DARWIN: Distributed and Adaptive Reputation mechanism for Wireless ad-hoc Networks

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Outline

- Introduction
- Basic Game Theory Concepts
- Network Model
- Prior Reputation Mechanisms
- New Reputation Scheme: DARWIN
- Conclusion / Further Work

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Introduction

- In mobile ad-hoc networks, cooperation among nodes is required.
  - In such networks, nodes are self-configuring and do not rely on an infrastructure to communicate.
  - Typically, a source communicates with a distant destination in a multi-hop fashion by using intermediate nodes as relays.
- There can be selfish users who want to maximize their own welfare.
- Incentive mechanisms are necessary to enforce nodes to cooperate with each other.
- Two types of incentive mechanisms:
  - Credit-exchange systems
  - Reputation-based systems

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Introduction (cont.)

- Credit-exchange systems
  - Node receives a payment every time they forward a packet.
  - This credit can be used to encourage others to cooperate.
  - Methods are needed to store credit without being tampered.
    - Tamper-proof hardware
    - Off-line central trusted authority
- Reputation-based systems
  - A node's behavior is measured by its neighbors.
  - Selfishness is deterred by the threat of partial or total disconnection from the network.
  - Due to packet collisions and interference, measurement is not perfect.
    - Sometimes, cooperative nodes will be perceived selfish.
    - This can trigger a retaliation situation.

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Introduction (cont.)

- Contributions
  - Analyze previously proposed reputation strategies.
    - Design a simple network model.
    - Provide an understanding of the impact of imperfect measurements on the robustness of reputation strategies.
  - Propose a new strategy called "DARWIN" (Distributed and Adaptive Reputation mechanism for Wireless ad-hoc Networks).
    - Prove DARWIN's following properties:
      - Achievement of full cooperation among nodes,
      - Robustness to imperfect measurements,
      - Collusion-resistant.

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Basic Game Theory Concepts

- The Prisoners' Dilemma
  - Two possible pure strategies: Cooperate (C) or Defect (D)
  - Payoffs corresponding to their actions:

		Player 2: Cooperate		Player 2: Defect	
Player 1	Cooperate	1	1	−1	2
	Defect	2	− 1	0	0

  - Strategy space S_i for player i: $S_i = \{C, D\}$
  - Strategy profile: an element of the product-space of strategy spaces of each player
    - For this example, there are four possible strategy profiles: (C, C), (C, D), (D, C), and (D, D).

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Basic Game Theory Concepts (cont.)

- Nash Equilibrium (NE)
  - A Nash equilibrium is a strategy profile having the property that no player can benefit by unilaterally deviating from its strategy.
- Repeated games (for infinite case)
  - Before *k*-th stage begins, *k-1* preceding plays are observed.
  - Total payoff of the game for player *i* is the discounted sum of the stage payoffs.
    - Player *i*'s total payoff: $U_i = \sum_{k=0}^{\infty} w^k u_i^{(k)}$
    - This game can be interpreted as a repeated game that ends after a random number of repetitions.
    - Game length is a geometric random variable with mean *1/(1-w)*.

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Basic Game Theory Concepts (cont.)

  - In a repeated game, a player's strategy specifies the action it will take at each stage, for each possible history of play through previous stages.
  - A subgame of the original game is defined to be a game starting at stage *k* with a given history h^k.
- Equilibrium path
  - For a given set of strategies that are in Nash equilibrium, history h^k is on the equilibrium path if it can be reached with positive probability if the game is played according to the equilibrium strategies, and is off the equilibrium path otherwise.

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Basic Game Theory Concepts (cont.)

- Subgame Perfect Nash Equilibrium (SPNE)
  - A Nash equilibrium is subgame perfect if the player's strategies constitute a Nash equilibrium in every subgame.
  - Subgame perfection is a stronger concept that eliminates "noncredible" equilibria.
- Game being continuous at infinity
  - A game is continuous at infinity if for each player *i*, the payoff U_i satisfies:

$$\sup_{h,\tilde{h}\ s.t.\ h^k=\tilde{h}^k} \left| U_i(h) - U_i(\tilde{h}) \right| \rightarrow 0\ as\ k \rightarrow \infty$$

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Basic Game Theory Concepts (cont.)

- One-Stage Deviation Principle
  - In an infinite-horizon multi-stage game with observed actions that is continuous at infinity, strategy profile *s* is subgame perfect if and only if no player *i* and strategy $\hat{s}_i$ that agrees with s_i except at a single stage *k* and h^k, and such that $\hat{s}_i$ gives a better payoff than s_i conditional on history h^k being reached.

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Network Model

- Nodes are selfish, but not malicious.
  - Selfish node is a rational user, so it wants to maximize its own welfare.
- Interaction among nodes is reciprocal.
  - Any two neighbors have uniform network traffic demands and need each other to forward packets.
  - Thus, it can be modeled as a two player's game.
- Time is divided into slots.
- In each time slot, each node decide whether to forward or drop the other's packet.
  - A mixed strategy is also possible by choosing a packet-dropping probability.

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Network Model (cont.)

- Payoff matrix of the packet forwarding game

		Node 2: Forward		Node 2: Drop	
Node 1	Forward	$\alpha - 1$	$\alpha - 1$	$-\alpha - 1$	α
	Drop	α	$-\alpha - 1$	$-\alpha$	$-\alpha$

- Normalized payoff matrix

		Node 2: Forward		Node 2: Drop	
Node 1	Forward	1	1	$\frac{-1}{2\alpha-1}$	$\frac{2\alpha}{2\alpha-1}$
	Drop	$\frac{2\alpha}{2\alpha-1}$	$\frac{-1}{2\alpha-1}$	0	0

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Network Model (cont.)

- Discounted average payoff
  - Perceived dropping probability

$$\hat{p}_{-i}^{(k)} = p_{-i}^{(k)} + (1 - p_{-i}^{(k)})p_e = p_e + (1 - p_e)p_{-i}^{(k)}$$

  - Average payoff at time slot *k*

$$u_i^{(k)} = (1 - p_i^{(k)})(1 - p_{-i}^{(k)}) + \frac{2\alpha}{2\alpha - 1}p_i^{(k)}(1 - p_{-i}^{(k)}) - \frac{1}{2\alpha - 1}(1 - p_i^{(k)})p_{-i}^{(k)}$$
$$= 1 + \frac{1}{2\alpha - 1}p_i^{(k)} - \frac{2\alpha}{2\alpha - 1}p_{-i}^{(k)}$$

  - Discounted average payoff of player *i* starting from time slot *n*

$$U_i^{(n)} = \sum_{k=n}^{\infty} w^{k-n} u_i^{(k)}$$

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Prior Proposals – Trigger Strategies

- *n*-step Trigger Strategy

$$\tilde{p}_{i\ nT}^{(0)} = 0$$
$$\tilde{p}_{i\ nT}^{(k)} = \begin{cases} 0 & if\ \hat{p}_{-i}^{(j)} \le T\ for\ all\ j \in \{k-n, \ldots, k-1\} \\ 1 & else \end{cases}$$

  - If node *i* cooperates, $\hat{p}_{-i}^{(k)} = p_e$ for all k. Thus, $T = p_e$ is optimal.
  - Actually, perfect estimation of p_e is not possible.
  - Thus, we have two cases:
    - If $T < p_e$ then $\tilde{p}_{i\ nT}^{(k)} = 1$ for $k \ge 1$, so cooperation will never emerge.
    - If $T > p_e$ then player $-i$ will be perceived to be cooperative as long as it drops packets with probability: $p_{-i}^{(k)} \le \frac{T - p_e}{1 - p_e}$
  - Therefore, full cooperation is never the NE point with trigger strategies.

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Prior Proposals – Tit For Tat

- Tit For Tat (TFT) Strategy

$$\tilde{p}_{i\ TFT}^{(0)} = 0$$
$$\tilde{p}_{i\ TFT}^{(k)} = \hat{p}_{-i}^{(k-1)} \ for\ k \geq 1$$

  - Milan *et al.* [15] proved that this strategy does not provide the right incentive either for cooperation in wireless networks.

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Prior Proposals – Generous Tit For Tat

- Generous Tit For Tat (GTFT) Strategy

$$\tilde{p}_{i\ GTFT}^{(0)} = 0$$
$$\tilde{p}_{i\ GTFT}^{(k)} = \max\{\hat{p}_{-i}^{(k-1)} - g, 0\} \ for\ k \geq 1$$

  - A generosity factor *g* is introduced to TFT.
    - TFT does not take into account the fact that it is not always possible to determine whether a packet was relayed or not due to collisions.
  - Lemma 1: If both nodes do not deviate from GTFT strategy then the generosity factor that maximizes the discounted average payoff is $g^* \geq p_e$.

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Prior Proposals – GTFT (cont.)

- Theorem 1: GTFT is subgame perfect if and only if

$$g \le p_e \ and \ w > \frac{1}{2\alpha(1-p_e)}.$$

- Corollary 1: If both nodes use GTFT strategy then the cooperation is achieved on the equilibrium path if and only if $g=p_e$.
- If the interaction between two nodes lasts long enough then GTFT is a robust strategy even if it is not able to achieve full cooperation.
  - No node can gain by deviating from the expected behavior.
- In summary, GTFT is not satisfactory because in order to achieve full cooperation we need a perfect estimate of p_e.

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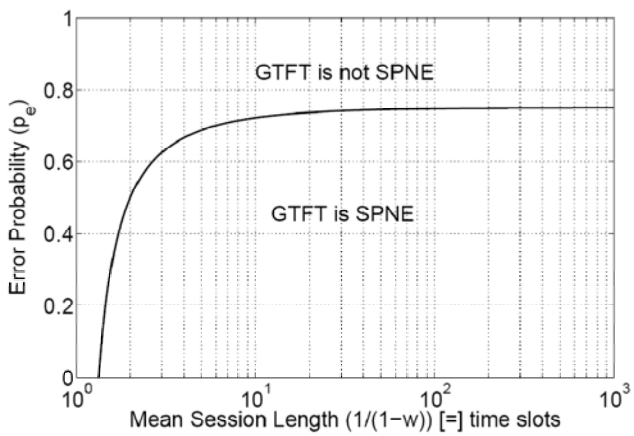
Prior Proposals – GTFT (cont.)

- GTFT's SPNE region for α=2



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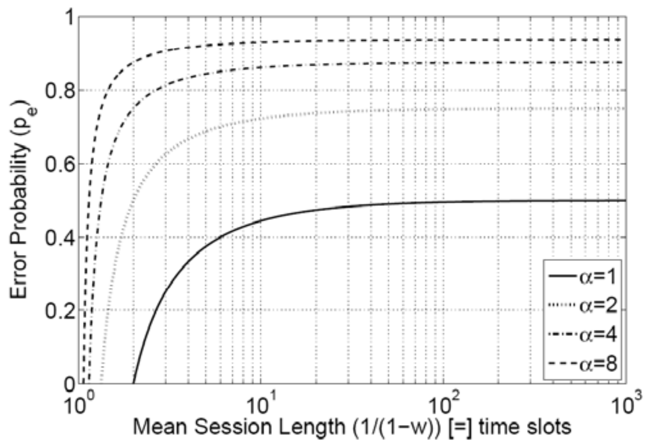
Prior Proposals – GTFT (cont.)

- Sensitivity of GTFT's SPNE region for different values of *α*



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DARWIN - Introduction

- Goal is to propose a reputation strategy that:
  - Does not depend on a perfect estimation of p_e to achieve full cooperation.
  - Is also more robust than previously proposed strategies.
- DARWIN is inspired by Contrite Tit For Tat (CTFT).
- CTFT strategy
  - Based on the idea of contriteness
  - A player that made a mistake and unintentionally defected should exercise contrition and try to correct error instead of going into a retaliation situation.

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DARWIN - Definition

- DARWIN strategy

$$\tilde{p}_{i\ DARWIN}^{(k)} = \left[\gamma\left(q_{-i}^{(k-1)} - q_i^{(k-1)}\right)\right]_0^1 \ for\ k \geq 0,$$

where for $i = \{1, 2\}$,

$$q_i^{(k)} = \begin{cases} \left[\hat{p}_i^{(k)} - \tilde{p}_{i\ DARWIN}^{(k)}\right]_0^1 & for \quad k \geq 0 \\ 0 & for \quad k = -1. \end{cases}$$

We define the function:

$$[x]_0^1 = \begin{cases} 1 & if \quad x \geq 1 \\ x & if \quad 0 < x < 1 \\ 0 & if \quad x \leq 0 \end{cases} .$$

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DARWIN – Performance Guarantees

- Theorem 2: Assuming $1 < \gamma < p_e^{-1}$, DARWIN is subgame perfect if and only if

$$w > \max\left\{\frac{1}{\gamma}, \frac{1}{2\alpha(1-p_e\gamma)+p_e\gamma}\right\}.$$

- Lemma 2: If both nodes use DARWIN then cooperation is achieved on the equilibrium path. That is, $p_i^{(k)} = p_{-i}^{(k)} = 0$ for all $k \geq 0$.
- Problem: We cannot obtain a exact value of p_e, then how do we determine a value of γ?
  - By using a estimate of p_e, $p_e^{(e)}$, we set $\gamma = \frac{1+p_e^{(e)}}{2p_e^{(e)}}$.

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DARWIN – Performance Guarantees (cont.)

- Robustness to an imperfect estimate of p_e
  - Estimated error probability is defined as

$$p_e^{(c)} = p_e + \Delta,$$

where $\Delta \in (-p_e, 1-p_e)$ is the estimation error.

  - Then, we have

$$\gamma = \frac{1 + p_e^{(e)}}{2p_e^{(e)}} = \frac{1 + p_e + \Delta}{2p_e + 2\Delta}.$$

  - The assumption of Theorem 2, $\gamma < p_e^{-1}$, is true if and only if

$$\Delta > -p_e \left(\frac{1 - p_e}{2 - p_e} \right).$$

  - Thus, an estimate that overestimates p_e is sufficient.

DARWIN – Collusion Resistance

- Scenario: a group of colluding nodes work together to maximize their own benefit regardless of the social optimum
  - Define the following notations:
    - $U_{i\ S_i|S_{-i}}^{(0)}$: discounted average payoff of player *i* using strategy S_i when it plays against player –*i* using strategy S_{-i};
    - $p_S \in (0, 1)$: probability that a node that implements DARWIN interacts with a colluding node;
    - $p_D \in (0, 1)$: probability that a colluding node interacts with a node implementing DARWIN.
  - Since DARWIN is the best any strategy S can achieve,

$$U_{i\ S|S}^{(0)} \leq U_{i\ D|D}^{(0)} \ \textit{for any strategy } S.$$

DARWIN – Collusion Resistance (cont.)

- As a consequence of Theorem 2, we also have that for any strategy $S \neq D$ = DARWIN,

$$U^{(0)}_{i\ S|D} < U^{(0)}_{i\ D|D}.$$

- Then, the average payoff to a cooperative node is

$$U(D) = p_S U^{(0)}_{i\ D|S} + (1 - p_S) U^{(0)}_{i\ D|D}.$$

- Similarly, we have that

$$U(S) = p_D U^{(0)}_{i\ S|D} + (1 - p_D) U^{(0)}_{i\ S|S}.$$

- The average payoff is bounded by

$$U(S) < \max\left\{U^{(0)}_{i\ S|D}, U^{(0)}_{i\ S|S}\right\}.$$

- A group of colluding nodes cannot gain from unilaterally deviating if and only if *U(S)* < *U(D)*, equivalently,

$$p_S\left[U^{(0)}_{i\ D|D} - U^{(0)}_{i\ D|S}\right] < U^{(0)}_{i\ D|D} - U(S).$$

DARWIN – Collusion Resistance (cont.)

- We obtain by using previous equations that

$$U^{(0)}_{i\ D|D} - U(S) > 0.$$

- Define strategy *S* to be a "sucker strategy" if

$$U^{(0)}_{i\ D|D} < U^{(0)}_{i\ D|S}.$$

- Then, we have the following theorem.
- Theorem 3: DARWIN is collusion resistant against a sucker strategy. Furthermore, it is resistant against a non-sucker strategy if and only if

$$p_S < \frac{U^{(0)}_{i\ D|D} - U(S)}{U^{(0)}_{i\ D|D} - U^{(0)}_{i\ D|S}}.$$

- Thus, if cooperative nodes mostly interact among each other then DARWIN can resist group attacks.

Simulations - Setting

- Settings
  - Network simulator: ns-2
  - Propagation model: two-ray ground reflection model
  - MAC Layer: IEEE 802.11 Distributed Coordination Function
  - Routing: Dynamic Source Routing protocol
  - Network Area: 670 x 670 m^2
  - Transmission range: 250 *m*
  - 50 nodes are randomly placed, and 5 nodes are selfish.
  - There are 14 source-destination pairs.
  - Each source transmit at a constant bit rate of 2 packets/s.
  - Simulation time: 800 seconds
  - γ =2

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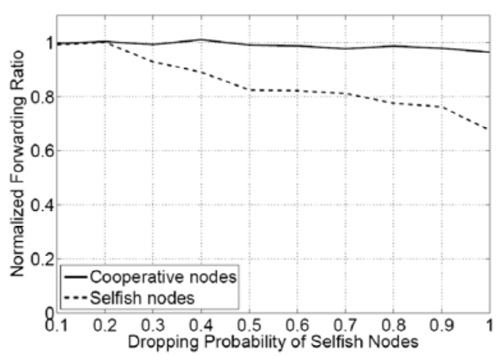
Simulations - Results

- Normalized throughput for different dropping ratios
  - Normalized forwarding ratio =
    (fraction of forwarded packets in the network under consideration) /
    (fraction of forwarded packets in a network without selfish nodes)



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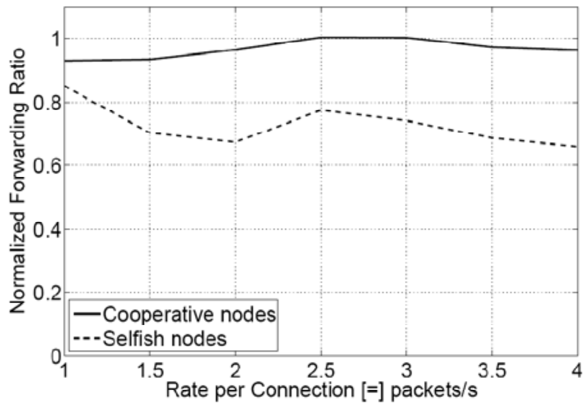
Simulations - Results

- Normalized throughput for different connection rates
  - Dropping probability of selfish nodes is equal to 1.



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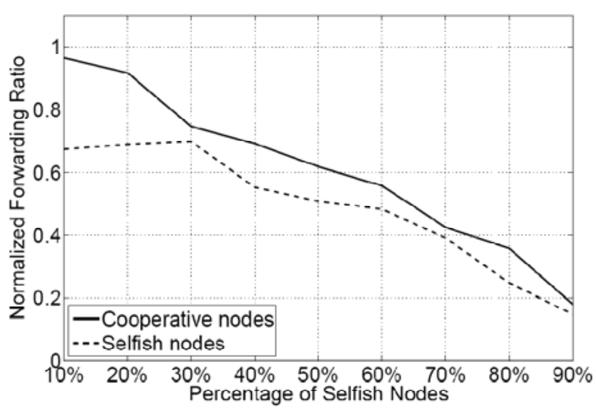
Simulations - Results

- Normalized throughput for different number of selfish nodes
  - Dropping probability of selfish nodes is equal to 1.



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Conclusions/Further Works

- Studied how reputation-based mechanisms can help cooperation emerge among selfish users.
  - Showed the properties of prior reputation mechanisms.
    - For full cooperation, they rely on the perfect measurement of packets dropped due to natural causes.
  - Proposed a new mechanism called DARWIN, which
    - Achieves full cooperation among nodes,
    - Is robust to imperfect measurements,
    - Is Collusion-resistant.
- Possible future works:
  - Study impact of lies about perceived probability
  - Study reputation mechanisms in the case of being malicious nodes in networks

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