Cooperation in Wireless Ad Hoc Networks

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May 6, 2008

Introduction

Wireless Ad Hoc Network

- Nodes can forward traffic for one another
- Energy constraints, like battery life, prevent nodes from forwarding all traffic
- Assuming that nodes are rational, how can traffic be routed to minimize throughput and maximize node lifetime?

Wireless Ad Hoc Network Model

- A finite set N of nodes(laptops, PDAs, etc)
- Power constraints on each node
- One session per time slot, one time slot per session
- Trade-off between routing traffic and battery-life
- Nodes route in a manner that is selfish, rational

Normalized Acceptance Rate(NAR)=

$$\frac{\text{successful relay requests made}}{\text{relay requests made}}$$

Contributions

- Assumes selfish nodes with known energy constraints and lifetime expectation
- Determines feasible set of NARs
- Identifies set of strategies that obtains a Pareto optimal Nash Equilibrium
  - Nash Equilibrium: No change in an individual node's strategy will improve it's NAR
  - Pareto optimal: No change in strategy will improve one node's NAR without decreasing another's
- GTFT algorithm that attains Nash equilibrium and Pareto optimality

Wireless Ad Hoc Network Model

- N nodes distributed among K classes
- Nodes in class i have energy constraint E_i and lifetime expectation L_i
- Average power constraint $\rho_i = E_i/L_i$ and $\rho_1 > \rho_2 > ... > \rho_k$
- In each timeslot, source chosen from uniform distribution on nodes
- Maximum number of relays M to reach destination
- Distribution on the number of relays used, $q(l)$. $q(0) = 0$, i.e. no direct transmissions.

Wireless Ad Hoc Network Model

- Relays randomly and uniformly selected from non-source nodes
- Relays accept or reject with ACKs
- If a single relay reject, session is blocked
- A session is type j if at least one node belongs to class j and all other nodes belong to class less than or equal to j.
- Node with smallest power constraint dominates a session's interaction
- Energy in transmit mode dominates energy for receiving and processing, so only transmission energy is considered

Wireless Ad Hoc Network Model

$B^j_h(k)$ number of relay requests made by node h for session type j until time k

$A^j_h(k)$ number of relay requests made by node h for session type j until time k that have been accepted

$$\phi^j_h(k) = A^i_h(k)/B^i_h(k)$$

$D^j_h(k)$ number of relay requests made to node h for session type j until time k

$D^j_h(k)$ number of relay requests made to node h for session type j until time k that have been accepted

$$\psi^j_h(k) = C^i_h(k)/D^i_h(k)$$

Rational and Pareto Optimal Operating Point

$$\lim_{k\to\infty} \phi_h^j(k) = \lim_{k\to\infty} A_h^i(k)/B_h^i(k) = \text{NAR}$$

This is the throughput for node h and session type j
NAR values

1. Energy constraints on each node met
2. Pareto optimal values attained
3. All rational agents find allocation fair

Rational and Pareto Optimal Operating Point

Average energy per session spent by a node p as a source

$$e_{pj}^{(s)} = \frac{1}{N} \times \text{NAR}$$

$$= \frac{1}{N} \sum_{l=1}^{M} \sum_{h_1,\ldots,h_j} q(l)\Gamma(l; h_1, \ldots, h_j)\tau_{1j}^{h_1} \ldots \tau_{jj}^{h_j}$$

- $1/N$ is the probability the node p is the source
- $\Gamma(l; h_1, \ldots, h_K)$ is a multivariate probability function conditioned on the fact that the session belongs to type j with l relays. h_i refers to the number of relays of class i participating in the session
- $\tau_{1j}^{h_1} \ldots \tau_{jj}^{h_j}$ represents the probability that all the relay nodes accept the request

Rational and Pareto Optimal Operating Point

Average energy per session spent by a node p as a relay

$$e_{pj}^{(r)} = \frac{1}{N}\sum_{l=1}^{M} lq(l) \sum_{h_1,\ldots,h_j} \Gamma(l-1; h_1, .., h_j)\tau_{1j}^{h_1} \ldots \tau_{jj}^{h_j} \tau_{class(p)j}$$

The feasible region for the τ_{ij} is defined by

$$\sum_{j=1}^{K}(e_{pj}^{(s)} + e_{pj}^{(r)}) \leq \rho_{class(p)} \; 1 \leq p \leq N$$

$$\tau_{class(p)j} \in [0, 1] \; 1 \leq j \leq K; 1 \leq p \leq N$$

Rational and Pareto Optimal Operating Point

- Feasible points given by the triangular region
- Pareto optimal values occur on the boundry line between $(0, 2\rho)$ and $(2\rho, 0)$
- Increasing one node's NAR decreases another's NAR
- By symmetry, (ρ, ρ) is the unique Pareto optimal Nash equilibrium

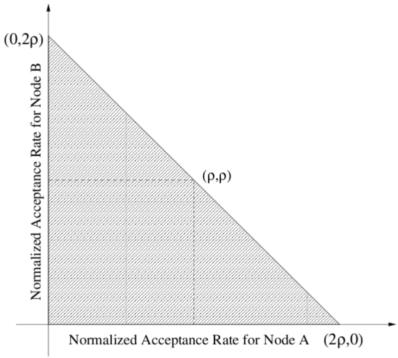

Fig. 1. Feasible Region for $N = 2$, $K = 1$, $\rho = 0.5$.

Rational and Pareto Optimal Operating Point

Lemma

$$\tau_{ij} = \tau_{jj} \quad 1 \leq i \leq j \leq K$$

One Class If all nodes are in the same class, then they will have the same NAR.

Multiple Classes If nodes are in multiple classes in the same session, then nodes with higher power have no incentive to accept with a higher probability than the lower powered nodes which are constraining the session.

Rational and Pareto Optimal Operating Point - Example

For $M = 1, q(1) = 1$:

$$e_i^{(s)} = \frac{1}{N(N-1)}\left[\sum_{k=1}^{i-1} n_k\tau_i + (n_i - 1)\tau_i + \sum_{l=i+1}^{K} n_l\tau_l\right]$$

$$e_i^{(r)} = \frac{1}{N(N-1)}\left[\sum_{k=1}^{i-1} n_k\tau_i + (n_i - 1)\tau_i + \sum_{l=i+1}^{K} n_l\tau_l\right]$$

$$e_i^{(s)} + e_i^{(r)} = \rho_i$$

For $K = 1$:

$$2 \cdot \left[\frac{\tau(N-1)}{N(N-1)}\right] = \rho$$

$$\tau = N\rho/2$$

Routing Strategy

Given that we can compute the optimal NAR values for all nodes, how can we determine when to except or reject relay requests?

- Stationary strategies are dominated by the *always-deny* selfish strategy
- Addaptive history-based strategies can prevent exploitation by selfish nodes
- Pareto optimal solution should be obtained and maintained across iterative turns

Prisoner's Dilemma

	Confess	Not Confess
Confess	$(-5, -5)$	$(0, -10)$
Not Confess	$(-10, 0)$	$(-1, -1)$

Single turn
: Nash Equilibrium (C,C) is Pareto dominated by (NC,NC)

GTFT
: Pareto optimal solution (NC,NC) is obtained by repeatedly playing the opponents previous move(occasionally cooperating regardless of previous move)

GTFT

Each node maintains

1. $\phi_h^i(k)$ ratio of accepted relay requests from h
2. $\psi_h^j(k)$ ratio of accepted relay requests to h

Reject iff

$$\psi_h^j(k) > \tau_j \text{ or } \phi_h^j(k) < \psi_h^j(k) - \epsilon$$

1. node h has relayed more traffic for type j sessions than what it should based on its optimal NAR
2. node h has relayed more traffic for type j than other nodes in type j have relayed for h

ϵ is the generosity parameter

m-GTFT

If the number of relays in a path is greater than 1, then the amount of cooperation provided is always greater than the amount of cooperation received. GTFT can be modified using a normalization factor

$$L_{ij} = \frac{\text{Prob}(h \text{ is served in a type } j \text{ session})}{\text{Prob}(h \text{ accepts to relay a type } j \text{ session})}$$

Reject iff

$$\psi_h^j(k) > \tau_j \text{ or } \phi_h^j(k) < L_{ij}\psi_h^j(k) - \epsilon$$

m-GTFT

Theorem

Consider a system with N nodes, K classes, $M > 1$, $q(l) > 0$, $l = 1, ..., M$, n_i nodes in class i, $i = 1, ..., K$, and energy constraints $\rho_1 > \rho_2 > ... > \rho_k$. Then,

1. *If all nodes except node h are employing m-GTFT, then* $\limsup_{k\to\infty} \phi_h^j(k) \leq \tau_j$
2. *If all nodes employ m-GTFT, then all $\phi_h^j(k)$ converge to* $\tau_j (h = 1, ..., N; i, j = 1, ..., K)$

GTFT and m-GTFT constitute a Nash Equilibrium and converge to the rational Pareto optimal operating points.

Results

GTFT Validated using simulations

- 25 nodes, 5 classes of nodes
- $\rho_1 = 0.03, \rho_2 = 0.025, \rho_3 = 0.02, \rho_4 = 0.015, \rho_5 = 0.01$
- Single relay sessions

m-GTFT Validated using simulations

- 12 nodes, 2 classes of nodes
- $\rho_1 = 0.03, \rho_2 = 0.015$
- One and two relay sessions

Results

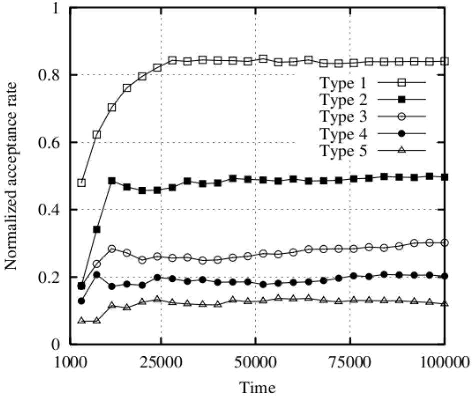

Fig. 2. NAR versus time when $N = 25$, $K = 5$, $q(1) = 1$, $M = 1$, and all nodes employ GTFT. NAR values converge to the optimal operating point.

Results - Generosity

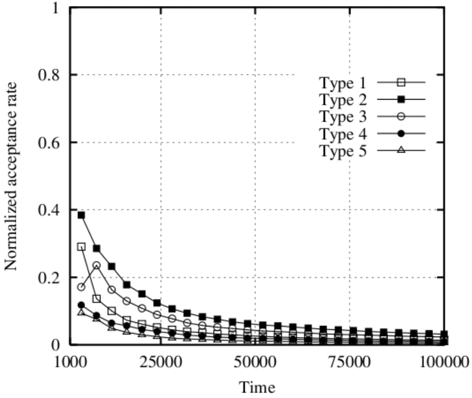

Fig. 3. NAR versus time when $N = 25$, $K = 5$, $q(1) = 1$, $M = 1$, all nodes employ GTFT, and $\epsilon < 0$. If nodes are not slightly generous ($\epsilon > 0$), GTFT fails to reach the optimal operating point.

Results - Parasitic Nodes

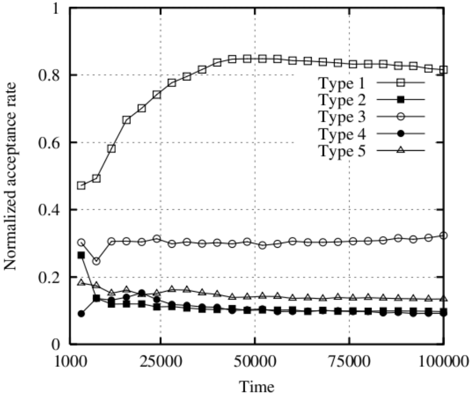

Fig. 4. NAR versus time when $N = 25$, $K = 5$, $q(1) = 1$, $M = 1$, and one node in class 2 and one node in class 4 are parasites while all other nodes employ GTFT. Performance of nodes in type 2 and type 4 sessions degrade showing that GTFT prevents parasitic behavior in rational users.

Results - m-GTFT

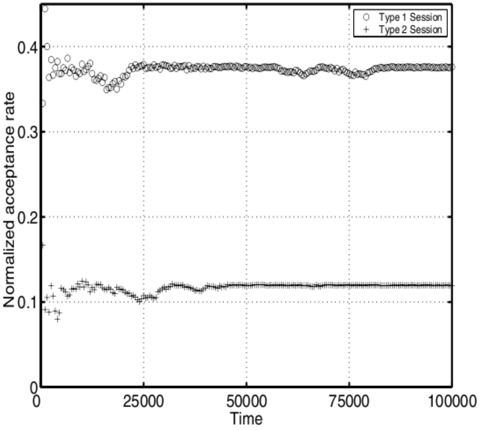

Fig. 5. Convergence of m-GTFT for $N = 12$, $K = 2$, $\rho_1 = 0.03$, $\rho_2 = 0.015$, $q(1) = q(2) = 0.5$, and $M = 2$.

Discussion

- GTFT adapts based on the optimal NAR values, but these must be computed, requiring every node to have knowledge of other nodes and their energy constraints
- Distributed mechanism necessary to disseminate infomation to all users
- Malicious irrational users can reduced the performance of networks by denying all requests, watchdog mechanism necessary to identify such nodes