DTN Routing as a Resource Allocation Problem

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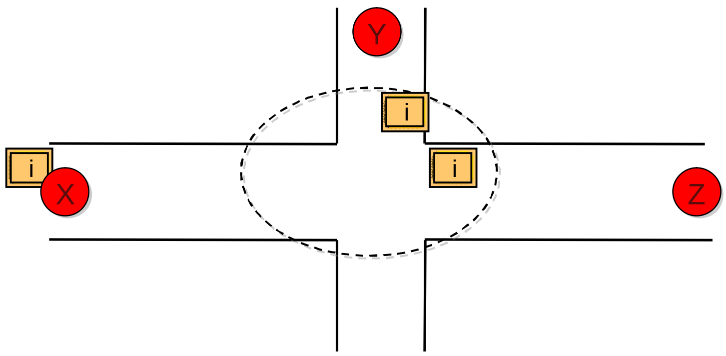
What are DTNs?

- Delay/Disruption Tolerant Networks
  - end-to-end path may *never* exist
  - routing must use pair-wise transfers staggered over time



Why useful?

- Infrastructure expensive or nonexistent
  - e.g., Daknet, Kiosknet, OLPC
- Infrastructure cannot be deployed
  - e.g., underwater, forests, outer space(!)
- Infrastructure limited in reach
  - e.g., Dieselnet, Cartel, Drive-thru-internet, VanLan

DTNs high delay, low cost, useful bandwidth

Why challenging?

Wired/Mesh/MANETs	DTNs
Known topology	Uncertain topology
Low feedback delay • Retries possible	Feedback delayed/nonexistent

Primary challenge: finding *a* path to the destination under extreme uncertainty

Existing routing mechanisms *Incidental*

- DTN routing mechanisms
  - Estimating meeting probability
  - Packet replication
  - Coding
  - Waypoint stores
  - **Prior knowledge**
  - **...**
- Metrics desired in practice
  - Minimize average delay
  - Maximize packets meeting their deadlines
  - …
- Goal: Design *Intentional* DTN Routing Protocol, RAPID

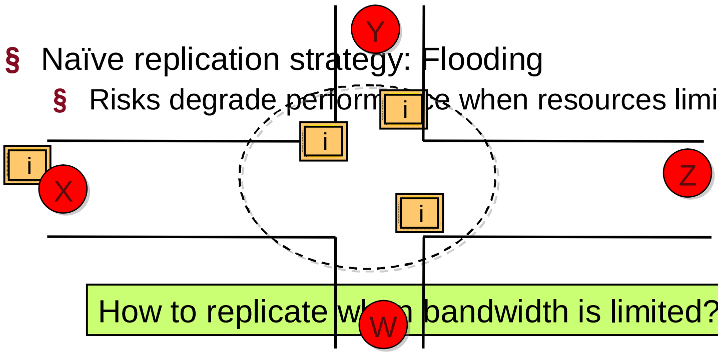
Roadmap

- Background and Motivation
- RAPID
  - Replication to handle uncertainty
  - Utility-driven resource allocation
  - Distributed algorithm
- Deployment and Evaluation

Replication to handle uncertainty

- Replication can address
  - Topology uncertainty
  - High delay feedback

- Naïve replication strategy: Flooding
  - Risks degrade performance when resources limited



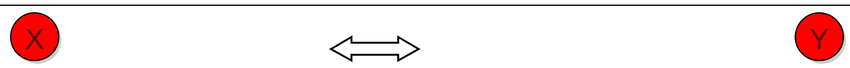
How to replicate when bandwidth is limited?

Routing as a resource allocation problem

- Problem
  - Which packets to replicate given limited bandwidth to optimize a specified metric

- RAPID: Resource Allocation Protocol For Intentional DTN Routing

RAPID: utility-driven approach



RAPID Protocol (X,Y):

1. Control channel: Exchange metadata

2. Direct Delivery: Deliver packets destined to each other

3. Replication: Replicate in decreasing order of marginal utility $\frac{\Delta U(i)}{s(i)}$ (Change in utility / Packet size)

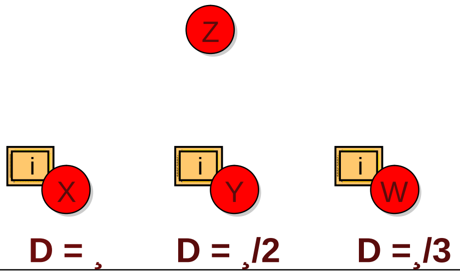
4. Termination: Until all packets replicated or nodes out of range

Translating metrics to utilities

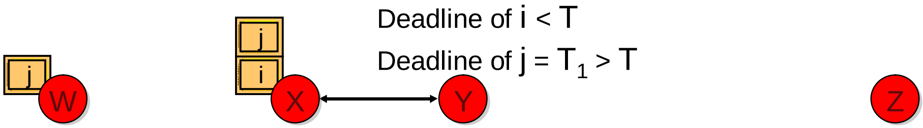
- Utility U(i): expected contribution of packet i to routing metric
- Example 1: Minimize average delay
  - U(i) = negative expected delay of i
- Example 2: Maximize packets delivered within deadline
  - U(i) = probability of delivering i within deadline
- Example 3: Minimize maximum delay
  - U(i) = negative expected delay of i if i has highest delay; 0 otherwise

Utility computation example

- U(i) = -(T + D)
  - T = time since created, D = expected remaining time to deliver
- Simple scenario
  - uniform exponential meeting with mean ¸
  - global view



Utility computation example



Deadline of i < T

Deadline of j = T_1 > T

Metric: Min average delay

$$\Delta U(i) = (T+\lambda) - (T+\frac{\lambda}{2}) = \frac{\lambda}{2}$$

$$\Delta U(j) = (T+\frac{\lambda}{2}) - (T+\frac{\lambda}{3}) = \frac{\lambda}{6}$$

Replicate i

Metric: Max packets delivered within deadline

$$\Delta U(i) = 0$$

$$\Delta U(j) = P(D(T+\lambda/3) < T_1) - P(D(T+\lambda/2) < T_1)$$

Replicate j

RAPID metrics

- Metrics: (i) min avg delay, (ii) min max delay, (iii) max # packets delivered by deadline
- RAPID replicates packets that *locally* improve routing metric most
- **For all three metrics, utility is function of delivery delay**

Roadmap

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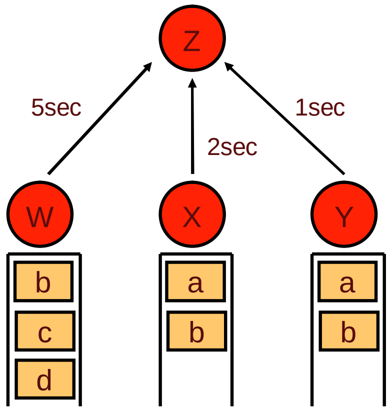
Distributed algorithm challenges

Meeting times unknown

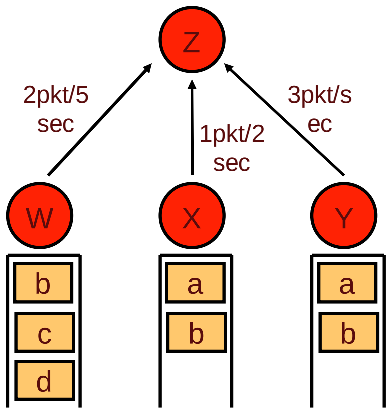


Distributed algorithm challenges

Meeting times unknown

Transfer size unknown

Replica locations unknown
(delivery unknown)



Distributed control channel to build local view of unknowns

Distributed control channel

per node
- Expected inter-meeting time
- Expected transfer size

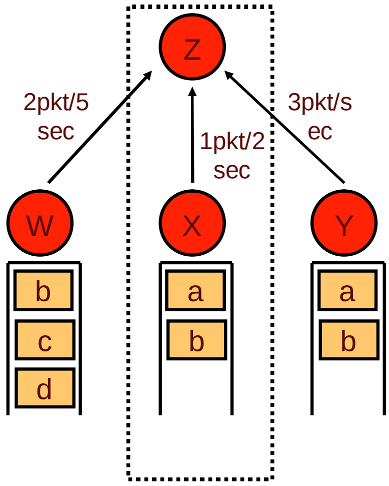
per packet
- Known replica locations
- Expected "local" delay

$D_{X,b} \sim 4sec$

Expected delay of packet b

$\sim \min(D_{W,b}, D_{X,b}, D_{Y,b})$

5 4 1



RAPID recap

RAPID Protocol (X,Y):

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Is RAPID optimal ?

DTN unknowns:
- Meeting schedule
- Packet workload
- Global view

- RAPID: No knowledge
- Complete knowledge
  - NP Hard
  - Approximability lower bound $\sqrt{n}$
- Partial knowledge
  - Average delay: arbitrarily far from optimal
  - Delivery rate: $\Omega(n)$-competitive

Empirically, RAPID is within 10% of optimal for low load

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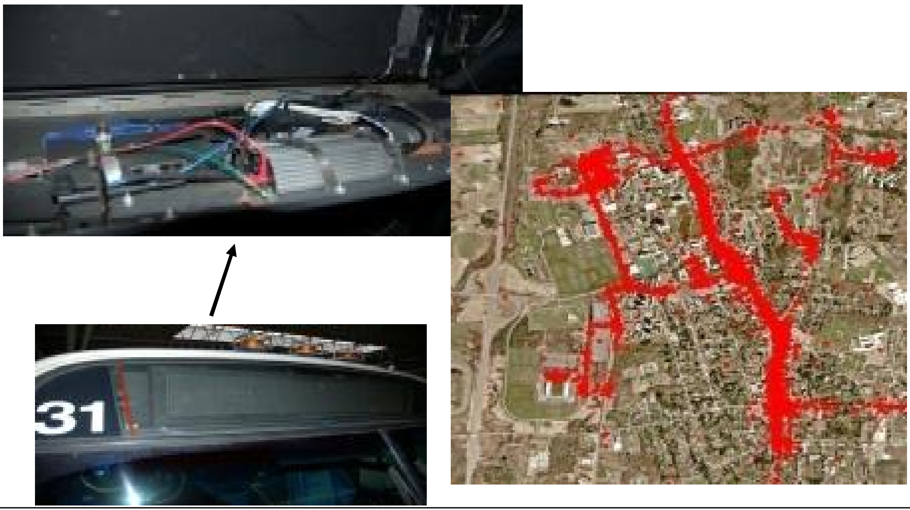
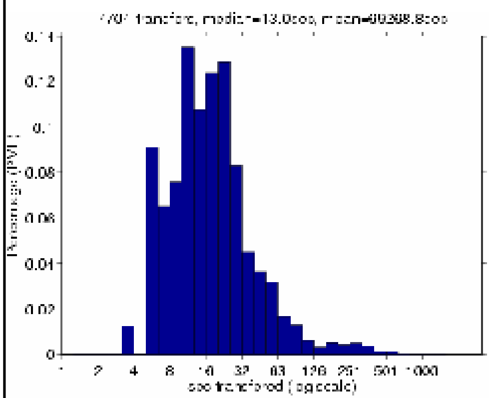
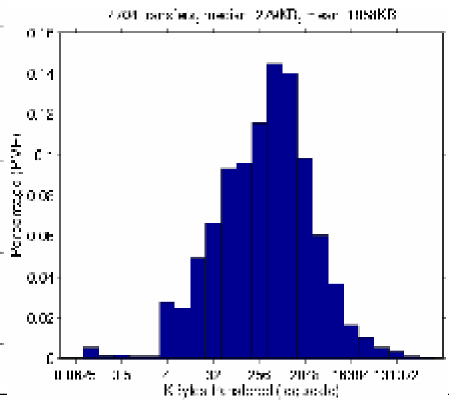
Deployment on DieselNet



Results from deployment

- Synthetic workload
- Deployed from Feb 6, 2007 until May, 14, 2007





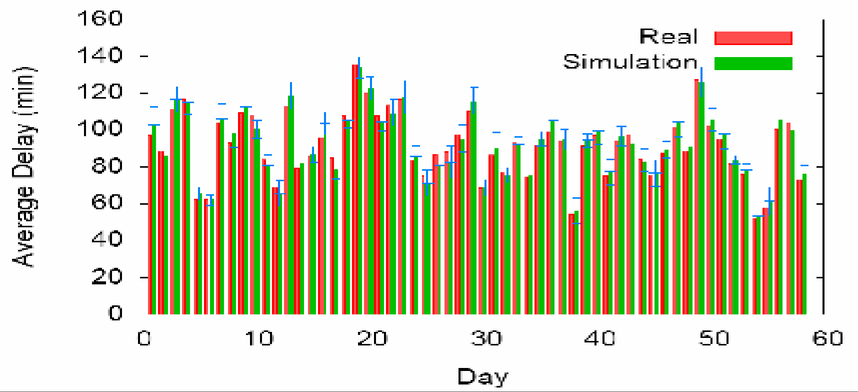
Results from deployment

- Per day stats

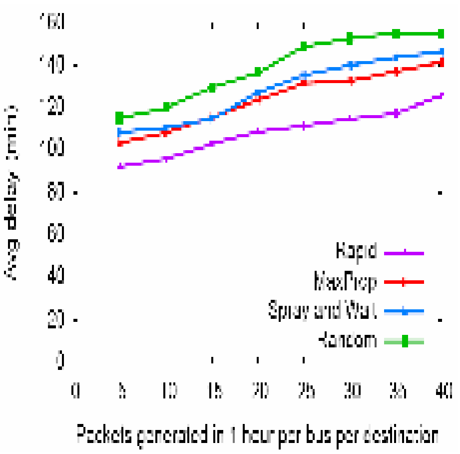
Avg number of buses on road	19
Avg number of meetings	147.5
Bytes transferred (MB)	261.4
Average packet delay (min)	**91.7**
% packets delivered	**88%**
% meta data exchanged	**1.7%**

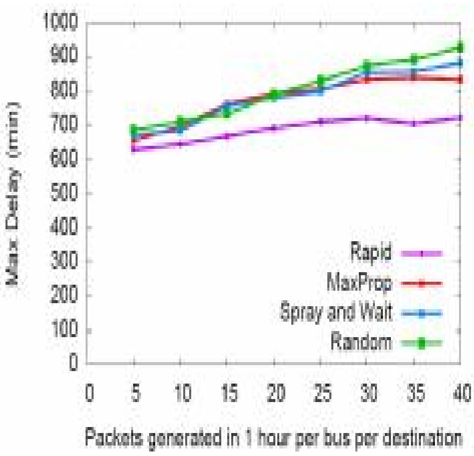
Validating the simulator

- Trace-driven simulator
- Simulation results within 1% of deployment

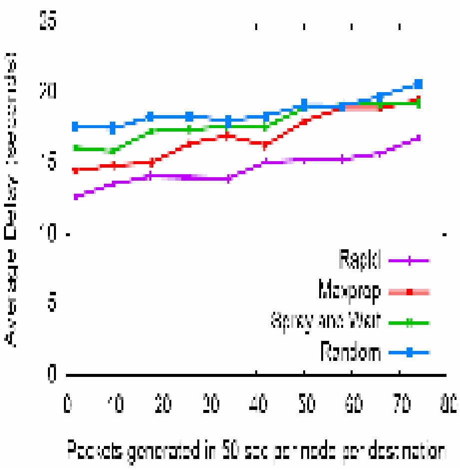


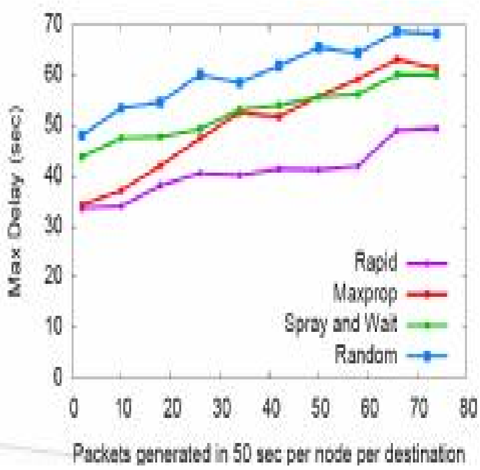
Results: Mobility from DieselNet traces





Results: Known mobility model





Conclusions

- Intentional DTN routing feasible despite high uncertainty
  - tunable to optimize a specific routing metric
- Simple utility-driven heuristic algorithm performs well in practice
  - DTN routing problem fundamentally hard
- Ongoing work
  - Application development on DTNs
  - Graceful degradation across mesh networks and DTNs

traces.cs.umass.edu

Questions?

Additional Slides

ILP Formulation

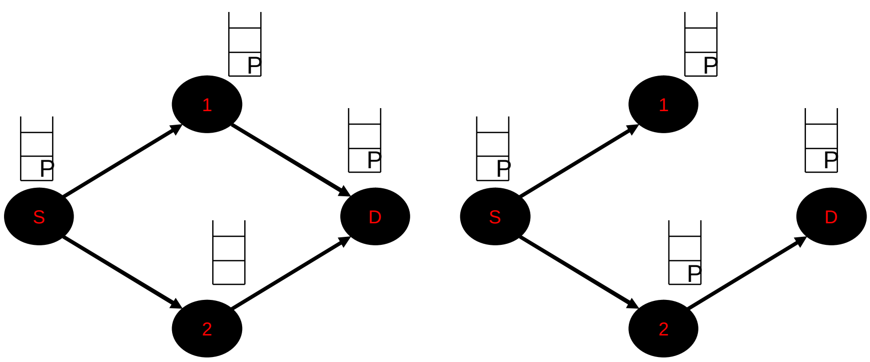
DTN Routing challenges

- Resource constraints
  - not enough bandwidth to exchange
- limited feedback from the network
  - end-to-end acks difficult
- Difficult to predict meetings

Two DTN Routing Approaches

- **Routing:Store and Forward**

Forwarding **Replication**



Two DTN Routing Approaches

- **Forwarding**
  - **Delivery rates low**
  - **No duplicates**
- **Replication**
  - **Delivery rate optimal**
  - **Several duplicates**
  - **What packets to replicate when bandwidth is low?**

Replication improves performance, but overloads the system with useless packets

Delay estimation heuristic

ALGORITHM ESTIMATE_DELAY

1. Let r_1, r_2, L be replicas of i with nodes 1, 2, L

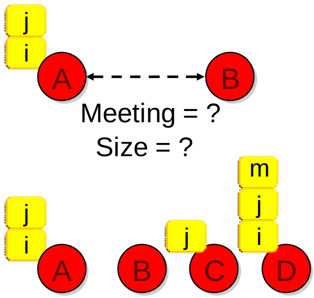
2. For replica r_k, compute delay distribution d_k of k delivering the packet (taking into account bandwidth)

3. Delivery delay distribution = Minimum(d_1, d_2,L)

- What if meeting times are unknown?
  - Estimate using meeting history

Distributed algorithm challenges

- Meeting times unknown
- Bandwidth unknown
- Replicas of i unknown
  - delivery unknown



Propagate meta data to build local view of unknowns