Social-Aware Routing in Delay Tolerant Networks

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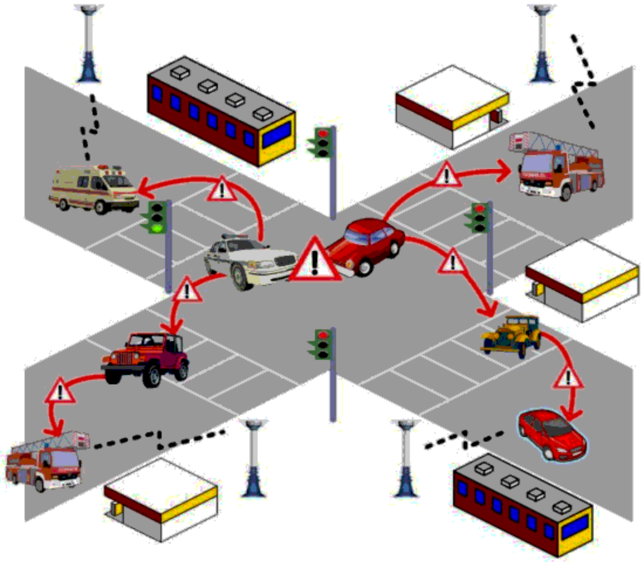
Challenged Networks

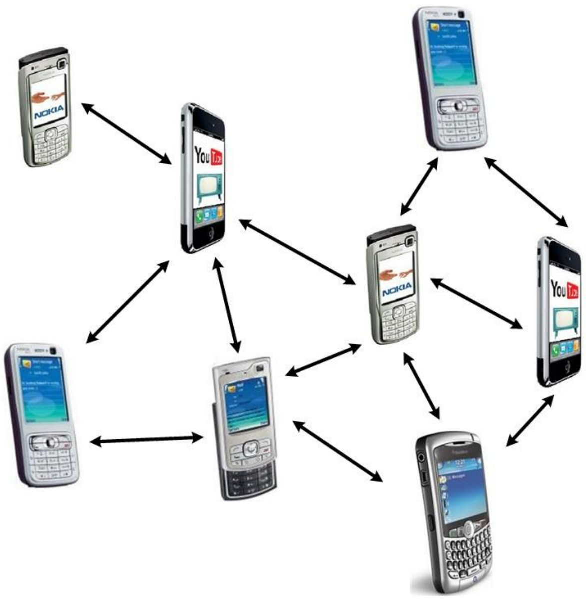
- Assumptions in the TCP/IP model are violated
  - DTNs
    - Delay-Tolerant Networks (also Disruption-Tolerant Networks)
  - Limited end-to-end connectivity
    - Due to mobility, power saving, or unreliable networks
  - Activities
    - IRTF's DTRNRG (Delay Tolerant Net. Research Group)
    - EU's Haggle project

Examples of DTNs

- Vehicular communication



- Social contact networks

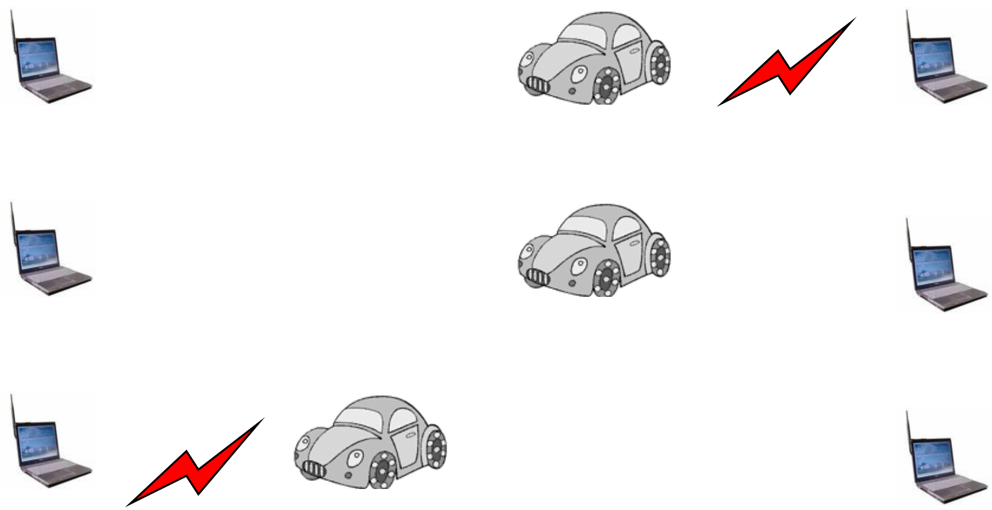


Store-Carry-Forward

- Movement-Assisted Routing

  Views node movement as a desirable feature

  - Store
  - Carry
  - Forward



Two Paradigms

- Random Mobility
  - E.g., epidemic routing
  - Sightseeing cars (random movement)

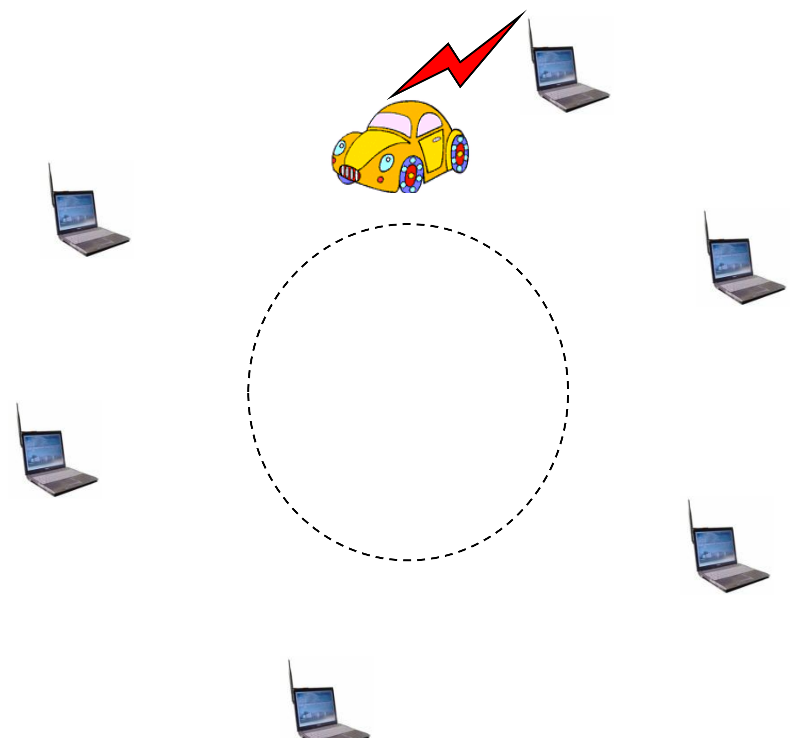
- Controlled Mobility
  - E.g., message ferrying
  - Taxi (destination-oriented)
  - Public transportation (fixed route)

Epidemic Routing (Vahdat & Becker 00)

- Nodes store data and exchange them when they meet
- Data is replicated through a random talk

Message Ferrying (Zhao & Ammar 03)

- Special nodes (ferries) have completely predictable routes through the geographic area



Key Techniques

- Knowledge
  - Global vs. local information (S. Jain 04)
  - Zero information
- Replication
  - Single vs. multiple copy: spray-and-wait (-focus)
  - Controlled copy: delegation forwarding
- Closeness (to destination)
  - Location information (of contacts and dest.)
  - Similarity (between intermediate nodes and dest.)

Spray-and-Wait (-Focus)
(Spyropoulous, Psounis, & Raghavendra 05 & 07)

Two phases

- Sprays a number of copies into the network
- Each copy waits until meeting with the destination
  - Wait : forward only to its destination
  - Focus : forward to destination or a "closer" node to the destination

Delegation Forwarding (Erramilli et al 08)

- The holder forwards the message to an encounter with a higher quality than all previous nodes seen so far
- The expected cost of the algorithms
  - Flooding: $O(N)$
  - Delegation forwarding: $O(\sqrt{N})$
- Extensions
  - Probabilistic delegation forwarding (Chen, Jian, Graves, & Wu 09)
  - Delegation forwarding in multicasting (Wang & Wu 10)

Key Challenges

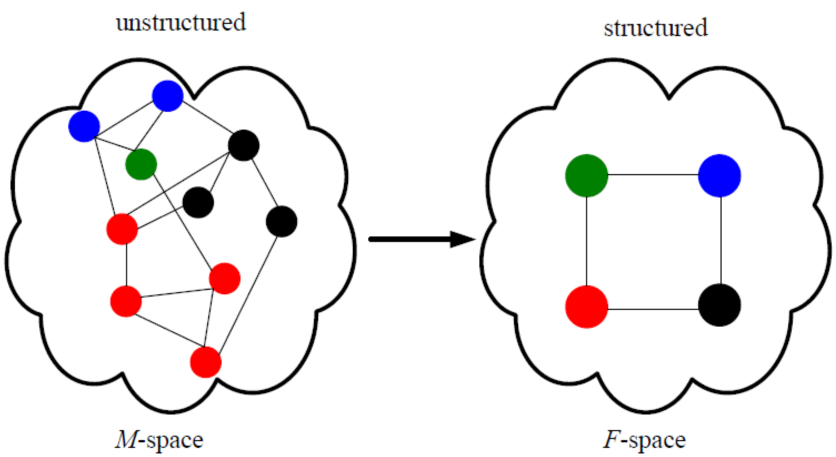
- Existing DTN routing
  - Contact history
  - Mobility pattern
- Collecting such information is costly
- Both contact and mobility are
  - Highly dynamic
  - Unstructured

Social-Aware Routing

- Based on coarse-grain social-aware approaches
  - Social features-based: semi-structured contacts
    (Wu & Wang 12)
  - Social home-based: semi-structured mobility
    (Wu, Xiao, & Huang 13)
- Differ from fine-grain social-aware approaches
  - Community, centrality, betweeness, and strong and weak ties, …
  - …

Social Feature-Based (Wu & Wang 12)

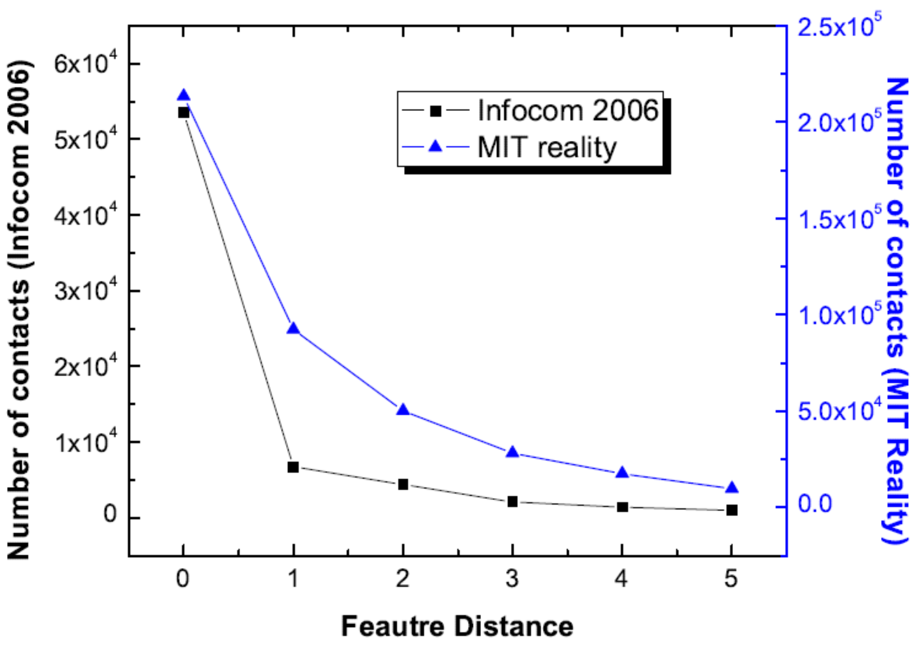
- Mobile & unstructured contact space (M-space) ⟶
  Static & structured feature space (F-space)



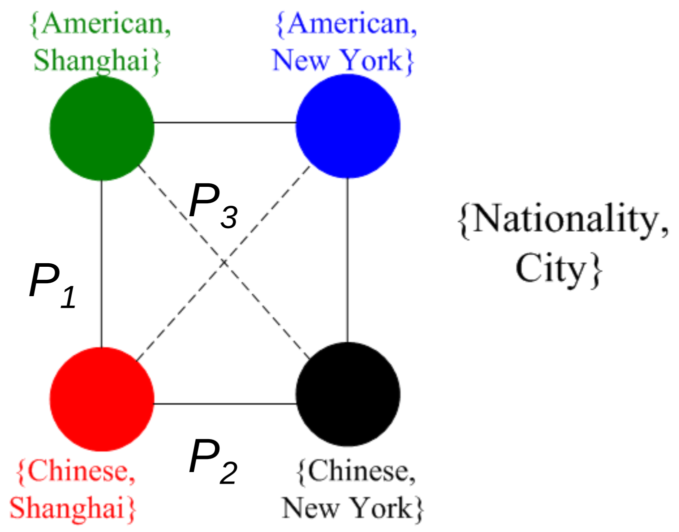
- Each individual with a social feature profile $\{F_1, F_2, \ldots\}$
- Individuals with the same features mapped to a group

Resolve Feature Difference

- Our approach
  - Feature-based (race, gender, language, …)
  - Resolve feature difference one at a time !
- Increase delivery rate: multiple copy
  - Flooding: *O(N)*
  - Delegation forwarding: *O(√N)*
  - Our approach: *log N**
  - N* is feature space size

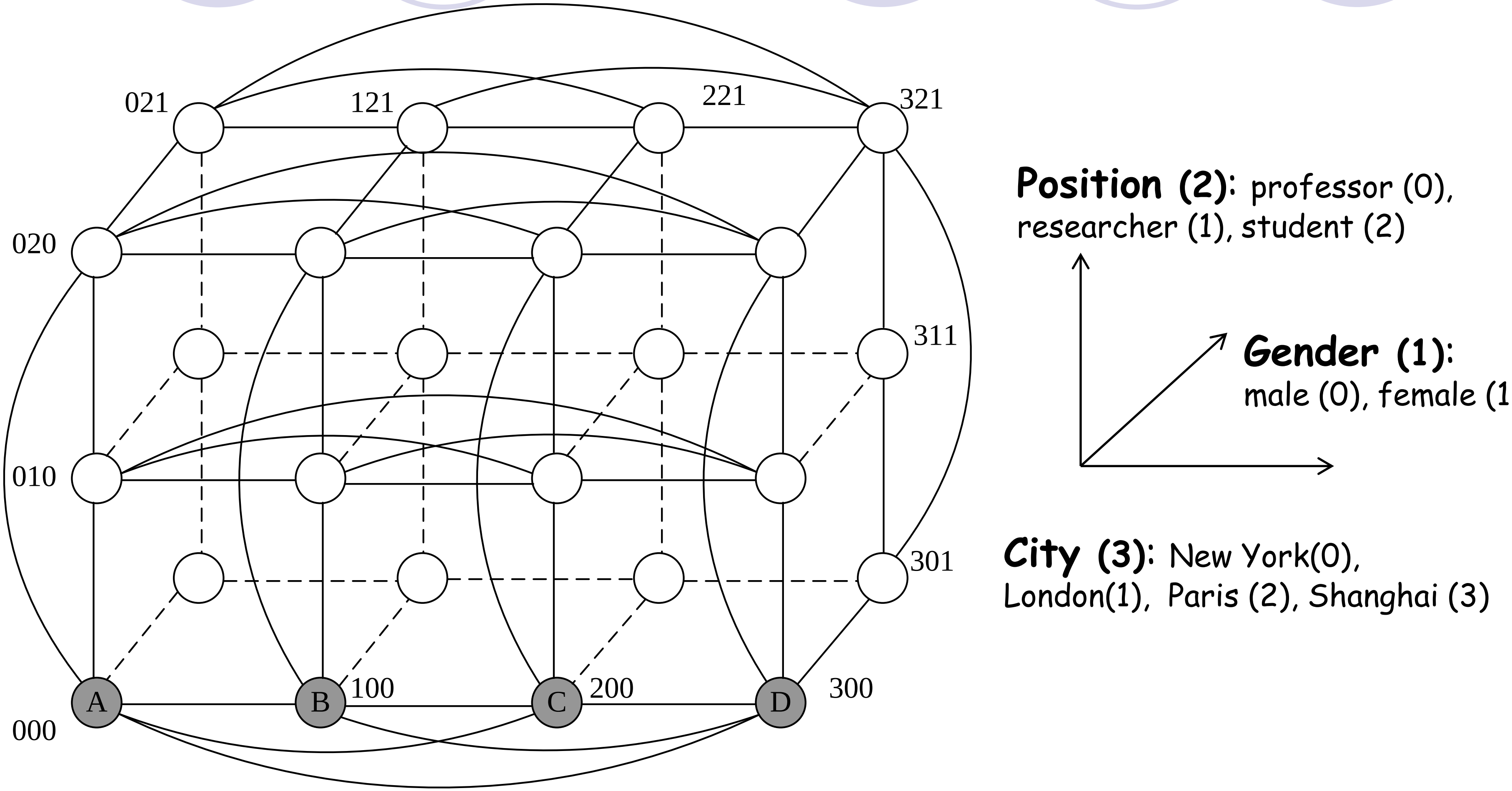


Feature-based Grouping Example



- People come in contact with each other more frequently if they have more social features in common (P_1>P_3, P_2>P_3)

A 3-dimensional (3-D) Hypercube



Example: "*311*": a female researcher lives in Shanghai

Feature Extraction

- Extract *m* most important features based on Shannon's entropy

$$E(F) = \sum_{i=1}^{l} p(x_i) \log p(x_i)$$

  - *E(F)* : entropy of feature *F*
  - *p:* feature probability mass function
  - $\{x_1, x_2, \ldots, x_l\}$: value set of feature *F*

Social Feature Entropy

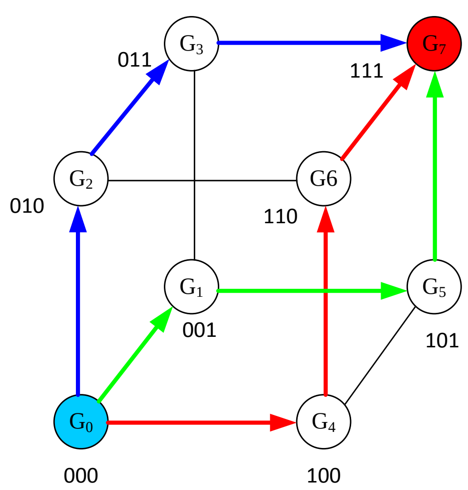
- The entropy of each social feature (Infocom 2006 trace)

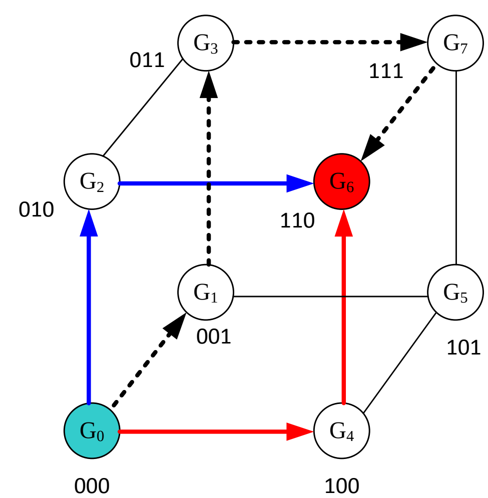
Social Feature	Entropy
Affiliation	4.64
City	4.45
Nationality	4.11
Language	4.11
Country	3.59
Position	1.37

Property of Hypercubes

Efficient routing in an *m*-d binary cube (*S* and *D* differ in *k* features)

- *k* shortest paths of length *k*
- *m-k* non-shortest paths of length *k+2*



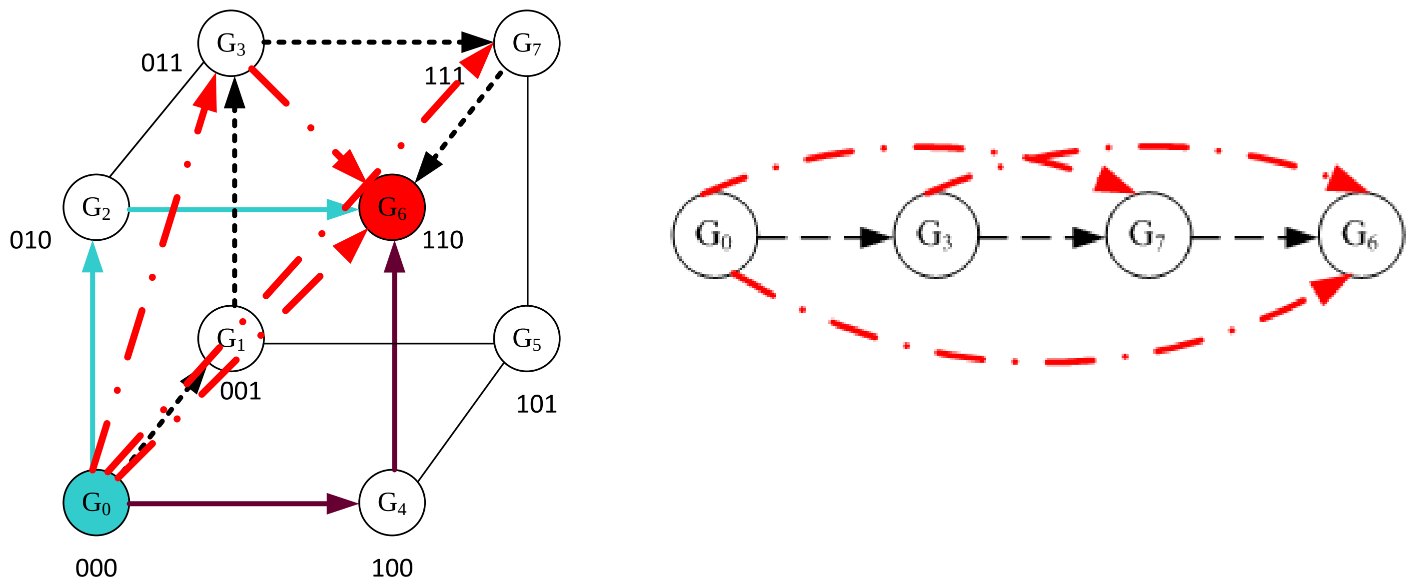


Hypercube Routing

- The relative address of the current group and destination group (a small string in the header)
  - calculated through XOR on S and D
  - sent, along with the packet, to the next node
- Any node in the group can forward to any node in the adjacent group
- Special treatment is needed at the destination group: spread-and-wait (-focus)

Shortcuts

- Feature matching shortcut can resolve the feature distance more than one at a time



- Shortcut reduces the number of forwardings while ensuring the path disjointness property

Recap and Extensions

- Multi-path routing in hypercubes
  - Feature-based, efficient copy management, and node-disjoint-based
- Extensions
  - General hypercubes
  - Analytical results: delivery rate and latency

Social Home-based

(Wu, Xiao, & Huang 13)

- Social characteristics

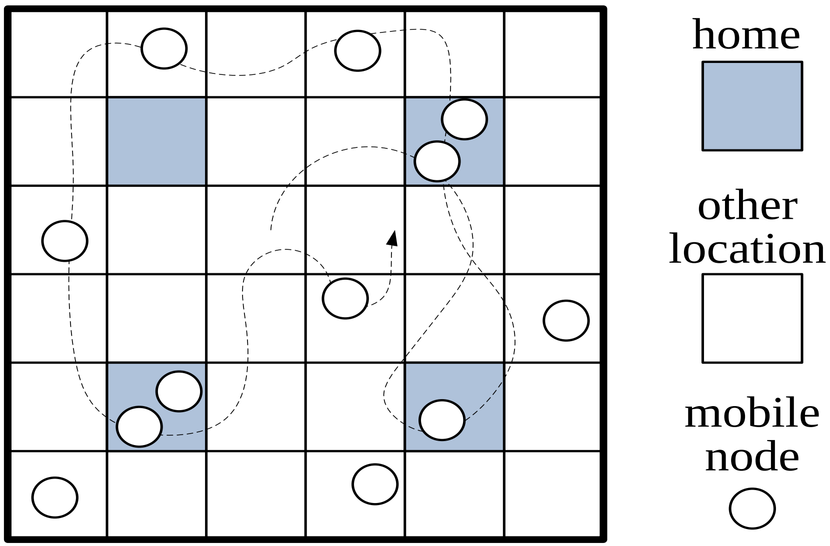
  Nodes visit some locations (homes) frequently, while visit other locations less frequently

- Real or virtual “throwbox”

  Each community home is equipped with a real or virtual “throwbox” so that it can store and forward messages

Problem

- Network Model
  - n mobile nodes in V
  - h homes: H = {1, 2,…, h} & m-h other locations: L = {h+1, h+2, …, m}



Italian student: {Italian town, school, dorm}

Female student: {shopping center, school, dorm}

Solution

- Homing Spread (HS)
  - Homing phase
    - The source sends message copies to homes quickly
  - Spreading phase
    - Homes with multiple copies spread them to other homes and mobile nodes
  - Fetching phase
    - The destination fetches the message when it meets any message holder

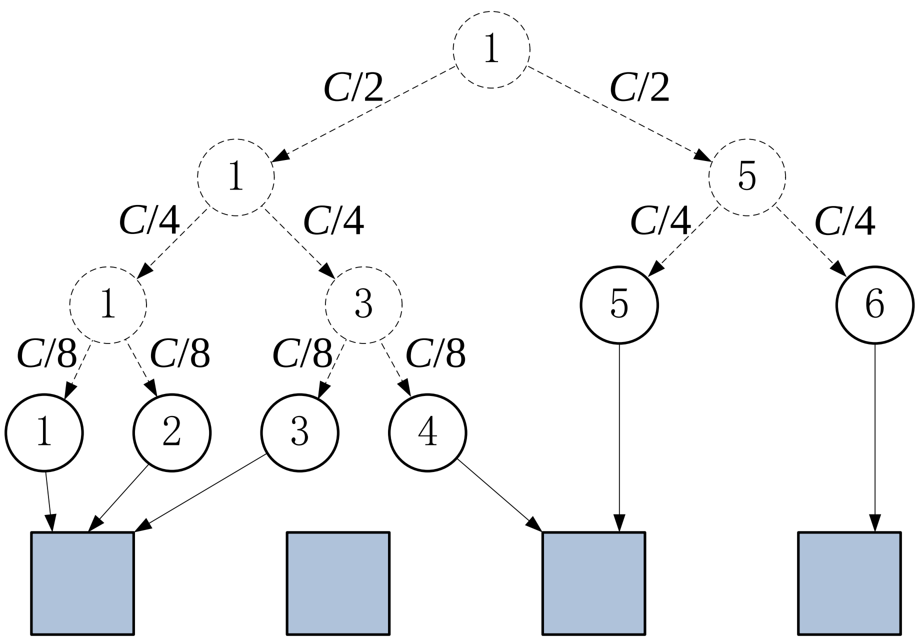
(Homing: meet at a home site. Roaming: at a non-home site.)

Challenges

- Given a fixed number of message copies C
  - What is the optimal way for a message holder to spread copies during homing and roaming?
  - Once a home receives some message copies, how should it further spread these copies?
  - What is a general way for a mobile destination to obtain a copy?

Homing Phase

- Binary Homing Scheme:
  - Each message holder sends all of its copies to the first (visited) home.
  - If the message holder meets another node before it visits a home, it binary splits the copies between them.



Homing Phase

- Assume
  - Inter-meeting time between any two nodes (a node and a home) follows the exponential distribution λ (Λ)
- Lemma 1
  - The binary homing scheme can spread the *C* message copies to the maximum number of nodes before they reach the homes
- Analysis
  - The expected delay of each message copy is always $1/h\Lambda$ no matter which splitting scheme is adopted
  - The maximum number of nodes (homes) received the message copies

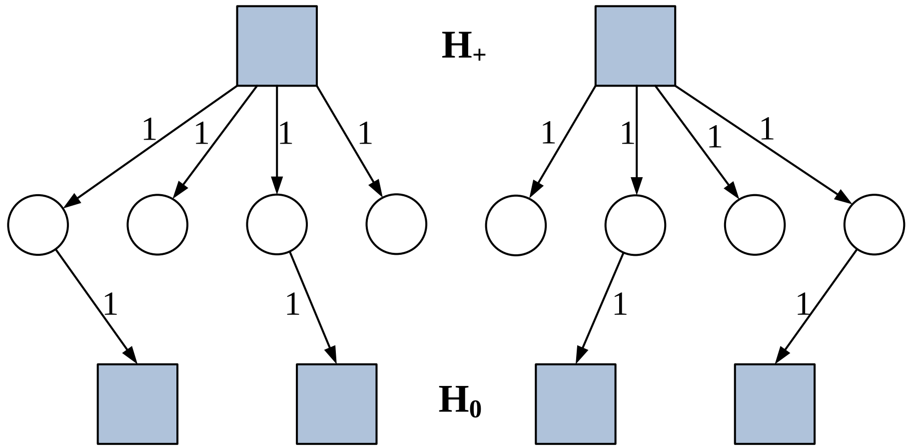
Spreading Phase

- 1-Spreading Scheme
  - Each home with more than one message copy spreads a copy to each visiting node until only one copy remains
  - If a node with one copy later visits another home, the node sends the copy to that home

- Analysis
  - Each home has at most one copy
  - If $C > h$, there are $C - h$ nodes outside the homes that have a copy
  - Home is always more important than a regular node as it can spread the message faster

Spreading Phase

- 1-Spreading Scheme

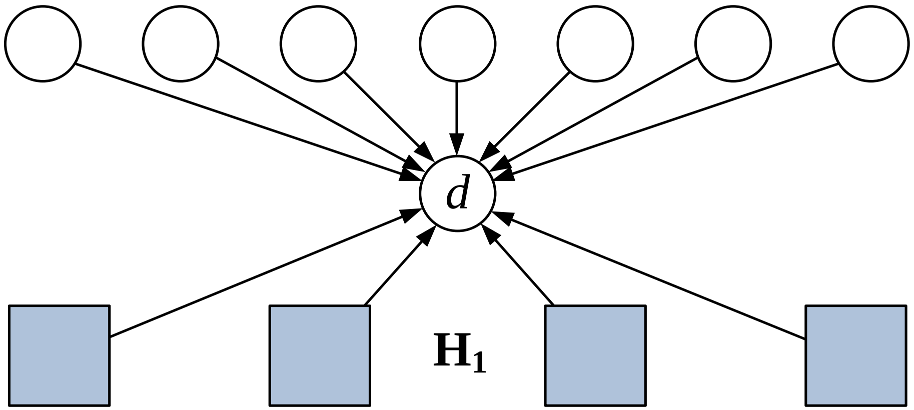


(H_+: multiple copies, H_1: one copy, H_0: no copy)

- Lemma 2
  - The 1-spreading scheme can spread copies from a home to the maximum number of nodes with the fastest speed.

Fetching Phase

- Fetching Scheme
  - The destination fetches the message once it meets a message holder



Distributed HS Algorithm

Algorithm 1 The Homing Spread (HS) algorithm

for each mobile node i **do**
  if node i encounters another node j **then**
    if node j is the destination **then**
      node i sends the message to j;
    if nodes i and j have r_i and r_j message copies **then**
      node i holds $\lceil r_i/2 \rceil + \lfloor r_j/2 \rfloor$ copies through exchange with node j;
  if node i visits a home h **then**
    node i sends all its copies to h;
    if $h \in H_+$ or i is the destination **then**
      h sends a copy to node i.

Continuous Markov Chain

- Expected delivery delay
- Number of copies needed for a given delay bound

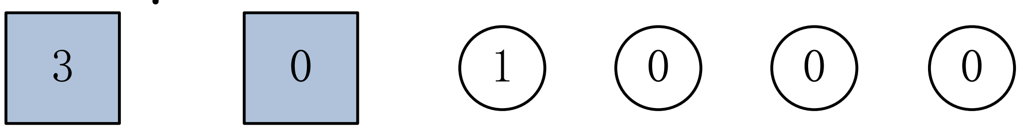
Network State

- State s is a vector with h+n components

$$s = \langle s_1, s_2, \ldots, s_h, s_{h+1}, \ldots, s_{h+n} \rangle,$$

s_i: copies held by the i-th home (if $i \le h$) or node i-h (if $i > h$)

- For example: $s = \langle 3, 0, 1, 0, 0, 0 \rangle$



- Start state: $s_t = \langle 0, 0, \ldots, 0, C, 0, \ldots, 0 \rangle$
- Optimal state: $s_o = \langle 1, 1, \ldots, 1, 0, \ldots, 0 \rangle$

Optimality of HS

- HS follows binary homing and 1-spreading schemes
- Lemmas 1 and 2 show that the HS is the fastest ways to turn a network state into the optimal state
- Each state transition based on binary homing and 1-spreading schemes can turn the current state into the best next state that has the minimum expected delivery delay

Expected Delivery Delay

Continuous Markov Chain

- **State space** s= $\langle s_1, s_2, \ldots, s_h, s_{h+1}, \ldots, s_{h+n} \rangle$

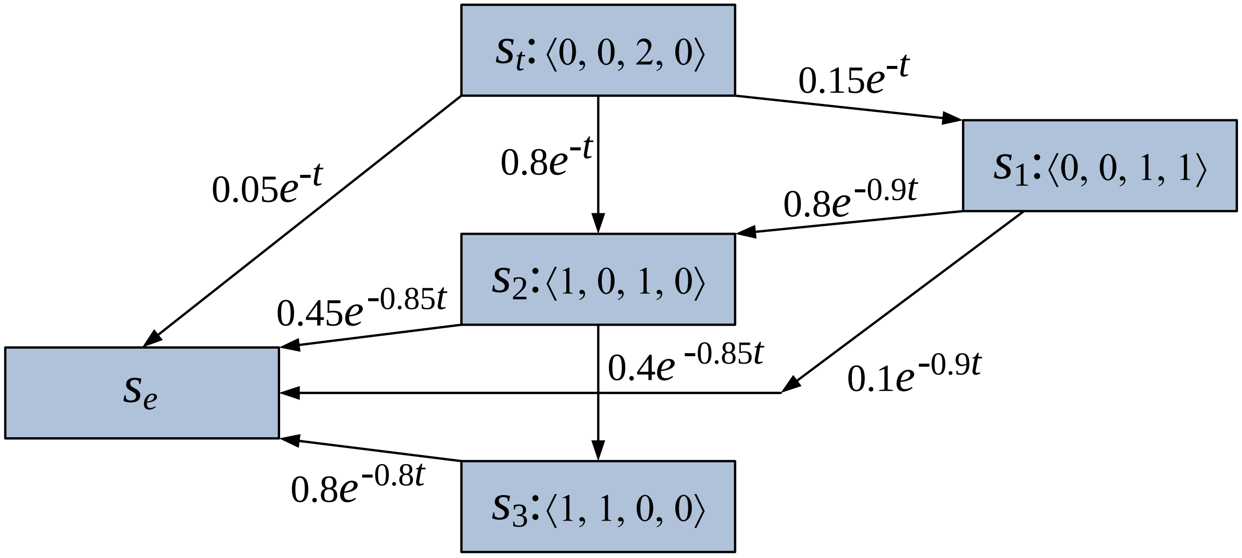
$$\sum_{i=1}^{h+n} s_i = C \ \ (s_1 \geq s_2 \geq \cdots \geq s_h; s_{h+1} \geq s_{h+2} \geq \cdots \geq s_{h+n})$$

- State transition graph
  - The binary homing scheme, the 1-spreading scheme
  - A directed acyclic graph
  - State transition function $\rho_{s,s'}(t)$

  Probability density function about the time *t* that it takes for state transition from s to s'

Expected Delivery Delay

- Derive the cumulative probability density function for the state transition from start to end state
- Calculate the expected delivery delay



Three Phases

Homing phase: average delay for the first copy reaching a home

$$D^{(1)} = \frac{1}{h\Lambda}$$

Spreading phase: average delay for each home to receive a copy

$$D^{(2)} \leq \frac{2}{\Lambda}$$

Fetching phase*: average delay after the first two phases in message fetching

$$D^{(3)} = \begin{cases} \frac{1}{C\Lambda} & , C \leq h \\ \frac{1}{h\Lambda + (C-h)\lambda} & , C > \mathrm{h} \end{cases}$$

Upper Bound

- Define

$$D' = \frac{1}{h\Lambda} + \frac{2}{\Lambda}$$

homing (first term) plus fetching (second term) delay

- The expected delay D of HS satisfies:

$$D \le \begin{cases} D' + \frac{1}{C\Lambda} & , C \le h \\ D' + \frac{1}{h\Lambda + (C-h)\lambda} & , C > \mathrm{h} \end{cases}$$

- *C* copies needed for a given delay bound $\Theta(\ge D')$

$$C = \begin{cases} \frac{1}{\Lambda(\Theta - D')} & , \quad \Theta \ge \frac{1}{h\Lambda} + D' \\ \frac{1}{\lambda} \cdot \left(\frac{1}{\Theta - D'} - h\Lambda\right) + h & , \quad D' < \Theta < \frac{1}{h\Lambda} + D' \end{cases}$$

Recap and Extensions

- Homing-spread
  - Optimal multi-copy routing in three phases: homing, spreading, and fetching
- Extensions
  - Heterogeneous homes: nodes having different homes
  - Heterogeneous visiting: nodes having different visit rates

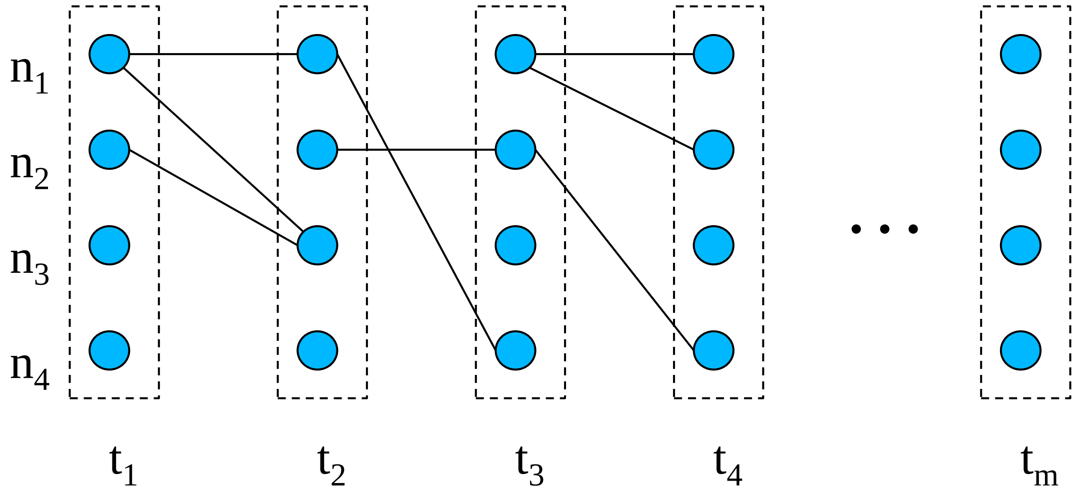
Big Picture: Network Science

- How the Overall Network System will Behave
  - Static network structure
  - Dynamic networks structure (more challenging)

- Epidemic and Other Spreading Processes
  - Epidemic is well studied in static networks
    - Susceptible-Infected (SI), SIR (recovered), SIS, and SIRS
  - Epidemic, especially controlled one, in dynamic networks
    - More challenging and not well understood

Evolving Graphs

- Time-space view



- Social-aware contacts
  - A special temporal-spatial link summary
- Challenges
  - Activity Level (AL) of each node evolves based on ALs of neighbors

Questions

- Collaborators
  - Yunsheng Wang

    Temple Univ. (and Kettering Univ.).
  - Mingjun Xiao

    Univ. of Sci. & Tech. of China