A Parsimonious Model of Mobile Partitioned Networks with Clustering

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Nokia & EPFL
Models and Algorithms for Mobile Networks
Models and Algorithms for Mobile Networks

- **Mobile Wireless Networks are different:**
  - No wires -> no links
  - Mobility -> uncertainty
  - Heterogeneity -> partition

- **Contribution**
  - A simple & tractable model capturing heterogeneity in connectivity and in mobility
  - Validation through data
  - Insights into DTN routing design space
Routing in Partitioned Networks

- Fixed high-density island = “concentration points”
- Route through mobile nodes: “island hopping”
- Mobile network nodes

Goal:
- Designing robust DTN routing algorithms
Heterogeneous Random Walk Model

**Definition:**
- $n$ nodes on square torus
- Each node performs independent (scaled) Brownian motion
- Fixed regions $A_l$ where mobility is slower, and $A_h$ where it is faster
- For example, $A_l = m$ random disks
HRW Model: Main Properties

- **Stationary distribution**
  - $\pi_{l,h} \sim \sigma_{l,h}^{-2}$
  - Density inverse of speed

- **Connectivity**
  - Rich connectivity inside $A_l$, scarce connectivity outside
  - Continuous percolation: ensure supercritical density in $A_l$, subcritical in $A_h$

  \[ \lambda_{l,h} r^2 = n \sigma_{l,h}^{-2} r^2 \leftrightarrow (\lambda r^2)_{cr} \approx 1.43 \]

- **Discrete-time version and “perfect simulation”**
  - Correction when crossing boundary
  - Starting simulation without transient
Validation

- **Data set:**
  - Fine-grained mobility of taxi cabs in the San Francisco Bay Area
  - 500 cars over one month
  - Position updates approx. every 10 sec
  - Other traces from Nokia Sportstracker dataset

- **Verifying features of model:**
  - Robustness and stability of clusters (persistent components)
  - Similarity of node mobility patterns
  - Speed-density relationship
Number of Components vs Radio Range

Multiple large components are robust w.r.t. transmission range.

Also confirmed that large clusters remain at same location, even though nodes move.
Statistical Similarity of Node Mobility

- One-day snapshots of individual visits to cells
Most nodes have indistinguishable mobility.
Does high density constrain speed? Is there an inverse relationship?
Some limited evidence for negative correlation between speed and density:
- high density does prevent high speed
- low density does not imply high speed
Example: Epidemic Dissemination

- **Experiment:** fit model to trace
  - $A_l = \text{highly connected areas}$
  - match average speed separately in $A_l$ and $A_h$

- **Metrics:**
  - delay, overhead (# copies), min-delay-path length

- **Comparison:**
  - Random walk
  - Random waypoint

- **Result:**
  - HRW best overall predictor
DTN Routing under Random Walk Mobility

- **Design space of DTN routing algorithms:**
  - Single or multiple copy
  - Forward and/or copy decisions
  - Control information (e.g., encounter frequency)

- **HRW: Markov chain, state = location**
  - No “predictability” of individual node’s future movements
  - Given current location, every node is equivalent

- **Question:**
  - Can we actually route in such a model, i.e., do better than random dissemination?
  - If we can, what information should nodes collect and exchange?
Single Copy and Spray-and-Wait in HRW Mobility

- **HRW model:**
  - Single copy: no benefit in relaying copy -> no control information needed
  - Spray-and-wait: set of relays is irrelevant -> min of i.i.d. delays

- **Beating spray-and-wait boundary**
  - Requires “continuous multi-copy” scheme, i.e., decisions after realization

- **Contrast with node-heterogeneous model:**
  - Assume each node has its own preferred (set of) location(s)
  - All indep. random walks, same aggregate node density
  - But: single copy and spray-and-wait benefits from control information
Beating Spray-and-Wait with HRW Mobility

- **Problem:**
  - How to make predictable progress under unpredictable mobility?

- **Key idea:**
  - Cannot control mobility of individual message
  - But can control mobility of set of copies of a message
  - Deferred copy and kill decisions at islands
Collaborative Graph Discovery

- **Assume no external signal**
  - No GPS or fixed beacon
  - No information about movement of self and others

- **Collaborative graph discovery:**
  - Stable islands with high connectivity: natural “beacons”!
  - Derive island graph only from observation of neighbors

- **Key idea:**
  - **Vertex labeling:**
    - Assign unique labels to islands
    - Maintain the labels stable as long as possible -> “voting for labels”
  - **Edge Discovery:**
    - Discover the labeled edges of the CP graph
    - Gossiping, aging, handling error conditions
Island Hopping for DTN Routing

- Node neighborhoods
- Collaborative Graph Discovery
- Island graph
- Last Encounter Routing
- Destination location
- Island Hopping
- Routing decisions
Key Points

- **Real DTN scenarios are heterogeneous**
  - Node mobility, connectivity

- **HRW model:**
  - Corner case: homogeneous nodes, heterogeneous space
  - Stable islands of connectivity, but “maximally unpredictable” nodes
  - Parsimonious, tractable

- **Validation**
  - San Francisco taxi trace + Nokia Sportstracker traces
  - Statistical similarity of nodes, clustering vs range, speed-density
  - Capturing “high connectivity” and “high mobility” regions

- **Routing:**
  - Random Walk: no predictability for individual nodes
  - But “deferred multi-copy” schemes can perform well
  - Optimal scheme and control information are open questions
Backup
Stable Concentration Points

- **CP graph:**
  - Vertices = CPs
  - Edges = flows of nodes between CPs

- **Worst-case connectivity & mobility model:**
  - Only nodes at the same vertex can communicate
  - A node in transit can not communicate with anyone
  - Nodes perform independent random walks on CP graph
Island Hopping through Mobility

- Only way from island to island is through movement of nodes
  - But how? Obvious approaches:
    - Epidemic: Flood entire network -> fast but costly
    - Wait-for-dest: slow but cheap
  - Make smart “hitchhiking decisions”
    - How to find the destination in a disconnected network?
    - Last Encounter routing on the CP graph
      -> try to move in “the right direction”

![Diagram](image-url)

- msg for •
- last encounter with •
Island-Hopping: Delay-Overhead Sweetspot

delay

wait-for-dest

Island Hopping

epidemic

transmission overhead
Execution Example COGRAD + IH

- 500 nodes on a 5x5 grid of concentration points
- No positioning information available to nodes
- Grid topology not known to nodes
- Destination position not known to nodes
Summary: Partitioned Mobile Networks

**References:**

- Last Encounter Routing (LER)
- EASE: Learning Efficient Routing in Mobile Environments
Conclusion

- Models for main aspects of mobile wireless networks
  - Model 1: Optimal Opportunistic Routing
  - Model 2: Routing under Mobility
  - Model 3: Partitions

- The right abstraction is half the solution
  - Depends on the problem
  - Should inform the solution

- Future research:
  - Heterogeneity and asymmetry: energy, communication, computation
  - Hybrid scenarios
  - Addressing information vs network entities: overlays, pub-sub,...