CREST: An Opportunistic Forwarding Protocol Based on Conditional Residual Time

Sunil Srinivasa[1] Sudha Krishnamurthy[2]

[1]Department of Electrical Engineering
University of Notre Dame, IN

[2]Deutsche Telekom Laboratories
Berlin, Germany

IEEE SECON 2009

Outline

Introduction

- Intermittently connected environments (ICE)
  - A fully connected path between source and sink may not always exist
  - Contact schedules of nodes not known in advance
  - E.g. ad-hoc environments without permanent networking infrastructure
- Opportunistic forwarding protocols
  - Leverage forwarding opportunities created by intermediate nodes
    - Portable, wireless communication devices embedded in mobile entities (e.g. humans, vehicles)
  - Nodes follow store and forward paradigm
  - Tolerant to delays and disruptions
  - Challenge: Choosing the best forwarding opportunity based on limited contact information

Related Work

- Focus: Analytical characterization of mobility traces
  - Aggregate inter-contact durations (ICD) between human pairs follows power-law distribution[Chaintreau]
  - ICD is dichotomous: power-law followed by exponential decay[Karagiannis][Cai]

Related Work

- Focus: Analytical characterization of mobility traces
  - Aggregate inter-contact durations (ICD) between human pairs follows power-law distribution[Chaintreau]
  - ICD is dichotomous: power-law followed by exponential decay[Karagiannis][Cai]
- Focus: Design of protocols based on different forwarding metrics

  Flooding, Direct hop: no forwarding metric

  MED: complete future contact schedules, mean expected delay

  MEED: mean expected delay

  PROPHET: delivery probability

  SimBet,Bubblerap: social structure of the network

Related Work

- Focus: Analytical characterization of mobility traces
  - Aggregate inter-contact durations (ICD) between human pairs follows power-law distribution[Chaintreau]
  - ICD is dichotomous: power-law followed by exponential decay[Karagiannis][Cai]
- Focus: Design of protocols based on different forwarding metrics

  Flooding, Direct hop: no forwarding metric

  MED: complete future contact schedules, mean expected delay

  MEED: mean expected delay

  PROPHET: delivery probability

  SimBet,Bubblerap: social structure of the network
- CREST
  - Forwarding metric based on characterization of mobility traces
  - Metric based on conditional residual time

Collection of Mobility Traces

- Environment profile
  - Open research lab environment
  - Mobile workspaces, meetings rooms, cafeteria
  - 4 floors
- Participant profile
  - 52 participants, each carrying Ekahau wireless tag
  - Researchers from 2 research groups, student interns
  - Project leaders in business divisions, department managers
  - System administrators, administrative staff
- Data Logging
  - Location coordinates: X, Y, floor
  - Timestamp, tag ID, signal quality
  - 30-day traces, 5 second interval
  - Pairs within 5 meters on same floor are considered to be in contact

Dataset Characterization

- Approach
  - Analyze the aggregate ICD of the office dataset
  - Derive bounds for the delay performance of DTN protocols
  - Model the pairwise ICD and propose a new link metric
  - Assume data transfer time negligible compared to wait time until next contact

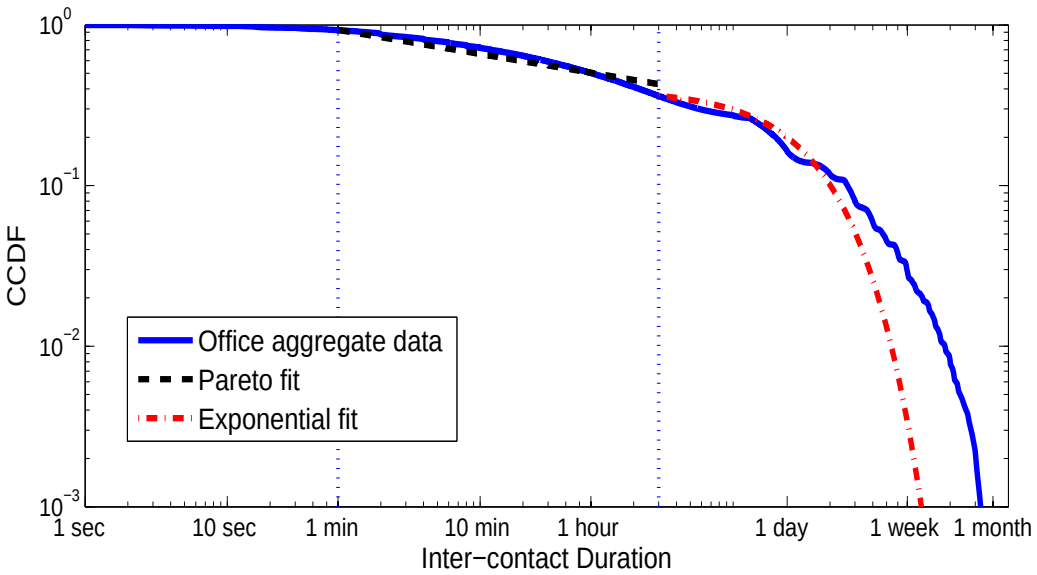
ICD

Time elapsed between two successive contacts of a pair of nodes.

Residual time:

Time remaining until next contact between nodes i and j.

Aggregate Inter-Contact Duration



- CCDF of aggregate ICD for office dataset is dichotomous
- Pareto ($\alpha = 0.1497$) followed by exponential tail ($\lambda = 7.87 * 10^{-6}$)
- Characteristic time = 3 hours

Delay Bounds

Direct hop protocol

- Single hop transmission to destination directly from source
- Mean end-to-end delay for office dataset 35 hours
  - Provides upper delay bound for DTN protocols

Delay Bounds

Direct hop protocol

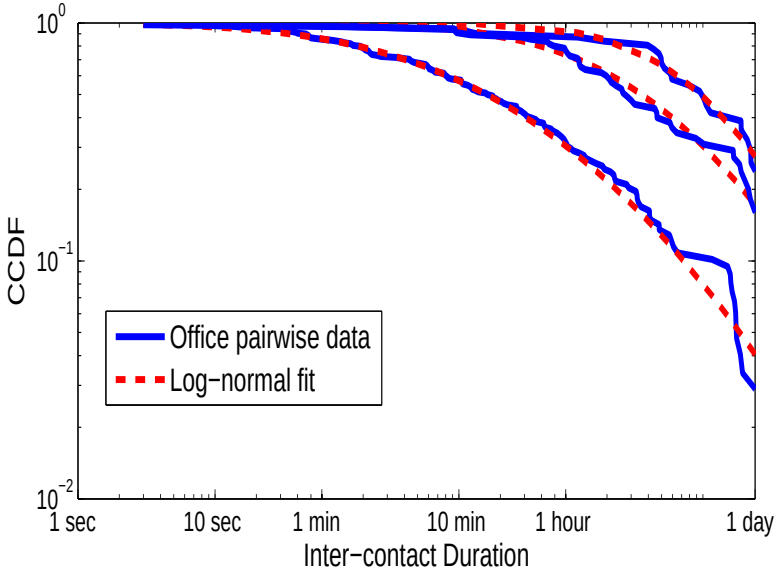
- Single hop transmission to destination directly from source
- Mean end-to-end delay for office dataset 35 hours
  - Provides upper delay bound for DTN protocols

Flooding protocol

- Forward copy of message to every node in contact that does not already have a copy
- Mean end-to-end delay for office dataset 4.66 hours
  - Provides lower delay bound for DTN protocols

Delay expression for pareto and exponential cases for both protocols derived in paper

Pairwise Inter-Contact Durations



- Aggregate ICD does not accurately represent contact behavior of different node pairs
- Pairwise ICD provides better basis for link metric
- Most pairwise ICD in office dataset lognormally distributed (K-S statistic)
  - Different parameters μ_{ij} and σ_{ij}
  - Means span over three orders of magnitude
  - Contact behavior between individual pairs not memoryless

CREST Link Metric

Conditional Residual Time (CRT)

Time remaining before node i and j meet, conditioned on the information that they last met t_{ij} time slots ago.

CREST Link Metric

Conditional Residual Time (CRT)

Time remaining before node i and j meet, conditioned on the information that they last met t_{ij} time slots ago.

- CREST uses median CRT as link metric
- Computed as $\tilde{t}_{ij} = \bar{F}^{-1}_{\hat{R}_{(i,j)}}(0.5)$

$$\bar{F}_{\hat{R}_{(i,j)}}(t) = Pr\left(\hat{R}_{(i,j)} > t \mid T_{(i,j)} > t_{ij}\right)$$

$R(i,j)$: r.v. denoting the CRT between pair (i,j)

$T(i,j)$: ICD of pair (i,j)

CREST Link Metric

Conditional Residual Time (CRT)

Time remaining before node i and j meet, conditioned on the information that they last met t_{ij} time slots ago.

- CREST uses median CRT as link metric
- Computed as $\tilde{t}_{ij} = \bar{F}^{-1}_{\hat{R}_{(i,j)}}(0.5)$

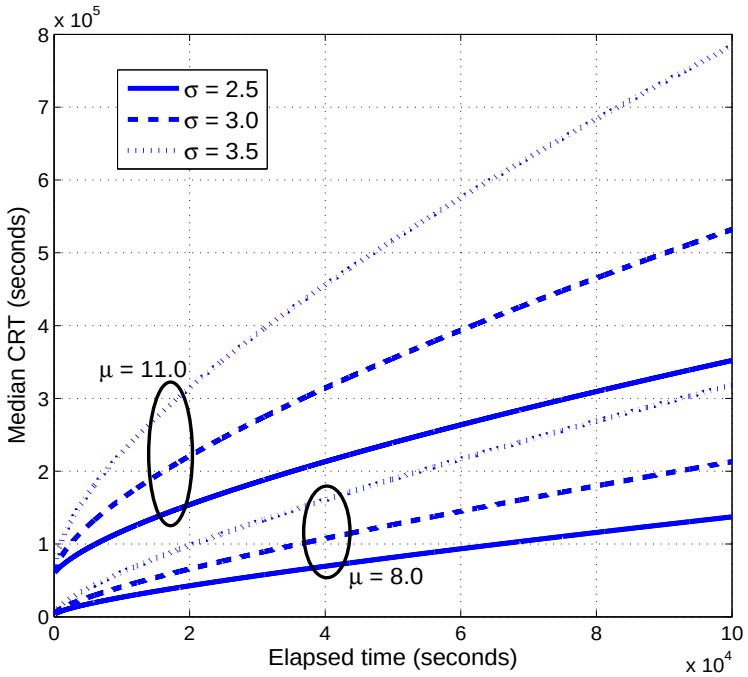
$$\bar{F}_{\hat{R}_{(i,j)}}(t) = \Pr\left(\hat{R}_{(i,j)} > t \mid T_{(i,j)} > t_{ij}\right)$$

$R(i,j)$: r.v. denoting the CRT between pair (i,j)
$T(i,j)$: ICD of pair (i,j)

For lognormal pairwise ICD ($T(i,j)$):

$$\tilde{t}_{ij} = \exp\left(\mathrm{erf}^{-1}\left(\frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{\ln t_{ij} - \mu_{ij}}{\sigma_{ij}\sqrt{2}}\right)\right)\sigma_{ij}\sqrt{2} + \mu_{ij}\right) - t_{ij}. \quad (1)$$

Median CRT



- Lognormal parameters for office dataset:
  - $8.0 \leqslant \mu_{ij} \leqslant 11.0$
  - $2.5 \leqslant \sigma_{ij} \leqslant 3.5$
- Behavior of median CRT depends on distribution of ICD

  Lognormal (not memoryless): monotonically increases with time elapsed since last contact (t_{ij})

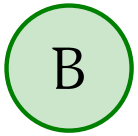
  Exponential (memoryless): residual time independent of t_{ij}

  Constant: decreases with t_{ij}

CREST Forwarding Protocol

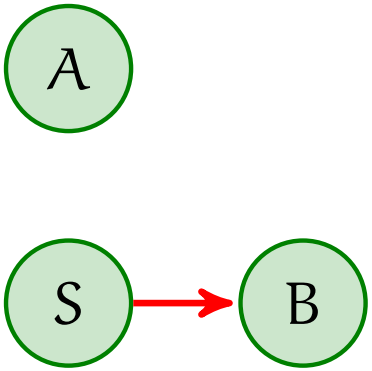
EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* $\cup$ FwdNode;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k $\in$ *PossRelays* with minimum $\tilde{t}_{kD}$;
if NextHopNode $\neq$ FwdNode **then**
    Forward message to *NextHopNode*;
    FwdNode = *NextHopNode*;
end

CREST Forwarding Protocol



EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* $\cup$ `FwdNode`;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k $\in$ *PossRelays* with minimum $\tilde{t}_{kD}$;
if NextHopNode $\neq$ FwdNode **then**
    Forward message to *NextHopNode*;

CREST Forwarding Protocol

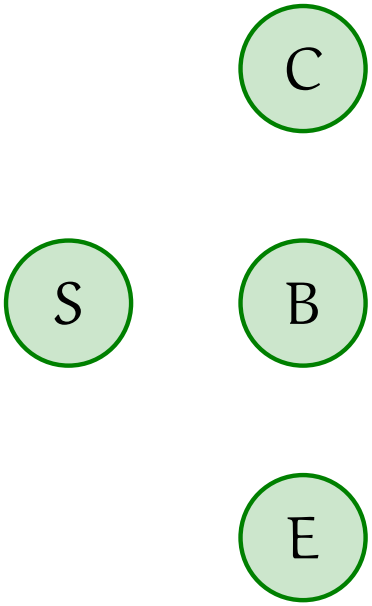


EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* ∪ FwdNode;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k ∈ *PossRelays* with minimum $\tilde{t}_{kD}$;
if NextHopNode ≠ FwdNode **then**
    Forward message to *NextHopNode*;

CREST Forwarding Protocol

EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* $\cup$ FwdNode;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k $\in$ *PossRelays* with minimum $\tilde{t}_{kD}$;
if NextHopNode $\neq$ FwdNode **then**
    Forward message to *NextHopNode*;
    FwdNode = *NextHopNode*;
end

CREST Forwarding Protocol

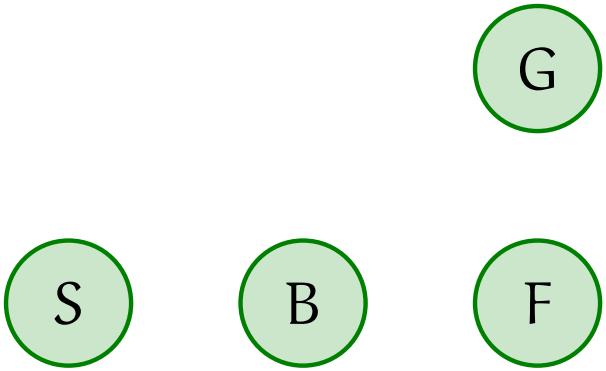


EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* $\cup$ `FwdNode`;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k $\in$
PossRelays with minimum $\tilde{t}$;

CREST Forwarding Protocol

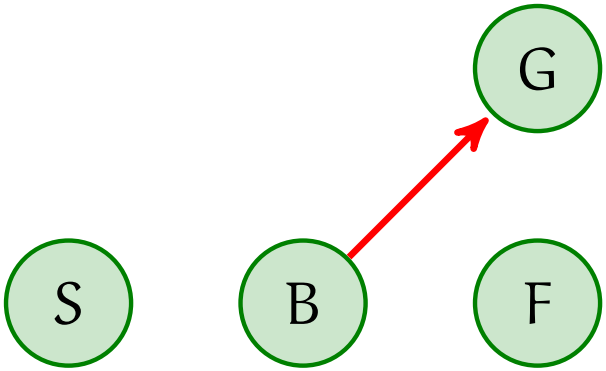
EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* $\cup$ FwdNode;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k $\in$ *PossRelays* with minimum $\tilde{t}_{kD}$;
if NextHopNode $\neq$ FwdNode **then**
    Forward message to *NextHopNode*;
    FwdNode = *NextHopNode*;
end

CREST Forwarding Protocol



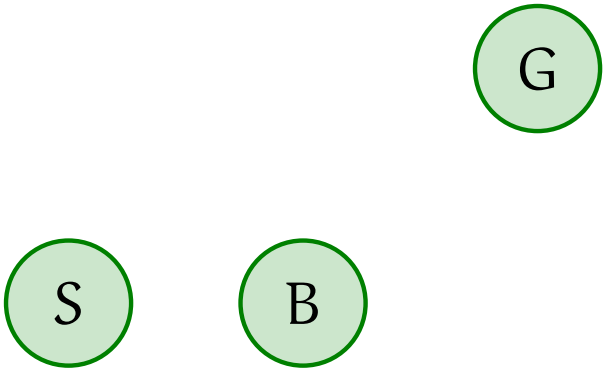
EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* ∪ FwdNode;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k ∈ *PossRelays* with minimum $\tilde{t}_{kD}$;
if NextHopNode ≠ FwdNode **then**
    Forward message to *NextHopNode*;

CREST Forwarding Protocol



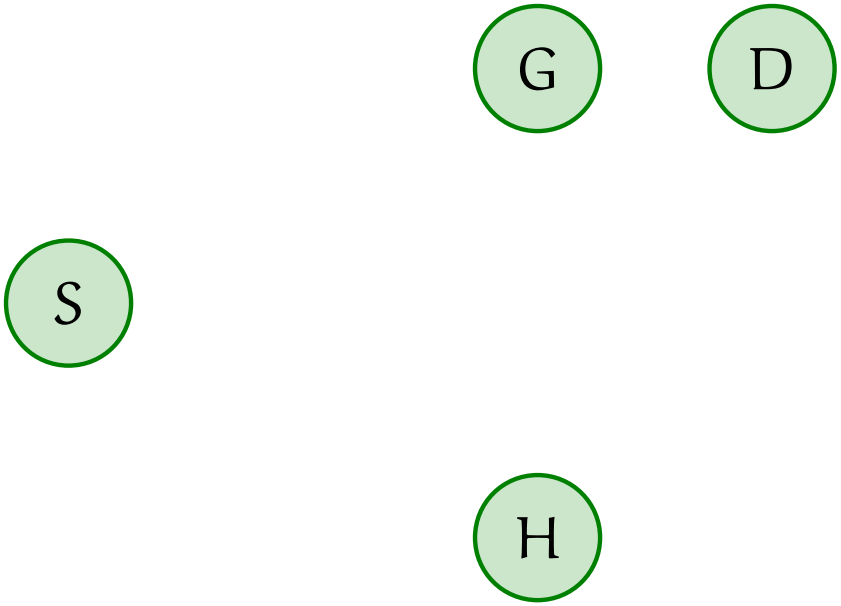
EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* ∪ FwdNode;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k ∈ *PossRelays* with minimum $\tilde{t}_{kD}$;
if NextHopNode ≠ FwdNode **then**
    Forward message to *NextHopNode*;

CREST Forwarding Protocol



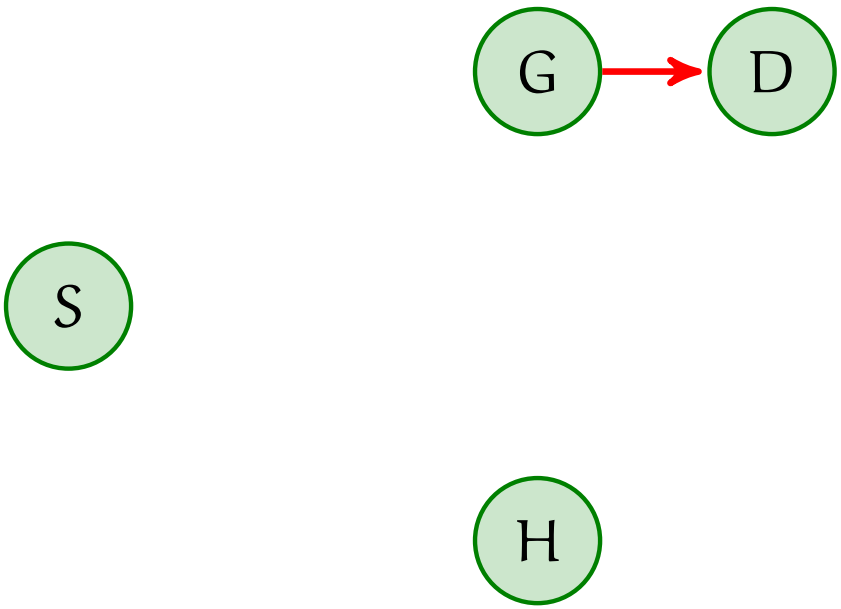
EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* $\cup$ FwdNode;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k $\in$ *PossRelays* with minimum $\tilde{t}_{kD}$;
if NextHopNode $\neq$ FwdNode **then**
    Forward message to *NextHopNode*;

CREST Forwarding Protocol



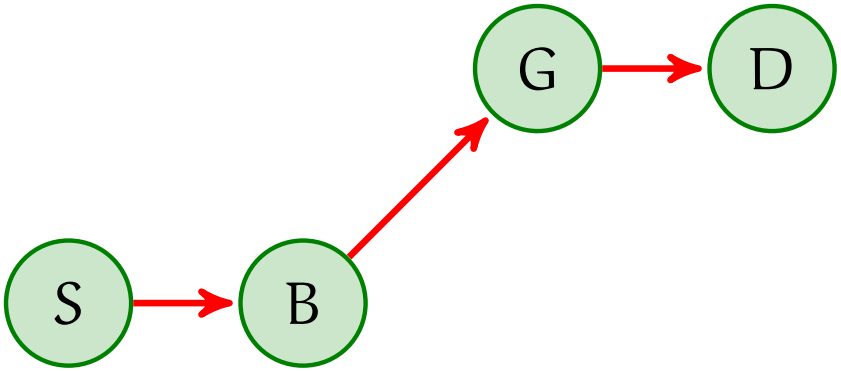
EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* $\cup$ `FwdNode`;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k $\in$ *PossRelays* with minimum $\tilde{t}_{\cdot D}$;

CREST Forwarding Protocol



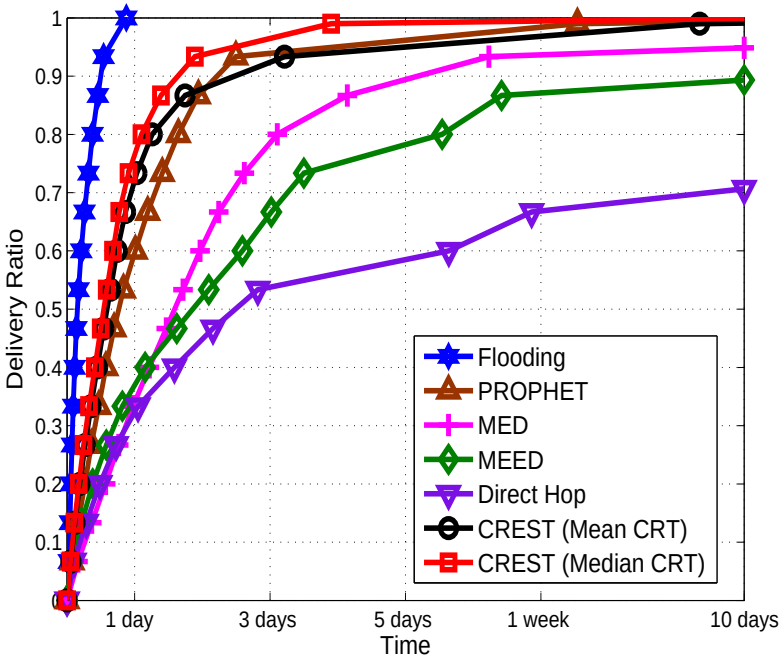
EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* ∪ `FwdNode`;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k ∈ *PossRelays* with minimum $\tilde{t}$;

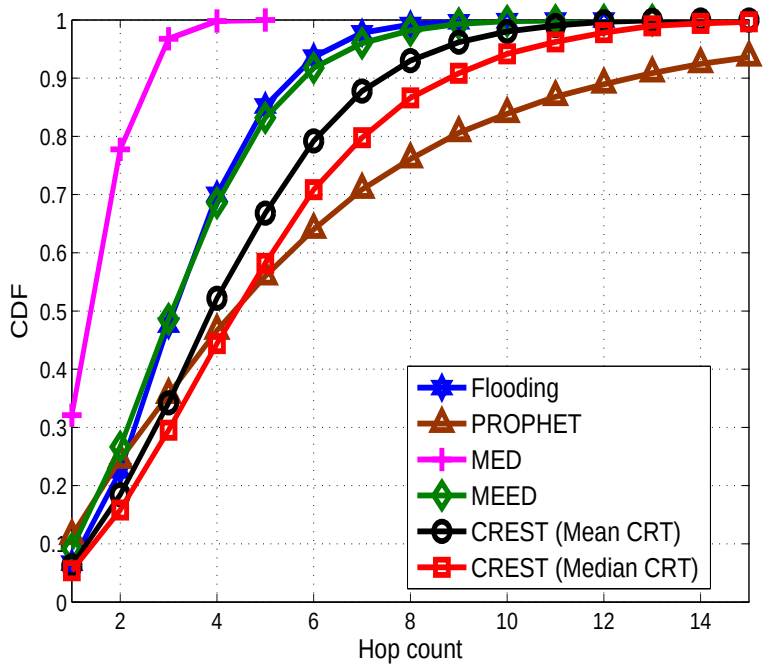
CREST Forwarding Protocol



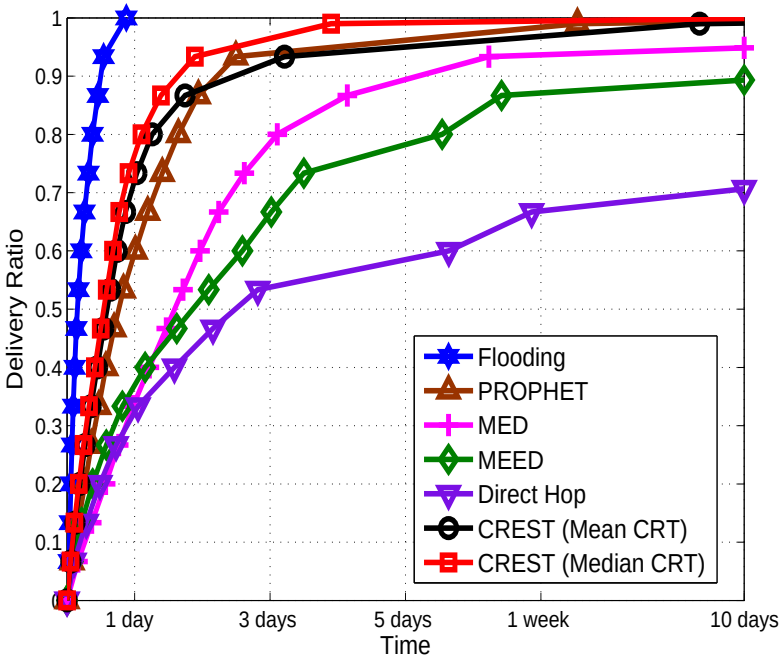
EncNodes = nodes currently in contact with *FwdNode*;
PossRelays = *EncNodes* ∪ FwdNode;
foreach node *i in PossRelays* **do**
    Compute median CRT $\tilde{t}_{iD}$;
end
NextHopNode = node k ∈ *PossRelays* with minimum $\tilde{t}_{kD}$;
if NextHopNode ≠ FwdNode **then**
    Forward message to *NextHopNode*;

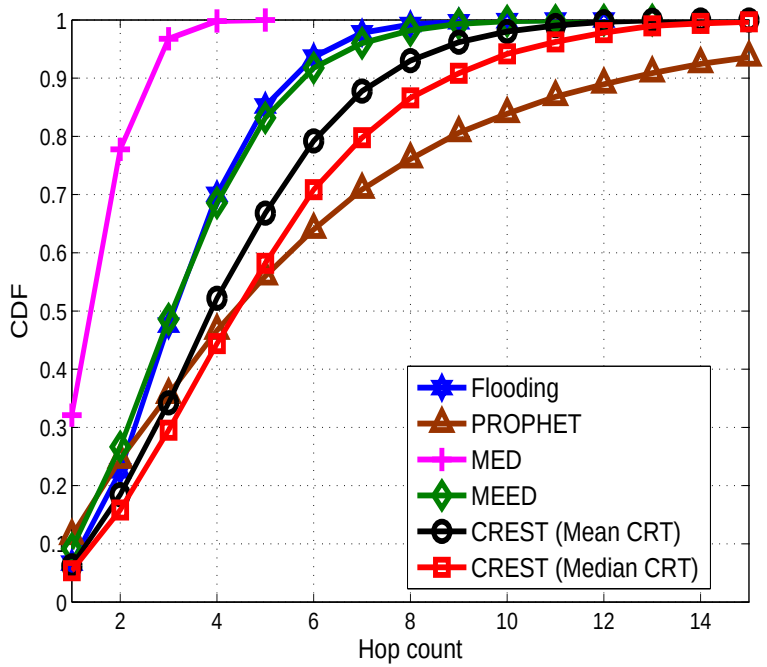
Office Dataset: Single Copy





Office Dataset: Single Copy

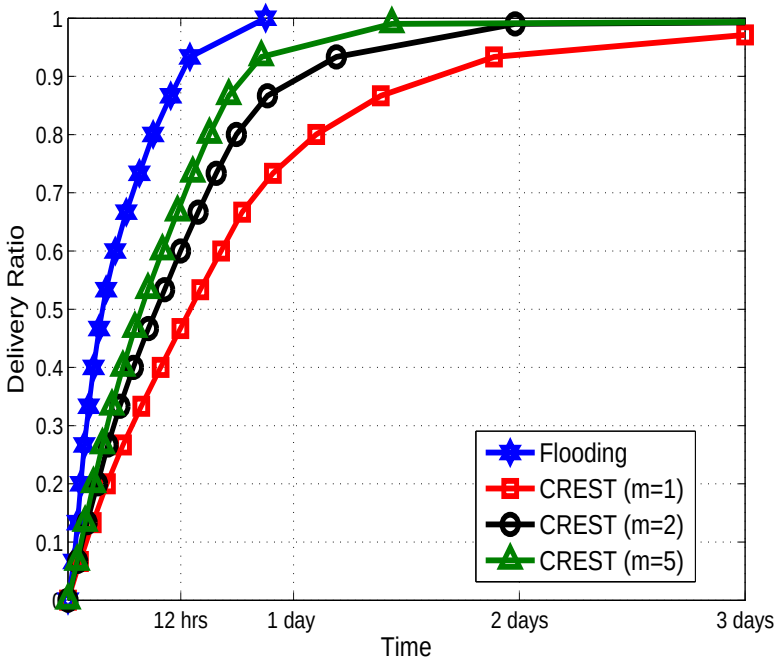




- DR within 1 day: Flooding (100% in 21 hours), CREST (80%), PROPHET (60%), MEED (36%), MED (34%)
- CREST more adaptive to ICD behavior compared to PROPHET

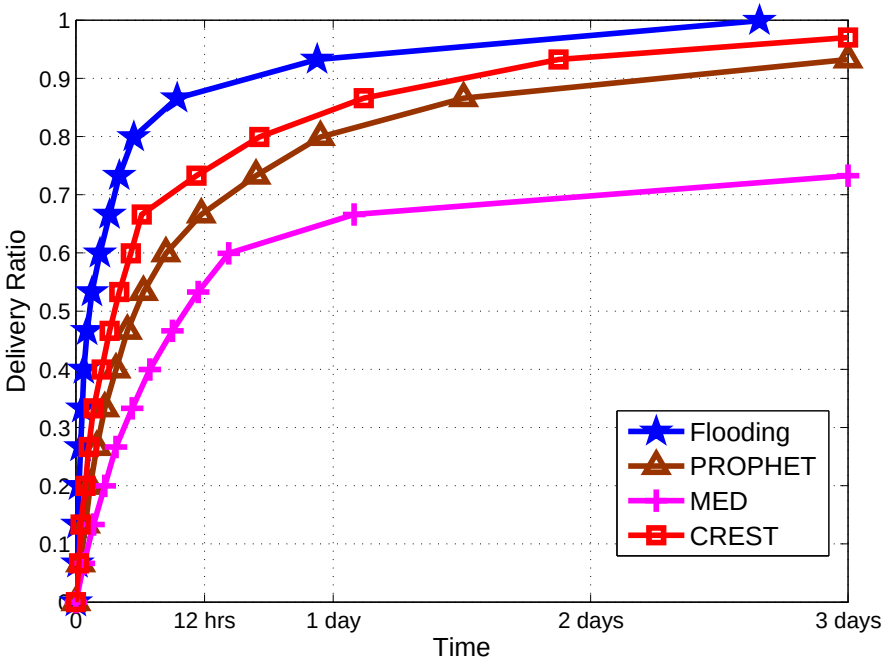
Office Dataset: Multiple Copies

Figure: Can CREST perform as well as Flooding but with fewer message copies?

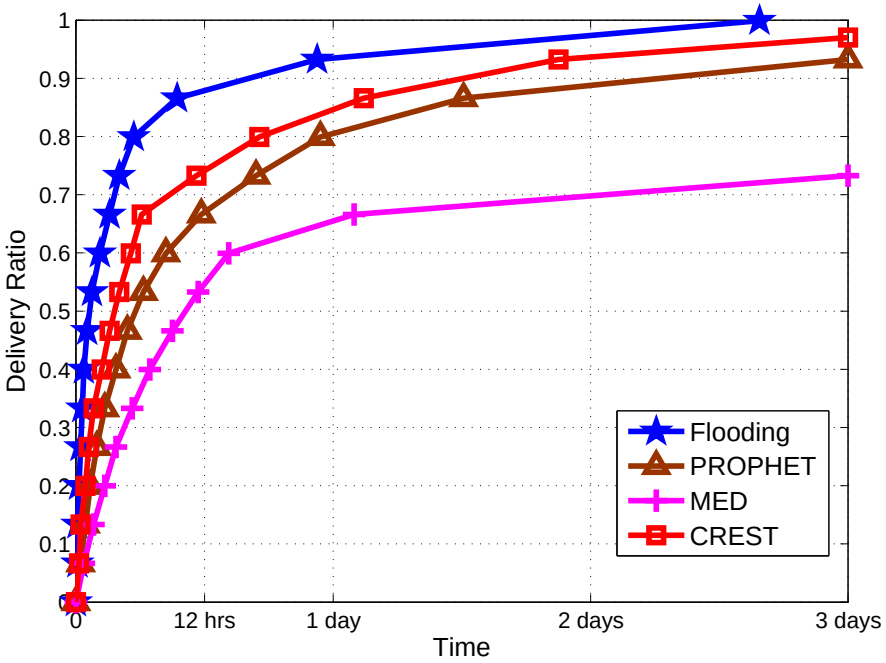


- Source generates m copies
- Delivery ratio improves with m
  - 90% DR: 40 hrs ($m = 1$)
  - 24 hrs ($m = 2$)
  - 18 hrs ($m = 5$)
- Performance stable beyond $m > 5$
- CREST has low overhead
  - CREST: 95% delivery in 21 hrs with $m = 5$
  - Flooding: 100% in 21 hrs with 196 transmissions

Haggle Dataset: Single Copy



Haggle Dataset: Single Copy



Inferences

- Contact data logged by iMotes
- 41 conference participants, 4-day period
- ICD is lognormal
- CREST has lower delay, higher delivery ratio compared to MED, PROPHET

Conclusions

- Data characterization
  - Mobility traces from real environments show human contact behavior not memoryless
  - Median CRT: a novel link metric for opportunistic forwarding

Conclusions

- Data characterization
  - Mobility traces from real environments show human contact behavior not memoryless
  - Median CRT: a novel link metric for opportunistic forwarding
- CREST protocol
  - Decentralized decision making based on local contact information
  - More effective in different ICEs
    - Low overhead
    - Performs better than protocols that use future contact schedules and global contact information

Conclusions

- Data characterization
  - Mobility traces from real environments show human contact behavior not memoryless
  - Median CRT: a novel link metric for opportunistic forwarding
- CREST protocol
  - Decentralized decision making based on local contact information
  - More effective in different ICEs
    - Low overhead
    - Performs better than protocols that use future contact schedules and global contact information
- Future work
  - Mobility-based metrics capture transient contact behavior
  - Combine with metrics that capture social structure