer look at the stability region when it is convex reveals more. Figure 5 shows the co-ordinates of all the corner points of the stability region when it is convex. Note that the stability region is the convex hull of the four corner points. We surprisingly find that for our reception model, *any* MAC protocol can stabilize only the rates shown in Figure 5. In other words, slotted ALOHA is optimal when the stability region is convex. Thus in effect, we have found a regime of spatial diversity where slotted ALOHA is optimal.

Theorem 2 *If*

$$\frac{Q_1}{q_1^{(1)}} + \frac{Q_2}{q_2^{(1)}} \leq 1$$

then, slotted ALOHA is optimal viz.*, slotted ALOHA can stabilize all rates which can be stabilized by any MAC protocol.*

Proof: We sketch an outline of the proof. The proof hinges on the fact that any MAC protocol essentially allows a (random or deterministic) subset of users to transmit during a slot. Since there are only finitely many distinct subsets of users, in the long run the departure rate for a user is a weighted combination of the probabilities of success of that user in all possible transmission scenarios in which he is involved. The weights depend on the proportion of time a particular subset of users is allowed to transmit. Under conditions of stochastic dominance ($Q_1 \geq 0$ and $Q_2 \geq 0$), it can be shown that the convex hull of all the points corresponding to the (marginal) probabilities of success of users for every possible subset of transmitting users is actually the set of rates stabilizable by any MAC protocol. If $\frac{Q_1}{q_1^{(1)}} + \frac{Q_2}{q_2^{(1)}} \leq 1$, by Theorem 1 the stability region of slotted ALOHA coincides with the convex hull of points just described above. For technical details refer to [9]. □

Perhaps the most surprising observation when the stability region is convex is the following: The stability region is the same as the stability region of slotted ALOHA when the retransmission probability vector is $[1, 1]$. This can be easily seen by using Lemma 1 for $\mathbf{p} = [1, 1]$. In other words, when the stability region is convex, both users should always transmit packets to stabilize *any* stabilizable rate. Note that with centralized scheduling, to stabilize a particular stabilizable rate the scheduler has to allocate a proportion of time for each possible subset of transmitting users. In order to do this, the scheduler also needs to know which users have packets. But our result implies that there is no need for "scheduling" any transmissions. Just dumb scheduling—transmit if you have packets—will do. The reason for this is that the users' queues empty out ever so often as a result of which there is a proportion of time when the users are transmitting alone. This *pseudo* scheduling of users automatically takes care of stabilizing the queues for the particular arrival rates. The implication for cross layer design is clear—if we can design a *reasonably* strong physical layer, then there is no need for a sophisticated MAC layer. Intuitively it is quite clear that as the ability of the physical layer to orthogonalize users increases, then the need for random access protocols doesn't arise. But, surprisingly we find that the point at which we could dispense the MAC layer comes well before we have an ideal physical layer. Further, equation (10) gives both the metric and condition for measuring the diversity provided by the physical layer.

What happens if the number of users is greater than 2? It can be shown from the results of [10] that for an $N > 2$ user system, with symmetric arrival rate, a symmetric MPR reception model and retransmission probability p, there is a regime (a condition on the MPR probabilities) for which the optimal ALOHA retransmission probability is one *i.e.* dumb scheduling is optimal. It is also obvious that for orthogonal channels, dumb scheduling would be optimal. But, apart from the above cases, we really don't know if such a result would carry over to the finite user case $(N > 2)$. However, we can still extrapolate our two user results for systems with $N > 2$ by orthogonalizing all users into groups of two and implementing ALOHA or dumb scheduling depending on the level of spatial diversity available in each group. Though this technique is suboptimal, it shows how a trade-off between MAC layer complexity and physical layer complexity can be achieved. If the physical layer is strong enough to orthogonalize users into groups of two and guarantee that (10) holds for every group, then the MAC layer is not needed.

V. Conclusions

In this paper, we considered the problem of stability of slotted ALOHA for a general reception model intended to capture the behavior of a multiple antenna wireless system. We characterized the stability region of slotted ALOHA for the two user case analytically. We showed that the stability region shows a characteristic phase transition as the degree of spatial diversity increases. We also characterized the structural properties of the stability region. We showed that after the critical phase transition slotted ALOHA is optimal in the sense that it can stabilize any rates that can be stabilized by any MAC protocol. Not only that when ALOHA is optimal, we found somewhat surprisingly that the best retransmission policy is for both users to transmit whenever they have packets. We can also extrapolate our two user results to the finite user $(N > 2)$ case, by orthogonalizing all users into groups of two and then scheduling transmissions of each group seperately. Future work would be directed towards generalizing our results for the finite $(N > 2)$ user case.

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