Achieving Cooperation in Multihop Wireless Networks of Selfish Nodes

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ABSTRACT

In a multihop wireless network, routing a packet from source to destination requires cooperation among nodes. If nodes are selfish, reputation-based mechanisms can be used to sustain cooperation without resorting to a central authority. Within a hop-by-hop reputation-based mechanism, every node listens to its relaying neighbors, and the misbehaving ones are punished by dropping a fraction of their packets, according to a Tit-for-tat strategy. Packet collisions may prevent a node from recognizing a correct transmission, distorting the evaluated reputation. Therefore, even if all the nodes are willing to cooperate, the retaliation triggered by a perceived defection may eventually lead to zero throughput. A classical solution to this problem is to add a tolerance threshold to the pure Tit-for-tat strategy, so that a limited number of defections will not be punished. In this paper, we propose a game-theoretic model to study the impact of collisions on a hop-by-hop reputation-based mechanism for regular networks with uniform random traffic. Our results show that the Nash Equilibrium of a Generous Tit-for-tat strategy is cooperative for any admissible load, if the nodes are sufficiently far-sighted, or equivalently if the value for a packet to the nodes is sufficiently high with respect to the transmission cost. We also study two more severe punishment schemes, namely One-step Trigger and Grim Trigger, that can achieve cooperation under milder conditions.

1. INTRODUCTION

In a multihop wireless network, a packet has to traverse all the nodes in the path from source to destination. Hence, a successful transmission involves cooperation, since every node has to relay the packets generated by or directed to other nodes. If all the nodes are obedient, such as in military systems programmed to behave correctly by a central authority, then cooperation can be taken for granted. On the other hand, a selfish node aims to maximize its own utility with no regard for the overall system-wide outcome; roughly speaking, a selfish node does not want to waste its time, energy or bandwidth resources, and it may drop all the packets belonging to any other node but itself. In the worst case, assuming that every node is selfish, this behavior will eventually give zero throughput to everyone, thus leading to the so-called "Tragedy of the Commons" [1]. The solution to this problem is to provide selfish users with some incentives, in the form of reward for cooperation or punishment for defection.

Proposed incentive schemes belong to two classes: micro-payments, and reputation-based mechanisms. In micro-payment schemes, such as Terminodes [2] or Sprite [3], the nodes possess a certain amount of virtual credit, and if a node wants to send a packet, it has to pay all the nodes in the path that agree to cooperate. So, an uncooperative node will eventually run out of credit and will stop transmitting. The drawback is that a central authority has to manage the transactions and periodically redistribute the credits. Moreover, Terminodes needs a tamper-proof hardware to prevent the users from forging false credits.

In a reputation-based mechanism, such as SORI [4] or Catch [5], every node keeps track of the reputation of its neighbors, *i.e.*, the fraction of packets forwarded by them. When a node has to relay a packet on behalf of a neighbor, it will forward it with the same probability with which the neighbor forwards its packets, with a Tit-for-tat strategy. Compared to micro-payments, the main advantage of these mechanisms is that they do not require any central authority or special hardware. However, it may not be possible to correctly estimate the real reputation of a neighbor. The reason is that now every retransmission has two receivers: a forward receiver, *i.e.*, the packet's recipient; and a backward receiver that listens to the channel to check if the transmission effectively takes place. Traditional medium access protocols such as the CSMA/CA of IEEE 802.11 [6] guarantee the absence of collisions only at the forward receiver side, while the backward receiver still suffers from the so-called Hidden Terminal problem [7]. These collisions do not affect the transmission of a packet, but only its correct detection by the listener [8]. If a transmission is perceived as a defection, a cooperating node can be unjustly punished. With a Tit-for-tat strategy, packet collisions may trigger a retaliation process that eventually leads to zero throughput.

In our previous work [9], we introduced a game-theoretic model, based on the classic Prisoner's Dilemma [10], and
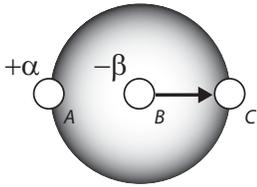
Figure 1: Relaying Model. If a packet is forwarded, the source A gains α units, while the relay B loses β units.

we showed that a Generous Tit-for-tat strategy was able to achieve cooperation in a linear network. In this paper, we prove that Generous Tit-for-tat is actually a rational strategy, and we extend our analysis to more general topologies. While such results are well-known in Game Theory, our main contribution is to study the impact of packet collisions on the emergence of cooperation. Further, we also characterize the impact of selfishness on network capacity.

The rest of the paper is organized as follows. Section 2 formally motivates the need to sustain cooperation in a network of selfish nodes. Section 3 provides an overview of proposed incentive mechanisms. Sections 4 explores the conditions for the emergence of cooperation between two isolated nodes adopting a reputation-based scheme, while Sections 5 and 6 extend the results to linear and regular grid networks. Section 7 interprets the conditions for cooperation in terms of network capacity. Section 8 studies two alternative schemes, theoretically more effective, but practically unstable. Section 9 suggests two algorithms to set the optimal tolerance threshold. Section 10 concludes the paper.

2. GAME-THEORETIC MODEL

Let us consider the three nodes in Fig. 1. Node A wants to send a packet to node C. Node B can decide either to cooperate and forward the packet, or to defect and drop it. If B forwards the packet, then A hears the transmission, and gains α utility units. On the other hand, since B has consumed its resources, it loses β utility units. We call α, the *Packet Value*, and β, the *Packet Cost*.

Throughout this paper, we will assume that the traffic demand is such that the interaction between two neighboring nodes is reciprocal. In the example above, this means that A has packets that have to go through B, and B has packets that have to go through A. In other words, two neighbors are directly dependent on each other [11]. Under this assumption, the interaction between two neighboring nodes in a multihop wireless network can be modeled as a two-player strategic game, where each player's strategy is the probability with which it drops the opponent's packets. Following a standard game-theoretic notation, we will write i to denote a generic player, and $-i$ to denote its opponent. Thus, we have the following

DEFINITION 1. *The* Packet Relaying Game *is the game*

$$G = \langle N, \{p_i\}, \{u_i\} \rangle$$

where

- $N = \{1, 2\}$ *is the set of players*
- $0 \le p_i \le 1$ *is the dropping probability of player i*

- $u_i = \beta p_i - \alpha p_{-i}$ *is the payoff to player i*

If the Packet Value α is greater than the Packet Cost β, it can be easily shown that the Packet Relaying Game is equivalent to a Single-stage Prisoner's Dilemma [10] with a continuous strategy space. Analogous to the Prisoner's Dilemma, it is straightforward to show that individual selfishness of the nodes leads to zero throughput.

LEMMA 1. *In the Packet Relaying Game, the Nash Equilibrium is mutual defection, i.e., $p_i = 1$ for $i = 1, 2$ is the unique Nash Equilibrium for G.*

PROOF. Observe that the payoff function of each player is monotonically increasing with its dropping probability. Therefore, the value of p_i that maximizes u_i is $p_i^* = 1$, independently of the opponent's strategy. In other terms, defection strictly dominates cooperation. Since no player can profitably deviate by cooperating with its opponent, the Nash Equilibrium of the Packet Relaying Game is the strategy profile in which $p_i^* = 1$ for $i = 1, 2$. □

While the above result indicates that mutual defection is the only Nash Equilibrium if the game is played only once, we will show in the rest of the paper that cooperation can emerge under certain conditions, if the game is repeatedly played.

3. PRIOR WORK ON INCENTIVES FOR COOPERATION

3.1 Micro-payment Schemes

Micro-payments schemes were among the first attempts to sustain cooperation in a network of selfish nodes. The one proposed in [12] is based on a so-called *nuglet* counter, that increases every time a node forwards a packet, and decreases by the number of intermediate nodes every time a packet is sent. A node is only allowed to send a packet if its nuglet counter will remain positive after the operation. Therefore, it is in the interest of a selfish node to cooperate, if it wants to be able to transmit. This scheme requires tamper resistant hardware, but trusting this kind of hardware may be problematic [13]. Sprite [3] avoids the use of tamper resistant hardware by storing receipts of forwarded packets. These receipts are later cleared with a central trusted authority, that distributes the credits to cooperative nodes. The drawback is an increased complexity of the system, and the need of an infrastructure to operate. In general, micropayments are implemented as end-to-end schemes, thus requiring the exchange of information between all the nodes in the path from source to destination.

3.2 Reputation-based Schemes

Early reputation-based schemes require nodes to perform two functions:: monitoring to overhear the packet retransmission, and routing traffic to avoid misbehaving nodes. In [8], once a misbehaving node is detected, only the source is informed of the event. Therefore, the mechanism only tries to avoid selfish nodes, but the behavior is not discouraged. CONFIDANT [14] spreads the reputation information, so that every node can form its own friends list.

A game-theoretic model of a reputation-based scheme was studied in [15]. In this model, if a node refuses to forward a

packet, it will inform the source about its decision, and uncooperative nodes will be punished with a Tit-for-tat strategy. Assuming that misbehaving nodes do not lie about their actual action, mutual cooperation can be proved to be a Nash Equilibrium.

More recently, research on reputation-based schemes has moved from an end-to-end approach, still influenced by micro-payment schemes, toward a hop-by-hop approach. For example, in SORI [4] and Catch [5], the spreading of reputation information is limited only to one-hop neighbors, to reduce communication overhead. SORI evaluates the reputation of a node by weighting the information of all its neighbors. However, the mechanism only works well on a light traffic load due to packet collisions. Catch uses control (ACM) messages, to reduce the impact of collisions on estimating reputation. It is claimed in [5] that this process results in close to 100% throughput. However, as we will see later, we believe that the reason for increased throughput in Catch, as compared with SORI for example, is not due to (ACM) messages only, but is really due to use of a Trigger strategy instead of a Tit-for-tat strategy. In [16] it has been shown that trigger strategies are more susceptible to noise. This claim has to be further investigated in the context of wireless networks.

OCEAN [17] is a hybrid scheme that uses both a reputation-based component to detect and punish selfish behavior, and a micro-payment component to encourage cooperation. The credit is earned for each immediate neighbor and it cannot be used to send packets in a different route. Finally, the scheme proposed in [18] not only decreases the reputation of the node that drops a packet, but punishes all the nodes in the path from source to destination. Both of these proposals are based on purely local reputation mechanisms, where the information is not shared among neighbors.

The purpose of our paper is to study the impact of retaliation strategies as functions of nodes' reputation, and to obtain conditions under which cooperation is possible without a central authority, in spite of the fact that reputation may be noisy. In addition, we also characterize the impact of such mechanisms on the network throughput.

4. COOPERATION WITHOUT COLLISIONS

If the nodes adopt a hop-by-hop reputation-based mechanism, then they have to take into account the future effects of their present actions. This implies that in this case the interaction between two neighboring nodes can be modeled as a repeated game.

DEFINITION 2. *The* Repeated Packet Relaying Game *is the multistage game*

$$\Gamma = \langle N, \{s_i\}, \{U_i\} \rangle$$

where

- $N = \{1, 2\}$ *is the set of players*

- $p_i^{(k)}$ *is the dropping probability of player i at stage k*

- $u_i^{(k)} = \beta p_i^{(k)} - \alpha p_{-i}^{(k)}$ *is the payoff of player i at stage k*

- $s_i : (\mathbf{p}^{(0)}, \dots, \mathbf{p}^{(k-1)}) \to p_i^{(k)}$ *is the strategy of player i*

- $U_i = \sum_{k \geq 0} \delta^k u_i^{(k)}$ *is the discounted payoff of player i*

The discount parameter $0 \leq \delta \leq 1$ is a measure of the subjective evaluation of the future by the players. The greater the discount parameter, the more important is the future for the players. For example if $\delta = 0$, then the players are myopic, and the game reduces to a single-stage form. The parameter δ can also be interpreted as the probability that each player continues to play after each stage [10]. According to this interpretation, the length of the game, expressed in number of stages, is a geometric random variable with expected value $1/(1-\delta)$. In networking terms, $1/(1-\delta)$ can be interpreted as the length of a session.

The simplest strategy to achieve cooperation in a Repeated Prisoners Dilemma is Tit-for-tat *(TFT)* [10], which prescribes the player to *"cooperate on the first stage, then do what the opponent did in the previous stage"*. *TFT* has three important properties: it is *nice*, because it is never the first to defect; it is *provokable*, because it immediately punishes a defection; and it is *oblivious*, because it immediately restores cooperation after a punishment. The next definition adapts the classical discrete *TFT* to the continuous strategy space of our game.

DEFINITION 3. *In a Repeated Packet Relaying Game, a strategy s_i is* TFT *if*

- $p_i^{(0)} = 0$

- $p_i^{(k)} = p_{-i}^{(k-1)}$ *for $k > 0$*

The fact that players take into consideration the future is the key for the emergence of cooperation. Indeed, the following result shows that if the discount parameter δ is sufficiently large, than both players have no incentive to deviate from *TFT*, and the outcome will be observationally equivalent to mutual cooperation.

THEOREM 1. *In the Repeated Packet Relaying Game, the Subgame Perfect Equilibrium is mutual cooperation if and only if*

$$\frac{\beta}{\alpha} \leq \delta \leq 1$$

PROOF. Observe that the discounted payoff of each player, if both of them use *TFT*, is 0. Without loss of generality, let us assume that player i unilaterally deviates only at stage 0 by setting its dropping probability equal to $p_i^{(0)} = p > 0$, and in the following stages it goes back to *TFT*. Since the opponent of player i is always using *TFT*, at stage 0 it cooperates, *i.e.*, $p_{-i}^{(0)} = 0$. But in the next stage it will punish i by setting its dropping probability $p_{-i}^{(1)} = p$. At the same time, player i cooperates, *i.e.*, $p_i^{(1)} = 0$. Therefore, the two players alternately cooperate and defect each other, and the payoff of player i will alternately be βp and $-\alpha p$.

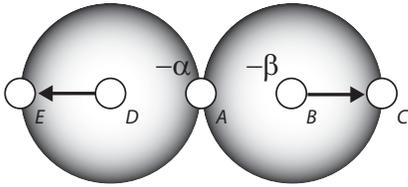| k	$p_i^{(k)}$	$p_{-i}^{(k)}$	$u_i^{(k)}$
0	p	0	$+\beta p$
1	0	p	$-\alpha p$
2	p	0	$+\beta p$
3	0	p	$-\alpha p$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

Figure 2: Relaying Model with Collisions. Packet collisions with "hidden terminals" may prevent a node from overhearing a correct transmission, and cooperation may be perceived as defection.
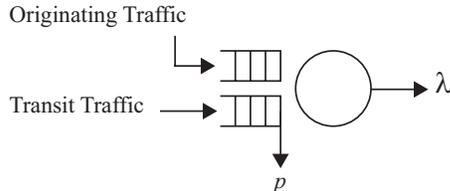

Figure 3: Queueing Model. Every node keeps two separate queues, one for the transit packets and one for its own packets. Under the infinite backlog assumption, the transmission rate λ is independent from the dropping probability.

Therefore, the discounted payoff of player i will be

$$
\begin{aligned}
U_i &= \beta p - \delta \alpha p + \delta^2 \beta p - \delta^3 \alpha p + \ldots \\
&= \beta p (1 + \delta^2 + \ldots) - \delta \alpha p (1 + \delta^2 + \ldots) \\
&= \frac{\beta - \delta \alpha}{1 - \delta^2} p
\end{aligned}
$$

Player i has no incentive to deviate from *TFT* if and only if $U_i \leq 0$, *i.e.*, if and only if $\beta \leq \delta \alpha$. From the one-step deviation principle [19], if deviating in one stage is not profitable, then it is not profitable to deviate in more than one consecutive stage. Hence, mutual cooperation is a Subgame Perfect Equilibrium. □

This result shows that cooperation can emerge in a network of selfish nodes, if they are sufficiently far-sighted, but this is not surprising [10]. However, our model still does not take into account the broadcast nature of the wireless medium. In the next section, we will extend this result to a more realistic scenario, in which packet collisions prevent a correct estimation of the reputation.

5. COOPERATION WITH COLLISIONS

Let us consider the example in Fig. 2. Again, node A wants to send a packet to C through B. But now, when B forwards the packet to C, node D transmits a packet to E. Observe that this is not a real collision, since the packet from B is actually received by C. Nevertheless, the two simultaneous transmissions prevent A from hearing whether B has forwarded the packet or not, and cooperation may be perceived as defection.

This situation can be modeled as a Prisoner's Dilemma with Noise [20]. Let λ be the probability with which each node attempts a transmission in each time instant. This probability could be the result of a medium access control (MAC) protocol, which we do not model explicitly here. We

can capture the distortion introduced by packet collisions by defining the perceived reputation of a node as the probability that a packet is dropped and the hidden terminal does not transmit, or that the hidden terminal transmits, so nothing can be said about the relaying node.

DEFINITION 4. *The* Perceived Defection *of player i at stage k, denoted by $\hat{p}_i^{(k)}$, is*

$$
\hat{p}_i^{(k)} = \lambda + (1 - \lambda) p_i^{(k)}
$$

This implies that we need also to redefine all the expressions that contained the node's reputation. In particular, we have to redefine the instantaneous payoff, the discounted payoff and the *TFT* strategy as follows.

DEFINITION 5. *The* Perceived Payoff *of player i at stage k, denoted by $\hat{u}_i^{(k)}$, is*

$$
\hat{u}_i^{(k)} = \beta p_i^{(k)} - \alpha \hat{p}_{-i}^{(k)}
$$

DEFINITION 6. *The* Perceived Discounted Payoff *of player i, denoted by $\hat{U}_i$, is*

$$
\hat{U}_i = \sum_{k \geq 0} \delta^k \hat{u}_i^{(k)}
$$

DEFINITION 7. *A strategy s_i is* TFT *if*

- $p_i^{(0)} = 0$
- $p_i^{(k)} = \hat{p}_{-i}^{(k-1)}$ *for $k > 0$*

Observe that we have implicitly assumed that the traffic load λ is a constant, and in particular it does not depend on the dropping probability. This is true if we adopt an infinite backlog queuing model. Every node i keeps its own packets and the transit packets coming from each neighbor in separate queues [21]. For simplicity, Fig. 3 represents only two queues, one for the packets originating from the node, and one for the packets coming from one neighbor. The packets originating from the node itself are never dropped, while the transit packets are dropped with probability p_i. Actually, every node is simultaneously playing against all its neighbors, but the dropping probabilities are chosen independently.

The queue for the originating traffic has an infinite number of packets waiting to be transmitted, and every node transmits whenever it can, either its own packets, or the transit packets. This means that under the infinite backlog assumption, the transmission rate of every node i is independent from the dropping probability p_i of the node itself.

The next result shows that the effect of packet collisions can be dramatic. Indeed, even if all the nodes are willing to cooperate, a perceived defection may be unjustly punished, and the TFT mechanism can trigger a retaliation process, that will eventually lead to zero throughput.

LEMMA 2. *In the Repeated Packet Relaying Game with collisions,* TFT *is not sufficient to sustain mutual cooperation*

PROOF. Assume that both players initially cooperate, *i.e.*, $p_i^{(0)} = 0$. Due to packet collisions, the perceived defection of each player will be $\hat{p}_i^{(0)} = \lambda$. Due to *TFT* strategy, at stage 1 both players will punish each other by defecting

with probability $p_i^{(1)} = \lambda$, and the perceived defection will be $\hat{p}_i^{(1)} = \lambda + (1-\lambda)\lambda$, and so on. At stage k, the real dropping probability of each player will be $p_i^{(k)} = 1 - (1-\lambda)^k$, and it will be perceived as $\hat{p}_i^{(k)} = 1 - (1-\lambda)^{k+1}$. Therefore, $\lim_{k\to\infty} p_i^{(k)} = \lim_{k\to\infty} \hat{p}_i^{(k)} = 1$, for both players. $\square$

A natural and classical solution to this problem is to add a tolerance threshold to the pure Tit-for-tat strategy, so that a limited number of defections will not be punished. The modified TFT is called Generous Tit-for-tat [20], and it is defined as follows.

DEFINITION 8. *A strategy s_i is* Generous TFT (GTFT) *if*

- $p_i^{(0)} = 0$

- $p_i^{(k)} = \max\{\hat{p}_{-i}^{(k-1)} - \gamma_i, 0\}$ *for $k > 0$*

where γ_i is the tolerance threshold of player i.

We will show now that if the discount parameter δ is sufficiently large, then there exists a *GTFT* strategy that achieves cooperation. First, we will show that the optimal tolerance threshold to achieve cooperation with GTFT is $\gamma_i = \lambda$.

LEMMA 3. *In the Repeated Packet Relaying Game with Collisions, it is rational for both players to use* GTFT *with tolerance parameter equal to $\gamma_i = \lambda$, if and only if*

$$\frac{\alpha}{\beta} \geq \frac{1}{(1-\lambda)^2}$$

PROOF. The instantaneous payoff of mutual cooperation is $-\alpha\lambda$. If player i deviates by setting a tolerance $\gamma > \lambda$, this will not affect the outcome of the game. Therefore, such a deviation does not increase its payoff. Then, assume that player i tries to deviate by setting a tolerance $\gamma < \lambda$. It is easy to verify that the following values of dropping probabilities are consistent with each other.

$$p_i^{(k)} = \frac{\lambda - \gamma}{1 - (1-\lambda)^2}$$

$$\hat{p}_i^{(k)} = \frac{\lambda - \gamma}{1 - (1-\lambda)^2}(1-\lambda) + \lambda$$

$$p_{-i}^{(k)} = \frac{\lambda - \gamma}{1 - (1-\lambda)^2}(1-\lambda)$$

$$\hat{p}_{-i}^{(k)} = \frac{\lambda - \gamma}{1 - (1-\lambda)^2}(1-\lambda)^2 + \lambda$$

Therefore, the instantaneous payoff of player i, is

$$\hat{u}_i^{(k)} = \frac{\beta - \alpha(1-\lambda)^2}{1 - (1-\lambda)^2}(\lambda - \gamma) - \alpha\lambda$$

Hence, player i will not increase its instantaneous payoff if this expression is not greater than $-\alpha\lambda$, *i.e.*, if and only if $\beta \leq \alpha(1-\lambda)^2$ $\square$

Now we prove that if both players use *GTFT* with tolerance equal to λ, then if the discount parameter δ is sufficiently large, it is not rational for the players to defect.

THEOREM 2. *In the Repeated Packet Relaying Game with Collisions, the Subgame Perfect Equilibrium is mutual cooperation if and only if*

$$\frac{\beta}{\alpha}\frac{1}{(1-\lambda)^2} \leq \delta \leq 1$$

PROOF. The perceived discounted payoff of each player, if both of them use *GTFT*, is $-\alpha\lambda/(1-\delta)$. Without loss of generality, let us assume that player i unilaterally deviates only at stage 0 by setting its dropping probability equal to $p_i^{(0)} = p > 0$, and in the following stages it goes back to *GTFT*. The perceived defection of player i at stage 0 is $\hat{p}_i^{(0)} = \lambda + (1-\lambda)p$. On the other hand, the opponent of player i cooperates at stage 0, *i.e.*, $p_{-i}^{(0)} = 0$, and its perceived defection is $\hat{p}_{-i}^{(0)} = \lambda$.

At stage 1, the dropping probabilities of the two players will respectively be $p_i^{(1)} = 0$ and $p_{-i}^{(1)} = (1-\lambda)p$, perceived as $\hat{p}_i^{(1)} = \lambda$ and $\hat{p}_{-i}^{(1)} = \lambda + (1-\lambda)^2 p$. Therefore, the two players alternately cooperate and defect each other, but due to the *GTFT* strategy, the defection will exponentially decay down to 0.

k	$p_i^{(k)}$	$\hat{p}_{-i}^{(k)}$	$\hat{u}_i^{(k)}$
0	p	λ	$-\alpha\lambda + \beta p$
1	0	$\lambda + (1-\lambda)^2 p$	$-\alpha\lambda - \alpha(1-\lambda)^2 p$
2	$(1-\lambda)^2 p$	λ	$-\alpha\lambda + \beta(1-\lambda)^2 p$
3	0	$\lambda + (1-\lambda)^4 p$	$-\alpha\lambda - \alpha(1-\lambda)^4 p$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

Therefore, the perceived discounted payoff of player i will be

$$
\begin{aligned}
\hat{U}_i &= -\alpha\lambda + \beta p \\
&\quad -\delta\alpha\lambda - \delta\alpha(1-\lambda)^2 p \\
&\quad -\delta^2\alpha\lambda + \delta^2\beta(1-\lambda)^2 p \\
&\quad -\delta^3\alpha\lambda - \delta^3\alpha(1-\lambda)^4 p \\
&\quad + \ldots \\
&= \frac{\beta - \delta\alpha(1-\lambda)^2}{1 - \delta^2(1-\lambda)^2}p - \frac{\alpha\lambda}{1-\delta}
\end{aligned}
$$

Player i has no incentive to deviate from *GTFT* if and only if $\hat{U}_i \leq -\alpha\lambda/(1-\delta)$, *i.e.*, if and only if $\beta \leq \delta\alpha(1-\lambda)^2$. From the one-step deviation principle, if deviating in one stage is not profitable, then it is not profitable to deviate in more than one consecutive stage. Hence, mutual cooperation is a Subgame Perfect Equilibrium. $\square$

If we compare Theorem 2 with Theorem 1, we can observe that the effect of packet collisions is an increase of the minimum value of the discount parameter δ by a factor $1/(1-\lambda)^2$. In other words, the higher the traffic load of the wireless network, the more far-sighted have to be the nodes in order to achieve cooperation.

So far, we have studied the conditions for the emergence of cooperation in a linear network, where the number of potentially colliding neighbors is equal to one. Following the early studies on multi-hop wireless networks [22], the next section will extend these results for networks with regular planar topology

6. THE EFFECT OF TOPOLOGY

To include the number of neighbors into our model, first we observe that the equation

$$\hat{p}_i^{(k)} = \lambda + (1 - \lambda)p_i^{(k)}$$

can be rewritten as

$$\hat{p}_i^{(k)} = 1 - (1 - p_i^{(k)})(1 - \lambda)$$

The term $(1 - p_i^{(k)})$ is the probability that a packet is forwarded. The term $(1 - \lambda)$ is the probability that the hidden terminal does not transmit. Therefore, the multiplication of the two terms is the probability that a forwarded packet is correctly heard by the source node. The perceived defection is equal to $1 - (1 - p_i^{(k)})(1 - \lambda)$.

If the number of potentially colliding neighbors is n, then the probability that none of them transmits is $(1 - \lambda)^n$. Hence, the expression for the perceived defection for a generic number of neighbors is

$$\hat{p}_i^{(k)} = 1 - (1 - p_i^{(k)})(1 - \lambda)^n$$

which can be conveniently rewritten as

$$\hat{p}_i^{(k)} = 1 - (1 - \lambda)^n + (1 - \lambda)^n p_i^{(k)}$$

Now, if we let $\mu = 1 - (1 - \lambda)^n$ be the probability that *at least* one neighbor transmits, we get

$$\hat{p}_i^{(k)} = \mu + (1 - \mu)p_i^{(k)}$$

which is in the same form of the one-neighbor case, after the substitution of λ with μ. Therefore, all the previous results still hold, if we change λ into $1 - (1 - \lambda)^n$. In particular, it is straightforward to extend the result of Theorem 2 with the following

THEOREM 3. *In the Repeated Packet Relaying Game with Collisions, the Subgame Perfect Equilibrium is mutual cooperation if and only if*

$$\frac{\beta}{\alpha} \frac{1}{(1 - \lambda)^{2n}} \leq \delta \leq 1$$

where n is the number of potentially colliding neighbors.

If we compare Theorem 3 with Theorem 2, we can observe that the effect of a linear increase of the number of neighbors is an exponential increase of the minimum value of the discount parameter δ. Moreover, Theorem 1 is the particular case of Theorem 3 with $n = 0$. This confirms the fact that the higher the interfering load of the wireless network, the more far-sighted have to be the nodes in order to achieve cooperation.

7. NETWORK CAPACITY

In the previous sections, we have shown how the traffic load λ plays a key role in the condition under which cooperation can emerge. However, from a network designer point of view, we may be interested in finding the answer to the following question. What is the maximum load sustainable by a multihop wireless network of selfish nodes? This leads us to define the following

DEFINITION 9. *The* capacity *of a multihop wireless network of selfish nodes is the maximum value of uniform traffic load λ such that cooperation is enforceable by a Generous Tit-for-tat strategy.*
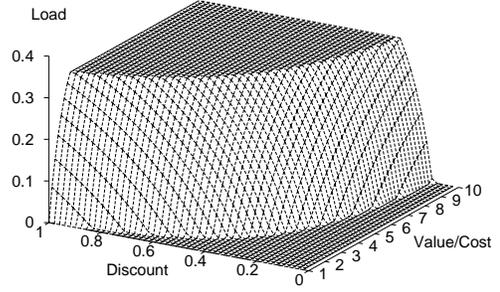

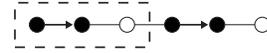**Figure 4: Capacity of a Linear Network.**

Figure 5: Linear Network. The achievable throughput is $1/3$.

To find the capacity of a multihop wireless network of selfish nodes, it is sufficient to invert the equation of Theorem 3 to get the following result

COROLLARY 1. *In the Repeated Packet Relaying Game with Collisions, the Subgame Perfect Equilibrium is mutual cooperation if and only if*

$$0 \leq \lambda \leq 1 - \sqrt[2n]{\frac{1}{\delta}\frac{\beta}{\alpha}}$$

If λ satisfies this condition, then the throughput of a wireless network of selfish nodes is equal to the throughput of a network of cooperative nodes, *i.e.*, all the traffic reaches its destination. However, due to the shared nature of the wireless medium, the maximum throughput λ_{max} of a wireless network is upper-bounded by the maximum number of simultaneous transmissions that the network can sustain [23], and this value depends on the network topology.

For example, consider the linear network in Fig. 5. In this case, the maximum throughput the network can sustain is $1/3$. In fact, to avoid packet collisions, the neighbor of every receiver cannot neither transmit nor receive. This implies that only one node out of three can simultaneously transmit without interfering with each other. Or, equivalently, every node can transmit $1/3$ of the time. Extending this considerations to hexagonal and square grid networks, depicted in Figures 7 and 9, we can observe how in both cases the maximum throughput is $1/4$.

Therefore, we refine the previous result with the following

COROLLARY 2. *The capacity of a multihop wireless network of selfish users is*

$$\lambda = \min\left\{1 - \sqrt[2n]{\frac{1}{\delta}\frac{\beta}{\alpha}}, \lambda_{max}\right\}$$
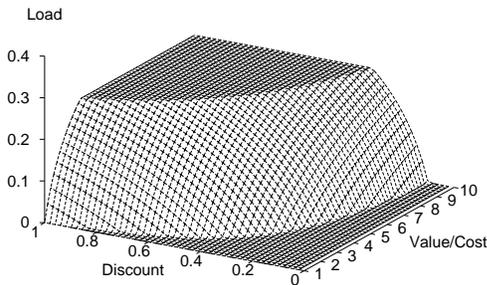
Figure 6: Capacity of a Hexagonal Grid Network.

Figure 7: Hexagonal Grid Network. The achievable throughput load is $1/4$.

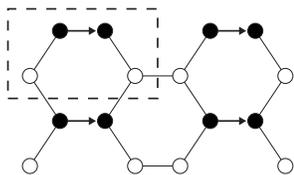**Figure 8: Capacity of a Square Grid Network.**

Figure 9: Square Grid Network. The achievable throughput load is $1/4$.

Figures, 4, 6 and 8 show the capacity of a linear ($n = 1$), hexagonal grid ($n = 2$) and square grid ($n = 3$) multihop wireless network, as a function of the discount factor δ and the value-cost ratio α/β. We can conclude that the capacity of a wireless network depends on several factors, namely the expected session length, the application type, the energy constraints and the network topology.

For example, consider a multimedia streaming source. Current multi-layer coding are designed so that the quality of the streaming is virtually unaffected by a limited number of packet losses. So, we can approximately say that a loss tolerant packet source can be characterized by a low packet value. On the other hand, since multimedia transfer sessions are usually several minutes long, we can say that the discount parameter is sufficiently close to one, and this could compensate the negative effect of a low packet value on the network capacity. But if the nodes are running out of battery, then the cost of every relayed packet can become too high to sustain cooperation at a high load. The same negative effect is determined by a high density of nodes in the same area, such as in an airport. Therefore, the design of a "cooperation layer" appears to be a challenging issue, as it involves the whole protocol stack.

8. MORE SEVERE PUNISHMENTS

In this section, we study two strategies alternative to *GTFT*, characterized by more severe punishment schemes. While in *GTFT* the punishment is linear with the amount of defection beyond the tolerance threshold, we want to see what happens when even the slightest perceived deviation from cooperation triggers a complete punishment. Therefore, we propose two strategies, namely *One-step Trigger* and *Grim Trigger*. For the sake of simplicity, we limit the analysis to a one dimensional linear topology.
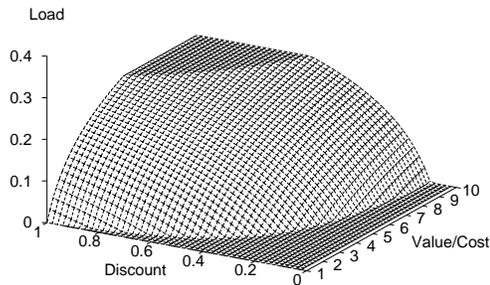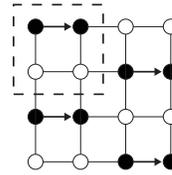
8.1 One-step Trigger

As in the case of *GTFT*, the One-step Trigger *(OT)* strategy is *nice*, *provokable* and *oblivious*. *OT* is never the first to defect, always punishes a defection, and it is immediately ready to restore cooperation after punishment. The only difference between *OT* and *GTFT* is that the slightest perceived deviation from cooperation triggers a dropping probability equal to one. More formally, we can write the following

DEFINITION 10. *A strategy s_i is* One-step Trigger (OT) *if*

- $p_i^{(0)} = 0$

- $p_i^{(k)} = \begin{cases} 0 & \text{if } \hat{p}_{-i}^{(k-1)} \leq \gamma_i \\ 1 & \text{else} \end{cases}$

where γ_i is the tolerance threshold of player i.

As functions of the perceived defection, *GTFT* can be depicted by a ramp shifted in γ_i, while *OT* can be depicted by a step shifted in the same position. The next result shows that if we do not take into account packet collisions, *OT* is equivalent to *GTFT*.

THEOREM 4. *In the Repeated Packet Relaying Game without Collisions, if the players use* OT*, the Subgame Perfect Equilibrium is mutual cooperation if and only if*

$$\frac{\beta}{\alpha} \leq \delta \leq 1$$

PROOF. The discounted payoff of each player, if both of them use *OT*, is 0. Let us assume that player i unilaterally deviates only at stage 0 by setting its dropping probability equal to $p_i^{(0)} = p > 0$, and in the following stages it goes back to *OT*. The opponent of player i cooperates at stage 0,

but in the next stage it will punish i by setting its dropping probability equal to $p_{-i}^{(1)} = 1$. At the same step, player i cooperates, *i.e.*, $p_i^{(1)} = 0$, but in the next step, it will counterpunish player $-i$ with $p_i^{(2)} = 1$. Therefore, the two players alternately fully cooperate and fully defect each other, and the payoff of player i will alternately be $+\beta$ and $-\alpha$. The only exception is the payoff at stage 0, which depends on p, being $+\beta p$.

k	$p_i^{(k)}$	$p_{-i}^{(k)}$	$u_i^{(k)}$
0	p	0	$+\beta p$
1	0	1	$-\alpha$
2	1	0	$+\beta$
3	0	1	$-\alpha$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

Therefore, the discounted payoff of player i will be

$$U_i = \beta p - \frac{\delta^2 \beta - \delta \alpha}{1 - \delta^2}$$

The value of dropping probability that maximizes the payoff is $p = 1$. With this substitution, we get this expression, which does not depend on p,

$$U_i = \frac{\beta - \delta \alpha}{1 - \delta^2}$$

Player i has no incentive to deviate from OT if and only if $U_i \leq 0$, *i.e.*, if and only if $\beta \leq \delta \alpha$. If deviating in one stage is not profitable, then it is not profitable to deviate in more than one consecutive stage. Hence, mutual cooperation is a Subgame Perfect Equilibrium. $\square$

The next result shows that if we take into account packet collisions, then OT can sustain cooperation under milder conditions than $GTFT$.

THEOREM 5. *In the Repeated Packet Relaying Game with Collisions, if the players use* OT, *the Subgame Perfect Equilibrium is mutual cooperation if and only if*

$$\frac{\beta}{\alpha} \frac{1}{(1 - \lambda)} \leq \delta \leq 1$$

PROOF. The discounted payoff of each player, if both of them use OT, is $-\alpha \lambda / (1 - \delta)$. For the same considerations of the previous proof, let us assume that player i unilaterally deviates only at stage 0 by setting its dropping probability equal to $p_i^{(0)} = 1$. The following actions are identical to the previous case, but due to packet collisions the perceived payoff of player i will alternately be $-\alpha \lambda + \beta$ and $-\alpha \lambda$.

k	$p_i^{(k)}$	$\hat{p}_{-i}^{(k)}$	$\hat{u}_i^{(k)}$
0	1	λ	$-\alpha \lambda + \beta$
1	0	1	$-\alpha$
2	1	λ	$-\alpha \lambda + \beta$
3	0	1	$-\alpha$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

The discounted payoff of player i will be

$$U_i = \frac{\beta - \alpha \lambda - \delta \alpha}{1 - \delta^2}$$

Player i has no incentive to deviate from OT if and only if $U_i \leq -\alpha \lambda / (1 - \delta)$. After simple manipulations, this condition reduces to $\beta \leq \delta \alpha (1 - \lambda)$. Once again, if this condition

holds, mutual cooperation is a Subgame Perfect Equilibrium. $\square$

The main conclusion we can draw after this result is that the more severe the punishment is, the less far-sighted the players have to be in order to sustain cooperation [16]. In the remaining part of this section, we will see what happens if we further increase the punishment severity, by studying a *non-oblivious* strategy.

8.2 Grim Trigger

A *Grim Trigger (GT)* strategy is *nice* and *provokable*, but it is not *oblivious*, because after a punishment it never restores cooperation. Hence, it is the most severe strategy, since its punishment results in a permanent disconnection of the misbehaving node. Formally, we can say that

DEFINITION 11. *A strategy* s_i *is* Grim Trigger (GT) *if*

- $p_i^{(0)} = 0$

- $p_i^{(k)} = \begin{cases} 0 & \text{if } \hat{p}_{-i}^{(j)} \leq \gamma_i \text{ for all } j < k \\ 1 & \text{else} \end{cases}$

where γ_i *is the tolerance threshold of player* i.

The next result shows that even if we do not take into account packet collisions, GT theoretically performs better than $GTFT$ and OT.

THEOREM 6. *In the Repeated Packet Relaying Game without Collisions, if the players use* GT, *the Subgame Perfect Equilibrium is mutual cooperation if and only if*

$$\frac{\alpha}{\beta} \geq \frac{1 - \delta + \delta^2}{\delta}$$

PROOF. The discounted payoff of each player, if both of them use GT, is 0. Let us assume that player i unilaterally deviates only at stage 0 by setting its dropping probability equal to $p_i^{(0)} = 1$. The opponent of player i cooperates at stage 0, but from the next stage on, it will punish i by setting its dropping probability equal to $p_{-i}^{(k)} = 1$ forever. Player i cooperates at stage 1, but in the next stages it will counterpunish player $-i$ forever. Therefore, from stage 2 on, the two players will mutually defect each other.

k	$p_i^{(k)}$	$p_{-i}^{(k)}$	$u_i^{(k)}$
0	1	0	$+\beta$
1	0	1	$-\alpha$
2	1	1	$-\alpha + \beta$
3	1	1	$-\alpha + \beta$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

The discounted payoff of player i will be

$$U_i = \frac{(1 - \delta + \delta^2)\beta - \delta \alpha}{1 - \delta}$$

Player i has no incentive to deviate from OT if and only if $U_i \leq 0$, *i.e.*, if $(1 - \delta + \delta^2)\beta \leq \delta \alpha$. If this condition holds, mutual cooperation is a Subgame Perfect Equilibrium. $\square$

Since $0 \leq \delta \leq 1$, it follows that $1 - \delta + \delta^2 \leq 1$. This means that, without packet collisions, cooperation under GT is a necessary condition for cooperation under either $GTFT$ or OT. The next result shows that this advantage is maintained if we take into account packet collisions.

THEOREM 7. *In the Repeated Packet Relaying Game with Collisions, if the players use* GT*, the Subgame Perfect Equilibrium is mutual cooperation if and only if*

$$\frac{\alpha}{\beta} \geq \frac{1 - \delta + \delta^2}{\delta} \frac{1}{(1 - \lambda)}$$

PROOF. The discounted payoff of each player, if both of them use GT, is $-\alpha\lambda/(1-\delta)$. Let us assume that the actions of the players are the same as the previous case.

k	$p_i^{(k)}$	$\hat{p}_{-i}^{(k)}$	$\hat{u}_i^{(k)}$
0	1	λ	$-\alpha\lambda + \beta$
1	0	1	$-\alpha$
2	1	1	$-\alpha + \beta$
3	1	1	$-\alpha + \beta$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

The discounted payoff of player i will be

$$U_i = \frac{(1 - \delta + \delta^2)\beta - \delta\alpha(1 - \lambda)}{1 - \delta} - \frac{\alpha\lambda}{1 - \delta}$$

Player i has no incentive to deviate from OT if and only if $U_i \leq -\alpha\lambda/(1 - \delta)$, *i.e.*, if $(1 - \delta + \delta^2)\beta \leq \delta\alpha(1 - \lambda)$. If this condition holds, mutual cooperation is a Subgame Perfect Equilibrium. $\square$

We summarize the conditions for cooperation with packet collisions under the three strategies in the following

COROLLARY 3. *In the Repeated Packet Relaying Game with Collisions, cooperation with GTFT implies cooperation with OT, and cooperation with OT implies cooperation with GT*

PROOF. The results follow directly by writing in an equivalent form the conditions for cooperation of the three strategies

$$(\text{GTFT}) \quad \frac{\alpha}{\beta} \geq \frac{1}{\delta} \frac{1}{(1 - \lambda)^{2n}}$$
$$(\text{OT}) \quad \frac{\alpha}{\beta} \geq \frac{1}{\delta} \frac{1}{(1 - \lambda)^{n}}$$
$$(\text{GT}) \quad \frac{\alpha}{\beta} \geq \frac{1 - \delta + \delta^2}{\delta} \frac{1}{(1 - \lambda)^{n}}$$

$\square$

In conclusion, increasing the punishment severity seems to increase the network capacity. Nevertheless, one has to be careful in implementing a severe punishment scheme [16]. In our analysis, we have assumed that the estimation error is negligible, while in real system it may happen that due to stochastic fluctuations, the measured defection rate is greater than the ideal value, and estimation errors may trigger unjust punishments. With a smooth scheme like $GTFT$, small errors produce a small and temporary performance loss. On the contrary, with OT, even small errors may produce a huge performance loss. And this degradation can last forever with GT. We leave the study of this trade-off between network capacity and equilibrium stability for future work.

9. TOLERANCE ESTIMATION

Whether the nodes implement a $GTFT$, OT or GT strategy, they need to set their tolerance threshold γ. Since the tolerance is a function of the traffic load λ and the number of colliding neighbors n, it is necessary for the nodes to estimate both these parameters. Since this task could be rather costly and complex to accomplish, we propose two alternative methods to set the optimal tolerance.

9.1 Gradient Ascent

For Lemma 3, the optimal tolerance is also individually rational, *i.e.*, it is the value that maximizes the individual utility. Therefore, if nodes adjust their tolerance to maximize their utility, they will naturally choose the optimal value. For example, this could be done with a *Gradient Ascent* algorithm, which iteratively increases and decreases the tolerance according to this equation

$$\gamma_i^{(i+1)} = \gamma_i^{(i)} + \eta \frac{\hat{u}_i^{(i)} - \hat{u}_i^{(i-1)}}{\gamma_i^{(i)} - \gamma_i^{(i-1)}} \text{ for } i \geq 1$$

where the step η is sufficiently small to achieve convergence. We denote the iterations with the top index i, and not k as in the previous sections, because this algorithm runs within each step k of the repeated game.

Despite its simplicity, this solution raises two issues. First, the nodes need to know the packet value α and the transmission cost β. But these two parameters are known only by the application and the physical layer, respectively. Therefore, such an implementation may require a cross-layer architecture. Second, setting the parameter η implies a trade-off between speed of convergence and stability. Both these issues are left for future research.

9.2 Anonymous Challenge Messages

An alternative solution to the tolerance setting problem is based on the direct estimation of the channel quality. This can be done with the help of the so-called Anonymous Challenge Messages (ACM), as implemented in Catch [8]. ACM packets are control messages, whose MAC address has been erased or scrambled, in order to hide the sender identity. Their content is not important, and the payload can be filled with padding, provided that ACM packets have the same size of data packets.

When a node needs to estimate the channel quality, it will send an ACM packet to a neighbor, which will have to broadcast it. Broadcasting is necessary because a unicast request may disclose some hints about the sender identity. The identity has to be kept secret because some nodes my be willing to cooperate with some nodes, and to defect others. The key idea is that the tested node is forced to broadcast the ACM packet by the threat of a severe punishment, like a long-term disconnection, if it fails to do so. Since the ACM dropping probability is $p_i^{ACM} = 0$, the perceived ACM defection rate reduces to

$$\hat{p}_i^{ACM} = 1 - (1 - \lambda)^n$$

which is actually the value of the optimal tolerance threshold required by the punishment strategy.

The main disadvantage of this solution is that it introduces a certain quantity of control overhead, that may reduce the network throughput. Therefore, a trade-off between small overhead and precise estimation is involved.

10. CONCLUSION

In this paper, we have proposed a game-theoretic model for the performance analysis of hop-by-hop reputation-based mechanisms for ad-hoc wireless networks. The main result is that the emergence of cooperation among selfish nodes without central authority is possible, and depends on a wide range of factors, *i.e.*, traffic load, expected session length, application type, energy constraints and network topology. Therefore, the design of a "cooperation layer" appears to be a challenging issue, as it involves the whole protocol stack.

We plan to extend our model to include irregular topologies and non-uniform routing, that will introduce perception and interaction asymmetries that could impair cooperation. However, nodes' mobility could turn out to be helpful, by producing a long-term uniformity. We also plan to use simulation to further extend our understanding of implementation issues not covered by our model, such as the rate of convergence of the algorithms to set the tolerance, the externalities introduced by an end-to-end congestion control, and the sensitivity of punishment strategies to errors in reputation estimation.

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