Mobility Assisted Networking

Romit Roy Choudhury
"I AM A DIGITAL WIRELESS INTERNET DEVICE!
IF YOU CALL ME A 'CELL PHONE' ONE MORE TIME, YOUR SERVICE WILL BE TERMINATED!"
Percolating Devices

- One clear trend:

  Communication + = Computation devices

  The quest for anytime, anywhere computing
Pervasive, Ubiquitous Access

- Ad hoc networks vision
  - P2P technology
  - Connective platform available anytime, anywhere

However, did not fly well ... why?
Several Reasons

- **Bootstrapping**
  - Critical density required for performance
  - Performance required for critical density

- **Wireless channel modeling remains elusive**
  - End to end connection difficult to sustain

- **Mobility**
  - Many real networks clustered, disconnected
  - Mobility is a challenge to cope with
Data is reflected to appropriate mobile agent. In this case, both agents have Data \{A, B\} after rendezvous.
Theoretical Result

- Mobility increases network capacity
  - Under stationary mobility models

- Intuition
  - In reality, network capacity bounded by interference footprint
  - Mobility can be used for transporting bits
  - Bandwidth consumption -- zero
  - Increasing latency
  - But, with higher node density, greater chance of meeting the destination -- higher capacity
Moving from intuition to protocol
Last Encounter Routing in Ad Hoc Networks

By
Grossglauser, Vetterli
(IEEE Infocom 2003)

Some slides from David Tse, UC Berkeley
Location Services

- **Challenge:** construct a distributed database out of mobile nodes

- **Approaches:**
  - Virtual Home Region: hash destination id to geographic region: rendez-vous point for source and dest (Giordano & Hamdi, EPFL tech. report, 1999)
  - Grid Location Service: quad-tree hierarchy, proximity in hashed id space (Li et al., Mobicom 2000)
  - DREAM: Distance Routing Effect Algorithm (Basagni & Chlamtac & Syrotiuk, Mobicom 1998)
Last Encounter History

- **Question:**
  - Do we really need a location service?

- **Answer:**
  - No (well, at least not always)

- **Observation:**
  - History of this local connectivity may be available for free

- **Claim:**
  - Collection of last encounter histories at network nodes contain enough information about current topology to efficiently route packets
Can we efficiently route a packet from a source to a destination based only on LE information, in a large network with n nodes?

Assumptions:
- Dense encounters: $O(n^2)$ pairs of nodes have encountered each other at least once
- Time-scale separation: packet transmission (ms) $\ll$ topology change (minutes, hours, days)
- Memory is cheap ($O(n)$ per node)

Basic idea:
- Packet carries with it: location and age of best (most recent) encounter it has seen so far
- Routing: packet consults entries for its destination along the way, “zeroes in” on destination
Definition: Last Encounter Table

encounter at X between A and B at t=10

X

A: loc=X, time=10
B: loc=X, time=10
C: ...
D: ...

A
B
Fixed Destination
Moving Destination
Exponential Age Search (EASE)

**time**

- $T$

**source**

**destination**

Time line with two paths and arrows indicating a search process from source to destination.
EASE: Messenger Nodes
EASE: Searching for Messenger Node

Search: who has seen dest at most $T/2$ secs ago?
EASE: Forwarding the Packet

Forwarding towards new position with $T := \text{new encounter age}$
EASE: Sample Route

**Def:**
anchor point of age \( T = \) pos. of dest. \( T \) sec ago

**EASE:**
- ring search nodes until new anchor point of age less than \( T/2 \) is found
- go there and repeat with \( T = \) new age
Performance of EASE

- Length of routes clearly depends on mobility
  - Cannot work with iid node positions in every step

- Model:
  - 2-D lattice, N points, fixed density of nodes
  - Each node knows its own position
  - Independent random walks of nodes on lattice

- Cost = forwarding cost + search cost
Cost of EASE Routes

- **Claim:**
  - The asymptotic expected cost for large $N$ of EASE routes is on the order of shortest route, i.e., total forwarding cost is $O(\text{shortest path})$.

- **Forwarding cost:**
  - Geometric series of ages $\rightarrow$ geometric series of EASE segments
  - Total length $= O(\text{shortest path})$
Search Cost

- Single step search cost is small compared to forwarding cost:
  - Show that density of messenger nodes around current anchor point is high
  - Depends on:
    - Number of unique messenger nodes encountered by destination = $O(\log T)$
    - Distance traveled by messenger nodes = same order as destination
Improvement: Greedy EASE
Simulation: Random Walk Model

- N nodes
- Positions i.i.d.
- Increments i.i.d.
Simulation: Random Walk Model

Empirical conditional mean of cost, conditional on $|X_s - X_d| \leq d$
Heterogeneous Speeds: Slow Dest
Heterogeneous Speeds: Fast Dest
Heterogeneous Speeds

Empirical conditional mean of cost, GREASE, conditional on $|X_s - X_d| \leq d$

- Blue circles: slow destinations
- Green squares: fast destinations

The graph shows the expected cost (E[|distance| <= d]) as a function of d, distinguishing between slow and fast destinations.
Simulation: Random Waypoint

- N nodes
- Positions i.i.d.
- Every node has a waypoint
- Moves straight towards waypoint at constant speed
- When reached, new waypoint selected uniformly over area
Pareto RW and Random Waypoint

Empirical conditional mean of cost, GREASE, conditional on $|X_s - X_d| \leq d$

- Red circles: Pareto increments
- Blue squares: random waypoint

Graph shows the empirical conditional mean of the cost, GREASE, as a function of $d$, for two different mobility models: Pareto RW and Random Waypoint. The graph illustrates how the expected cost decreases as the distance constraint $d$ increases.
Related Idea: 
Last Encounter Flooding

- With coordinate system
  - Last-encounter information: time + place
  - EASE/GREASE algorithms

- Blind, no coordinate system
  - Last-encounter information: time only
  - FRESH algorithm: flood to next anchor point
  - Henri Dubois-Ferrière & MG & Martin Vetterli, MOBIHOC 03
FRESH: Last Encounter Flooding
Summary: Last Encounter Routing

- Last Encounter Routing uses position information
  - Diffused for free by node mobility
  - Mobility creates uncertainty, but also provides the means to diffuse new information

- No explicit location service, no transmission overhead to update state!
  - Only control traffic is local “hello” messages

- Rich area for more research:
  - Prediction
  - Integration with explicit location services & routing protocols
  - More realistic mobility models
What’s Missing?

- LER takes advantage of mobility
  - But not fully

- Nodes do not carry messages
  - Mobility based disconnection still an issue
Theory to Protocol

- Translate mobility into opportunity
  - Not a peril

- Use local storage as carrier of bits
  - Storage technology improving drastically

- Of course latency increases with mobility
  - But, several applications may be tolerant
  - E.g., mobile sensors, sending emails, messaging
  - Also, delayed ubiquity better than disconnection
Why Might This Fly?

- No end to end sessions
  - Batches of packets (called bundles) travel one-shot
    - Non pipelined transmission
    - One link at a time
  - We understand link by link transmission well

- Disconnection not a problem
  - Some performance feasible even w/o critical density

- Storage technology improving
  - One-time set up latency + high throughput
Pocket Switched Networks:
Real-world Mobility and its Consequences for
Opportunistic Forwarding

Jon Crowcroft, Pan Hui (Ben)
Augustin Chaintreau, James Scott,
Richard Gass, Christophe Diot

Slides adapted from author’s slides
PSN: Motivations

- Not always connected, “internet connectivity islands”

- Huge amount of untapped resources in devices
  - Local wireless bandwidth
  - Storages
  - CPUs

- A packet can reach destination using network connectivity or user mobility

- MANET/DTN
Give it to me, I have 1G bytes phone flash.

I have 100M bytes of data, who can carry for me?

I can also carry for you!

Thank you but you are in the opposite direction!

Don’t give to me! I am running out of storage.

Reach an access point.

Search La Bonheme.mp3 for me

There is one in my pocket...

Finally, it arrive...
Pocket switched networks

- Make use of global, local network connectivity and user mobility
- Under more general
  - MANET
  - DTN [Fall]
Applications

- Asynchronous, local messaging
- Automatic address book or calendar updates
- Ad-hoc Google
- File sharing, bulletin board
- Commercial transactions
- Alerting, tracking or finding people
Measuring Human Mobility

Mobility is a double-edged sword, it potentially increases the bandwidth, but also provides challenges for communication.
Why measure human mobility?

- Mobility increases capacity of dense mobile network [Tse/Grossglauser>Gupta/Kumar]

- Also create dis-connectivities[e.g. Tschudin]

- Human mobility patterns determine communication opportunities
Experimental setup

- **iMotes**
  - ARM processor
  - Bluetooth radio
  - 64k flash memory

- **Bluetooth Inquiries**
  - 5 seconds every 2 minutes
  - Log \{MAC address, start time, end time\} tuple of each contact
Experimental devices
Infocom 2005 experiment

- 54 iMotes distributed
- Experiment duration: 3 days
- 41 yielded useful data
- 11 with battery or packaging problem
- 2 not returned
Brief summary of data

- 41 iMotes
- 182 external devices
- 22459 contacts between iMotes
- 5791 contacts between iMote/external device
- External devices are non-iMote devices in the environment, e.g. BT mobile phone, Laptop.
Contacts seen by an iMote

iMoites

External Devices

Contact traces for iMoites and External Devices.
Analysis of Conference Mobility Patterns
Contact and Inter-contact time

- Inter-contact is important
  - Affect the feasibility of opportunistic network
  - Nature of distribution affects choice of forwarding algorithm
  - Rarely studied
Contact and Inter-contact Distribution

Contacts

Inter-contacts

0.1 chance of talking for more than 10 min

Large fraction should be around 30 min duration...

Heavy tailed. Protocols need to cope with this
What do we see?

- Power law distribution for contact and inter-contact time
- Both iMotes and external nodes
- Does not agree with currently used mobility model, e.g. random way point
- Power law coefficient < 1
Implication of Power Law Coefficient

- Large coefficient $\Rightarrow$ Smaller delay
- Consider 2-hops relaying [tse/grossglauser] analysis [TechRep]
- Denote power law coefficient as $\alpha$
- For $\alpha > 2$
  Any stateless algorithm achieves a finite expected delay.
- For $\alpha > (m+1)/m$ and $\#\{\text{nodes}\} \geq 2m$ :
  There exist a forwarding algorithm with $m$ copies and a finite expected delay.
- For $\alpha < 1$
  No stateless algorithm (even flooding) achieve a bounded delay (Orey’s theorem).
Frequency of sightings and pairwise contact

Most nodes inside network
Many pair-wise contacts. May not hold for public networks

One person has huge external contacts
What do we see?

- Nodes not equal, some active and some not
  - Does not agree with current mobility model, equally distributed.

- iMotes seen more often than external address

- More iMotes pair contact
  - Identify Sharing Communities to improve forwarding algorithm
How generic is this result?

- Other nodes (bluetooth phone/pda)
- Other nets (WiFi)
- Other communities (kids, random, HK)

- Are there cliques in the set/community
  - tight-knit sub-communities
  - Popular people/places?
Influence of time of day
What do we see?

- Still a power law distribution for any three-hour period of the day

- Different power law coefficient for different time
  - Maybe different forwarding algorithm for different time of the day
Inter-contact for Workplace and University Environment
Inter-contact time for WiFi traces
Consequences for mobile networking

- Mobility models need to be redesigned
  - Exponential decay of inter contact is wrong
  - Mechanisms tested with that model need to be analyzed with new mobility assumptions

- Stateless forwarding does not work
  - Can we benefit from heterogeneity to forward by communities?
  - Should we consider different algorithm for different time of the day?
Future Work

- Continue mobility measurement in different network environments
- Continue mathematical analysis
- Create representative mobility models
- Design and evaluate forwarding algorithms for PSN
- Prototyping PSN applications, e.g. distributed file sharing and newsgroups
Routing on Delay Tolerant Networks
The next step ...
Thoughts ...

- Some observations from EASE and Pocket Net
  - Humans are reasonably social
  - Can obey power law ... some heavy tailed behavior
  - Residual charge between recharging
    - Around ~ 60%
  - Storage not a problem
  - If random walk (or random waypoint)
    - Memory can be useful
  - When mobility patterns exhibit affinity
    - EASE may not work as well

- Can we exploit all these properties?
Mingling and Gossiping

encounter at location X between A and B at t=10

A: loc=X, time=10

B: loc=X, time=10
Mingling and Gossiping

A: loc=X, time=10
B: loc=X, time=10
C: loc=Z, time=19
D: loc=Y, time=15

A: loc=X, time=10
B: loc=Z, time=19
C: loc=Z, time=19
D: loc=Y, time=15
Brownian Gossip
Brownian Gossip Routing

- Each node can find approx location in cache
  - Performs geographic forwarding
  - Includes location, and time stamp

Packet Header
Src: loc=L, time=43
Dst: loc=M, time=24

- Each intermediate node forwards towards M
  - If its own time for Dst < 24
  - Else, replaces <Dst: Loc, Time> with recent value
  - Forwards packet
Will Routes Converge?

- Network will show spatial locality
  - For random walk (and similar mobility)
  - For i.i.d will not hold

- Spatial locality
  - Spatial neighborhood of a node is likely to have met the node more recently

- As packets go closer to the Dst
  - The trajectory gets better corrected
  - Convergence can happen quickly: $O(\text{shortest path})$
Latency for RWP

Random Waypoint Mobility Delay vs Node Densities

Average Delay to Target vs Number of Nodes

- Optimal
- Gossip
- Broadcast
Some Issues

- What if Destination move too fast
  - New dest location may be depopulated
  - Many nodes may have stale cache

- Use Gossip-K
  - Propagate K queries in diff directions
  - Redunancy --> reliability
Gossip-K

Delay for Gossip with k Initial Packets

Average Delay to Target

Initial Packets

- RandomWayPoint
- Clustered
Questions?
Deadline today @ 11:59pm

- Brian, Ashwin, Roman: sensor network on maps
- Pradeep, Thilee: smart gossip idea + implement
- Ola, Soji, Tom: Space-Time scheduling
- Michael, Kunal: ??
- TingYu, Gary, Yuanchi: intrusion detection in SN
- Ian, William: Routing in DTNs with beacons
- Wayne, Tray: beam overlap not harmful
- Deepak, Karthik, Boyeum: Spatial reuse in wireless
- Tong: ??
- Shawn, Simrat: Flash crowd MAC protocols
Mingling and Gossiping

encounter at location X between A and B at t=10

A: loc=X, time=10

B: loc=X, time=10
Thank You

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Any-contact and inter-any-contact

- Any-contact: the duration of staying with at least one node
- Inter-any-contact: the duration between two any-contact
Any-contact and Inter-any-contact distribution
Interpretation: Distance Effect and Mobility Diffusion

- Observation: required precision of destination’s location can decrease with distance
  - DREAM algorithm: exploit distance effect to decrease state maintenance overhead
  - When a node moves by \( d \) meters, inform other nodes in disk of radius \( c \times d \) meters
  - Relax separation of location service and routing service

- Basic idea behind last encounter routing:
  - Exploit mobility of other nodes to diffuse estimate of destination’s location “for free”
  - Concurrently for all nodes
Simulation: Pareto Random Walk

- $N$ nodes
- Positions i.i.d.
- Increments i.i.d., heavy-tailed distance distribution