Journées non-thématiques RESCOM 2019

Performance of a fixed reward incentive scheme for two-hop DTNs with competing relays

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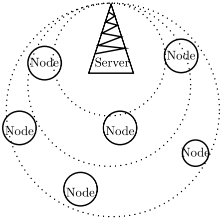
Outline

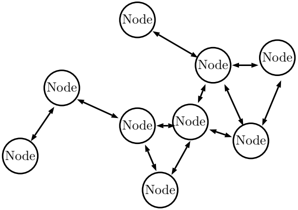
Incentive Mechanisms for DTNs

Mobile Ad-hoc Networks (MANETs)

- A MANET is a network in which mobile devices can communicate wirelessly without any pre-existing infrastructure.



Infrastructure-based Network



Mobile Ad-hoc Network

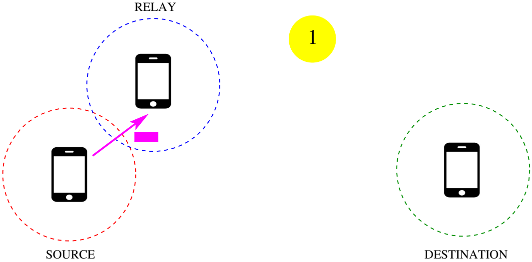
- Topology discovery and packet delivery are executed by the nodes themselves
- Specific routing protocols are used to maintain up-to-date routes in spite of constant topological changes

Delay Tolerant Networks (DTNs)

- A MANET in which network partitioning is the rule
  - Communication opportunities are short and sporadic
  - End-to-end connectivity is only intermittent
- How to deliver packets to their destination in spite of network partitioning and with only limited information about the network?
  - Store-carry-and-forward paradigm: mobile nodes play the role of relays which store the message and carry it until they can forward it to the destination or to another relay.
  - Replication-based routing: the network is flooded with many copies of the same message in hopes that one of the copies will eventually reach the destination.

Two-hop routing

- A relay cannot forward the message to another relay.



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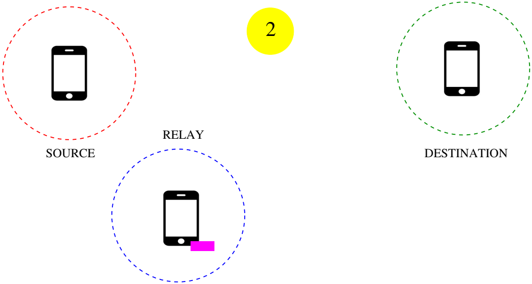

Two-hop routing

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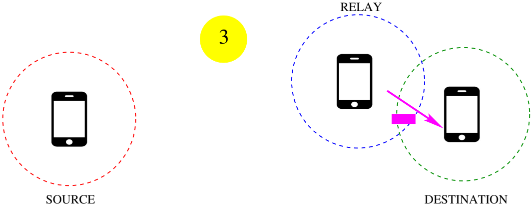


Incentive mechanisms for DTNs

- Replication-based routing implicitly assumes that mobile nodes accept to use their scarce energy resources for relaying messages of others out of altruism,
- Free-rider problem: nodes use network resources but do not provide anything in return
- How to persuade mobile nodes to participate in relaying messages?
  - Reputation-based schemes: record the behaviour of nodes and propagate this information to all nodes.
  - Barter-based schemes: based on immediate exchange of services (e.g. Tit for Tat in BitTorrent)
  - Credit-based schemes: money (or some virtual currency) is given in exchange for a service

Objective

- Analysis of an incentive mechanism in which the source promises to each relay a fixed reward R, but only the first one to deliver the message gets it.
- Decision problem: when it meets the source, each relay decide whether to accept or not the message, and how long to keep it, so as to minimize

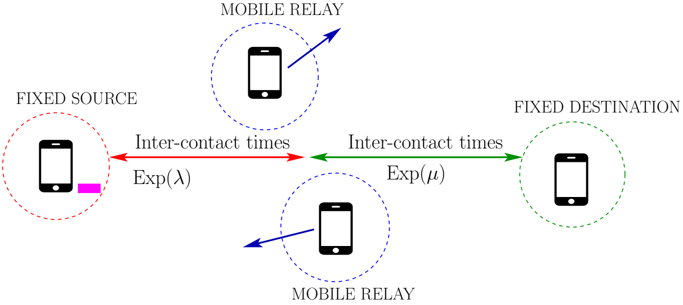
$$\text{expected delivery cost} - R \times \text{probability to win}$$

- Competitive game: the optimal decision of a relay depends on the strategies of the other relays
    - ✔ Formulation as a Bayesian Game to account for the unknown meeting times of the other relays with the source
- Characterization of the symmetric equilibria of this game
- Explicit expressions of delivery ratio and mean delivery time
    - ✔ help the source provide an adequate reward

Assumptions and Game Description

Players

- Network of wireless nodes with one source and one destination, both are fixed, and N mobile relays
  - ✔ homogeneous mobility, exp. distributed inter-contact times



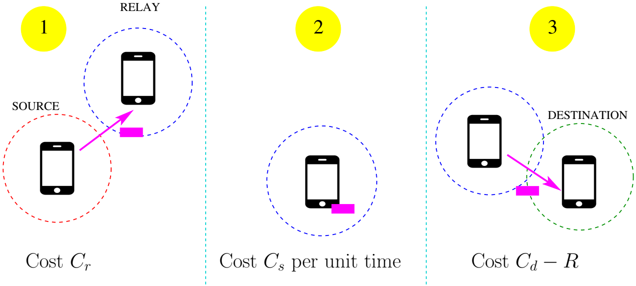
- Source proposes messages to the relays one by one.

Actions and types

- Actions – when it meets the source, relay i chooses $s_i \in \mathcal{S}_i = [0, +\infty)$
  - ✔ $s_i = 0$ implies that the message is rejected,
  - ✔ $s_i > 0$ implies that the message is accepted and kept for s_i time units
- Types – the type of relay i is its meeting time $t_i \in \mathcal{T}_i = [0, +\infty)$ with the source, relative to the generation instant of the message
  - ✔ The type of the other relays is unknown (private information)
  - ✔ Each relay i has a belief on the type of the other relays $\implies$ joint density $d\hat{\Phi}_{-i}(\mathbf{t}_{-i} \mid t_i)$
- A pure strategy for relay i is a function $\pi_i : T_i \to S_i$ that determines the strategy for each possible type of player i.

Cost Structure

- Fixed reward R for the first relay to deliver a message.
- Cost structure



- $\bar{R} = R - C_d$ is the net reward won by the first relay to deliver a message
- We assume that $R > R_{min} = C_r + \frac{C_s}{\mu} + C_d$.

Cost Structure (2)

- Let $\rho_i(\tau; s_i, \pi_{-i}(\mathbf{t}_{-i}); t_i, \mathbf{t}_{-i})$ be the probability of relay i winning the reward
- Cost of relay i

$$u_i(s_i, \pi_{-i}(\mathbf{t}_{-i}); t_i, t_{-i}) = \begin{cases} 0 & \text{if } s_i = 0; \\ C_r + F_i(s_i, \pi_{-i}(\mathbf{t}_{-i}); t_i, \mathbf{t}_{-i}) & \text{if } s_i > 0. \end{cases}$$

where

$$F_i(s_i, \pi_{-i}(\mathbf{t}_{-i}); t_i, \mathbf{t}_{-i}) = \int_0^{s_i} \left\{ C_s \tau - \bar{R} \rho_i(t_i + \tau; s_i, \pi_{-i}(\mathbf{t}_{-i}), t_i, \mathbf{t}_{-i}) \right\} \mu e^{-\mu\tau} d\tau$$
$$+ e^{-\mu s_i} C_s s_i,$$

is the cost of keeping the message for duration s_i given t_i, s_{-i}, t_{-i}.

Bayesian Nash equilibrium (BNE)

- The strategy profile vector (π_i^*, π_{-i}^*) is a pure strategy BNE if

$$\begin{aligned}\pi_i^*(t_i) &= \text{argmin}_{s_i} \mathbb{E}_{\mathbf{t}_{-i}} \left[u_i(s_i, \pi_{-i}^*(\mathbf{t}_{-i})); t_i, \mathbf{t}_{-i}) \right] \\ &= \text{argmin}_{s_i} \int u_i(s_i, \pi_{-i}^*(\mathbf{t}_{-i})); t_i, \mathbf{t}_{-i}) d\hat{\Phi}_{-i}(\mathbf{t}_{-i}|t_i),\end{aligned}$$

  for all i.

- The existence of an equilibrium for games with continuum of types and actions is not known in general.

Symmetric Bayesian Nash Equilibrium

Characterization of BNE

- Expected cost of relay i

$$\begin{aligned}\bar{u}_i(s_i, \pi_{-i}; t_i) &= \mathbb{E}_{\mathbf{t}_{-i}}\left[u_i(s_i, \pi^*_{-i}(\mathbf{t}_{-i})); t_i, \mathbf{t}_{-i})\right], \\ &= \begin{cases} 0 & \text{if } s_i = 0; \\ C_r + G_i(t_i, t_i + s_i) & \text{if } s_i > 0. \end{cases}\end{aligned}$$

where

$$G_i(t, t+s) = \int_0^s \left[C_s\tau - \bar{R}p^i(t+\tau)\right] \mu e^{-\mu\tau} d\tau + e^{-\mu s} C_s s,$$

and

$$p^i(\tau) = \int \rho_i(\tau; s_i, \pi_{-i}(\mathbf{t}_{-i}), t_i, \mathbf{t}_{-i}) d\hat{\Phi}_{-i}(\mathbf{t}_{-i}|t_i)$$

is the (unconditional) probability of success of relay i

- The strategy profile vector (π^*_i, π^*_{-i}) is a pure strategy BNE iff $\pi^*_i(t_i) \in \text{argmin} \bar{u}_i(s_i, \pi_{-i}; t_i)$ for all i.

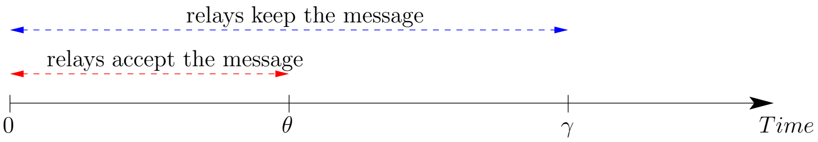
Characterization of BNE (2)

Theorem (Threshold-type policy)

Given the strategies of the other relays, there exist θ^i and $\gamma^i > \theta^i$ such that $\pi_i^*(t; \pi_{-i}) = 0$ if $t > \theta^i$ and $\pi_i^*(t; \pi_{-i}) = max(0, \gamma^i - t)$ otherwise.

$$\gamma^i = \sup\{x : p^i(x) > \frac{C_s}{\mu \bar{R}}\},$$

$$\theta^i = \sup\{x : C_r + G_i(x, \gamma^i) < 0\}.$$



- At a pure BNE, if any, all players use a threshold-type policy.
- A pure BNE can be asymmetric or symmetric.

Symmetric BNE

Theorem (Symmetric BNE for first message)

There exists a unique symmetric BNE with $\theta > 0$ if and only if $\bar{R} \geq C_r + \frac{C_s}{\mu}$. Moreover, the equilibrium thresholds are finite if and only if

$$1 + \mu \frac{C_r}{C_s} < \frac{(1+b)^N - 1}{N\, b},$$

where $b = \sigma^{-1}\left[1 - \left(\frac{C_s}{\mu \bar{R}}\right)^{\sigma/(N-1)}\right]$ and $\sigma = (\mu - \lambda)/\lambda$.

- Similar result for subsequent messages.

Symmetric BNE

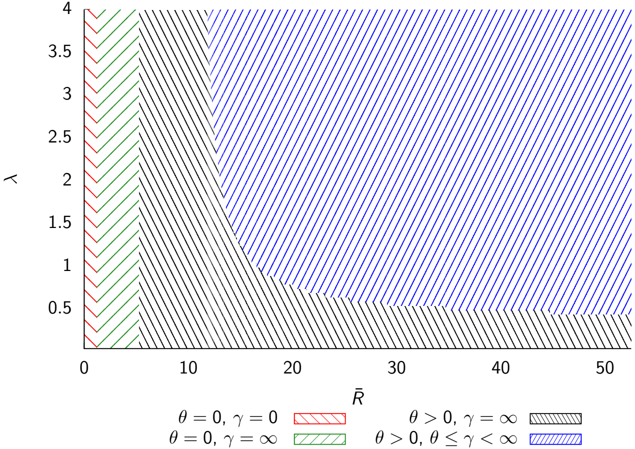


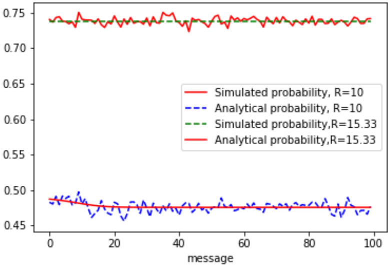
Figure: Existence of a symmetric Nash equilibrium for 3 relays.

Performance Metrics

Message delivery ratio

Delivery ratio of the k^{th} message

$$\xi_k = 1 - p_k(\gamma_k)^{N/N-1}$$



Comment: When $\gamma_k < \infty$, then ξ_k is a constant,

$$\xi_k = 1 - \left(\frac{C_s}{\mu \bar{R}}\right)^{N/N-1}$$

Expected Delivery Time

Proposition

$$D_k = \frac{1}{\zeta_k} \int_{\theta_{k-1}}^{\gamma_k} \left(p_k(t)^{\frac{N}{N-1}} - p_k(\gamma_k)^{\frac{N}{N-1}} \right) dt$$

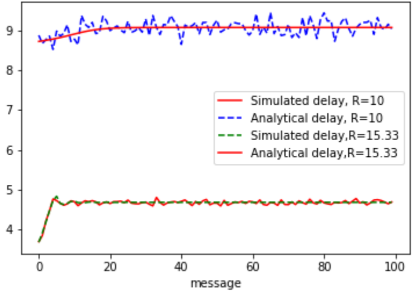
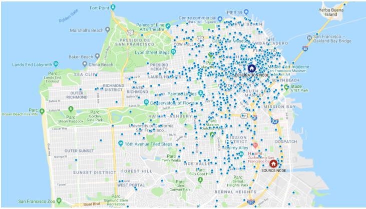


Figure: $R = 10$ ($\gamma_k = \infty$) and $R = 15.33$ ($\gamma_k < \infty$).

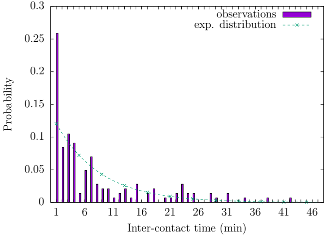
Validation against real mobility traces

GPS-based mobility traces of cabspotting project

- Collected in May 2008 in San Francisco: 30-days, 536 taxi cabs
- Source and a destination nodes in San Francisco, and 4 taxi cabs.



(a) Node positions



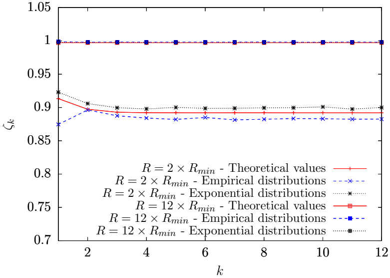
(b) Inter-contact times

- We choose $\frac{1}{\lambda}$ (resp. $\frac{1}{\mu}$) as the mean residual inter-contact time with the source (resp. destination)

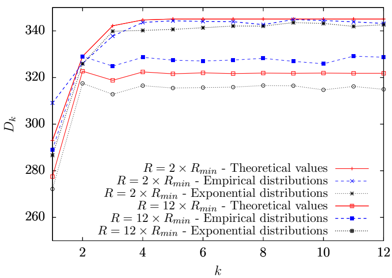
$$\frac{1}{\lambda} = \frac{m_2^s}{2m_1^s} \text{ and } \frac{1}{\mu} = \frac{m_2^d}{2m_1^d}$$

Validation against real mobility traces

- $R = 2R_{min}$ and $R = 12R_{min}$
- Event-driven simulations (100,000 sample paths) using inter-contact times randomly drawn from the empirical distributions.



(a)



(b)

Figure: (a) Delivery ratio and (b) expected delivery time of the first twelve messages.

Questions ?