Incentive-Aware Routing in DTNs

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DTNs

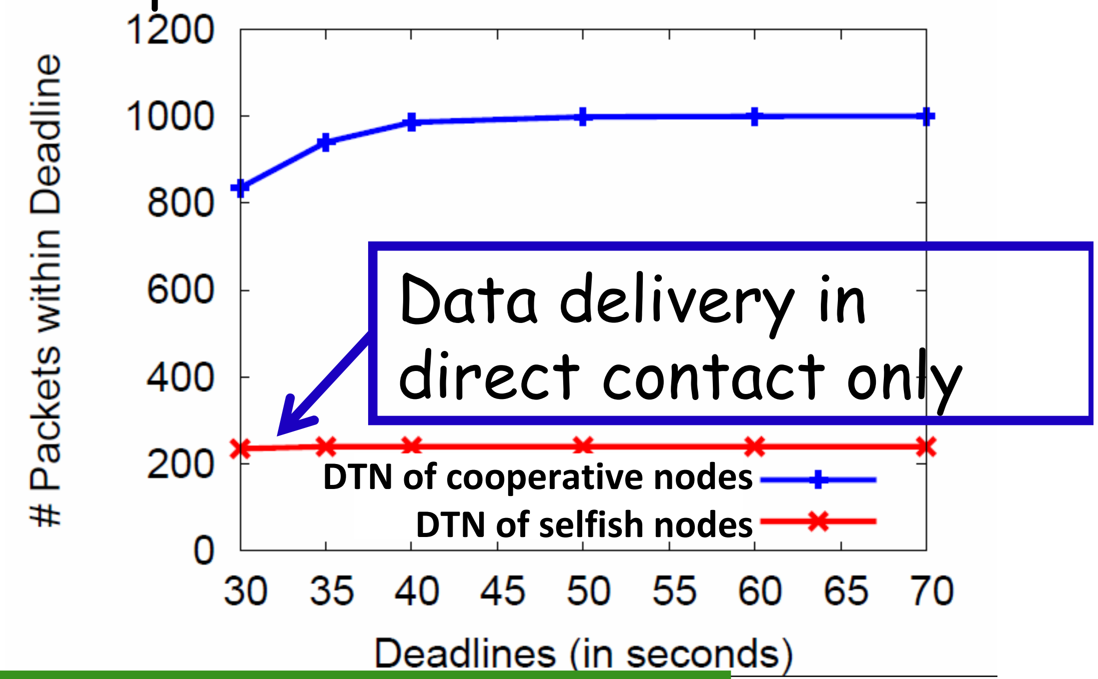
- Disruption toler... ...works
  - No contempor...
  - Opportunistic ... -fwd fashion

- Applications
  - Princeton Zebra...
  - MIT CarTel
  - Cambridge Haggle
  - UWaterloo KioskNet
  - UMass DieselNet, MSR VanLAN
  - NASA Interplanetary Internet

Selfish behavior in DTN routing

- Rational strategy: only consider node's own performance criteria
  - Not to relay traffic for anyone else
  - Disseminate excessive replicas

Performance metric: # packets arrive at destination before delivery deadline



Selfish behavior can cause significant performance degradation

Challenges

- Common solutions don't work in DTNs
  - Strong detection and punishment of misbehaviors
    - Cannot assume full-time monitoring of nodes
  - Credit-based protocol
    - Difficult to provide centralized credit bank
- Challenges to DTN routing
  - Lack of contemporaneous path
  - High variation in network conditions
  - Difficulty to predict mobility patterns
  - Long feedback delay

Need incentive-aware routing that works in DTNs

Incentive-aware protocol overview

- Incentivize DTN protocol
  - Tit-for-tat (TFT) as basic incentive mech.
  - Bootstrap incentive via generosity
  - Prevent protracted vendetta via contrition

Incentive mechanism in our solution:
TFT + generosity + contrition

TFT as incentive mechanism

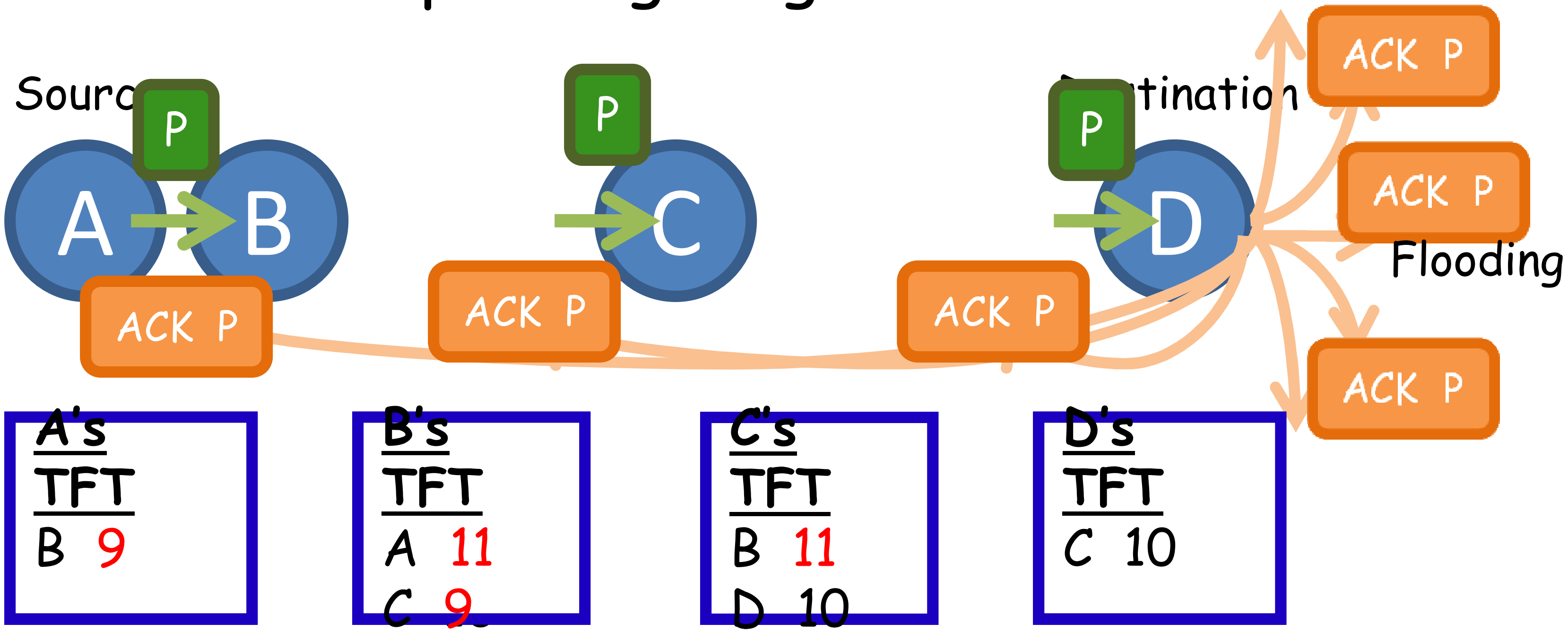
- Tit-for-tat (TFT)
  - Simple
  - Solid foundation in game theory
  - Proven good performance in other domains
  - TFT reciprocate good or bad behavior only between neighbors

$T_{A,B}$: total traffic node *A* relays for *B*

$$T_{A,B} = T_{B,A} \quad \forall \text{node A, B}$$

TFT as incentive mechanism

- Tit-for-tat (TFT)
  - TFT score: # of packets a node can send/relay to the corresponding neighbor



TFT as incentive mechanism

- Tit-for-tat (TFT)
  - Simplicity
  - Solid foundation in game theory
  - Proven good performance in real systems
  - TFT reciprocate good or bad behavior only between neighbors

$T_{A,B}$: total traffic node *A* relays for *B*

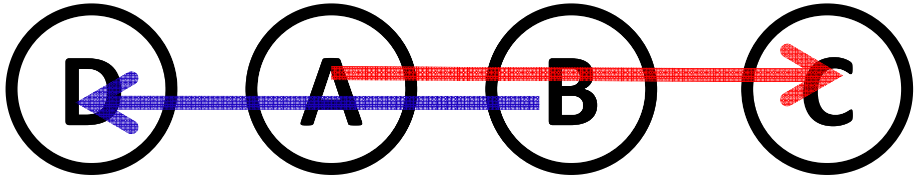
$$T_{A,B} = T_{B,A} \quad \forall \text{node A, B}$$

0 0

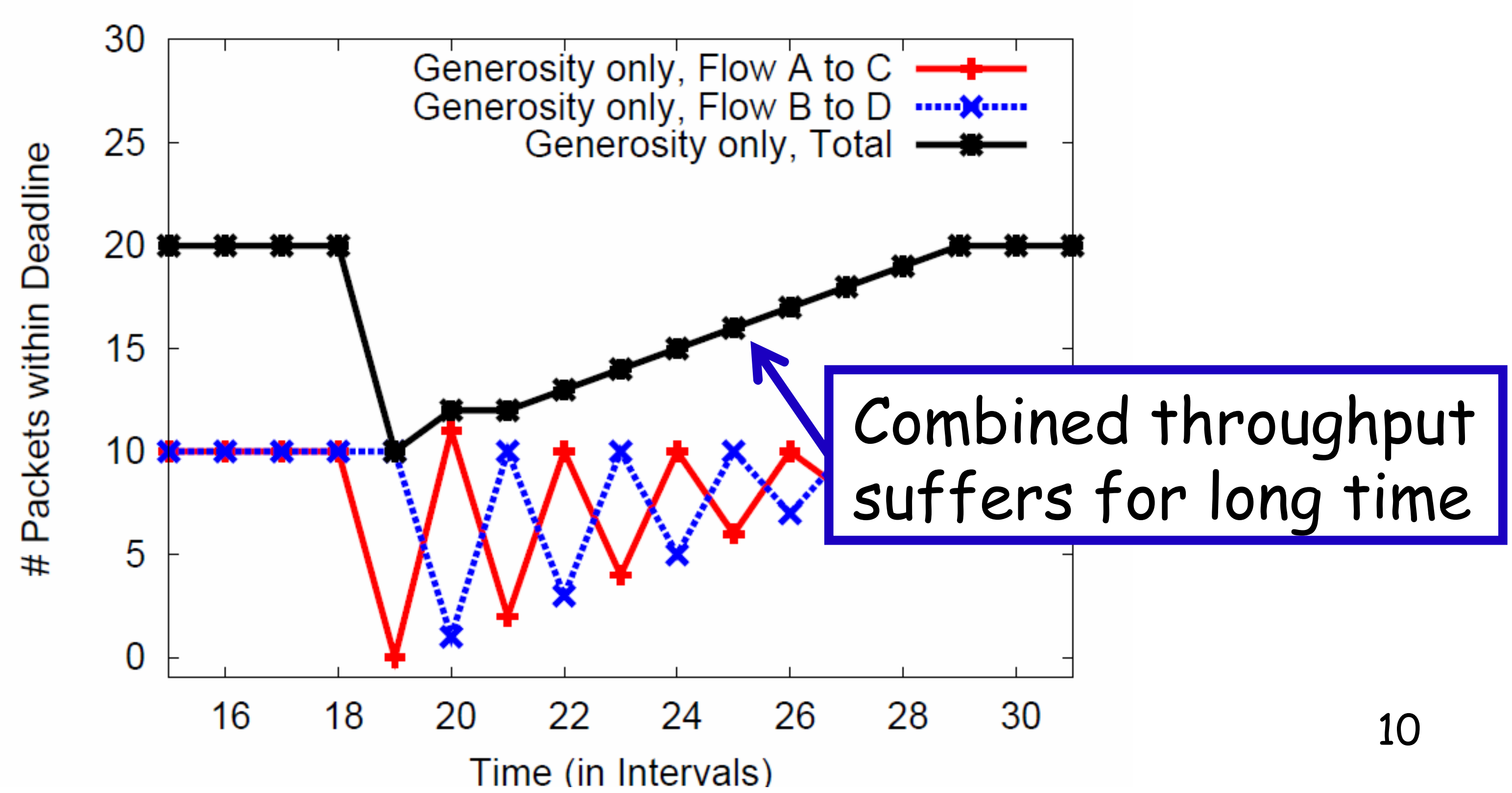
TFT with generosity

- Problem: bootstrapping
- Bootstrap incentive via generosity
  - Allows nodes to send up to ε number of packets more than it has received from others previously
- Mitigates asymmetric traffic demands
  - Absorbs traffic imbalance up to ε
- Bound exploitation by selfish nodes to ε

Protracted vendetta

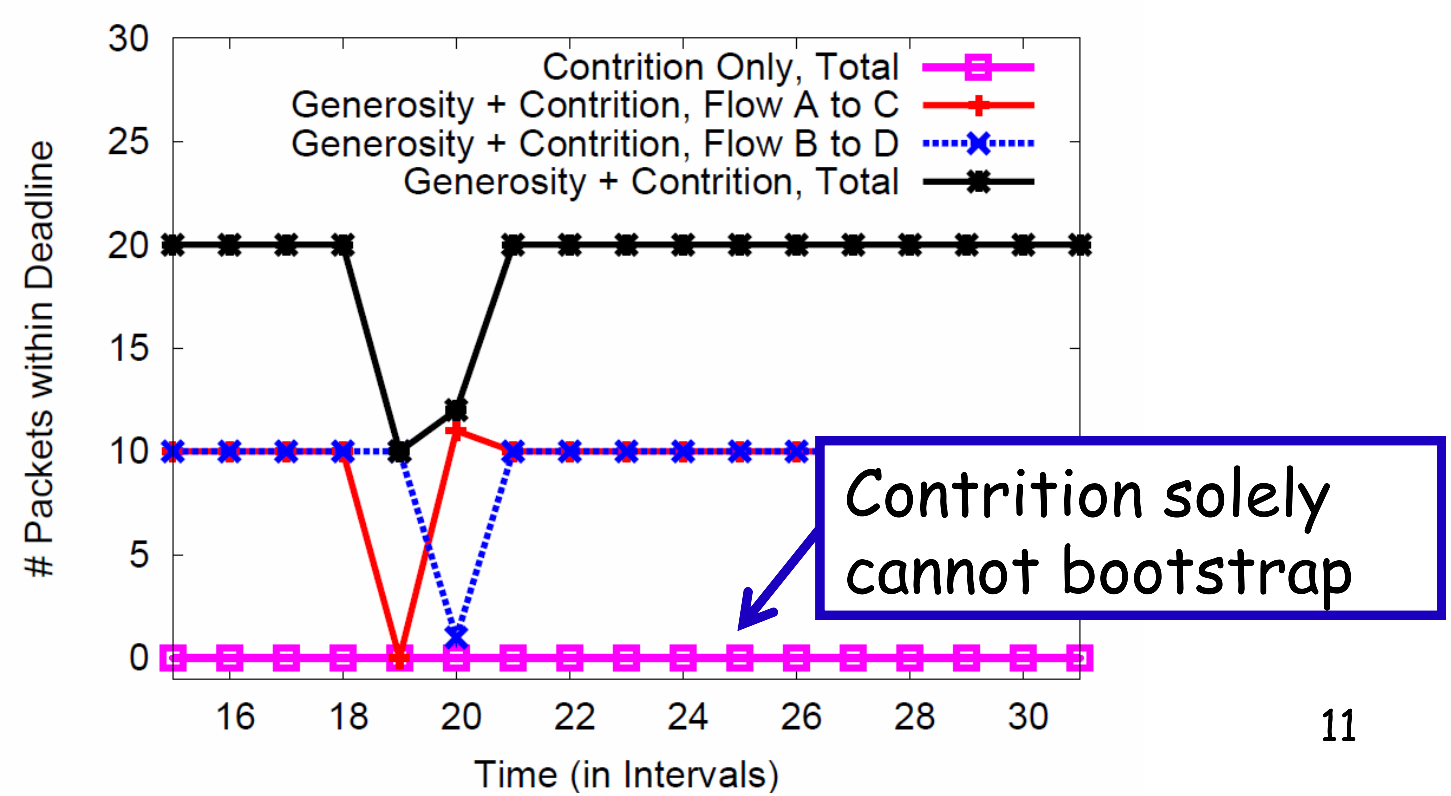


Demand:
10 packet/interval
Generosity ε :
1 packet/interval



TFT with contrition

- Contrition
  - Refrain from reacting to a valid retaliation to its own mistake
  - Cannot be exploited



Protocol overview

For every interval:

	Signaling
From every nodes	- Link state dissemination
From destinations	- Feedback collection

At sources	**Routing**
	- Path performance estimation
	- Path selection

At relays	**Incentive-aware forwarding**
	- Enforce TFT constraint

Signaling

- Link state dissemination
  - OSPF-like flooding of neighboring link state (link delay, loss rate, capacity) to every node
  - Purpose: to guide routing
- Feedback: flooding of end-to-end ACK
  - Reliable and fast way to give feedback
  - Proof of successful relay through the path
  - Update TFT constraint in relay nodes
  - Integrity guaranteed by digital signatures

Route computation

At the beginning of every interval, source nodes

Enumerate all possible paths to destination within 3 hops (#paths $O(n^2)$) for each flow

↓

Predict lower-bound of delivery ratio for each path

↓

Sort paths in the order of decreasing delivery ratio

↓

Update routing strategy by greedily moving traffic from the worst path to the best

Path performance estimation

- Metric: delivery ratio under given deadline
  - Even in DTN, deadline needed for protocol
- Challenge: hard to predict delay distribution
  - High mobility, dynamicity of network condition
- Solution: distribution-free envelope
  1. Get mean and variance of delay from link states
  2. Use Chebyshev's inequality to construct a conservative envelope of delivery ratio

$$Pr(X \le D) \ge 1 - \left(\frac{\sigma}{D-\mu}\right)^2$$

X: total wait time

D: deadline

Enforcing TFT constraints

- At each relay node
  - Drop traffic if neighbor violates tit-for-tat

    $T_{A,B}$: total traffic node *A* relays for *B*

$$T_{A,B} \le T_{B,A} + \varepsilon$$

  - Applies contrition upon perturbation
- Little overhead of TFT states
  - O(#neighbors)
- Delivery increases until link capacity is full or TFT constraints are violated

Evaluation methodology

- Routing schemes
  - Cooperative DTN without TFT
    - Best achievable performance
  - Cooperative DTN with TFT
    - Pays the cost of incentive mechanism via LP
  - **Selfish DTN with TFT**
    - Pays the cost of selfishness + incentive mechanism
  - Selfish DTN without TFT
    - Data delivery in direct contact only

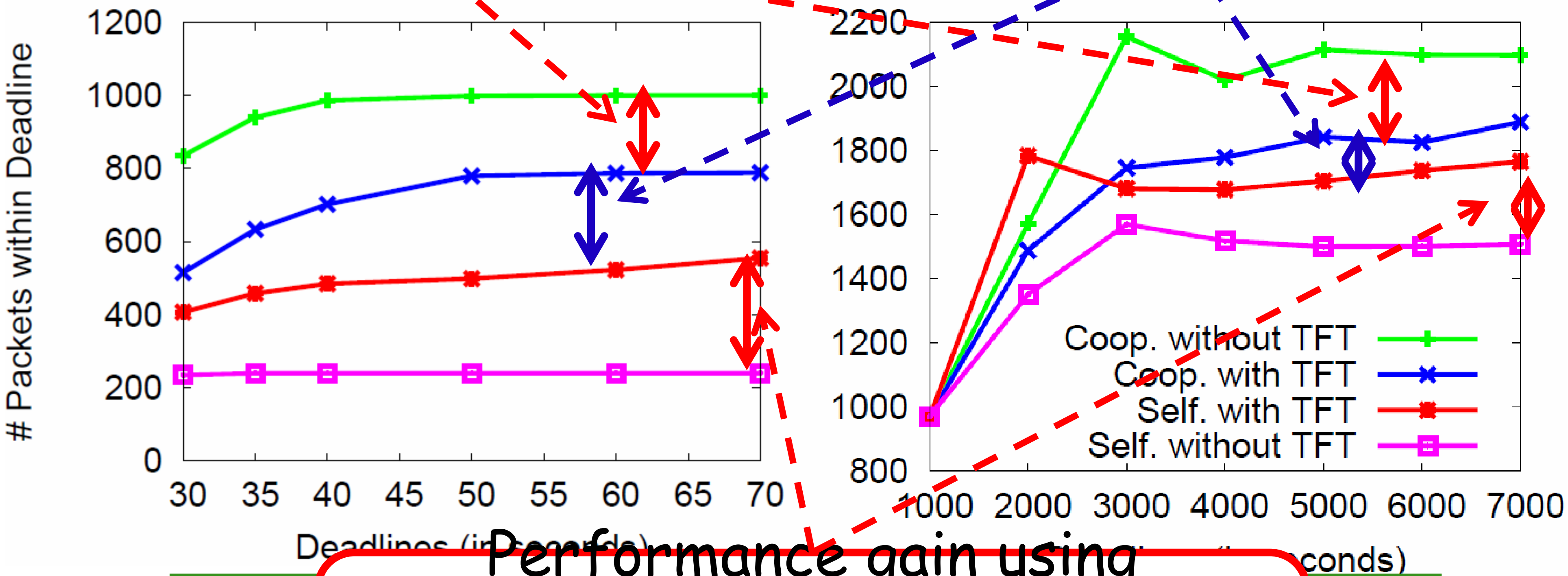
Offline route computation

Evaluation methodology

- Mobility traces
  - Synthetic traces
    - 20 nodes, 114 links, 1 sec ON, *N(10, 0.5)* sec OFF
  - Haggle
    - 41 iMotes, trace collected during INFOCOM conference
  - ZebraNet
    - 20 zebra movements, 6 x 6Km field, radio range 500m
- More results in the paper

Performance loss due to incentive mechanism: 20% synth, 10.5% Haggle

Performance loss due to the selfishness: 25% synth, 6% Haggle



Performance gain using Incentive-aware routing protocol 150% synth, 20% Haggle

Ince…
impr…

Related work

- DTN routing
  - Opportunistic routing
    - Epidemic routing, Jain '04
  - Erasure coding based routing
    - Wang '05
  - Utility-based replication
    - RAPID Balasubramanian '07
- Incentive mechanisms
  - Strong identification of misbehaving nodes and isolate them
    - Mahajan '05, Marti '00
  - Credit-based protocols awarding incentives to cooperative nodes
    - Buttayan '00, Zhong '03
  - Game theoretic foundation on TFT e.g.
    - DARWIN Jaramillo '07, Srinivasan '03, Milan '06
  - Other domains
    - BitTorrent , BAR Gossip Li '06, Flightpath Li '08

Conclusion

- Contributions
  - Study the impact of selfish behavior in DTNs
  - First work on incentive-aware DTN routing
  - Demonstrate the effectiveness of our routing scheme using real DTN traces
- Future work
  - Incentive-aware control-plane in DTNs
  - Analyze routing algorithm in more diverse DTNs

Thank you!

Cooperative DTN

- Maximize total delivery ratio for all flows

  $X_{f,i}$: traffic allocation of flow *f* on path *i*

  $P_{f,i}$: lower bound of delivery ratio when *f* is routed through *i*

  Cap_i : smallest capacity of all links on path *i*

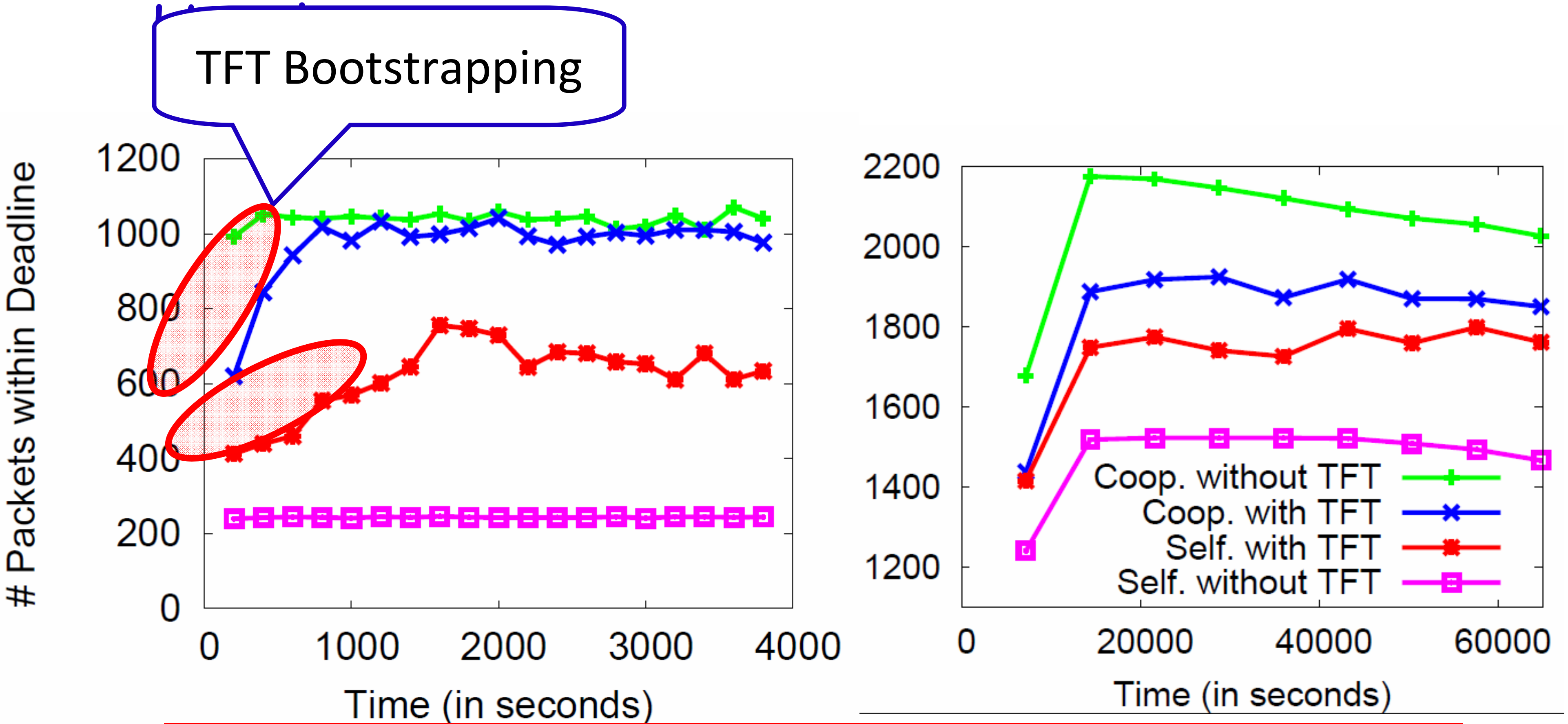
$$
\begin{aligned}
&Input : Flows, Demand(f), P_{f,i}, Cap_i \\
&Output : X_{f,i} \\
&\textbf{max:} \quad \sum_{f \in Flows} \sum_i X_{f,i} P_{f,i} \\
&\textbf{Subject to:} \\
&[C1] \quad \sum_{f \in Flows} X_{f,i} \leq Cap_i \quad \forall i \\
&[C2] \quad \sum_i X_{f,i} \leq RepFactor * Demand(f) \quad \forall f
\end{aligned}
$$

Difference from TFT in P2P

	TFT in file sharing systems	TFT-based routing in DTN
Peering relationship	File shared bilaterally between two nodes only	Multiple relay nodes apply TFT to their peers
Network condition	Persistent, less variable connection over relatively long interval	bootstrapping and exploitation problem due to high uncertainty in network
Feedback mechanism	Instant TFT feedback from neighboring peer	Large feedback delay requires end-to-end acknowledgement scheme

Effects of time intervals

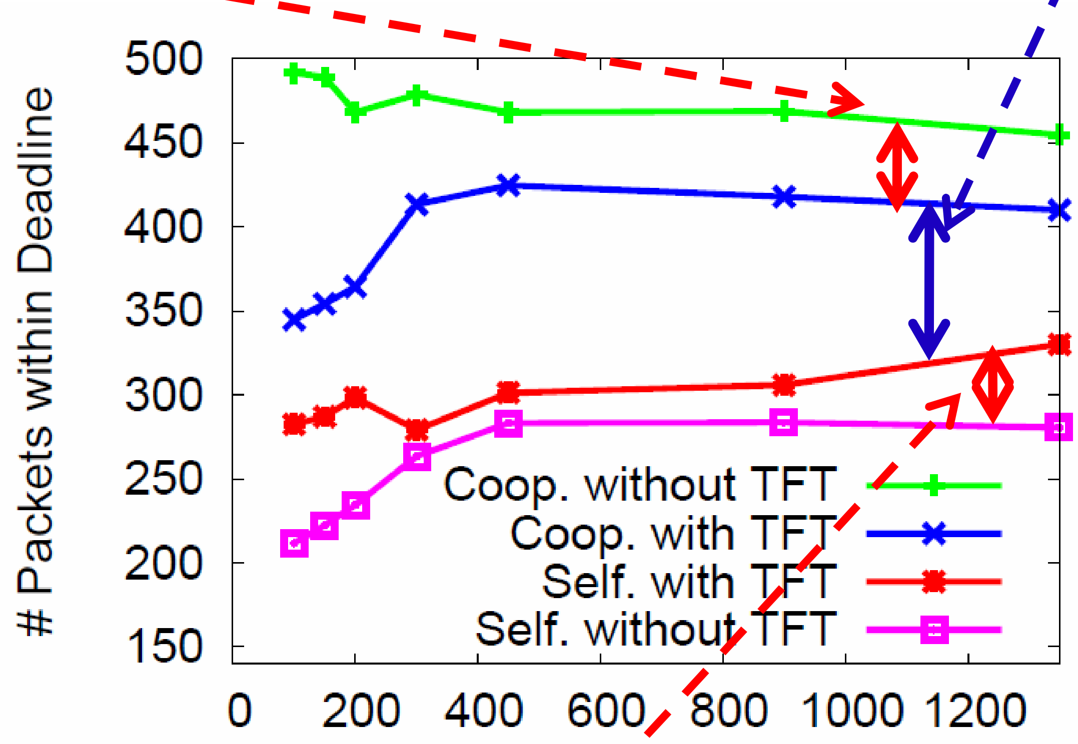
- Deadlines: 70 sec for synthetic, 7000 for



While performance of different cooperation schemes varies to traces, the rank remains the same

Performance loss due to incentive mechanism:
12% ZebraNet

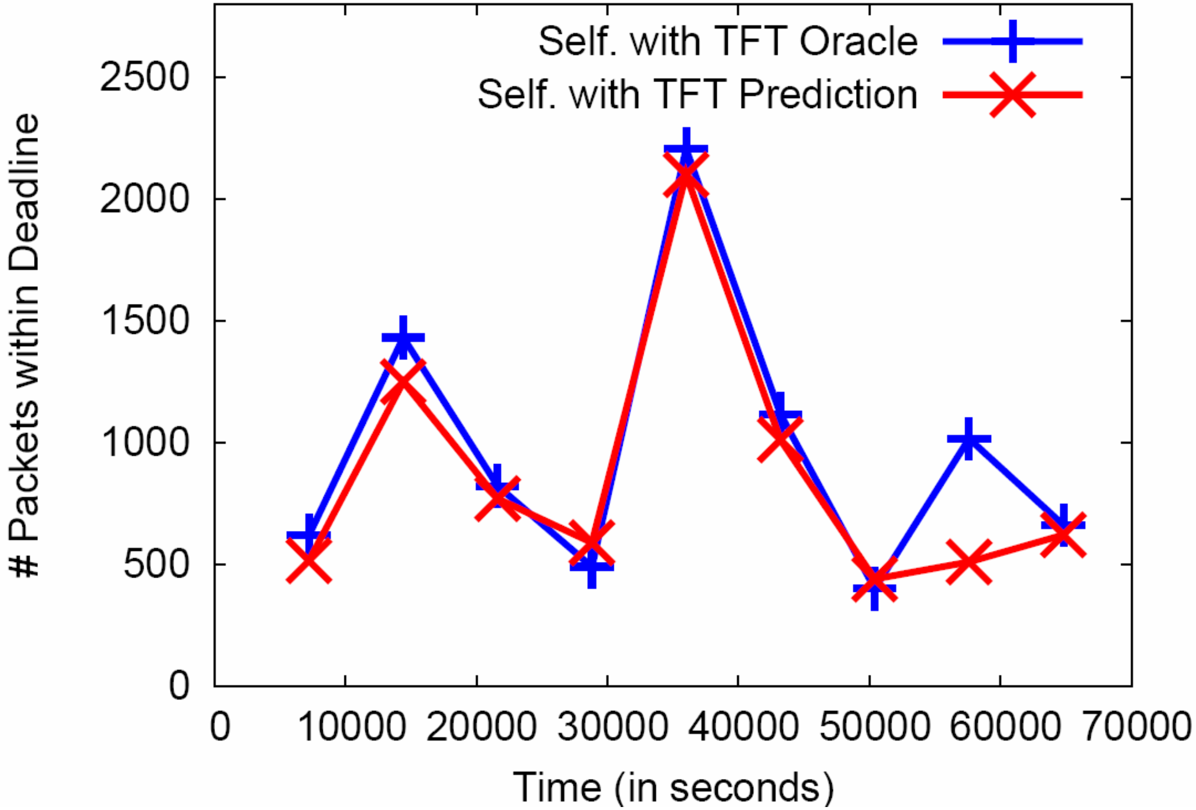
Performance loss due to the selfishness:
21% ZebraNet



Performance gain using Incentive-aware routing protocol
18% ZebraNet

Temporal variation in mobility

- Estimate next interval's link characteristics using EWMA



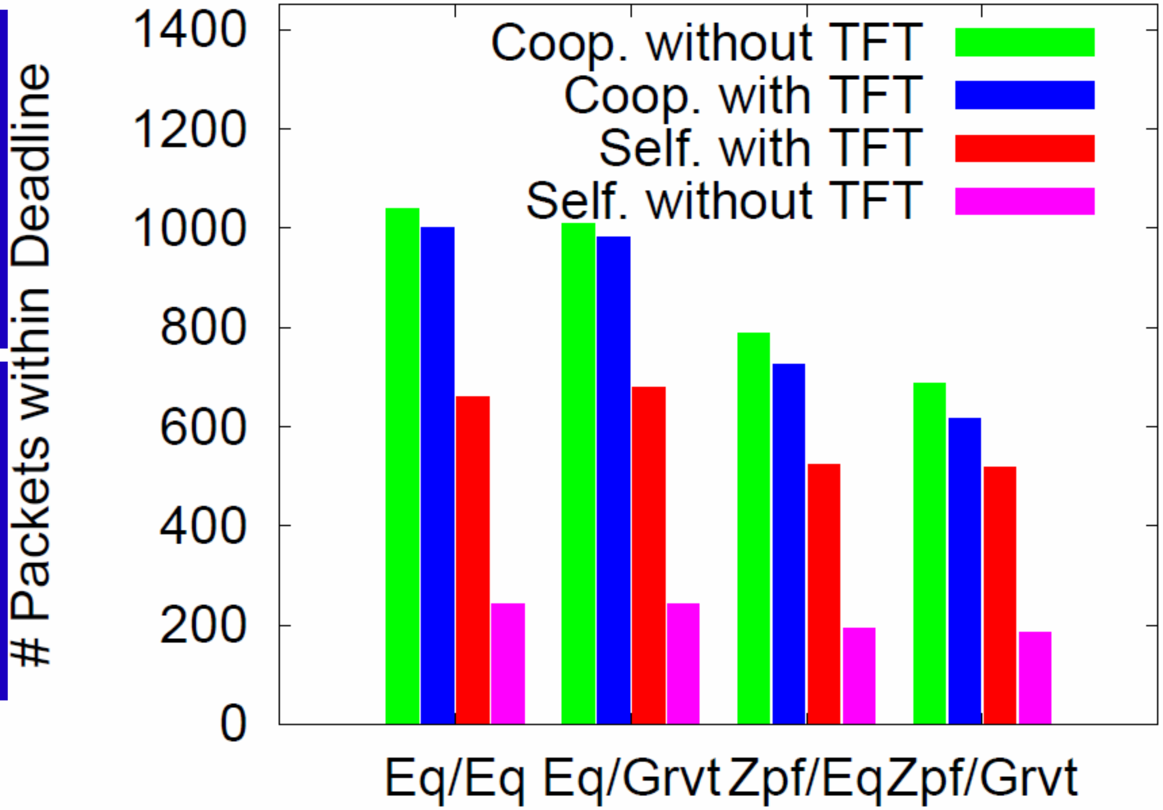
EWMA prediction scheme performs within 10% of the oracle for Haggle

Impact of spatial variation in traffic demands

- Routing schemes under more realistic traffic demand scenarios

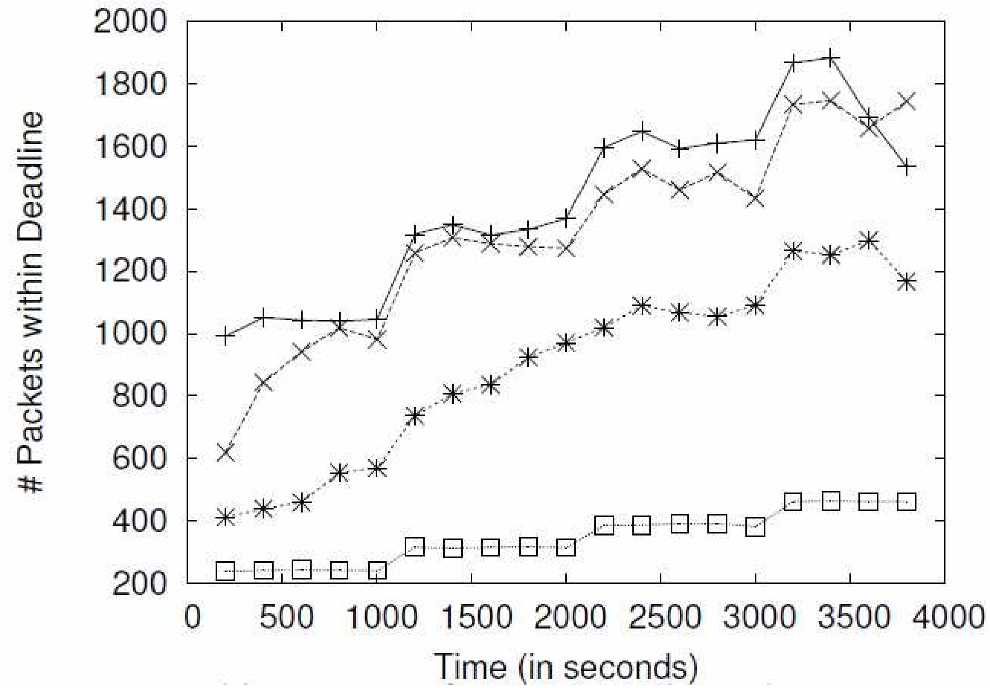
flows from src: equal or Zipfian distr

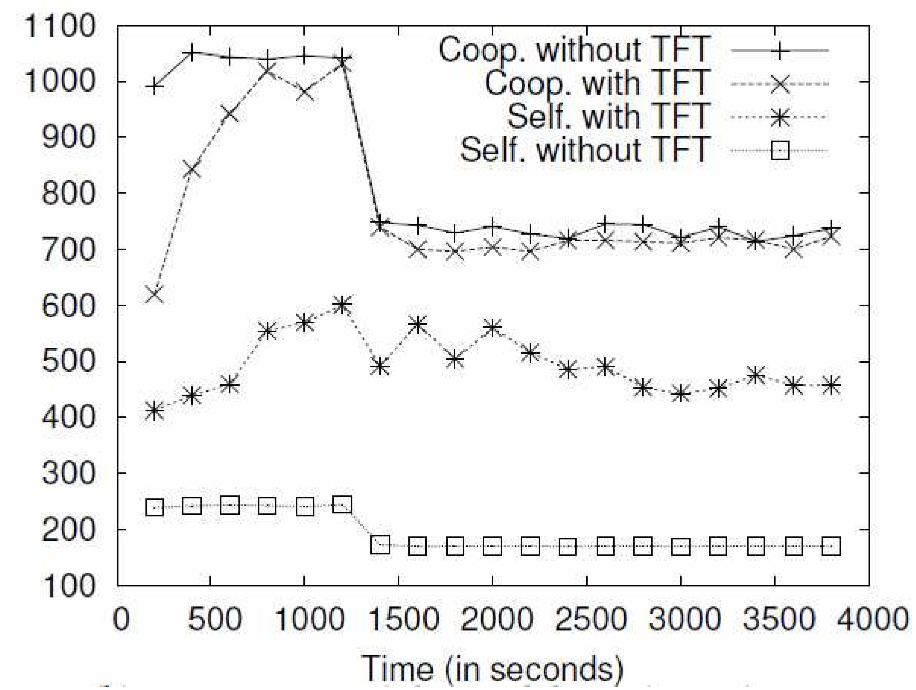
Destination selection: equal prob. or Gravity model



Impact of temporal variation in traffic demands

- Tests the responsiveness of different routing schemes to demand changes

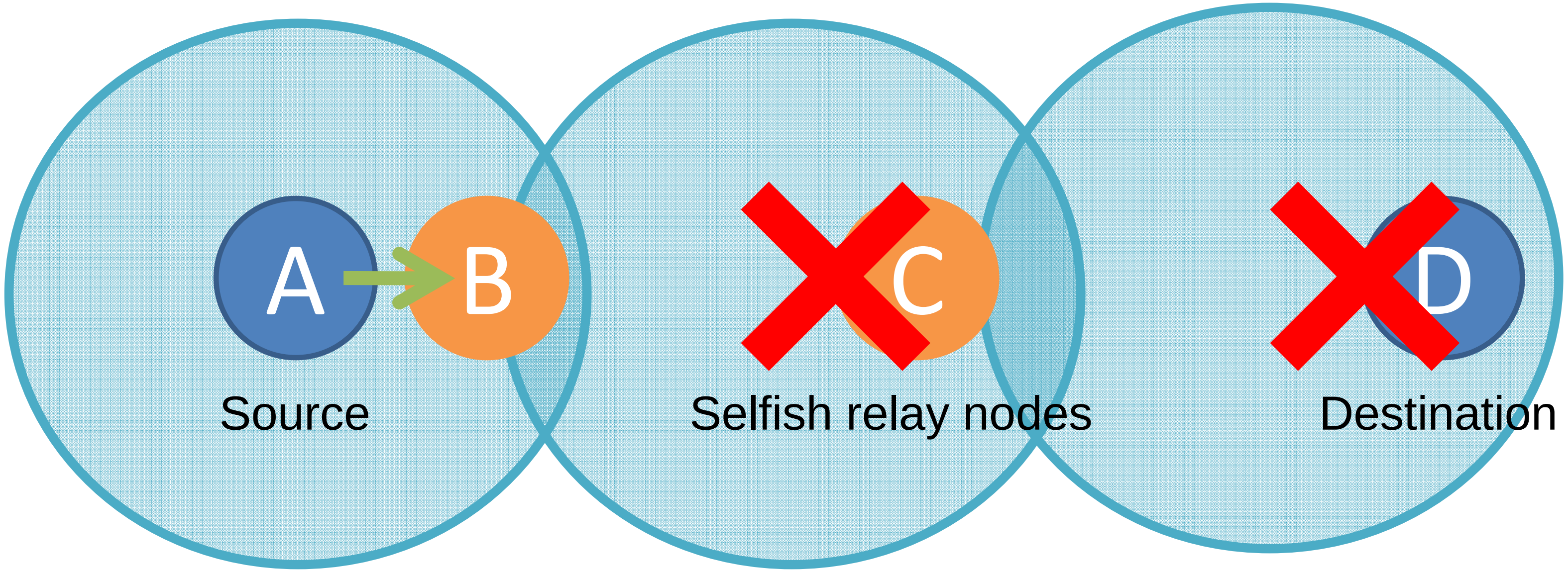




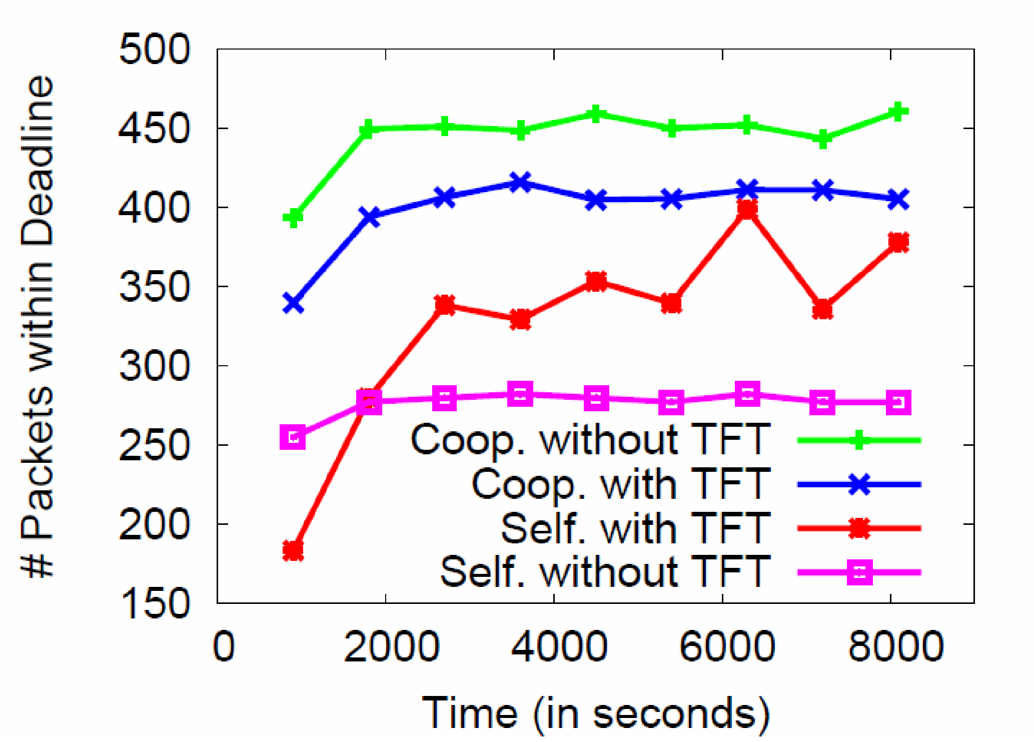
Delivery rate adapts quickly with the change

Motivation

- Selfish behavior in Disruption Tolerant Networks (DTNs) leads to serious performance degradation



ZebraNet per time



Incentive-aware protocol overview

- Incentivize DTN protocol
- DTN Routing protocol

OSPF like flooding of link state

– Link state dissemination	Every node
– Path performance computation – Route computation	Source node
– TFT constraint enforcement	Relay nodes
– Feedback dissemination	Destination