Adaptive Backbone-based Routing in Delay Tolerant Networks

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Introduction

- Delay/Disruption tolerant networks (DTNs)
  - Support interoperability
  - Tolerate delay and disruption
  - Intermittent/Scheduled/opportunistic communication links
- DTN-oriented routing
  - New problem
  - Challenges: mobile, power-limited, intermittently-available links
  - Also help to provide off-loading for centralized wireless communication
- Node mobility in DTNs
  - Large scale movement causes disconnection
  - Realizes message delivery
    - "store-carry-forward" mode adopted

DTN Routing

- Categories
  - Deterministic routing
  - History or predication-based routing
  - Epidemic routing
- Rational
  - For most DTNs, node mobility is not entirely random
    - Carried by human beings
- Promising solution
  - Aggregate contacts in the past
  - Use social graph
  - Predict future contact likeliness
  - Use metrics from complex network analysis
  - Make forwarding decisions

In this work

- Design a modeling approach for DTNs
  - Weighted graph derived
- Put forward the concept of a delay-tolerant network backbone
  - Used for message forwarding in DTNs
- Develop the delay-tolerant connected dominating set (DTCDS) concept and problem
  - To approximate the delay-tolerant network backbone
- Propose heuristic localized solutions
  - to the minimum equally effective DTCDS problem
- Study the performance of the proposed methods

Preliminaries

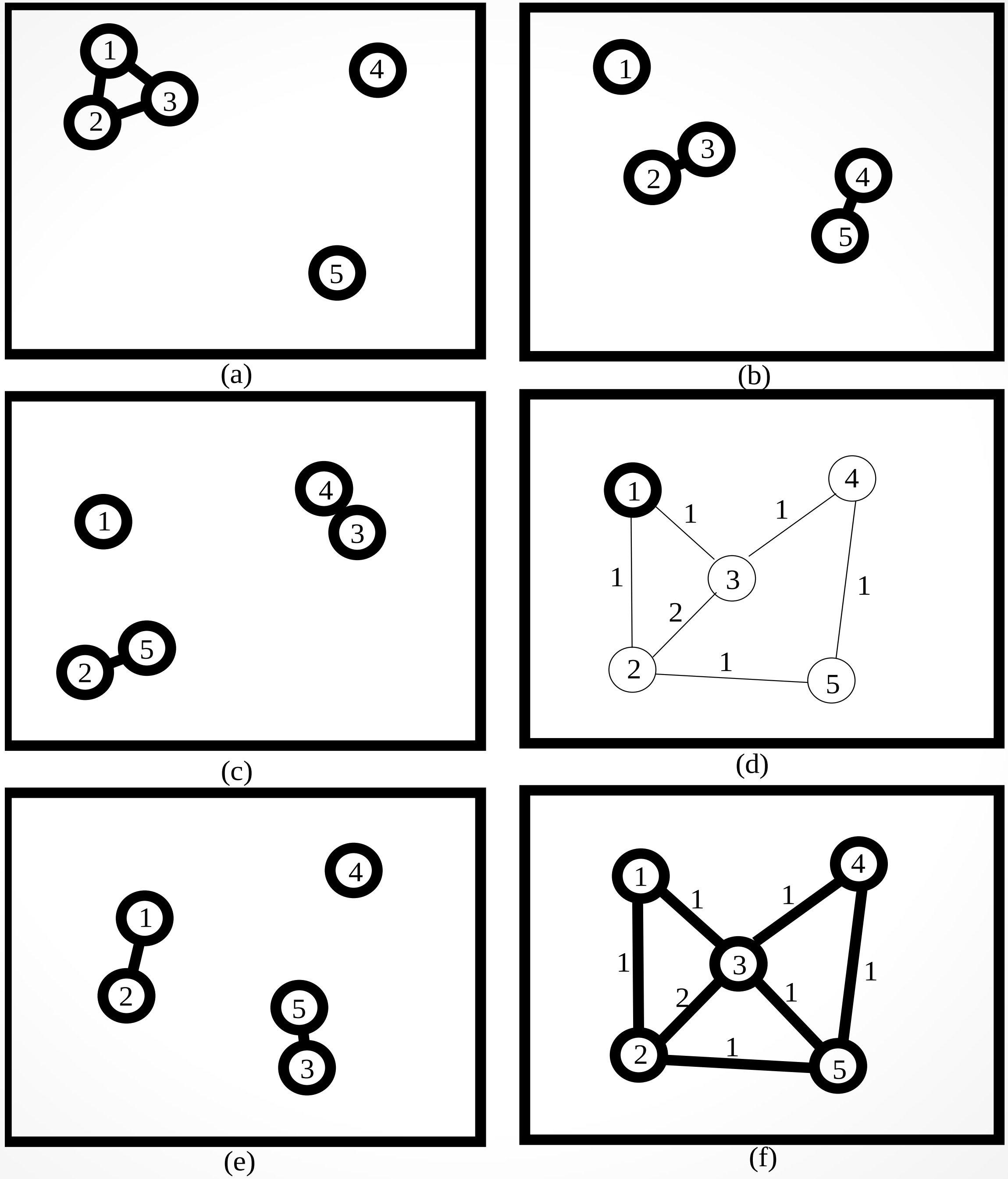
- Routing in DTNs
  - Epidemic routing (blind flooding)
    - No prediction
    - Optimal latency
    - Large buffer capacity
  - Deterministic routing
    - Network movement is (partially) scheduled
    - The shortest path can be calculated
    - Node trajectory is designable to assist routing performance
  - In between
    - Use past information to predict future movements
    - Each node makes a decision upon each received message: cost expensive
  - Proposed work
    - Use past information to derive a weighted graph, and
    - Form a network "backbone" for message forwarding, to
    - Limit the copies of messages & provide a latency guarantee

Preliminaries

- Connected dominating set (CDS)
  - In mobile ad hoc networks (MANETs) and wireless sensor networks (WSNs)
  - Used to approximate a virtual network backbone
  - Each node is either in the CDS or has a one-hop neighbor in the set
  - Minimum CDS: NP-complete
- CDS construction
  - Localized approach
    - Local h-hop information
    - No propagation
  - Existing algorithms
    - Marking process
    - Rule k
    - Coverage condition

Network Model

- A DTN with n nodes,
  - f_{uv} : meeting frequency (MF)
  - $E(l_{uv}) = \frac{1}{f_{uv}}$: expected data delivery latency
  - $E(l_R) = \sum_{i=1}^{m-1} \frac{1}{f_{i(i+1)}}$: the expected data delivery latency of path $R = a_1, a_2, ..., a_m$
- Derived weighted graph for a DTN
  - $G = (V, E, w)$
  - A time-space model
  - $w(u, v) = f_{uv}$
  - $f_{uv} = 0$: no link between nodes


(a)
(b)
(c)
(d)
(e)
(f)

Delay Tolerant Network Backbone

- A subset of nodes in the derived weighted graph
  - Each node can send a message to any other node
  - Only nodes in the backbone will forward messages
  - Note: forwarding is not broadcasting
- Design goals
  - Efficiency
    - small backbone to limit message copies
  - Effectiveness
    - expected end-to-end delay is bounded

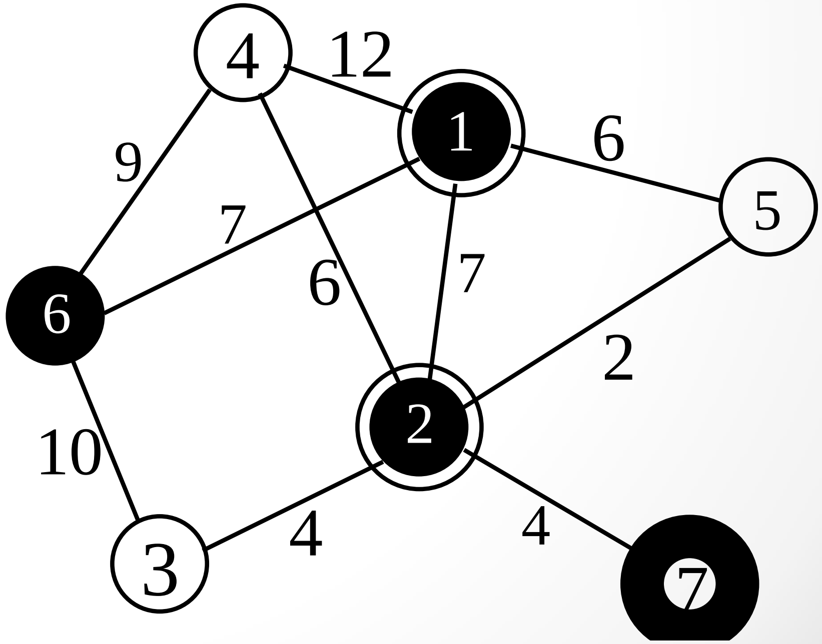
The Delay Tolerant Connected Dominating Set (DTCDS)

- A subset of the DTN graph, such that
  - The subsets are connected among themselves
  - Every non-selected node has at least one selected node as a neighbor
- DTCDS is the same with CDS
- A smaller DTCDS is desired

The Minimum Equally Effective DTCDS

- The DTCDS
  - With the smallest number of selected nodes
  - The expected delivery latency between any two nodes is the same with that when all nodes forward messages

Traditional CDS: 1, 2
Minimum Equally Effective DTCDS: 1, 2, 6



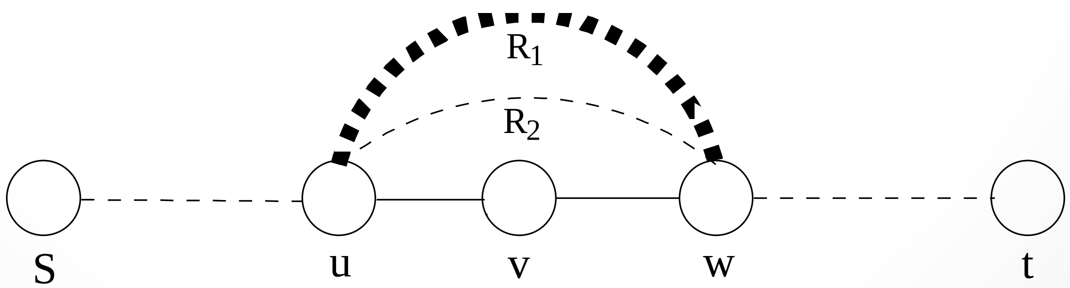
Localized Heuristic Solution

- Accumulated delivery latency
  - Inspired by the flow network concept
  - The meeting frequency of two nodes via different paths can be added
  - With d node disjoint paths connecting two nodes:

$$E(L_{uv}) = \frac{1}{\sum_{i=1}^{d} \frac{1}{E(l_{R_i})}}$$

Localized Heuristic Solution

- Accumulated Node Coverage Condition (ANCC)
  - A node, v, is withdrawn from the DTCDS if, for any two neighbors of it, u and w, a group of disjoint path exists, such that
    - Each intermediate node on any path has a higher priority than node v, and
    - The accumulated delivery latency of the group of paths is smaller than or equal to the delivery latency of path u, v, w.



Localized ANCC algorithm

Algorithm 1 ANCC algorithm

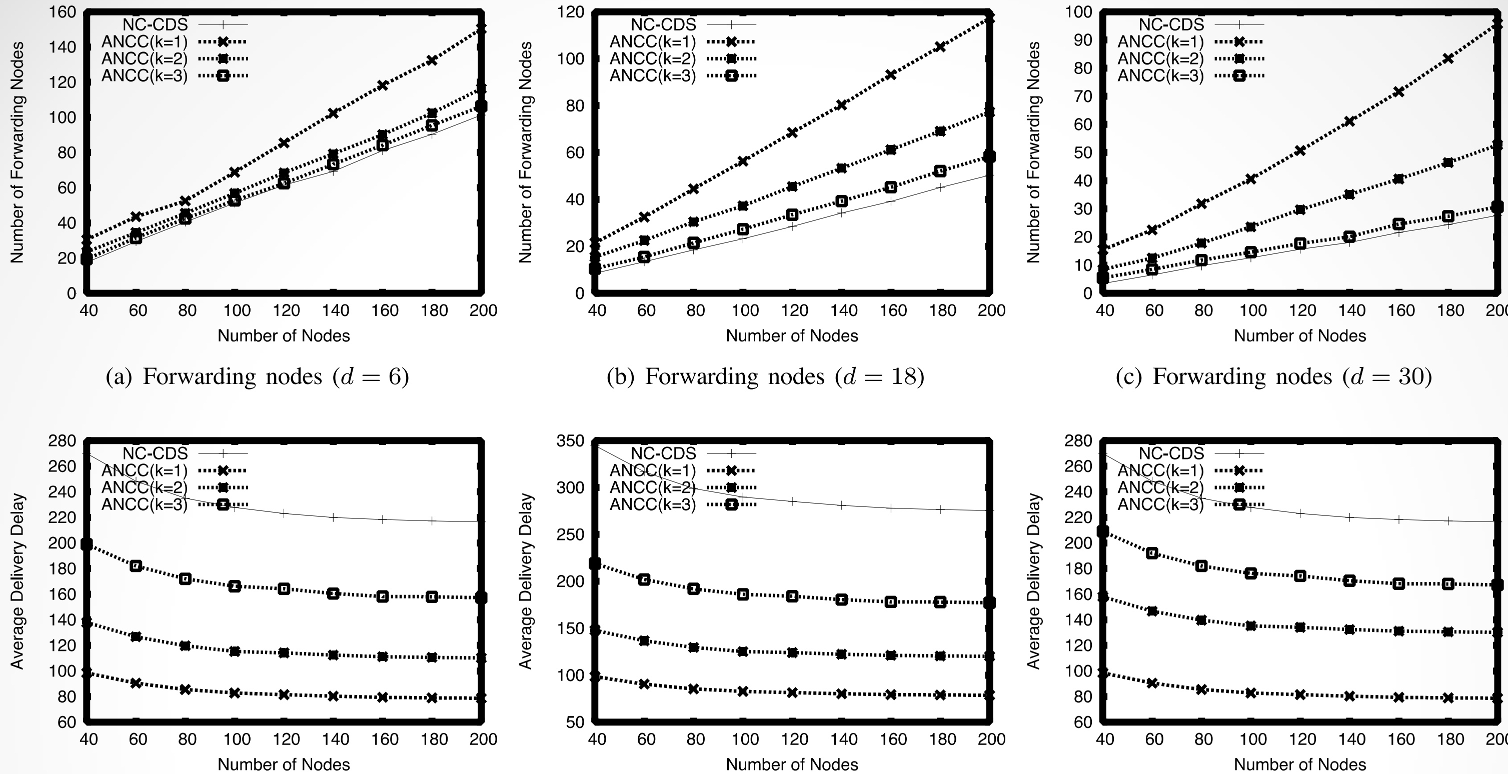
[1.] Each node sets up the meeting frequency for each neighbor by recording its having met with them, and exchanges this information with neighbors.
[2.] Each node determines its status (marked/unmarked) using the accumulated node coverage condition.

Discussion

- Routing with only marked nodes by ANCC forwarding has the same performance as routing with all nodes forwarding, in terms of message delay
- The ANCC algorithm is adaptive
  - Smaller forwarding node set with more accumulated knowledge on nodes' contacts
  - Existing DTN routing can be applied to ANCC to reduce forwarding when there is no optimal latency requirement
  - ANCC can be relaxed to achieve a smaller forwarding set with an acceptable increased latency
    - The accumulated delivery latency of the group of paths is smaller than or equal to k times the delivery latency of path u, v, w.
  - When deriving the graph with the weight being contact probability, the forwarding set generated by ANCC guarantees an optimal end-to-end delivery ratio

Simulation

- Adjustable parameters
  - Number of nodes n: 20~160
  - Average node degree d: 6, 18, 30
  - Number of hops of local information h: 2, 3, 4
  - Range of meeting frequency for weight assignment r: 10, 50, 100
  - Relaxation factor k: 1, 2, 3
- Performance metrics
  - The size of the forwarding node set
  - Expected average message delivery latency



(a) Forwarding nodes ($d = 6$) (b) Forwarding nodes ($d = 18$) (c) Forwarding nodes ($d = 30$)

(d) Delay ($h = 2$) (e) Delay ($h = 3$) (f) Delay ($h = 4$)

(g) Range ($r = 10$) (h) Range ($r = 50$) (i) Range ($r = 100$)

Fig. 5. Comparisons of ANCC and NC-CDS with different parameters (k, h, d, and r).

Simulation Summary

- Forwarding set size
  - ANCC reduces the size of forwarding set by 50% to 80%, with different graph densities
  - More local information helps to reduce the size
  - A graph being more dense helps to reduce the size
- The expected delivery latency
  - when k is 2, it is 1.5 times of that of the optimal solution, and
  - 2 times that of when k is 3

Conclusion & Future Work

- A modeling method for DTNs
- A concept of delay-tolerant network backbone
  - Reduced number of message copies
  - Optimal performance in terms of end-to-end delay
- A formalized minimum equally-effective delay-tolerant connected dominating set problem
  - Approximate delay-tolerant network backbone
- A heuristic localized algorithm
- Future work: consider more realistic system settings, limited buffer size, etc.

Questions?

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Thank you!