Delay Tolerant Networks

Network's scalability (Quantitatively)

Scalability of Mobile Ad Hoc Networks (with respect to N):

It has been shown [Gupta, Kumar 2000] that in mobile ad hoc networks *Θ(N)* successful transmissions can be scheduled simultaneously. I.E., the *network rate* is *Θ(N)* ➔ log R / log N → 1 . Thus, to be regarded as scalable with respect to network size

$$\Psi_N \leq 1$$

For example, for the class of networks considered here (assumptions a.1-a.8)

$$\Psi_N = 1.5$$

⇒ **networks under study are not *scalable* w.r.t. to network size**

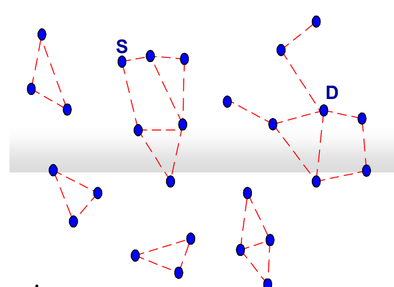
Network's scalability (Quantitatively)

Scalability of Mobile Ad Hoc Networks (with respect to N)
Delay Tolerant Networks:

- average path length may be reduced to 2 ($\Theta(1)$
  provided that applications can tolerate infinite delivery delays and mobility pattern is random ([Groossglauser&TSE, Infocom 2001])
- thus, network *scalability factor* with respect to network size Ψ_N is equal to 1. (N nodes X traffic rate X constant path length)

Thus, those ad hoc networks (random mobility and capable of accepting infinitely long delays) are the only class of ad hoc networks that are scalable with respect to network size.

What is different?



- A wireless network that is very sparse and partitioned
  - disconnected clusters of nodes
- Nodes are (highly) mobile making the clusters change often over time
- No contemporaneous end-to-end path

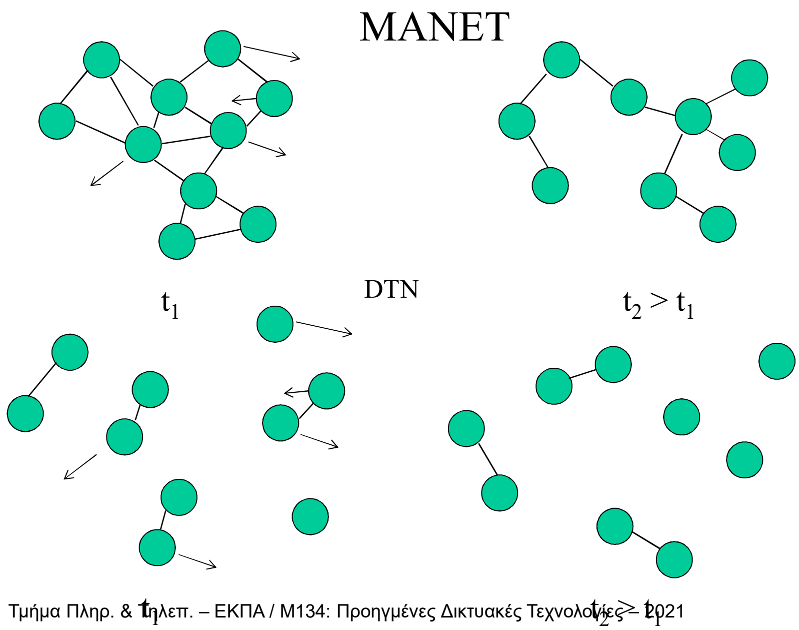
Reactive/Proactive approaches would not work

- Reactive Protocols
  - route request cannot reach destination
  - path breaks right after or even while being discovered
- Proactive Protocols
  - will fail to converge
  - flood with topology-update packets

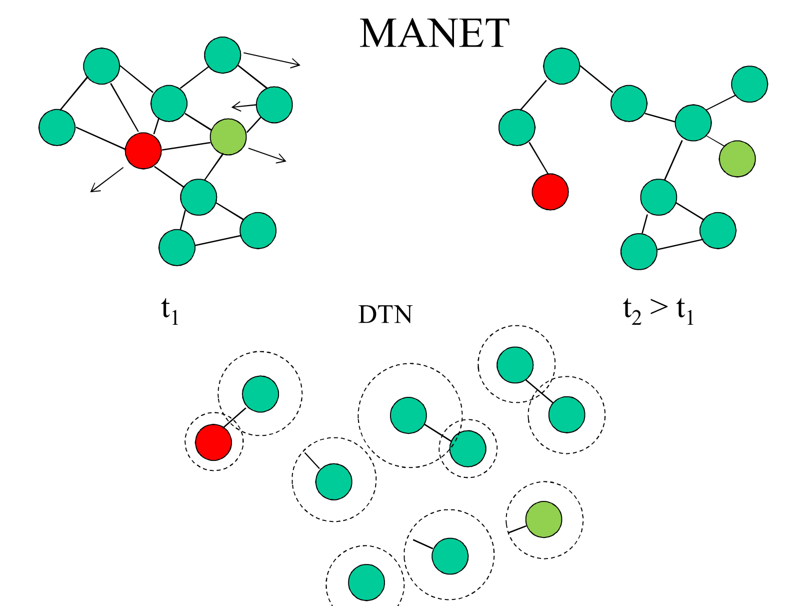
A possible approach

- Exploit node mobility to deliver messages
  (Tse et al. exploit mobility to increase capacity)
- A snapshot of connectivity graph is always disconnected.
  Idea: If we overlap many snapshots over time, an end-to-end path will be formed eventually!
- Store-and-forward model of routing:
  1. a node stores a message until an appropriate communication opportunity arises
  2. a series of independent forwarding decisions {time + next hop} that will eventually bring the packet to its destination

MANET vs. DTN



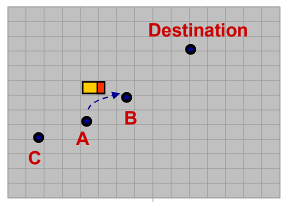
MANET vs. DTN



Choosing A Next Hop

A local and intuitive criterion: A forwarding step is efficient if it reduces the expected distance from destination

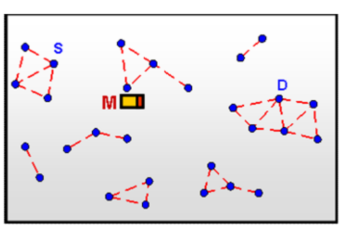
usually: reduction of expected distance => reduction of expected hitting time



Efficient Routing : *Ensure that each forwarding step on the average reduces distance to or hitting time with destination*

Single/Multiple Copy

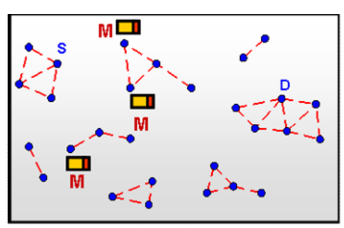
- "Single-Copy": only a single copy of each message exists in the network at any time
- "Multiple-Copy": multiple copies of a message may exist concurrently in the network



Single Copy

+ lower number of transmissions

+ lower contention for shared resources



Multiple Copy

+ lower delivery delay

+ higher robustness

Epidemic Routing

- Each host maintains a buffer of messages unsent (originated or relayed by it)
- Every time it encounters another host, it exchanges info about the pending packets and after the receiver's reply, it forwards to the latter whatever has not been sent yet
- This process is repeated at every meeting

Epidemic Routing – performance

- Expect 100% delivery ratio even under the worst delay case
- In case of no interference (low traffic load, source-destination pairs), it provides the lowest delay
- **But!** Too much overhead, as it floods the network with copies

Other approaches

- **Direct Transmission**
  - Forward message only to its destination (simplest strategy)
  - Its expected delay is an upper bound for every other protocol
- **Two-hop Relay**
  - Deliver messages to the first n nodes it encounters
  - The relays will deliver the message only to the destination
- **Tree-based Flooding**
  - Similar to the above (the task of making copies is distributed to other nodes as well, not only the source node)

Randomized Routing

- Node A forwards message to node B with probability p. Notice that:

P(B closer to destination D than A)
=
P(A closer to destination D than B)

yet, because transmission speed is faster than the speed of movement it can be shown that

The randomized policy results in a reduction of the expected hitting time to destination at every step

Message Ferrying

- Exploit existing or introduce non-randomness in node mobility, to enhance communication in an environment with intermittent or otherwise no connectivity

- Network devices are classified as regular nodes and message ferries (could be devices that move independently of the need for data delivery – like buses, or specific nodes that move according to the need for connectivity)

Utility-Based Routing

- Define an appropriate utility function $U_A(Y)$ of node *A* with respect to (destination) node Y.
- **Utility-based routing**: *Node A forwards a message for node D* to node B *iff:*

$$U_B(D) > U_A(D) + U_{th}$$

- **Example Utility Function:** Define $U_X(Y)$ based on the timer value $T_X(Y)$ that node X has regarding (destination) node Y; this could be the time elapsed since node X hit node Y for the last time in the past.
  - e.g. $U_X(Y)$ = - expected hitting time given timer value
- In essence, destination's location gets indirectly logged in a timer upon encounter and nodes' location info gets diffused through mobility process.

Hybrid Methods…

- Seek phase: If utility around node is low, perform **randomized forwarding** to quickly search nearby nodes

- Focus phase: When a high utility node (i.e. above a threshold) is discovered, switch **to utility-based forwarding**
  - look for a *good lead* to the destination and follow it

Oracle-Based, Optimal…

- *Assume* all nodes trajectories (future movements) are known
- Then, *the algorithm picks the sequence of forwarding decisions that minimizes delay*

- Note that flooding (multi-copy strategy) has the same delay as this algorithm when there is no contention

Shortcomings

- Flooding
  - too many transmissions (energy-efficiency concerns)
  - unbounded number of copies per message (scalability issues)
  - under high traffic, high contention for buffer space and bandwidth results in poor performance

- Utility-based
  - high threshold U_{th}: significant delay increase; source takes a very long time until it finds a good next hop (slow start)
  - low threshold U_{th}: degenerates to flooding

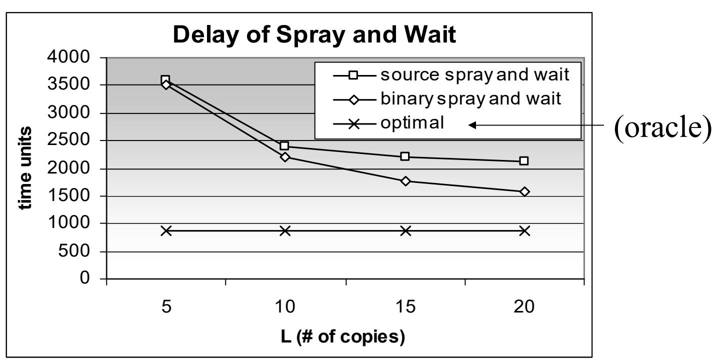
Efficient Routing: Design Goals

- Performance goals:
  - ✓ perform significantly fewer transmissions than flooding-based schemes under all conditions
  - ✓ better delay than existing single and multi-copy schemes; close to optimal
- Additional goals:
  - ✓ scalability: good performance under a wide range of values for various parameters (e.g. number of nodes)
  - ✓ simplicity: require little knowledge about the network

Spray and Wait

- Source Spray and Wait (Also, 2-hop relaying)
  - Source starts with L copies
  - whenever it encounters a new node, it hands one of the L copies
  - this is the slowest among all (opportunistic) spraying schemes
- Optimal Spray and Wait (Binary)
  - source starts with L copies
  - whenever a node with n > 1 copies finds a new node, it hands half of the copies that it carries
  - The optimal, spreads the L copies faster than any other spraying schemes

Spraying Matters!



100x100 network with 100 nodes

1. Efficient spraying becomes more important for large L
2. Few copies suffice to achieve a delay only 2x the optimal!

On the Effects of Cooperation in DTNs

or

resilience to misbehaviors

or

reconsider protocol efficiency in the presence of misbehaviors

Reference:
http://cgi.di.uoa.gr/~ioannis/publications/2007COMSWARE.pvs.pdf

Performance of DTN routing

Investigated w.r.t. the impact of:

- Environment characteristics
  - -network size
  - -node density
  - -message spreading rules
- Node behaviour
  - -mobility

Assumption: Fully cooperative environment!

Consider non-cooperative DTN environment

- The copy is dropped or forwarded with some probability
  (simple non-cooperative environment / strategy)

3 routing algorithms are studied in terms of:
- Induced delay
- Transmission overhead

Cooperation in DTNs

Shaped by the willingness (due to node misbehavior), or ability (due to buffer or energy limitations) of the node to participate in spreading.

2 types of cooperation considered:

-**Type I**: the node drops the message with probability P_{drop} (cooperation degree = $1-P_{drop}$)

- **Type II**: the node maintains the copy and forwards it with probability $P_{forward}$ (cooperation degree = $P_{forward}$)

The 3 routing algorithms

- **Epidemic routing:** (unlimited copies)
  - At each node encounter, all copies are exchanged
  - Minimum message delivery delay but high buffer occupancy and bandwidth utilization in fully cooperative environments
- **Two-hop routing:** (limited copies)
  - The source forwards one of its copies to the node (with no copy) it encounters
  - Only the source node forwards copies to others than the destination
- **Binary spray-and-wait routing (BSW):** (limited copies)
  - Every one gives half its copies to a node (with no copy) it encounters
  - Faster than two-hop relaying when all cooperate

Metrics

- Delay until delivery of the message

- Overhead in terms of number of transmissions

  The *Total* overhead has two components:
  - Till delivery: Transmissions required until message delivery
  - Additional: Transmissions wasted after the message delivery, affected by spreading process termination **(*)**

Spreading process termination

The spreading process is naturally terminated if all the potential spreaders of a copy are eventually informed of the message delivery or all copies are already spread.

Expedite natural termination through a delivery notification mechanism, activated upon message delivery: **(*)**

- A node that becomes aware of the message delivery becomes as notifier.
- Every node that contacts a notifier is informed of the message delivery and becomes a notifier itself.

Protocol sensitivity to cooperation degree

Two checks are used, by comparing performance for a certain degree of cooperation with that achieved

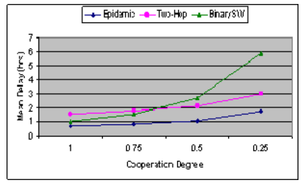
a. in a fully cooperative environment
b. in the *Fully Cooperative Equivalent (FCE) network* (only for Type I)

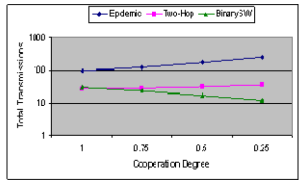
The FCE network of N nodes is defined as a network of N' fully cooperative nodes, where $N'=N(1- P_{drop})$.

Non-cooperative environment

Simulations: up to 100 nodes uniformly distributed in 8km x 8km area; Mobility: Random Direction Model with a speed of 3m/sec; Transmission Range: 200m;

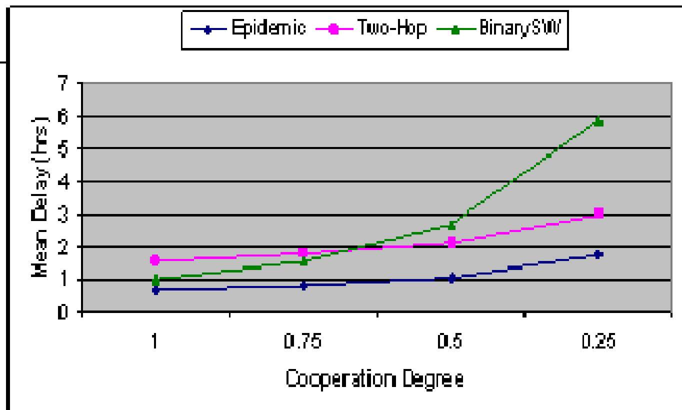
- **Epidemic** always provides for minimum delivery delay at the expense of significantly more transmissions in all environments.
- **BSW** achieves lower delivery delay in fully cooperative environments than two-hop; the rate at which the delivery delay achieved by **2-hop routing** increases in non-cooperative environment is lower than that of BSW.
- The overhead induced by BSW decreases in less cooperative environments contrary to what observed in two-hop.





Key Observation:

2-hop: outperforms BSW for low cooperation



Study of Two-Hop Message Spreading in DTNs

http://cgi.di.uoa.gr/~istavrak/publications/2009ADHOCJournal.pvs.pdf
http://cgi.di.uoa.gr/~ioannis/publications/2007WIOPT.pvs.pdf

Delay Tolerant Networks

Connectivity established through (low frequency) node encounters

DTN message transport

- Mobility-assisted
- typically, multiple message spreading is needed

Some DTN message transport /routing schemes

Epidemic routing: (unlimited copies)
- At each node encounter, all copies are exchanged
- Minimum message delivery delay but high buffer occupancy and bandwidth utilization

Binary spray-and-wait routing (BSW): (limited copies)
- Every one gives half its copies to a node (with no copy) it encounters
- Faster than other limited copies schemes

2-hop routing: (limited copies)
- The source forwards one of its copies to a node (with no copy) it encounters
- Only the source forwards copies to others than the destination

Focus

Consider a DTN environment where the source is in **full control of message spreading: 2-hop relay**

Only the source is allowed to spread the copies.

Intermediate nodes are not allowed to spread a message copy they may have to any node other than the destination. Robustness against intermediate node misbehavior or limitations.

Limits the max number of copies in the network (overhead concern)

Limits the lifetime of copies (overhead or QoS concern)

Model description

$N+1$ nodes moving within a square size of L^2.

Exponential node inter-meeting times (i.e. the time elapsed between two consecutive encounters for a given pair of nodes - fairly accurate in case of $R \ll L$, and random waypoint model)

Mean rate of encounters λ for a given node (exp parameter):

$$\lambda = cvR/L^2,$$

c: constant depending on the mobility model used
v: relative speed
R: communication range
L: size of the network area

Source – intermediate node differentiation

Diverse inter-meeting times for the source (λ) and the other nodes (λ_o)
- May capture diverse transmission range (power) or/and speed or even, indirectly, the cooperation degree

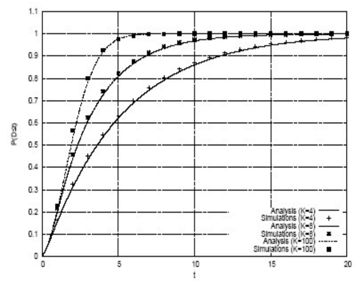
The parameters capturing differentiation could be considered as:
- Non-tunable (e.g., misbehaviour)
- Tunable (e.g., adjustment of transmission range)

Theory and simulations

Exact analytical expressions for the delivery delay cdf

Derived via Markov Chain formulation and solving the obtained equations

Closeness of simulation with analytical results indicates the validity of the exponential encounter times for nodes moving under the random Waypoint model



Results shown for: N=100, K=4, 8, 100, λ=0.08 and λ_o=0.04

Closed form* approximation for delay *cdf*

(* *facilitates parameter selection to achieve a given delay target)*

A much simpler expression that approximates fairly accurately the exact one is derived by bounding the *accurate cdf* (for a specific number of copies K ≤ N) by two *cdfs*:

the *maximum-copy cdf*
the *zero-spreadtime cdf*

Note:

A general approach to bounding performance amounts to modifying the operation of the protocol in 2 ways, such that:

(1) the auxiliary protocol 1 yields a worse performance than the real protocol

(2) the auxiliary protocol 2 yields a better performance than the real protocol.

And the analysis of the auxiliary protocols is simple.

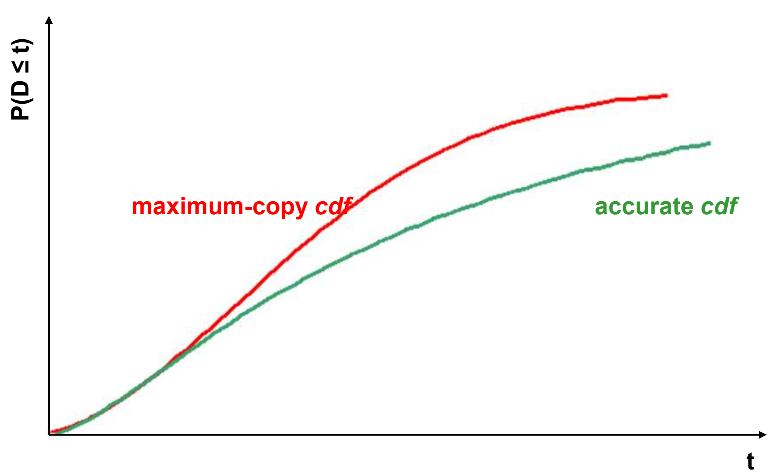
The maximum-copy *cdf*

It refers to a modified algorithm where the number of copies employed in the network equals the number of nodes (K=N):

[P(D ≤ t)] $$Q_N(t) = 1 - e^{-\lambda N t}\left(1 + \frac{\lambda}{\lambda_d}\left(e^{\lambda_d t} - 1\right)\right)^{N-1}$$

The modified algorithm has exactly the same behaviour until the first K copies are spread in the network. Afterwards, the performance is enhanced due to the advantage of the surplus copies (N-K)

The maximum-copy *cdf*



The zero-spreadtime *cdf*

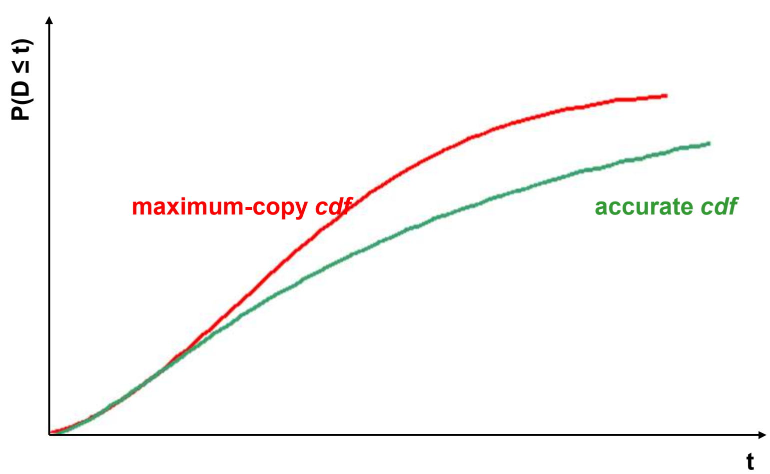
It refers to a modified algorithm where all K copies are instantly spread in the network

[P(D ≤ t)] $Q_{\acute{K}}(t) = 1 - e^{-(\lambda + \lambda_o (K-1))t}$

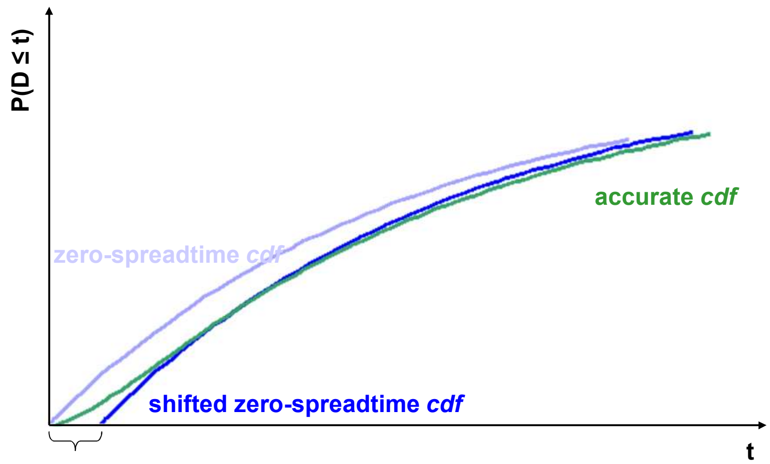
The modified algorithm has identical behavior with the original after the original has spread all K copies. Better performance for small t, converging to the original one for large t.

It is expected and indeed observed that when this *cdf* is shifted by some t_o so as to be tangent (at some time t_{cr}) to the maximum-copy one (and this occurs at some time t_{cr}), the part of the *cdf* from t_{cr} and afterwards approximates accurately the original *cdf*

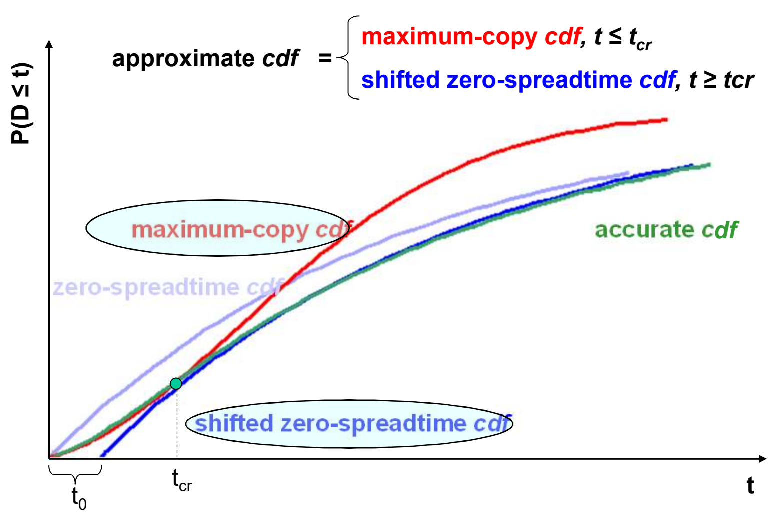
Constructing the approximate *cdf*



Constructing the approximate *cdf*



Constructing the approximate *cdf*



The approximate *cdf*

Thus, the approximate expression may be defined as a two-part function:

the maximum-copy *cdf* until t_{cr}

the shifted zero-spreadtime one after t_{cr}

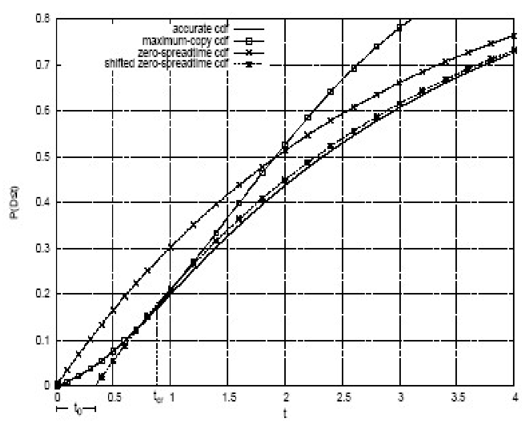
$$\hat{Q}_K(t) = \begin{cases} Q_N(t) = 1 - e^{-\lambda N t}\left(1 + \frac{\lambda}{\lambda_d}\left(e^{\lambda_d t} - 1\right)\right)^{N-1}, \\ 0 \le t \le t_{cr}; \\ Q_{\dot{K}}(t - t_0) = 1 - e^{-(\lambda + \lambda_o (K-1))(t - t_0)}, \\ t \ge t_{cr}, \end{cases}$$

where: $\lambda_d = \lambda - \lambda_o$,

t_o is the time shift of the zero-spreadtime *cdf* needed to be tangent to the maximum-copy one

t_{cr} is the contact point of the above *cdfs*

Results for the approximate *cdf*



For the case of N=100, K=8, λ=0.08 and λ_o=0.04:

Solving design problems

The approximation may be used in order to obtain closed form solutions to design problem where the exact analysis allows only for a numerical solution

For instance, **the value of K to achieve a specific delivery ratio Q_d within a specific delay bound t** may be estimated:

$$K_{approx} = \frac{-\lambda_d(N + (N-2)(N+1)\lambda t)}{\lambda_o(N - 2\lambda t)} + \frac{\lambda(N + (N(N-1)-1)\lambda t + \ln(1 - Q_d)) \pm \sqrt{C}}{\lambda_o(N - 2\lambda t)},$$

where *C* is a function of the network parameters. The positive value that fulfills the condition $t_o \leq t_{cr}$ should be selected

Calculation of the overhead

In DTNs is typically measured in terms of the number of transmissions induced **until the message delivery** to the destination (or dropped if time constrained)

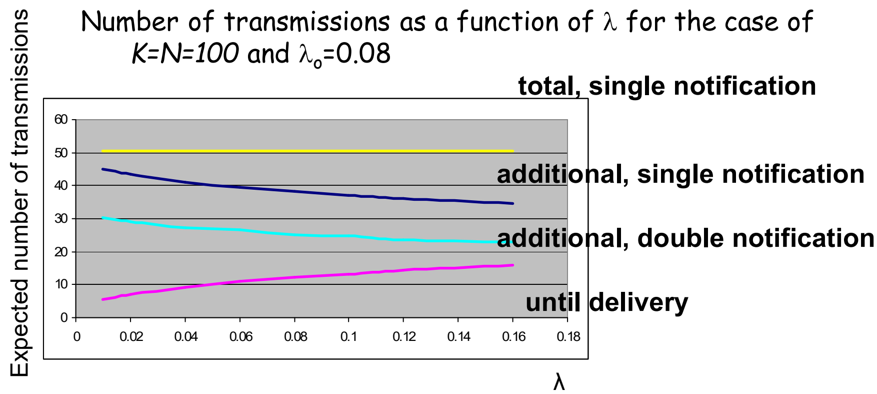
Here, we also measure the **additional overhead** induced until the spreading process is actually terminated (the source node becomes aware of the message delivery through some notification mechanism)

Here, the additional overhead is calculated for two distinct cases:

- Until the source meets the destination (single notification)
- Until it meets either the destination or the intermediate node that delivered the message to the destination (double notification)

Besides the number of transmissions, energy overhead considerations are introduced for the case of a network of nodes that employ different transmission powers.

Results



- ❑ "till delivery" OH increases with λ

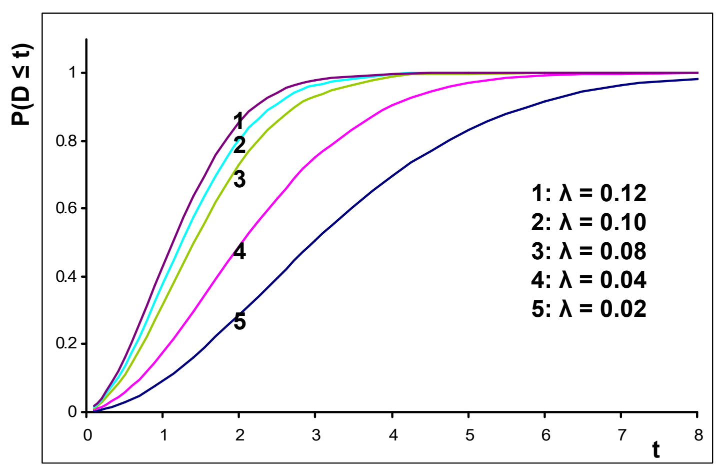
(but want to increase λ for better delivery ratio – see next)

- ❑ "additional OHs higher than "till delivery" – should not be neglected
- ❑ "additional OHs" decrease with λ;
- ❑ "total OH, single-notification" remains about the same, so ok. to increase λ

Results

shorter delivery delays as λ increases

Cdf of the delivery delay for the case of K=N=100 and λ_o=0.08



SUMMARY and Contributions

Study analytically the 2-hop relay algorithm (source-controlled spreading)

cdf of message delivery delay – delivery ratio

Closed form approximate cdf for delay, allowing for setting design parameters and shape the delivery ratio – overhead trade off.

Consideration and calculation of the overhead not only until the message delivery but also until the message spreading is actually terminated.

Differentiation between the source and intermediate nodes, capturing the effects of a more realistic, generally heterogeneous DTN environment, in terms of: transmission power, speed, cooperation degree, etc.