Distributed Privacy-Protecting Routing in DTN: Concealing the Information Indispensable in Routing *

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* Majority was done when at Clemson

Outline

- Introduction
- System Design
- Performance Evaluation
- Conclusion

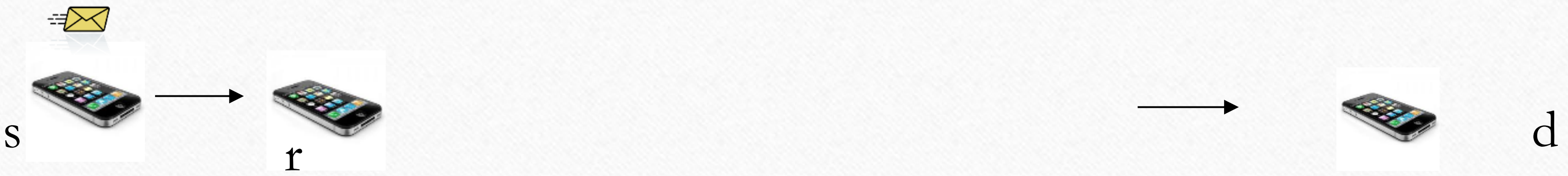
Introduction

- Delay/Disruption Tolerant Networks (DTNs)
  - A challenging form of mobile network
  - Nodes are sparsely distributed
  - Opportunistic node encountering
  - No infrastructure, only Peer-to-Peer communication

- Network Features
  - Limited resources
  - Frequent network partition and disconnection
  - End-to-end path cannot be ensured

Introduction

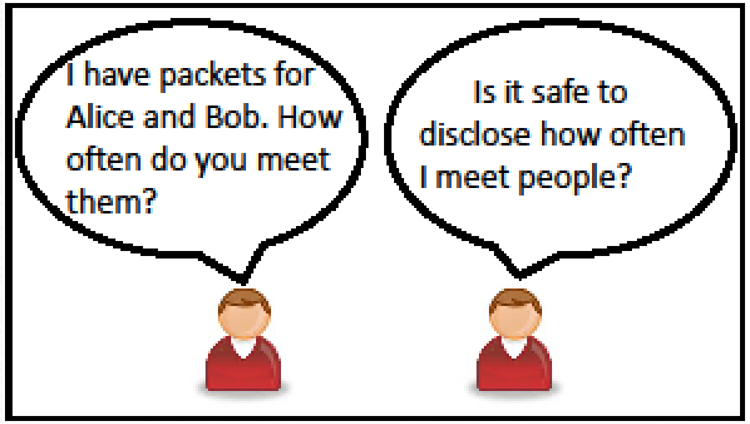
- Routing is possible
  - Often in a store-carry-forward manner



  - Utility based routing principle
    - Define a utility that represents how likely to meet a node (directly) or deliver a packet to a node (indirectly)
    - When two nodes meet, they exchange and compare routing utilities for each destination, and always forward a packet to the node with a higher utility value
  - Common utility definitions
    - Meeting frequency; social closeness; network centrality, etc.

Introduction

- Privacy concerns
  - Those routing utilities contain much private information
    - Meeting frequency, social relationship, locations, etc.
    - More severe in DTNs involving human-operated devices
      - Pocket switched network, Vehicular DTNs, etc.
  - Malicious nodes could take advantage of them
    - Fabricate routing utilities to attract and drop packets
    - Disseminate virus to specific targets or locations



Introduction

- Challenges
  - On one side, disclosing routing utilities is not privacy preserving
  - On the other side, DTN routing requires nodes to exchange such information
- Goal
  - Harmonizing both needs
  - Anonymizing such information by
    - Carefully disclosing partial routing utility information that is enough for correct routing
    - Altering the packet forwarding sequences

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System Design : Utility Anonymity

- Some definitions
  - Routing utility: $U_{ij} = \{n_i, n_j, v_{ij}\}$,
    - v_{ij} denotes n_i's utility value for n_j
  - Commutative encryption: $E(\cdot)$
    - $E_{k_1}\left(E_{k_2}(M)\right) = E_{k_2}\left(E_{k_1}(K)\right)$ for encryption key k_1 and k_2
  - Order-preserving hashing: $\mathrm{H}(\cdot)$
    - If $v_1 > v_2$, $\mathrm{H}(v_1) > \mathrm{H}(v_2)$

System Design : Utility Anonymity

- Observations
  - $U_{ij} = \{n_i, n_j, v_{ij}\}$ is anonymized when any of the three elements is anonymized (assume enough nodes in the network)
  - To ensure correct routing, two nodes just need to know the order of their utility values for the same destination
- Solution
  - Nodes exchange partially encrypted/hashed routing utility
  - Nodes could identify and compare routing utility for the same destination node
  - But at least one of three element is not disclosed to the other node

System Design : Utility Anonymity

- Illustration scenario
  - n_1 meets n_2 for packet forwarding
  - n_1 is selected as the node that will do utility comparison
  - n_1 pick key k_1 and hashing function H_1, n_2 pick key k_2 and hashing function H_2
- Step 1

$$n_1 \rightarrow n_2 : U'_{1x} = \left(n_1, E_{k_1}(n_x), v_{1x}\right)$$
$$n_2 \ generates \ U''_{1x} = \left(n_1, E_{k_2}(E_{k_1}(n_x)), H_2(v_{1x})\right)$$
$$n_2 \rightarrow n_1 : U''_{1x}$$

$$n_2 \rightarrow n_1 : U'_{2x} = \left(n_2, E_{k_2}(n_x), H_2(v_{2x})\right)$$
$$n_1 \ generates \ U''_{2x} = \left(n_2, E_{k_1}(E_{k_2}(n_x)), H_2(v_{2x})\right)$$

System Design : Utility Anonymity

- Step 2 n_1 *now has*
  $U''_{1x} = \left(n_1, E_{k_2}(E_{k_1}(n_x)), H_2(v_{1x})\right)$
  $U''_{2x} = \left(n_2, E_{k_1}(E_{k_2}(n_x)), H_2(v_{2x})\right)$
  Due to commutative encryption, routing utilities with the same n_x could be identified
  Due to order-preserving hashing, their utility values ($H_2(v_{1x})$ and $H_2(v_{2x})$) could be compared

- Step 3 n_1 *informs* n_2 *those destinations that it has a higher utility value*
  $n_1 \rightarrow n_2 : E_{k_2}(n_x)$ *if* $H_2(v_{1x}) > H_2(v_{2x})$

  n_2 decrypts and knows that n_1 is the forwarder for which dest. and informs n_1
  It further knows itself is the forwarder for which dest.

System Design : Utility Anonymity

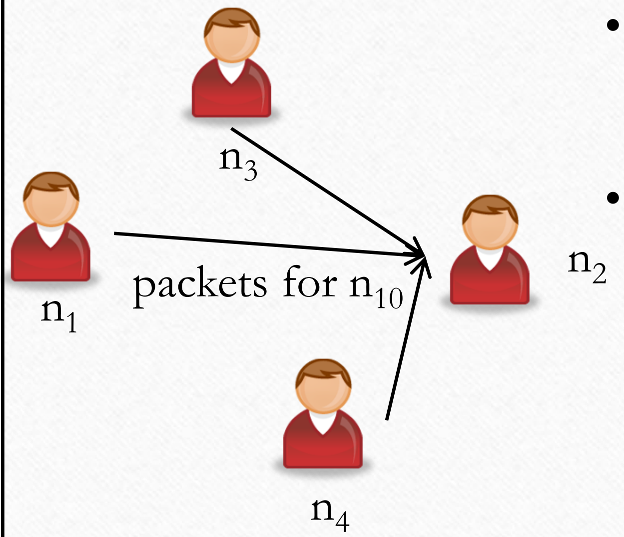
- Summary

Node	Information
n_1	$\mathcal{U}'_{1x} : \{\mathcal{E}_{k_1}(n_x), v_{1x}, n_1\}$
	$\mathcal{U}''_{1x} : \{\mathcal{E}_{k_2}(\mathcal{E}_{k_1}(n_x)), \mathcal{H}_2(v_{1x}), n_1\}$
	$\mathcal{U}'_{2x} : \{\mathcal{E}_{k_2}(n_x), \mathcal{H}_2(v_{2x}), n_2\}$
	$\mathcal{U}''_{2x} : \{\mathcal{E}_{k_1}(\mathcal{E}_{k_2}(n_x)), \mathcal{H}_2(v_{2x}), n_2\}$
n_2	$\mathcal{U}'_{2x} : \{\mathcal{E}_{k_2}(n_x), \mathcal{H}_2(v_{2x}), n_2\}$
	$\mathcal{U}'_{1x} : \{\mathcal{E}_{k_1}(n_x), v_{1x}, n_1\}$
	$\mathcal{U}''_{1x} : \{\mathcal{E}_{k_2}(\mathcal{E}_{k_1}(n_x)), \mathcal{H}_2(v_{1x}), n_1\}$

  - Anonymity is attained:
    - Each node can only get the utilities with at least one element encrypted/hashed
  - Routing is ensured
    - Routing utilities are successfully compared

System Design : Forwarder Anonymity

- Forwarder
  - The node that holds the packet (i.e., the node with the highest utility for the destination of the packet)
  - Such information is private too
    - Targeting a specific destination by tracking packets destined to the destination



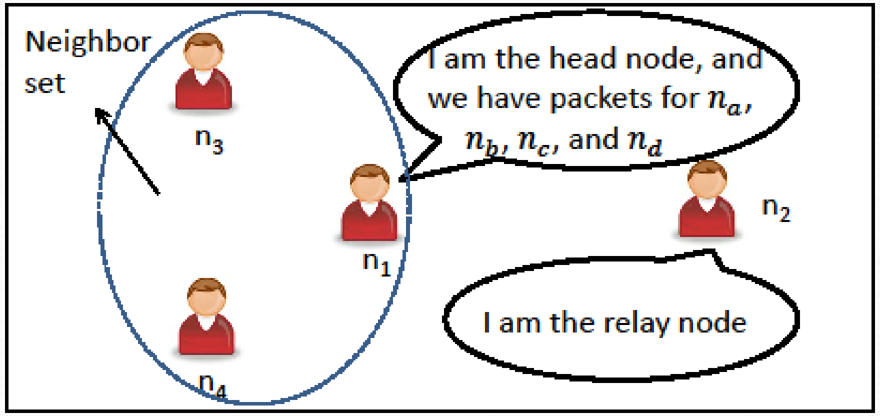
- n_2 has the highest utility value for n_{10} among all neighbors.
- It is the forwarder for packets destined to n_{10}

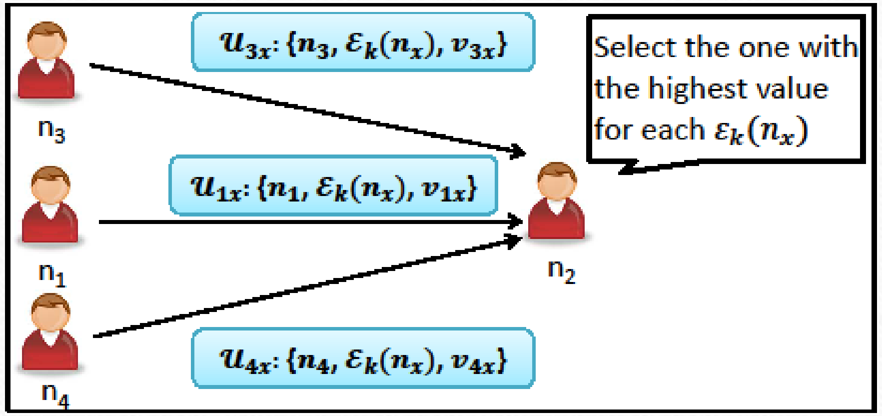
System Design : Forwarder Anonymity

- How to protect such forwarder information?
  - Forwarder information contains two parts: <dest., forwarder>
  - Hide one by changing the process of routing utility comparison and packet forwarding
    - Choose a relay node among the group of encountered nodes
    - The relay node knows the forwarder for each **encrypted** destination
  - Only applies when a group of nodes meet
    - No way to hide when only two nodes meet

System Design : Forwarder Anonymity

- Illustration scenario
  - n_1, n_2, n_3, n_4 meet for packet forwarding
  - n_2 is selected as the relay node, the remaining form the Neighbor set
  - n_1 is the head of the neighbor set and decides a group key k_n
- Step 1
  - Each node in the neighbor set encrypts its routing utility with k_n and send to n_2





System Design : Forwarder Anonymity

- Step 2

  n_1 and n_2 compare routing utilities from the neighbor set and those on n_2 following the method for Utility Anonymity.

- Step 3

  n_2 builds a relay table as the following

k_n-encrypted destination	Forwarder
$\mathcal{E}_{k_n}(n_a)$	n_1
$\mathcal{E}_{k_n}(n_c)$	n_3
$\mathcal{E}_{k_n}(n_d)$	n_4

System Design : Forwarder Anonymity

- Step 4

  n_1, n_3 , *and* n_4 *encrypt its packets' destination with* k_n *and send to* n_2 for relay

  n_2 searches the relay table and forward the packet if there is a hit, or keep the packet if not (itself is the forwarder)

- Summary
  - n_2 only knows the forwarder for each k_n-encrypted destination, so it cannot know the complete forwarder information
  - Others only know that packets are relayed by n_2

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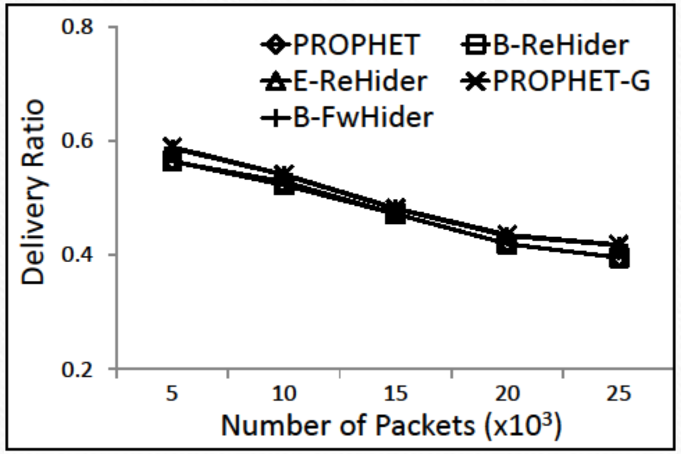
Evaluation

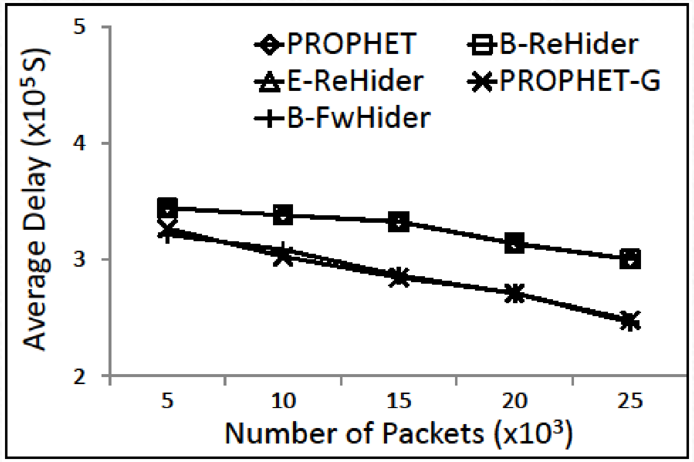
- Traces
  - Haggle: encountering of mobile devices in a conference
  - MIT Reality: encountering of mobile devices on a campus
- Methods
  - Privacy protection is analyzed in the paper
  - Measuring the routing performance with the proposed methods
    - Using PROPHET* as the baseline routing algorithm
    - PROPHET-G denotes extended pair-wise encountering assumption

*A. Lindgren, A. Doria, and O. Schelen, Probabilistic routing in intermittently connected networks. Mobile Computing and Communications Review, vol. 7, no. 3, 2003.

Evaluation : Routing Performance

- MIT Reality trace

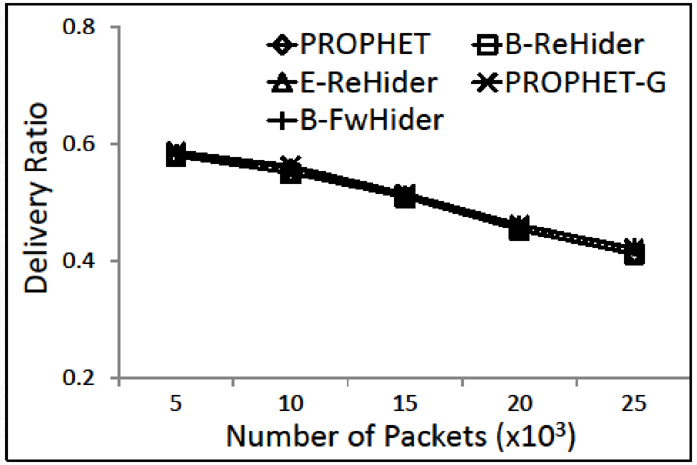


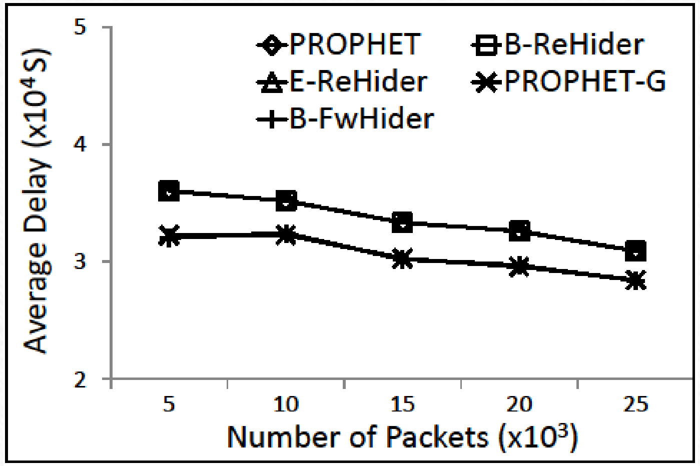


- B-ReHider and E-ReHider indicate utility anonymity and its extended version
- B-FwHider and E-FwHider indicate forwarder anonymity and its extended version
- Routing efficiency is not affected with the privacy protection schemes

Evaluation : Routing Performance

- Haggle trace





- The same result as in the MIT Reality trace

Conclusion

- Routing utilities in DTNs contain much privacy information but need to be disclosed for correct routing
- Solution:
  - Careful encryption to let nodes only share partial utility information that is enough for correct routing
  - Altering the packet forwarding sequences to further anonymity forwarder information
- Future work:
  - Energy consumption
  - Loose the limit and allow a white-list

Thank you!

Questions & Comments?