

An Analysis of Generalized Slotted-Aloha Protocols

Richard T.B. Ma, Vishal Misra, Dan Rubenstein
 tbma@ee.columbia.edu, misra@cs.columbia.edu, danr@ee.columbia.edu
 Columbia University

Abstract—Aloha and its slotted variation are commonly deployed Medium Access Control (MAC) protocols in environments where multiple transmitting devices compete for a medium, yet may have difficulty sensing each other’s presence (the “hidden terminal problem”). Competing 802.11 gateways, as well as most modern digital cellular systems, like GSM, are examples. This paper models and evaluates the throughput that can be achieved in a system where nodes compete for bandwidth using a generalized version of slotted-Aloha protocols. The protocol is implemented as a two-state system, where the probability that a node transmits in a given slot depends on whether the node’s prior transmission attempt was successful. Using Markov Models, we evaluate the channel utilization and fairness of this class of protocols for a variety of node objectives, including maximizing aggregate throughput of the channel, each node selfishly maximizing its own throughput, and attacker nodes attempting to jam the channel. If all nodes are selfish and strategically attempt to maximize their own throughput, a situation similar to the traditional Prisoner’s Dilemma arises. Our results reveal that under heavy loads, a greedy strategy reduces the utilization, and that attackers cannot do much better than attacking during randomly selected slots.

Index Terms—slotted-Aloha, short-term fairness, Markovian decision, Prisoner’s Dilemma, Stackelberg Game, MAC protocols.

I. Introduction

In many communication networks, the communication medium is often shared by multiple users who must compete for access. In Ethernet [1], nodes use CSMA/CD [2], [3] as a MAC protocol. In order to reduce the probability of collisions, each node implements CSMA/CD, sensing the medium to ensure the medium is available prior to transmitting. However, for wireless ad-hoc networks or sensor networks, carrier sensing may not be effective. This is because nodes may not be able to sense one another’s presence, yet their transmissions may still interfere. Ad hoc networks, sensor networks, and competing “hotspot” 802.11 gateways are examples where this so-called “hidden terminal problem” occurs.

The Aloha protocol [4] is a fully decentralized medium access control protocol that does not perform carrier sensing. The subsequent slotted-Aloha protocol [5] was introduced to improve the utilization of the shared medium by synchronizing the transmission of devices within time-slots. Today, various forms of slotted-Aloha protocols are widely used in most of the current digital cellular networks, such as the Global System for Mobile communications (GSM)¹.

In this work, we consider a generalization of the slotted-Aloha protocol. Like slotted-Aloha, the decision to transmit within a slot has a random component. However, in traditional

slotted-Aloha, the user continues transmission in subsequent slots until a collision occurs. In our generalized version, the user may cease transmitting with some fixed (non-zero) probability. We model a system of N users implementing this generalized protocol with tunable parameters via Markov Models that allow us to measure the rate at which nodes attempt to transmit packets (cost), and their rates of success (throughput). In parts, we impose budget constraints that restrict the nodes’ costs, such that the fraction of slots within which a node attempts transmissions is bounded. In practice, these additional constraints may be due to energy constraints, or bandwidth limitations.

This generalized version of slotted-Aloha is worth studying for several reasons. First, it is derived from a protocol that is commonly used today. Second, introducing additional states to capture backlog or number of successive collisions more closely emulates binary exponential backoff protocols, e.g., the 802.11 family of MAC protocols; however, this generalized version of slotted-Aloha retains the simplicity and elegance of the original Aloha approach. Third, we will show that the generalized versions can outperform the original version, both in terms of aggregate throughput, as well as the ability to cope with malicious users. Fourth, by using this generalized slotted-Aloha protocol, we provide a framework to study the user behaviors in cooperative, competitive and adversarial environments.

We begin by exploring an environment where N users *cooperate* and set the protocol parameters to maximize the total system throughput while sharing the bandwidth evenly. We find that the throughput is bounded by $N/(2N - 1)$ and that to achieve this utilization, users who gain access to the channel must transmit over a large number of consecutive slots. We then explore how throughput decreases as “short-term fairness” is more strictly enforced, reducing the expected number of consecutive slots.

Next, we consider *selfish* users who wish to maximize their own throughput, perhaps at the expense of the nodes against whom they compete for medium access. We first identify a Nash equilibrium for short-sighted selfish users where the aggregate throughput is zero. We then formulate a Stackelberg game, where a leader node strategically chooses its parameters and a follower node subsequently modifies its parameters in response to short-sightedly maximize its own throughput. Under this model, we find that performance of the protocol depends on nodes’ budgets, and takes on three distinct types of behavior. When nodes’ budgets are low, the aggressive strategy is optimal. When nodes’ budgets fall within a medium range, all nodes achieve the same throughput in a unique equilibrium, but the throughput is less than what would be

¹In the GSM network, the control channels of the TDM channels use slotted-Aloha.

obtained in a cooperative setting. When nodes' budgets fall within the highest range, the leader node obtains much higher throughput than the follower node. We further model two strategic selfish nodes using a simultaneous move game, where multiple equilibria exhibit that the Prisoner's Dilemma can occur. We develop an additional enhancement to the protocol that can be implemented by cooperative nodes which will encourage selfish users to tune their protocol parameters to match those of a cooperative node, maximizing the aggregate throughput.

Last, we consider an *attacking* node that, with a limited budget, seeks to minimize the throughput of the other nodes in the system. We show that when the attacker's budget is small, selecting random slots (i.e., via a Bernoulli process) is optimal. When the budget is large, the optimal strategy is to mimic a greedy user. Our analysis provides insights on the limits of success a jammer can have in disrupting a slotted-Aloha like network.

We summarize the main contributions of this paper as follows:

- 1) We formulate different user behaviors under a generalized slotted-Aloha protocol where users make transmission decisions using a two-state system.
- 2) We identify throughput bounds for a system of cooperative users and explore the trade-off between user throughput and short-term fairness.
- 3) Under selfish behavior of the users, we identify a Prisoner's Dilemma phenomenon and propose methods to detect and prevent nodes from acting selfishly without regard for other nodes' throughput.
- 4) Under adversarial behavior of one user, we measure the maximum possible deterioration of the system and try to understand the behavior of an attacker.

We organize our paper as follows. In Section II, we review related work. In Section III, we motivate the protocol and construct a Markov Model for the generalized slotted-Aloha protocol. In Section IV, we measure the system throughput in a cooperative environment where users want to maximize the total throughput of the system. In Section V and VI, we evaluate both the aggregate and individual user throughput where selfish users exist in the system. We formulate a Stackelberg game [6] and identify a Prisoner's Dilemma situation in Section V, and in Section VI present strategies that cooperative nodes can implement to detect and prevent selfish user behaviors. In section VII, we explore a system in which an attacker tries to minimize the throughput of the remaining nodes. Section VIII concludes.

II. Related Work

The Aloha protocol and its slotted version have been studied for decades. Because slotted-Aloha exhibits an instability as the number of transmitting nodes increases [7], [8], [9], [10], [11], [12], early research focused on stabilization [12], [13]. For instance, Rivest [13] proposed a pseudo-Bayesian algorithm, which utilizes feedback to estimate the number of current backlogged nodes in the system. Subsequent studies utilized dynamic controls [14], [9] to stabilize the systems.

However, today's networks avoid stabilization challenges by implementing an admission control procedure that limits the number of simultaneous users in the system.

In this work, we focus on the performance of stable slotted-Aloha type systems, where only a finite number of users will access the shared medium simultaneously. Early work on slotted Aloha with finite number of users can be found in [7]. Not only does our work evaluate the throughput bounds for a finite slotted-Aloha type system, but it also considers the performance of individual users under different types of user behavior. Many prior works [15], [16] show that users always have incentive not to follow the designed protocol (i.e., not backoff) in order to achieve higher throughput. Consequently, game-theoretic analysis can be applied [6], [17].

Recent work using Game Theory to analyze user behavior in MAC protocols and wireless ad-hoc networks can be found in [18], [19], [15] and [20], [21] respectively. More specifically, game-theoretical analysis of the Aloha protocols can be found in [22], [23], [24], [25], [26], [27].

MakKenzie and Wicker's work [24], [25] discussed the stability of slotted-Aloha with selfish user behavior and perfect information. Our work is different in three ways. First, we focus on performance (attainable throughput) instead of stability. In terms of data backlog at the users, we consider scenarios of *elastic transfers*, where users always have data to send and utilize whatever bandwidth is available, and hence classical stability results do not apply to our analysis. Second, we assume that nodes do not know the number of transmitting nodes a particular slot a priori, and know only whether or not their transmission succeeded after the fact. Third, we consider cooperative and attacking strategies in addition to selfish strategies.

Jin and Kesidis's work [26] discusses the equilibria of a non-cooperative game for Aloha protocols. In their non-cooperative game formulation, each user only uses one transmitting probability (i.e., always in a backlogged state). Moreover, utility functions and payments are specified for each user. Our work, on the other hand, formulates generalized slotted-Aloha protocol that considers the Markovian decisions depending on whether the most recent transmission is a success (in a Free State) or a failure (in a Backlogged State). Also, we do not impose payments.

Altman et al. [27] analyze slotted-Aloha systems as both cooperative and non-cooperative games with partial information. Their work assumes that there are a finite number of bufferless sources. The arrival of packets to each source follows a Bernoulli process. As in typical slotted-Aloha, users only control the backlog probability in both systems. In our work, we assume saturated arrivals (*elastic transfer*) where each user always has packets to transmit. Our users' strategies are more broad, because users are permitted to choose a non-zero probability to back off even their previous transmissions are successful. In addition, we analyze an adversarial game where an attacker wants to minimize other users' throughput.

III. Protocol Description and Model

In this section, we describe a generalized slotted-Aloha MAC protocol and construct a Markov Model from which

its throughput can be analyzed. We first overview the original slotted-Aloha protocol:

- 1) Time is divided into slots, and each node can attempt to send one packet in each time-slot.
- 2) If a node has a new packet to send, it attempts transmission during the next time-slot.
- 3) If a node successfully transmits one packet, it can transmit a new packet in the next time-slot.
- 4) If a node detects a collision, it retransmits the old packet in each subsequent time-slot with a pre-determined probability, p , until the packet is successfully transmitted. Returning to step 3 after a successful transmission.

The slotted-Aloha protocol described above can be implemented as a two-state system, where the state maintains the outcome of the previously attempted transmission. A node is in its *Free State* if the most recent transmission from that node is a success; otherwise, the node is in its *Backlogged State*. In the Free State, a node transmits during the next slot with probability 1, and in the Backlogged State, it transmits during the next slot with probability p . Our generalization of the above protocol is to allow a node to vary the probability with which a node transmits a packet when it resides within the Free State. Later, we will see that this generalization enables us to model selfish as well as malicious behaviors of users.

Our evaluation will consider a network of N contentious nodes, which always have a backlog of data packets to transfer. We assume that data packets are fragmented into lengths which can be transmitted within a time-slot, and that nodes are able to coordinate slot transmission times and can estimate the number of nodes N with which they compete for bandwidth. However, because nodes' transmissions may interfere but cannot be recovered, methods to prevent slot contention that require explicit communication and coordination among the competing members (e.g., TDMA, RTS-CTS) cannot be used. In practice, many real systems implement admission control mechanisms which constraint the number of users in the system. In practice, a system can often rely on a centralized authority to broadcast the number of competing users (e.g., this information can be embedded in beacon messages).

Each node x can tune its protocol using two parameters: p_1^x , the transmitting probability in the Free State, and p_2^x , the transmitting probability in the Backlogged State. Given N and the transmitting probabilities for each of the nodes in each of the states, we can compute the following performance metrics:

- T_x , the *throughput* of node x , which is the fraction of slots within which x successfully completes a transmission and is the only device to attempt transmission.
- C_x , the *cost* for node x , which is the fraction of slots within which x attempts transmission (regardless of whether the transmission fails or succeeds).

Each node's decision to transmit within a particular slot depends only on the outcome of its previous attempt (success or failure), and does not depend on the state of other nodes. Hence, this protocol can be easily implemented in a distributed manner. Moreover, each node's decision is Markovian, as it depends only on its previous attempt's outcome.

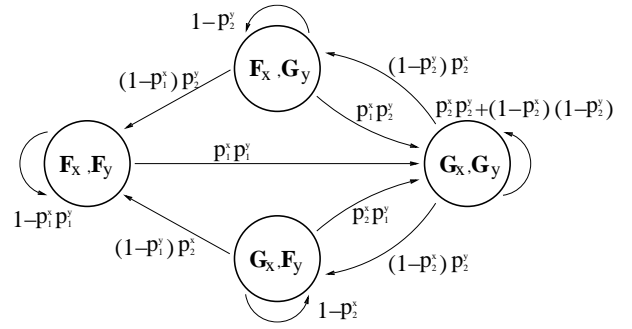


Fig. 1. Two-node Markov Chain.

Figure 1 shows the state transition diagram for a two-node system with node x and y . F_x and G_x represent that node x is in a Free State and a Backlogged State respectively. A system for N nodes is easily modeled by as a Markov Model where the chain would consist of 2^N states. By numbering the states $(F_x, F_y), (F_x, G_y), (F_y, G_x), (G_x, G_y)$ to be 1, 2, 3, 4, the transition matrix for a two-node Markov Model is:

$$P = \begin{pmatrix} 1 - p_1^x p_1^y & 0 & 0 & p_1^x p_1^y; \\ (1 - p_1^x) p_1^y & 1 - p_2^y & 0 & p_1^x p_2^y; \\ (1 - p_1^x) p_2^y & 0 & 1 - p_2^x & p_1^y p_2^x; \\ 0 & p_2^x (1 - p_2^y) & p_2^y (1 - p_2^x) & p_{44} \end{pmatrix}$$

where $p_{44} = p_2^x p_2^y + (1 - p_2^x)(1 - p_2^y)$.

If $p_1^x, p_1^y, p_2^x, p_2^y > 0$, the Markov Model is positive-recurrent. The steady state distribution is the following:

$$\vec{\pi} = \begin{pmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \end{pmatrix} = \frac{1}{k_1 + k_2 + k_3 + k_4} \begin{pmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{pmatrix}$$

where

$$\vec{k} = \begin{pmatrix} p_2^x p_2^y [(1 - p_1^x) p_2^x (1 - p_2^y) + (1 - p_2^x) p_2^y (1 - p_1^y)] \\ p_1^x p_1^y (p_2^x)^2 (1 - p_2^y) \\ p_1^x p_1^y (p_2^y)^2 (1 - p_2^x) \\ p_1^x p_1^y p_2^x p_2^y \end{pmatrix} \quad (1)$$

The corresponding *throughput* and *cost* of node x are:

$$T_x = \pi_1 (p_1^x) (1 - p_1^y) + \pi_2 (p_1^x) (1 - p_2^y) + \pi_3 (p_2^x) (1 - p_1^y) + \pi_4 (p_2^x) (1 - p_2^y). \quad (2)$$

$$C_x = \pi_1 (p_1^x) + \pi_2 (p_1^x) + \pi_3 (p_2^x) + \pi_4 (p_2^x). \quad (3)$$

Nodes may have physical limitations (e.g. power consumption constraints or application throughput constraints) that may bound its cost function. We bound allowed cost by a *budget*, B_x , such that a node's parameters must produce a cost $C_x \leq B_x$.

When we consider cooperative nodes that seek to maximize throughput, we are also interested in system *fairness*: all nodes should get an equal share of the aggregate throughput. In addition, we assume that it is undesirable for any one node to "capture" the medium for an extended number of slots -

a long-term capture can be thought of as unfair over a short duration. Koksals's work [28] gives an analysis of the short-term fairness of MAC protocols. It provides some insight into why MAC protocols exhibit bad short-term fairness using two different fairness indexes. In this paper, we measure short-term fairness via a more fundamental quantity defined as the following:

Definition 1: Let D_x be the number of consecutive slots following an initially successful transmission over which node x successfully transmits packets (i.e., if there are k successful consecutive transmissions, then $D_x = k - 1$). The system is said to be **M -short-term fair** to all nodes if $E[D_x] \leq M$ for all nodes x . ■

Remark: By definition, if a system is M -short-term fair, it is also N -short-term fair for any $N > M$. If short-term fairness is enforced, then a node cannot “capture” the channel for an excessive amount of time, i.e., that the medium is shared more evenly on smaller time scales.

IV. Cooperative Performance Analysis

In this section, we assume that nodes cooperate to fairly (i.e., equally) share the available bandwidth and to maximize the aggregate system throughput. By doing so, each node achieves the maximum throughput possible in a fair allocation when limited to protocols that cannot sense the wireless medium. Clearly, if it were permissible to bias the allocation toward one of the nodes, the system could achieve full utilization by allowing only one node to always transmit. If a centralized scheduler or carrier sensing mechanism were permitted, we could also make fair share of the medium with almost 100% utilization. Here, we seek an unbiased and distributed solution for all nodes such that nodes will achieve the same average throughputs.

Our goal in this section is to answer the following questions:

- 1) What are the values of p_1^x and p_2^x for each node x that maximize the total throughput of the system?
- 2) What is this maximum achievable throughput of the system?
- 3) What is the short-term fairness of the optimal allocation, and how can that short-term fairness be improved?

Theorem 1: For two homogeneous nodes with $p_1^x = p_1^y = p_1$ and $p_2^x = p_2^y = p_2$, $\sup\{T_x + T_y\} = 2/3$.

Proof: Substitute all the transmitting probabilities with p_1 and p_2 into Equation (1) and (2), we have

$$\vec{k} = \begin{pmatrix} 2p_2(1-p_2)(1-p_1) \\ (1-p_2)p_1^2 \\ (1-p_2)p_1^2 \\ p_1^2 \end{pmatrix},$$

and

$$\begin{aligned} T_x &= \pi_1 p_1(1-p_1) + \pi_2 p_1(1-p_2) \\ &\quad + \pi_3 p_2(1-p_1) + \pi_4 p_2(1-p_2) \\ &= \beta p_1(p_1^2 - \alpha p_1 + \alpha) / (p_1^2 - \alpha \beta p_1 + \alpha \beta), \end{aligned}$$

where

$$\alpha = 2p_2, \quad \beta = (1-p_2)/(3-2p_2).$$

When $p_1 = 1$, $T_x = \beta = (1-p_2)/(3-2p_2)$ and $\beta \rightarrow 1/3$ as $p_2 \rightarrow 0$. By symmetry, $T_x + T_y \rightarrow 2/3$ as $p_2 \rightarrow 0$.

Next, we want to show $T_x < 1/3$ for all $p_1, p_2 \in (0, 1]$. It is equivalent to show the following:

$$\begin{aligned} &\beta p_1(p_1^2 - \alpha p_1 + \alpha) / (p_1^2 - \alpha \beta p_1 + \alpha \beta) < 1/3 \\ \iff &3\beta p_1(p_1^2 - \alpha p_1 + \alpha) < p_1^2 - \alpha \beta p_1 + \alpha \beta \\ \iff &3\beta p_1^3 - (3\alpha \beta + 1)p_1^2 + 4\alpha \beta p_1 - \alpha \beta < 0. \end{aligned}$$

We define $f(p_1) = 3\beta p_1^3 - (3\alpha \beta + 1)p_1^2 + 4\alpha \beta p_1 - \alpha \beta$. Two boundary conditions are $f(0) = -\alpha \beta < 0$ and $f(1) = 3\beta - 1 < 0$. Since $f(p_1)$ is a cubic function of p_1 , it is sufficient to show that the local maximum is less than zero, so as to prove that for any $p_1 \in (0, 1]$, $f(p_1) < 0$. At the local maximum,

$$f'(p_1^*) = 9\beta(p_1^*)^2 - 2(3\alpha \beta + 1)p_1^* + 4\alpha \beta = 0.$$

Using the above condition, it is equivalent to show

$$f(p_1^*) = -(1/3)(3\alpha \beta + 1)(p_1^*)^2 + (8/3)\alpha \beta p_1^* - \alpha \beta < 0.$$

The maximum of the above function is

$$[(4/3)(3\alpha \beta + 1)\alpha \beta - ((8/3)\alpha \beta)^2] / [-(4/3)(3\alpha \beta + 1)].$$

The denominator is negative, while the numerator is positive because

$$\begin{aligned} &(4/3)(3\alpha \beta + 1)\alpha \beta - ((8/3)\alpha \beta)^2 > 0 \\ \iff &(4/3)(3\alpha \beta + 1) - (64/9)\alpha \beta > 0 \\ \iff &\alpha \beta < 3/7 \\ \iff &2p_2(1-p_2)/(3-2p_2) < 3/7 \\ \iff &14p_2^2 - 20p_2 + 9 > 0. \end{aligned}$$

Finally, because the local maximum $f(p_1^*) < 0$, we conclude that $f(p_1) < 0$ for all $p_1 \in [0, 1]$. ■

Theorem 1 upper-bounds the maximum fair throughput at $2/3$, which is achieved in the limit as both nodes choose $\{p_1 = 1, p_2 \rightarrow 0\}$. This solution is intuitive: collisions are less likely to occur in a carrier-sense free environment when nodes are very unlikely to start transmitting, but hold the medium until a subsequent collision.

Theorem 2: For N homogeneous nodes with $p_1 = 1, p_2 \rightarrow 0$, the total throughput approaches $\frac{N}{2N-1}$.

Proof: Consider in each time-slot, the whole system is in certain state. We aggregate all the system states into the following two states. One state is the “Busy” state where only one of the nodes is transmitting in the time-slot. The other state is the “Idle or Collision” state where no node or more than one node are transmitting in the time-slot. The state transition diagram is shown in Figure 2.

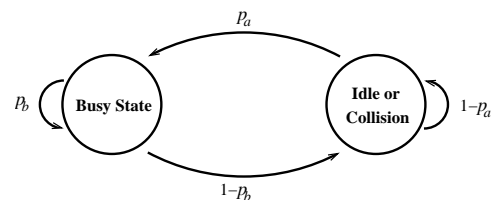


Fig. 2. N -node Markov Chain with $\{p_1 = 1, p_2 \rightarrow 0\}$.

We define the transition probabilities as $p_b = (1-p_2)^{N-1}$ and $p_a = Np_2(1-p_2)^{N-1}$. p_b indicates the probability that all

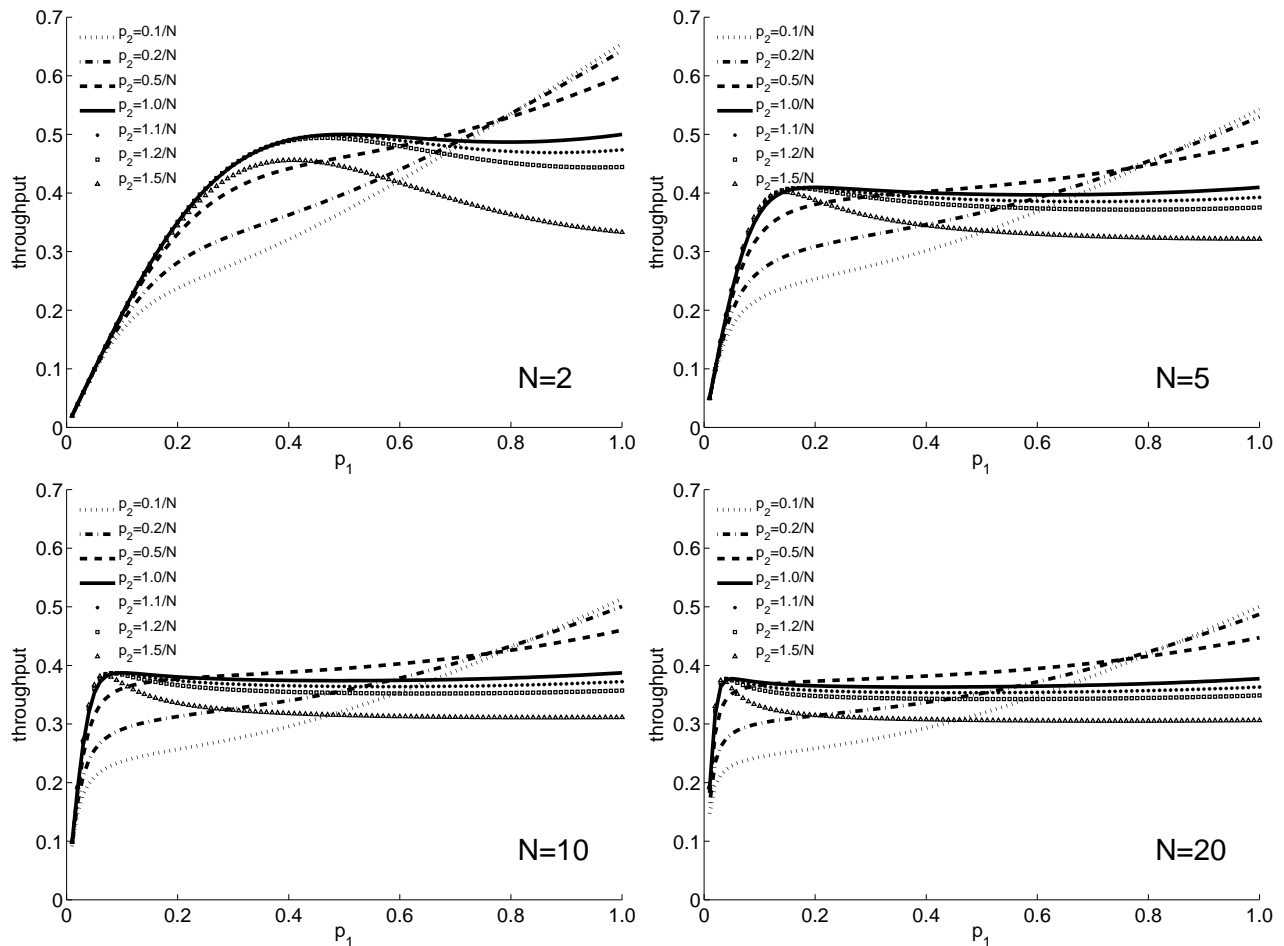


Fig. 3. Aggregate throughput for fixed p_2 .

of the $N - 1$ backlogged nodes do not transmit. p_a indicates the probability that only one of the N nodes transmits. The system utilization becomes

$$\begin{aligned}
 \rho &= \pi_{busy} = p_a / (1 - p_b + p_a) \\
 &= \frac{N p_2 (1 - p_2)^{N-1}}{1 - (1 - p_2)^{N-1} + N p_2 (1 - p_2)^{N-1}} \\
 &= N / \left(\frac{1 - (1 - p_2)^{N-1}}{p_2} + N \right) \\
 &= N / \left(\frac{1 + (1 - p_2) + (1 - p_2)^2 + \dots + (1 - p_2)^{N-2}}{(1 - p_2)^{N-1}} + N \right).
 \end{aligned}$$

Therefore, $\rho \rightarrow \frac{N}{2N-1}$ as $p_2 \rightarrow 0$. ■

Intuitively, when the number of nodes increases in the system, with higher probability, the channel is jammed with more than one node transmitting at the same time. Consequently, the aggregate system throughput decreases. However, Theorem 2 shows that the throughput does not drop to zero: even when the number of nodes tends to infinity, the aggregate throughput remains larger than one half. Note that this result differs from the traditional performance bound ($1/e$) of slotted-Aloha because our generalized model permits the capture of the resource. This allows a node to use the channel for very long but bounded intervals (given a fixed and non-zero value of p_2) of slots while all other nodes back off. An alternative analysis of this capture phenomenon can be found in [7].

Both Theorem 1 and Theorem 2 focus on the class of

solutions where $p_1 = 1$ and $p_2 \rightarrow 0$. For $N = 2$, we proved in Theorem 1 that the optimal throughput is achieved at $\{p_1 = 1, p_2 \rightarrow 0\}$. Nevertheless, the maximum throughput is also achieved at $\{p_1 = 1, p_2 \rightarrow 0\}$ for $N > 2$. The formal proof can be found in our technical report [29]. Here, we present some evidence which shows the optimality of $\{p_1 = 1, p_2 \rightarrow 0\}$. We start with the following observation.

Theorem 3: For N homogeneous nodes, the solutions $\{p_1 = p_2 = 1/N\}$ and $\{p_1 = 1, p_2 = 1/N\}$ both achieve the throughput $(1 - 1/N)^{N-1}$.

Proof: When $\{p_1 = p_2 = 1/N\}$, each node tries to transmit at each time-slot independently with probability $1/N$. Therefore, the throughput is just the probability that if and only if one of the N nodes transmits:

$$\rho = \binom{N}{1} (1/N) (1 - 1/N)^{N-1} = (1 - 1/N)^{N-1}.$$

When $p_1 = 1$ and $p_2 = 1/N$, we can adopt the Markov Chain in Figure 2. We have the transition probabilities: $p_b = (1 - p_2)^{N-1} = (1 - 1/N)^{N-1}$ and $p_a = N p_2 (1 - p_2)^{N-1} = (1 - 1/N)^{N-1}$. The throughput is

$$\rho = \pi_{busy} = p_a / (1 - p_b + p_a) = p_a = (1 - 1/N)^{N-1}. \blacksquare$$

Theorem 3 provides a reference point to divide the solution space into groups. Figure 3 plots the throughput for systems

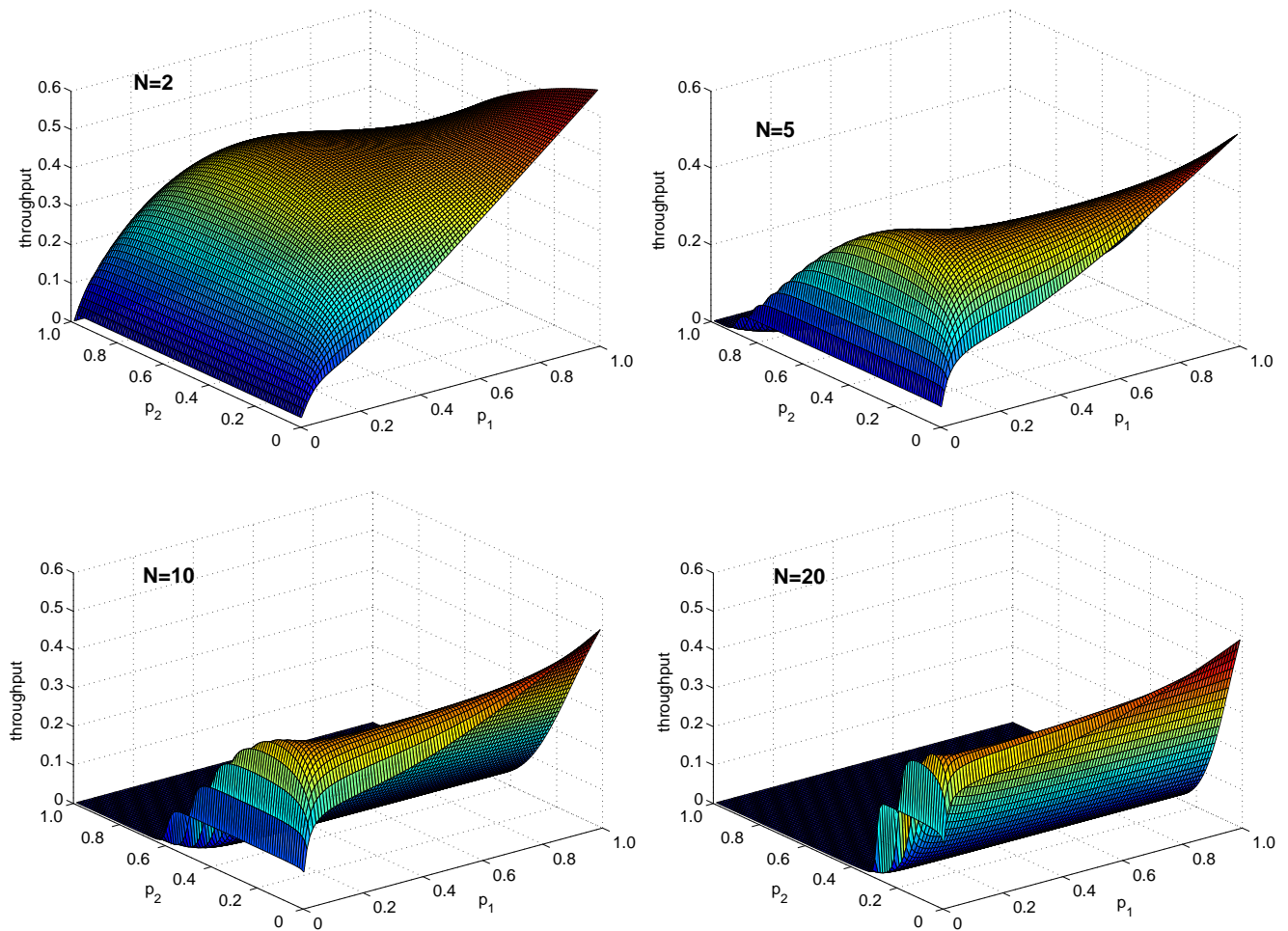


Fig. 4. Aggregate throughput.

of $N = 2, 5, 10$ and 20 . In each subplot, p_1 varies along the x -axis, and different curves plot different values for p_2 . For any N , we use the curve $p_2 = 1/N$ (from Theorem 3, we know the exact value when $p_1 = 1$ or $p_1 = 1/N$) as a reference to divide solutions into two groups: $p_2 < 1/N$ and $p_2 > 1/N$. We plot the curve $p_2 = 1/N$ in solid lines. We compare the solution within each group and across groups, and make the following observations:

- When the value of p_2 increases from $1/N$, the throughput decreases. The curve of $p_2 = 1/N$ is above all curves of $p_2 > 1/N$.
- When the value of p_2 decreases from $1/N$, the throughput curve becomes lower in the region $p_1 \in (0, 1/N)$, but the maximum of each curve is at $p_1 = 1$. This maximum increases when p_2 decreases.

In Figure 4, we plot the surface of throughput for systems with various number of nodes. In each subplot, p_1 varies along the x -axis (on the right); p_2 varies along the y -axis (on the left). By increasing the number of nodes N in system, the surfaces bend down dramatically in the region of small p_1 and large p_2 (left corner). The high throughput is reached in the region of large p_1 and small p_2 (right corner). In particular, the maximum is achieved at $p_1 = 1, p_2 \rightarrow 0$.

Although the solution $\{p_1 = 1, p_2 \rightarrow 0\}$ might maximize throughput, it is not short-term fair, in which a single transmitter gains exclusive access of the medium for a long time. As $p_2 \rightarrow 0$, we have $E[D_x] \rightarrow \infty$. We now consider how to enforce short-term fairness:

Theorem 4: For N homogeneous nodes with $p_1 = 1$ and $p_2 \geq 1 - \sqrt[N-1]{1 - 1/M}$, the system is M -short-term fair² to all nodes.

Proof: Because D_x is a geometric random variable with parameter $1 - p_b$, we have

$$E[D_x] = \frac{1}{1 - (1 - p_2)^{N-1}}.$$

Since $p_2 \geq 1 - \sqrt[N-1]{1 - 1/M}$, we have $E[D_x] \leq M$. By definition, the system is M -short-term fair to all nodes. ■

Theorem 4 quantifies how to select p_2 to achieve a certain short-term fairness. In particular, in order to achieve M -short-term fairness, we can choose the following value of p_2 :

$$p_2 = 1 - \sqrt[N-1]{1 - 1/M}. \quad (4)$$

²see Definition 1

The total throughput becomes a function of M :

$$\rho = \frac{Np_2(1-p_2)^{N-1}}{1+(Np_2-1)(1-p_2)^{N-1}} \quad (5)$$

$$\Rightarrow \rho = \frac{N(M-1)}{N(M-1) + \frac{1}{1 - N^{-1}\sqrt{1-\frac{1}{M}}}}. \quad (6)$$

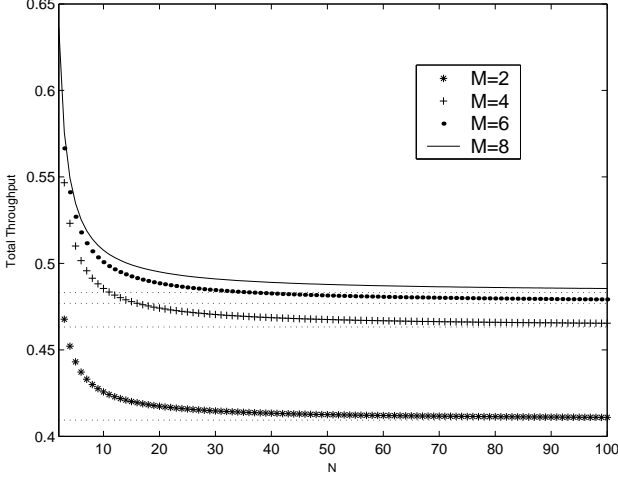


Fig. 5. Throughput under different fairness conditions.

Figure 5 plots the total throughput under different short-term fairness constraints (M) as the number of nodes, N , varies along the x -axis. This figure shows the tradeoff between short-term fairness and throughput. However, without sacrificing much throughput, the system achieves desirable short-term fairness. For example, if we want the system to be 8-short-term fair, which means each node can successfully transmit no more than 8 consecutive slots on average when it captures the channel, we can achieve a total throughput close to $1/2$ even for large N . In fact, when $N \rightarrow \infty$, the total throughput does not collapse to zero. We will discuss the throughput limits in the next theorem.

Lemma 1: For any constant $M > 0$, if $p_2 = 1 - N^{-1}\sqrt{1-1/M}$, then Np_2 is monotonically decreasing with N .

Proof: Let $\alpha = 1 - 1/M$ and $\beta = \alpha^{N^{-1}}$. We have

$$p_2 = 1 - N^{-1}\sqrt{1-1/M} = 1 - \alpha^{N^{-1}} = 1 - \beta.$$

First, p_2 is strictly decreasing in N , because $dp_2/dN = \ln \alpha \frac{\beta}{(N-1)^2} < 0$. We define $f(N) = (N-1)p_2$.

$$\begin{aligned} df(N)/dN &= (N-1)[\ln \alpha \frac{\beta}{(N-1)^2}] + 1 - \beta \\ &= ((N-1)^{-1} \ln \alpha - 1)\beta + 1 \\ &= (\ln \beta - 1)\beta + 1 \\ &= \beta \ln \beta - \beta + 1 < \ln \beta - \beta + 1 < 0. \end{aligned}$$

The last inequality holds because of the following. We define $g(\beta) = \ln \beta - \beta + 1$. $g(\beta)$ is a strictly concave function, because $g'(\beta) = 1/\beta - 1$ and $g''(\beta) = -1/\beta^2$. Since $g(1) = 0$, $g'(1) = 0$ and $g''(1) = -1 < 0$, we see $g(\beta)$ attains its maximum value 0 at $\beta = 1$. $\beta < 1$ holds under our context; therefore, the last inequality holds.

Finally, $Np_2 = (N-1)p_2 + p_2$, and consequently, $dNp_2/dN = df(N)/dN + dp_2/dN < 0$. ■

Theorem 5: Under any short-term fairness condition $E[D_x] = M$, the total throughput, ρ , is lower-bounded by $\frac{-(M-1)\ln(1-\frac{1}{M})}{1-(M-1)\ln(1-\frac{1}{M})}$.

Proof: We choose the value of p_2 in Equation (4) to satisfy the short-term fairness condition. Accordingly, from Equation (6), we have

$$\frac{1}{M-1} \frac{1}{\frac{1}{\rho} - 1} = \left(1 - N^{-1}\sqrt{1-\frac{1}{M}}\right)N = \frac{1 - N^{-1}\sqrt{1-\frac{1}{M}}}{\frac{1}{N}}.$$

The right hand side is of the form $\frac{0}{0}$ as $N \rightarrow \infty$. By L'hospital's rule,

$$\lim_{N \rightarrow \infty} \frac{\ln(1-\frac{1}{M}) N^{-1}\sqrt{1-\frac{1}{M}}(N-1)^{-2}}{-N^{-2}} = -\ln\left(1-\frac{1}{M}\right)$$

$$\therefore \lim_{N \rightarrow \infty} \frac{1}{M-1} \frac{1}{\frac{1}{\rho} - 1} = -\ln\left(1-\frac{1}{M}\right)$$

$$\Rightarrow \lim_{N \rightarrow \infty} \rho = \frac{-(M-1)\ln(1-\frac{1}{M})}{1-(M-1)\ln(1-\frac{1}{M})}.$$

On the other hand,

$$\frac{1}{M-1} \frac{1}{\frac{1}{\rho} - 1} = \left(1 - N^{-1}\sqrt{1-\frac{1}{M}}\right)N = Np_2.$$

Thus, by Lemma 1, ρ is monotonically decreasing in N (as well as in Np_2). Therefore, ρ is lower-bounded by $\frac{-(M-1)\ln(1-\frac{1}{M})}{1-(M-1)\ln(1-\frac{1}{M})}$. ■

Theorem 5 provides the lower bounds for the curves in Figure 5. We draw the limits of the throughput in dotted lines under each throughput curve. We see, for M to be reasonably large (e.g. $M = 8$), the throughput lower limit is close to $1/2$. Indeed, when M tends to infinity, this limit also tends to $1/2$. In practice, a fairness requirement M can be achieved by choosing a suitable p_2 for all users. Like the information of the number of users (N), we suggest that the p_2 value can be broadcasted in the beacon messages by the system infrastructure.

V. Competitive Performance Analysis

In the previous section, we identified the lower bounds of the obtainable throughput among cooperative nodes, additionally considering short-term fairness constraints. In this section, we assume that each node is autonomous and sets its protocol parameters to maximize its own throughput. We start from a short-sighted selfish strategy that maximizes one's own throughput given any fixed parameters of other nodes. We show that this strategy induces a zero-throughput Nash equilibrium in the system. After that, we construct a *Stackelberg game* [6] by formulating a constrained optimization problem for each node. In particular, the leader player in the Stackelberg game strategically sets the parameters by taking the other node's reaction into account. Last, we form a simultaneous move game where nodes all strategically set parameters, and reveal that a *Prisoner's Dilemma* [6] phenomenon can occur.

A. Short-sighted Selfish Behavior

Suppose N nodes are originally cooperative and use $p_1 = 1$ and $p_2 = 1 - \sqrt[N-1]{1 - 1/M}$ to achieve the maximum M -short-term fair aggregate throughput. In this system, each node x obtains throughput:

$$T_x = \rho/N = (M - 1)/[N(M - 1) + 1/p_2].$$

If one node deviates from this cooperative solution and sets $p_2 = 1$ instead, its throughput increases to

$$T'_x = p_b = (1 - p_2)^{N-1} = 1 - 1/M.$$

Its throughput now equals the probability that no other node is transmitting in each time-slot. Comparing the above two equalities, we have:

$$\frac{T'_x}{T_x} = \frac{N(M - 1) + 1/p_2}{M} = N + \frac{1 - Np_2}{Mp_2}.$$

Hence, by unilaterally changing p_2 to be 1, a selfish node can usually increase its throughput at least N times (if $Np_2 < 1$). This selfish behavior sacrifices the throughput of all other nodes, because they can no longer obtain any throughput. In fact, given all other nodes' parameters fixed, to set $p_1 = p_2 = 1$ is always the best strategy to maximize one's own throughput. However, unfortunately, this implies a Nash equilibrium of the system with zero aggregate throughput.

B. Stackelberg Game

As shown above, multiple short-sighted selfish users can drive the system throughput to zero. Here, we extend this selfish behavior into a more sophisticated strategy which takes other nodes' short-sighted selfish behavior into account. We formulate a *Stackelberg game* [6], which enables one of the nodes (the leader) to anticipate the short-sighted selfish behavior of the other node (the follower) and to choose its optimal parameters. Stackelberg games have been applied to different areas of networking protocols (e.g. routing strategies [30], [31]) in order to achieve efficient equilibria.

In this Stackelberg game, we consider a network that consists only of two selfish nodes x and y , each of which wants to maximize its own throughput. In addition, we assume that each has budget constraints $C_x \leq B_x$ and $C_y \leq B_y$ respectively. C_x and C_y are the costs of both nodes as defined in Equation (3). $B_x, B_y \in (0, 1]$ are two budget constants that physically restrict the average number of packets the node can transmit in each time-slot. We impose these budget constraints in order to model the nodes in a wireless ad-hoc network or a sensor network. Because nodes in these networks are very sensitive to power consumption, and transmitting packets consumes a lot of battery power. Consequently, the behavior of nodes may largely depend on their budget constraints.

We formally describe the Stackelberg game as follows:

Players:	The leader node x and the follower node y .
Strategy:	$S^x = \{p_1^x, p_2^x\}$ for x ; $S^y = \{p_1^y, p_2^y\}$ for y .
Payoff:	T_x and T_y for x and y respectively.
Game rule:	Given any x 's strategy $\{p_1^x, p_2^x\}$, y chooses the best response $\{p_1^y, p_2^y\}$ accordingly.

Follower's Problem:

In the Stackelberg competition, the follower y is modeled as a short-sighted selfish node that always tunes its parameters, responding to the other node's parameters, to maximize its own throughput. Formally, for any given \widetilde{S}^x , the follower node y solves:

$$\hat{S}^y(\widetilde{S}^x) = \arg \max T_y(\widetilde{S}^x, \hat{S}^y)$$

$$\text{Subject to: } C_y(\widetilde{S}^x, \hat{S}^y) \leq B_y.$$

Leader's Problem:

In the Stackelberg competition, the leader x applies the strategy that takes the follower's behavior into account. It maximizes its own throughput by anticipating the short-sighted strategy of the follower. Formally, the leader node x solves:

$$\hat{S}^x = \arg \max T_x(\hat{S}^x, \hat{S}^y(\hat{S}^x))$$

$$\text{Subject to: } C_x(\hat{S}^x, \hat{S}^y(\hat{S}^x)) \leq B_x.$$

In practice, users might not know one another's strategies. The Stackelberg game assumes that the follower will adjust its parameters to maximize its throughput given any fixed parameters of the leader, x , and will maintain fixed parameters so long as x does as well. Both the leader and the follower are not necessarily very different; however, the leader is more strategically sophisticated and the follower is simply a throughput maximizer.

To solve this Stackelberg game mathematically, we first solve the follower's problem for every possible strategy taken by node x . Thus, we obtain the best response strategy of y as a function of node x 's strategy. After that, the leader decides its optimal strategy according to node y 's best response strategy. This procedure is often referred to as *backwards induction*³ [17]. The corresponding game solution is often referred to as a Stackelberg equilibrium. We derive numerical results based on Equation (2) and (3).

C. Three Stackelberg Equilibrium Regions

We solve the above Stackelberg game for nodes who have the same budget constraints, i.e., $B_x = B_y$.

Figure 6 and Figure 7 show the throughput and costs of both players in the Stackelberg equilibrium. The x-axis represents the budget constraint for both players. The change in the throughput as a function of the budget behaves differently in three different solution regions:

- 1) When the budget is less than $1/3$, both players achieve the same throughput, and they both use up their budgets. Within this region, an increase of budget improves the achieved throughput. The throughput is mainly limited by the budget constraints rather than the competition between these two players.
- 2) When the budget is between $1/3$ and $2/3$, both players again achieve similar throughput and use up their budgets. However, an increase of budget deteriorates each player's throughput. In this region, competition between these two players further reduces the throughput as well.

³Backward induction is actually a more general procedure to identify the Subgame Perfect Nash Equilibria in any finite dynamic game with perfect information.

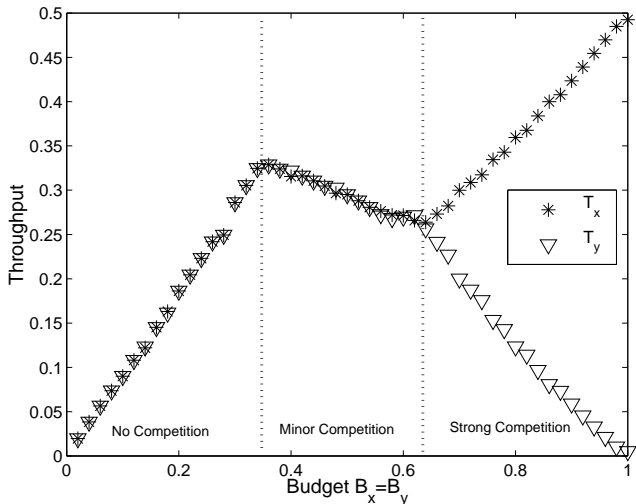


Fig. 6. Throughput in the Stackelberg equilibrium.

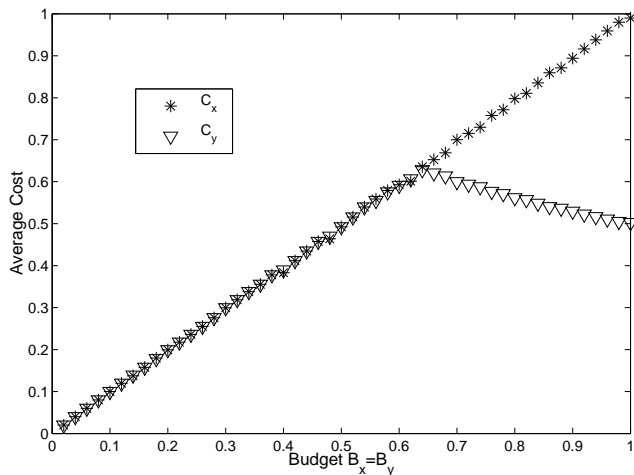
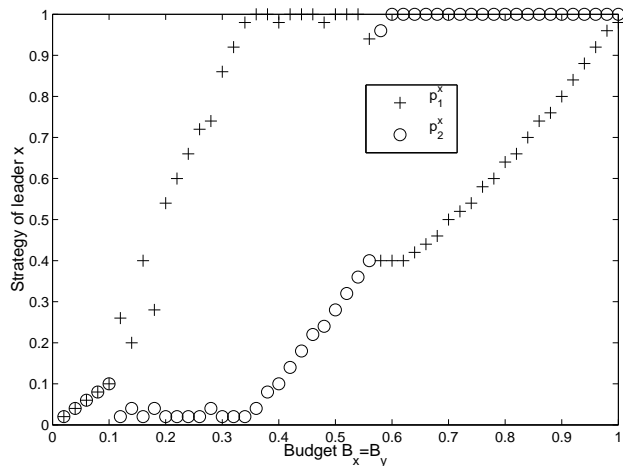


Fig. 7. Cost in the Stackelberg equilibrium.

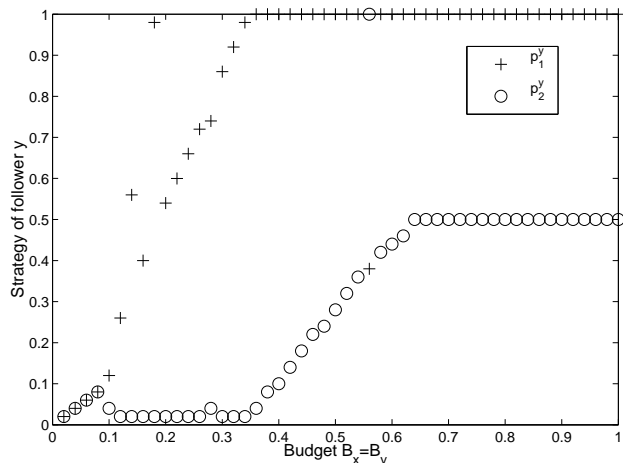
- 3) When the budget is more than $2/3$, the leader can select parameters that give it a larger fraction of the throughput. As the budget increases, this unfair allocation of throughput exacerbates and the follower, still wishing to maximize its own throughput, actually becomes less aggressive and uses a partial budget. In this region, the Stackelberg game benefits the leader by sacrificing the throughput of the follower.

Figure 8 plots values of p_1 and p_2 , revealing the strategies of both players in Stackelberg equilibrium. In the first two solution regions, both players use similar strategies. As a result, it does not matter (to a node) whether it is the leader or the follower, because both players achieve similar throughput. In particular, when the budgets are close to $1/3$, the strategies selected by the players are similar to what would be selected by cooperative players, and the aggregate throughput approaches $2/3$. As the budgets are further increased, the nodes' additional contention on the medium and the rate of interference become significant.

When the budgets exceed $2/3$, the leader's strategy changes



(a) Leader's Strategy



(b) Follower's Strategy

Fig. 8. Strategies in Stackelberg equilibrium.

dramatically. Instead of setting $p_1 = 1$, it sets $p_2 = 1$. This implies that if a transmission fails in a slot, it will attempt to retransmit during the next slot. This makes sense intuitively because the follower, attempting to maximize its own throughput with its confined budget, must back off with high probability after a collision, and the "safest" time for the follower to transmit will be following a previous successful transmission. Because the leader uses $p_2 = 1$, the follower can only successfully transmit when the leader is in the Free State. Therefore, the follower must not fully use its budget, since it has to reduce the collision probability that leads the leader to a Backlogged State.

Note that at around a budget of 0.55 , where the leader starts to set $p_2 = 1$, the follower's strategy begins to mimic the leader's strategy to maximize its own throughput. When the budget is further increased, the follower cannot use the same aggressive strategy to maximize its own throughput.

D. Simultaneous Move Game and Prisoner's Dilemma

The Stackelberg game assumes that the leader is strategically more sophisticated than the follower. To relax this bias, we now assume that both nodes, not being able to

anticipate the other party's strategy, will decide their strategies simultaneously. This models situations in wireless network where users do not know other users' backoff rates, which can be any strategy of p_1 and p_2 , in advance. We focus on three representative budget scenarios and the corresponding strategies (from Figure 8) that would be played in the Stackelberg game:

- Low budget region: $B_x = B_y = 0.34$. Strategy $S_C = S^x = S^y = \{p_1 = 0.98, p_2 = 0.02\}$.
- Medium budget region: $B_x = B_y = 0.5$. Strategy $S_M = S^x = S^y = \{p_1 = 1, p_2 = 0.28\}$.
- High budget region: $B_x = B_y = 0.8$. Strategy $S_L = S^x = \{p_1 = 0.64, p_2 = 1\}$, and $S_F = S^y = \{p_1 = 1, p_2 = 0.5\}$.

Strategy S_C in the lower budget region is similar to the strategy played by the nodes in a cooperative environment. Strategy S_M , more aggressive than S_C , is played by both the leader and the follower in the medium budget region. Finally, S_L and S_F are the strategies of the leader and the follower in the high budget region.

We consider two simultaneous move games, where two nodes must choose their parameters to maximize their individual throughput without knowing what their opponent chooses to do. Each game models a budget scenario where nodes are confined to use some of representative strategies above.

To be "cooperative" or to be "greedy"?

First, we consider a game in which two nodes, each with a budget of 0.5, must decide whether they will perform a cooperative-type of strategy or behave in a greedy manner (i.e., should the node set its parameters according to S_C or S_M ?) We evaluate Equation (2) for both nodes, and list the throughput in the following table.

	S_C	S_M
S_C	(0.3246,0.3246)	(0.0034,0.9288)
S_M	(0.9288,0.0034)	(0.2951,0.2951)

Here, we see a typical Prisoner's Dilemma [6]. Although from a global perspective, both players know the best solution is (S_C, S_C) , from any hypothetical local point, strategy S_M should always be played. This is because, for any fixed strategy by the opponent, choosing S_M is always better than choosing S_C . Strategy S_M is called the *dominating strategy* [6] for both players and the solution (S_M, S_M) is the unique *Nash equilibrium* [6] solution of this game.

To be "aggressive" or to be "mild"?

In the second game, we assume that nodes have budgets in the third region. As in the Stackelberg game, the leader player is better off by playing an aggressive strategy; however, now the nodes must also decide whether to choose the leader-type of strategy or the follower-type of strategy, without knowing the other player's response in advance. Notice that there is no actual leader or follower in the simultaneous move game. Here, nodes are restricted to the strategies S_L and S_F used by the leader and the follower in the Stackelberg game.

	S_F	S_L
S_F	(0.25,0.25)	(0.1233,0.3595)
S_L	(0.3595,0.1233)	(0,0)

Here, a node's best strategy is not clear. A node is always better off choosing the opposing strategy of its competitor. Choosing the follower strategy is more conservative. A throughput of at least 0.1233 is ensured, but the throughput can be at most 0.25. If the leader strategy is chosen, throughput of 0.3595 is possible, but throughput of 0 is also a possible outcome. Interestingly, this game has two symmetric Nash equilibrium solutions, i.e., (S_F, S_L) and (S_L, S_F) .

From the results of the above two simultaneous move games, we can further explain the three solution regions of the Stackelberg game in figure 6. When the budget is between $1/3$ and $2/3$, both nodes are afford to use classes of cooperative (e.g. S_C) or competitive (e.g. S_M) strategies. The uniqueness of the Nash equilibrium solution implies that nodes would similar strategies regardless it is the leader player or the follow player. As the budget increases, it is affordable for the nodes to use any strategy. From the symmetric Nash equilibria in the simultaneous move game, the leader player can always take advantage to choose a favorable equilibrium in the Stackelberg game.

VI. Selfish Behavior Detection and Prevention

In the previous section, we used non-cooperative games of two nodes to show that selfish behavior of nodes deteriorates the overall throughput obtained across the transmission medium, as well as that of the individual nodes. In this section, we discuss how cooperative nodes can identify and prevent selfish behavior in a general N -node system.

A. Transmitting is a Dominating Strategy

Consider any node i at any time-slot t . If it attempts to transmit, the probability of success is

$$\prod_{j \neq i} (1 - p^j),$$

where p^j is the probability (p_1^j or p_2^j depending on j 's state) that node j transmits in that time-slot. Without any budget constraint, node i can achieve the highest throughput by transmitting a packet during every time-slot. However, if node i transmits a packet in every time-slot, other nodes transmission attempts will always fail. Over time, this phenomenon can be easily observed. Here, we consider how cooperative nodes can alter their parameters if their perceived *success rates* are too small in such a way that selfish nodes become "encouraged" to set their parameters to mimic the behavior of cooperative nodes.

B. Selfish Behavior Detection

Theorem 6: For an M -short-term fair cooperative environment, where each node uses $p_1 = 1$ and $p_2 = 1 - \sqrt[N-1]{1 - 1/M}$, the *success rate* defined by T_x/C_x for any node x is lower-bounded by $\frac{(M-1)(M-2)}{(M-1)(M-2)+1}$.

Proof:

$$\frac{T_x}{C_x} = \frac{NT_x}{NC_x} = \frac{\rho}{NC_x},$$

where NC_x is equal to the total average cost for all nodes. Suppose all N nodes are in backlogged state. Let Q be the

number of nodes that decide to transmit in a time-slot. Then $Pr\{Q = i\} = q_i = \binom{N}{i} p_2^i (1-p_2)^{N-i}$, where Q is a binomial random variable with parameters p_2 and N .

$$\begin{aligned} N C_x &= \rho + (1-\rho) \sum_{j=2}^N j q_j / (1-q_1) \\ &= \rho + (1-\rho) (E[Q] - q_1) / (1-q_1) \\ &= \rho + (1-\rho) (N p_2 - q_1) / (1-q_1). \end{aligned}$$

Since $q_1 = N p_2 (1-p_2)^{N-1} = N p_2 (1 - \frac{1}{M})$ and $\frac{1}{\rho} - 1 = \frac{1}{M-1} \frac{1}{N p_2}$, we obtain

$$\begin{aligned} T_x / C_x &= \rho / [\rho + (1-\rho) (N p_2 - q_1) / (1-q_1)] \\ \Leftrightarrow \frac{1}{T_x / C_x} - 1 &= \left(\frac{1}{\rho} - 1 \right) (N p_2 - q_1) / (1-q_1) \\ \Leftrightarrow \frac{1}{T_x / C_x} - 1 &= \frac{1}{M-1} \frac{1}{N p_2} (N p_2 - N p_2 (1 - \frac{1}{M})) / (1-q_1) \\ \Leftrightarrow \frac{1}{T_x / C_x} - 1 &= \frac{1}{M-1} \left(\frac{1}{M} \right) / (1-q_1) \\ \Leftrightarrow \frac{1}{T_x / C_x} - 1 &= \frac{1}{M-1} \left(\frac{1}{M} \right) / (1 - N p_2 (1 - \frac{1}{M})). \end{aligned}$$

By Lemma 1, $N p_2$ is monotonically decreasing in N . When $N = 2$, $N p_2 = 2/M$ is the maximum for $N > 1$. Substituting $N p_2$ with $2/M$, we have

$$\begin{aligned} \frac{1}{T_x / C_x} - 1 &= \frac{1}{M-1} \left(\frac{1}{M} \right) / (1 - N p_2 (1 - \frac{1}{M})) \\ \Rightarrow \frac{1}{T_x / C_x} - 1 &\leq \frac{1}{M-1} \left(\frac{1}{M} \right) / (1 - \frac{2}{M} (1 - \frac{1}{M})) \\ \Rightarrow \frac{1}{T_x / C_x} - 1 &\leq \frac{1}{M-1} / (M - 2(1 - \frac{1}{M})) < \frac{1}{M-1} \frac{1}{M-2} \\ \Rightarrow T_x / C_x &> [(M-1)(M-2)] / [(M-1)(M-2) + 1]. \end{aligned}$$

Theorem 6 provides a guideline for how cooperative nodes can, in a distributed fashion, detect the existence of any selfish node. A fraction of at least $\frac{(M-1)(M-2)}{(M-1)(M-2)+1}$ of a cooperative node's transmissions should be successful. For instance, when M equals 8, this average success rate lower-bound is $\frac{42}{43}$. When M is larger, the success rate is even higher. Notice that this success rate is different from the throughput that a node achieves. With the increase of the number of nodes, each node's throughput decreases however the success rate lower-bound remains the same. In practice, each node can measure this quantity to infer if there is any selfish node in the system.

C. Selfish Behavior Prevention

In order to prevent selfish behavior in the system, each cooperative node can implement a new strategy when they detect selfish nodes. The new strategy uses a $p'_2 (> p_2)$ that reduces the throughput of the selfish node to a level below what it would have achieved if p_2 were used by all cooperative nodes. Knowing that such a reduction will occur, selfish nodes have the necessary incentive to remain cooperative.

Suppose after all cooperative nodes activate the new strategy p'_2 , the selfish node obtains throughput T'_x . T'_x has to be less than ρ/N , which is the fair share throughput gained in a cooperative environment:

$$\begin{aligned} T'_x &= (1-p'_2)^{N-1} < \rho/N \\ \Leftrightarrow 1-p'_2 &< \sqrt[N-1]{\rho/N} \\ \Leftrightarrow p'_2 &> 1 - \sqrt[N-1]{\rho/N}. \end{aligned}$$

From Theorem 2, we know that ρ is lower-bounded by $1/2$. Hence, we can substitute in $1/2$ for ρ when calculating the lower-bound of p'_2 as an approximation.

Figure 9 shows the cooperative strategy p_2 and the selfish prevention strategy p'_2 . We see $1 - \sqrt[N-1]{1/2N}$ is a good approximation for the lower-bound for p'_2 .

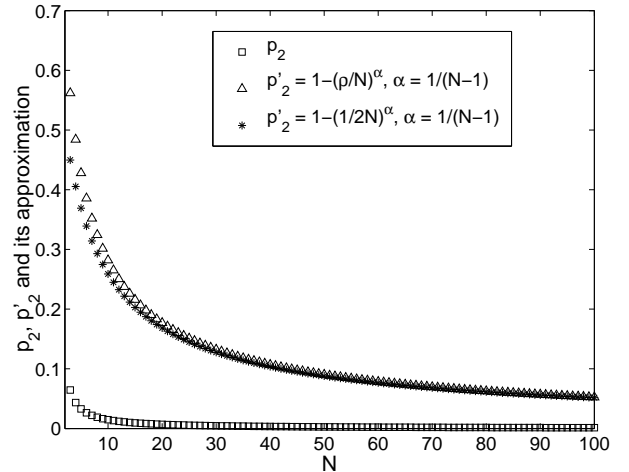


Fig. 9. Cooperative p_2 , selfish preventive p'_2 and its approximation.

VII. Adversarial Model Analysis

All previous scenarios assume that each node, whether cooperative or selfish, is interested in maximizing its own throughput. In this section, we consider an attacking node whose goal is to use its restricted budget to minimize the throughput of the other nodes in the system, i.e., to cause as many of its packets to collide with what would otherwise be successful transmissions. We first discuss how much damage an adversary node can inflict if it uses a random (stateless) attack. Next, we formulate this attack model as another Stackelberg game.

A. Pure Random (Stateless) Attack

If an attacking node is able to transmit a packet in every time-slot, it can clearly jam all transmissions. We assume that the adversary node has a budget $B \in (0, 1]$, allowing it to transmit in at most a fraction B of the slots. This budget represents as the highest frequency of transmission under which an attack cannot be detected.

Definition 2: An adversary node is said to use a **p -pure random attack** if it transmits a packet in each time-slot independently with probability p . ■

By Definition 2, an adversary node with a budget B can use a p -pure random attack for any $p \leq B$. We can imagine that a p -pure random attack for a communication channel is identical to a lossy channel where a packet is lost with probability p .

Theorem 7: Suppose there are two nodes x and y in the system. If node x is an adversary node that uses a p -pure random attack, then regardless of the strategy of player y , y 's throughput T_y is equal to $(1-p)C_y$.

Proof: Substitute p_1^x and p_2^x with p in the corresponding throughput for y as in Equation (2). We have

$$\begin{aligned} T_y &= (\pi_1, \pi_3, \pi_2, \pi_4) \begin{pmatrix} p_1^y(1-p_1^x) \\ p_1^y(1-p_2^x) \\ p_2^y(1-p_1^x) \\ p_2^y(1-p_2^x) \end{pmatrix} \\ &= (1-p)(\pi_1, \pi_3, \pi_2, \pi_4) \begin{pmatrix} p_1^y \\ p_1^y \\ p_2^y \\ p_2^y \end{pmatrix}. \end{aligned}$$

Since the corresponding cost function for y as in Equation (3), we have

$$C_y = (\pi_1, \pi_3, \pi_2, \pi_4) \begin{pmatrix} p_1^y \\ p_1^y \\ p_2^y \\ p_2^y \end{pmatrix}.$$

Therefore, $T_y = (1-p)C_y$. ■

Theorem 7 formalizes the intuitive result that a p -pure random attack reduces the capacity to be $1-p$ of the original capacity. Interestingly and counter-intuitively, if we have more than one cooperative node, the damage caused by a p -pure random attack is often larger than a factor of $1-p$.

Theorem 8: Suppose originally there are N homogeneous nodes that use $p_1 = 1$ and $p_2 < 1/N$ in the system. They achieve an aggregate throughput ρ . If an adversary node joins the system and uses p -pure random attack, then the aggregate throughput of the N cooperative node is less than $(1-p)\rho$.

Proof: Before the adversary node comes into the system, we can model the system as in Figure 2. The transition probabilities are $p_b = (1-p_2)^{N-1}$ and $p_a = Np_2(1-p_2)^{N-1}$. After the adversary node comes, we define the corresponding transition probabilities to be p'_b and p'_a . Because a successful packet from a normal node happens only if the adversary node does not transmit, we have $p'_b = (1-p)p_b$ and $p'_a = (1-p)p_a$. From Equation (5), we obtain

$$\rho = \frac{Np_2(1-p_2)^{N-1}}{1 + (Np_2 - 1)(1-p_2)^{N-1}}.$$

The new throughput ρ' is

$$\rho' = \frac{p'_a}{1 - p'_b + p'_a} = \frac{Np_2(1-p_2)^{N-1}}{\frac{1}{1-p} + (Np_2 - 1)(1-p_2)^{N-1}}.$$

Therefore,

$$\frac{\rho'}{\rho} = \frac{1 + (Np_2 - 1)(1-p_2)^{N-1}}{\frac{1}{1-p} + (Np_2 - 1)(1-p_2)^{N-1}} < 1-p.$$

The last inequality holds if $p_2 < 1/N$. ■

An explanation of this result is that as more nodes participate in the cooperative process, the expected number of slots between transmissions in the Backlogged State grows at a faster rate than the expected number of slots between transmissions in the Free State. A random seeding of losses forces more nodes to spend increased time in the Backlogged State, and as a result, each node attempts fewer transmissions over time, yet still loses a fraction p of the attempts to the random loss process.

B. Adversary Stackelberg Game

Now, we compute the reduction in throughput caused by an adversary node when it maximizes its attack power under a two-state system. As in Section V-B, we model this system as a Stackelberg game. The difference between the previous model and this model is that we assume the leader node x is the attacker and its sole objective is to minimize the throughput of node y . Because the leader has an advantage over the follower, making the adversary node the leader maximizes its potential for damage. We still assume that node x and y have budget constraints: $C_x \leq B_x$ and $C_y \leq B_y$ respectively. The adversary Stackelberg game can be formally described as follows:

Player: The leader node x and the follower node y .
Strategy: $S^x = \{p_1^x, p_2^x\}$ for x ; $S^y = \{p_1^y, p_2^y\}$ for y .
Payoff: $-T_y$ and T_y for x and y respectively.
Game rule: Given any x 's strategy $\{p_1^x, p_2^x\}$, y chooses the best response $\{p_1^y, p_2^y\}$ accordingly.

Follower's Problem:

For any given \tilde{S}^x , the follower node y solves:

$$\begin{aligned} \hat{S}^y(\tilde{S}^x) &= \arg \max T_y(\tilde{S}^x, \hat{S}^y) \\ \text{Subject to : } &C_y(\tilde{S}^x, \hat{S}^y) \leq B_y. \end{aligned}$$

Leader's Problem:

The leader node x solves:

$$\begin{aligned} \hat{S}^x &= \arg \min T_y(\hat{S}^x, \hat{S}^y(\hat{S}^x)) \\ \text{Subject to : } &C_x(\hat{S}^x, \hat{S}^y(\hat{S}^x)) \leq B_x. \end{aligned}$$

C. Two Stackelberg Equilibrium Regions

By backward induction, we solve the above adversary Stackelberg game for nodes who have the same budget constraints, i.e., $B_x = B_y$.

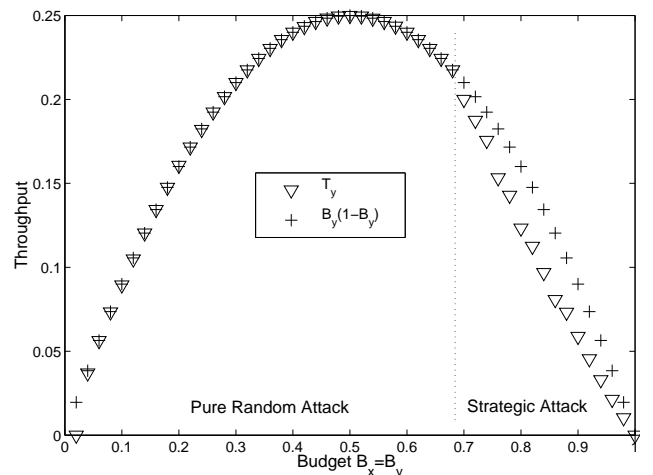


Fig. 10. Throughput in (adversary) Stackelberg equilibrium.

Figure 10 plots the throughput of the follower (non-attacking) node y when x chooses the optimal attacking strategy of the Stackelberg game. It also plots the curve $B_y(1-B_x)$, which gives the throughput of node y when the attacker uses a p -pure random attack with $p = B_x$. Figure

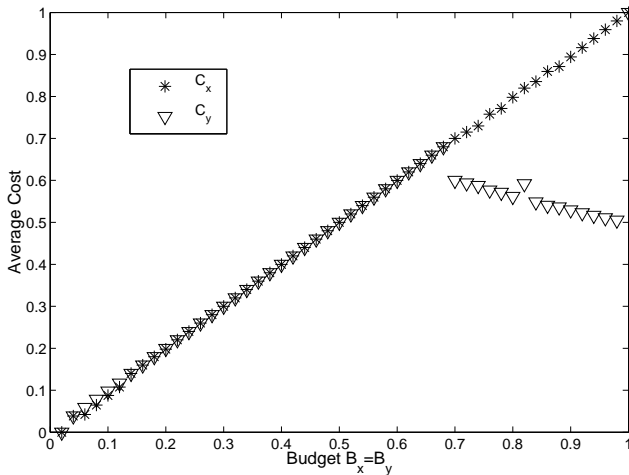


Fig. 11. Cost in (adversary) Stackelberg equilibrium.

11 shows the costs incurred by both players. We identify two regions in the Stackelberg equilibrium solutions:

- 1) When the budget is less than $2/3$, both players use up their budgets. Player y achieves identical throughput when attacked by the adversarial leader player and by a p -pure random attacker.
- 2) When the budget is larger than $2/3$, player y achieves slightly but observably lower throughput when attacked by the adversarial leader player than attacked by the p -pure attacker.

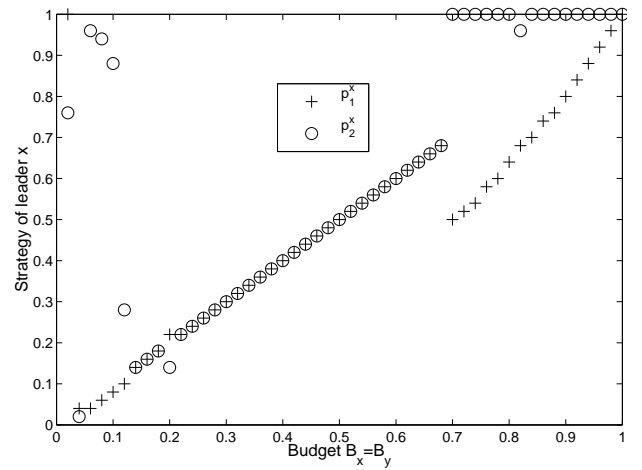
Intuitively, the attacking node will always use up its budget to attack. But surprisingly, a strategic, two-state attack cannot do better than pure random attack if the adversary node does not have a budget larger than $2/3$. When the budget is larger than $2/3$, the two-state attack is only slightly more effective.

D. Random Attack Vs. Strategic Attack

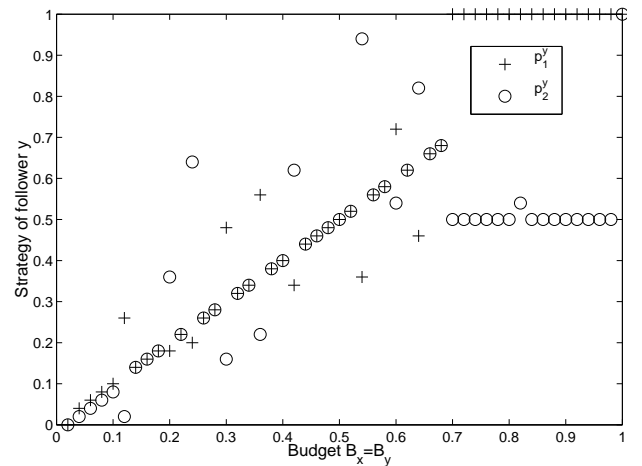
We show the strategy solutions of both players in Figure 12. We find that the strategies played in the two budget regions are quite different.

Not surprisingly, when the budget is less than $2/3$, the attacking node uses the pure random strategy $p_1^x = p_2^x = B_x$. Theorem 7 explains why the throughput T_y is so close to curve $B_y(1 - B_x)$ in the lower budget region. It turns out that player y has multiple strategies to maximize its throughput, but all of these strategies use up the budget B_y . Therefore, although the strategies played by node y seem to be irregular, node y always gains a throughput that is close to $B_y(1 - B_x)$. Notice that when the budget is very small (e.g. $N \leq 0.2$), the probability of a collision is extremely small. Therefore, there are multiple optimal strategies that can maximize throughput. Of course, $p_1^x = p_2^x = B_x$ should be one of the optimal strategies that maximizes throughput.

After comparing the strategies played by both nodes in the larger budget region with those used by two non-cooperative, non-attacking nodes in Figure 8, we notice that they are strikingly similar. This means that an adversary node x chooses a strategy very similar to what is chosen by a node who wishes



(a) Leader's Strategy



(b) Follower's Strategy

Fig. 12. Strategies in Stackelberg equilibrium.

to selfishly maximize its own throughput. Of course, node y would therefore use the same response strategy.

In conclusion, if bandwidth requirements/capabilities are low, an attacker cannot do much better than attacking at random points in time. If the bandwidth requirements and capabilities are high, then an attacker behaves similarly to a node seeking to maximize its own throughput.

VIII. CONCLUSION

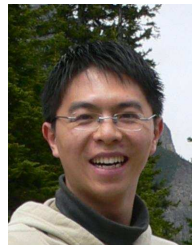
In this paper, we generalize the slotted-Aloha protocol to a two-state protocol and construct its Markov Model. We find that if all nodes cooperate in an effort to maximize the aggregate throughput, an aggregate throughput of at least one half ($\rho > 1/2$) can be achieved regardless of the number of nodes competing for bandwidth. If all nodes are selfish and attempt to maximize their own individual throughput, both the aggregate throughput and system fairness will be compromised. In a Stackelberg game, a leader node can achieve much higher throughput than a follower node with large budget limits. In a simultaneous move game, where nodes both strategically choose parameters, a situation similar to the traditional Prisoner's Dilemma arises. Finally, we showed that adversary nodes with limited budgets can do little better than

a random attack, and nodes with large budgets should behave like their selfish counterparts.

The generalized slotted-Aloha provides a framework to analyze different behavior of autonomous nodes in system. Some analytical observations from different behavioral models provide guidelines for building robust and efficient media access protocols, from which systems can obtain higher aggregate throughput, as well as the ability to cope with selfish and malicious users.

REFERENCES

- [1] "Ethernet, a local area network: Data Link Layer and Physical Layer Specifications (version 1.0)," *Digital Equipment Corporation, Intel, Xerox*.
- [2] R. M. Metcalfe and D. R. Boggs, "Ethernet: Distributed packet switching for local computer networks," *Communication of the ACM* 19(7), p. 395-404, July, 1976.
- [3] L. Kleinrock and F. A. Tobagi, "Packet switching in radio channels: Part I-carrier sense multiple-access modes and their throughput-delay characteristics," *TRANSCOM COM-23(12)*, p. 1400-1416, 1975.
- [4] N. Abramson, "The Aloha system - another alternative for computer communications," *AFIPS Conference Proceedings*, vol. 36, 1970, pp.295-298.
- [5] L. Roberts, "Aloha packet system with and without slots and capture," *ACM SIGCOMM Computer Communication Review*, Vol. 5, Issue 2, 1975.
- [6] M. J. Osborne and A. Rubinstein, *A course in game theory*. The MIT Press Cambridge, Massachusetts, 1994.
- [7] R. Rom and M. Sidi, *Multiple access protocols: performance and analysis*. Springer-Verlag New York, Inc., 1990.
- [8] D. Bertsekas and R. Gallager, *Data Networks*. Prentice-Hall, Englewood Cliffs, New Jersey, 1992.
- [9] Y.Yu, X.Cai, and G.B.Giannakis, "On the instability of slotted Aloha with capture," *Proc. IEEE WCNC, Atlanta, GA*, 2004.
- [10] L. Kleinrock and S. Lam, "Packet switching in a multi access broadcast channel: Performance evaluation," *IEEE Trans. Commun.*, vol. COM-23, pp. 410-422, 1975.
- [11] A. Carleial and M. Hellman, "Bistable behavior of Aloha-type systems," *IEEE Trans. Commun.*, vol. COM-23, pp. 401-410, 1975.
- [12] S. Ghez, S. Verd, and S. Schwartz, "Stability properties of slotted-Aloha with multipacket reception capability," *IEEE Trans. Automatic Control*, vol AC-33, no. 7, p. 640-649, July, 1988.
- [13] R. Rivest, "Network control by Bayesian broadcast," *IEEE Trans. on Information Theory*, vol 33, no. 3, p. 323-340, 1987.
- [14] S. Lam and L. Kleinrock, "Packet switching in a multi access broadcast channel: Dynamic control procedures," *IEEE Trans. Commun.*, vol. COM-23, pp. 891-904, 1975.
- [15] J. Konorski, "A game-theoretic study of CSMA/CA under a backoff attack," *IEEE/ACM Transactions on Networking*, vol. 14, no. 6, Dec 2006.
- [16] P. Kyasanur and N. H. Vaidya, "Selfish MAC layer misbehavior in wireless networks," *IEEE Transactions on Mobile Computing*, vol. 4, no. 5, Sep 2005.
- [17] A. Mas-Colell, M. D. Whinston, and J. R. Green, *Microeconomic theory*. New York : Oxford University Press, 1995.
- [18] G. Tan and J. Guttag, "The 802.11 MAC Protocol Leads to Inefficient Equilibria," *IEEE INFOCOM*, March 2005.
- [19] M. Cagalj, S. Ganeriwal, I. Aad, and J.-P. Hubaux, "On selfish behavior in CSMA/CA networks," in *IEEE INFOCOM*, Miami, FL, March 2005.
- [20] Z. Fang and B. Bensaou, "Fair bandwidth sharing algorithms based on game theory frameworks for wireless ad-hoc networks," in *Proceedings of the IEEE Infocom*, 2004.
- [21] V. Srinivasan, P. Nuggehalli, C. Chiasserini, and R. Rao, "Cooperation in wireless ad-hoc networks," in *Proceedings of IEEE Infocom*, 2003.
- [22] R. T. B. Ma, V. Misra, and D. Rubenstein, "Cooperative and non-cooperative models for slotted-Aloha type MAC protocols," in *Proceedings of The Seventh Workshop on Mathematical performance Modeling and Analysis, Banff, AB, Canada.*, 2005.
- [23] —, "Modeling and analysis of generalized slotted-Aloha mac protocols in cooperative, competitive and adversarial environments," in *Proceedings of The 26th International Conference on Distributed Computing Systems (ICDCS), Lisbon, Portugal, July 4-7, 2006*.
- [24] A. MacKenzie and S. Wicker, "Selfish users in Aloha: a game theoretic approach," *Proceedings of the Fall 2001 IEEE Vehicular Technology Conference*, 2001.
- [25] —, "Stability of multipacket slotted Aloha with selfish users and perfect information," *Proceedings of IEEE INFOCOM*, 2003.
- [26] Y. Jin and G. Kesidis, "Equilibria of a noncooperative game for heterogeneous users of an Aloha network," *IEEE Communication Letters* 6 (7) p.282-284, 2002.
- [27] E. Altman, R. E. Azouzi, and T. Jimnez, "Slotted Aloha as a game with partial information," *Computer Networks: The International Journal of Computer and Telecommunications Networking Vol. 45 Issue 6*, 2004.
- [28] C. E. Koksal, H. Kassab, and H. Balakrishnan, "An analysis of short-term fairness in wireless media access protocols (poster session)," *Proceedings of the ACM SIGMETRICS*, 2000.
- [29] R. T. Ma, D. Rubenstein, and V. Misra, "An analysis of generalized slotted-aloha protocols," *Technical Report, Columbia University, EE Department, Oct 2007 [Online] Available: http://dnawsl.cs.columbia.edu/pubsub/citation/paperfile/156/TR.pdf*.
- [30] Y. A. Korilis, A. A. Lazar, and A. Orda, "Achieving network optima using Stackelberg routing strategies," *IEEE/ACM Transactions on Networking*, vol. 5, no. 1, pp. 161-173, 1997.
- [31] A. A. Economides and J. A. Silvester, "Priority load sharing: an approach using Stackelberg games," *Proceedings of the 28th Annual Allerton Conference on Communication, Control, and Computing*, 1990.



Richard T. B. Ma received his B.Sc. (first-class honors) in Computer Science in July 2002 and M.Phil. in Computer Science and Engineering in July 2004, both from the Chinese University of Hong Kong. He is currently working toward the Ph.D. degree at Columbia University, New York, NY. His research interests are in network economics and game theory.



Vishal Misra is an Associate Professor in Computer Science and Electrical Engineering at Columbia University. He has received an NSF CAREER Award, a DoE CAREER Award and an IBM Faculty Award. His research emphasis is on mathematical modeling of computer systems, bridging the gap between practice and analysis. His recent work includes the areas of overlay security, congestion control mechanisms, wireless modeling and efficient scheduling policies. He has served as the guest editor for the Journal of Performance Evaluation, co-chair of the Opensig 2003 and NYMAN 2002 workshops, and participated as member of program committees for conferences such as IEEE Infocom, ACM SIGMETRICS, ACM SIGCOMM, IFIP Performance and IEEE ICNP.



Dan Rubenstein (M'00) received the BS degree in mathematics from MIT, the MA degree in math from UCLA, and the PhD degree in computer science from the University of Massachusetts, Amherst. He is now an associate professor of electrical engineering and computer science at Columbia University. He is generally interested in the design and performance of networked systems, and also has interests in the security and integrity of such systems, as well as the general design of distributed communication algorithms. He has received an US National Science Foundation CAREER Award, an IBM Faculty Award, an IEEE ICNP Best Paper Award, and (as a student) an ACM SIGMETRICS Best Student Paper Award. He is a member of the IEEE.