TOKYO METROPOLITAN UNIVERSITY

An Analysis of Onion-Based Anonymous Routing in Delay Tolerant Networks

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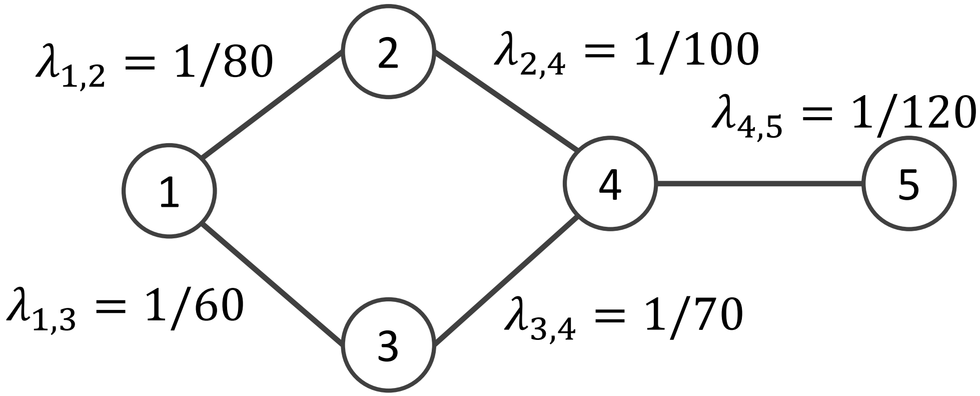
June 27-30, 2016

Outline

1. Introduction
2. Preliminary and Related Works
3. Abstract Onion-Based Anonymous Routing
4. Analyses
5. Simulations
6. Conclusions

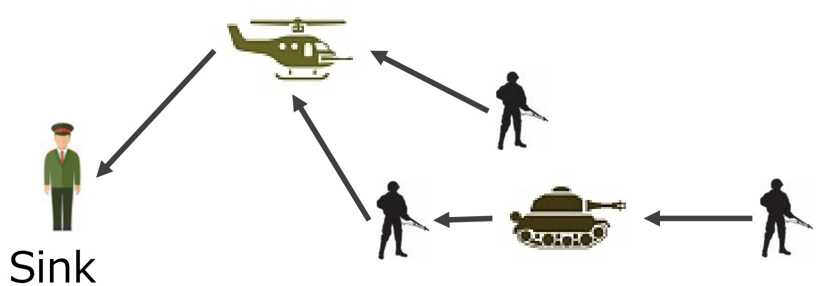
1. Introduction

- Delay tolerant networks (DTNs)
  - Intermittently disconnected, store-and-carry forwarding
- The network model of a DTN
  - A graph representation is contact-based
  - The link weight between two nodes is defined by contact frequency, $\lambda_{i,j}$



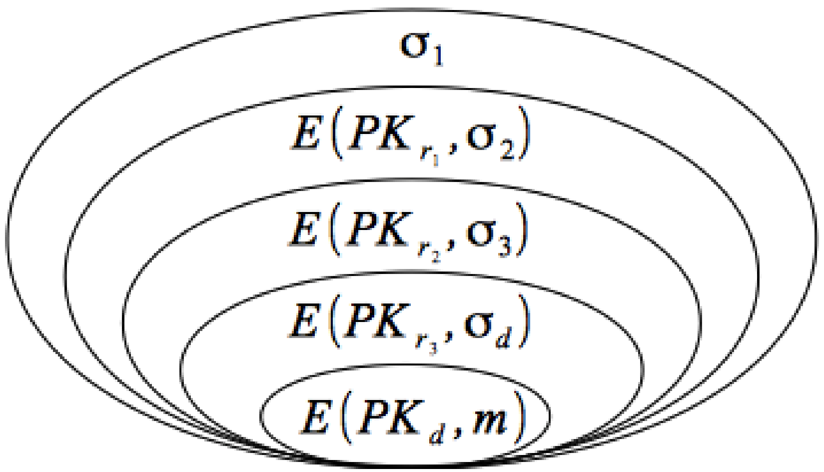
Introduction (Cont.)

- Anonymous communications
  - Protect the privacy of end hosts
  - Prevent from traffic analyses
  - Intermediate nodes never know where a packet comes from and goes to
- Applications
  - Critical communications, e.g., battle fields

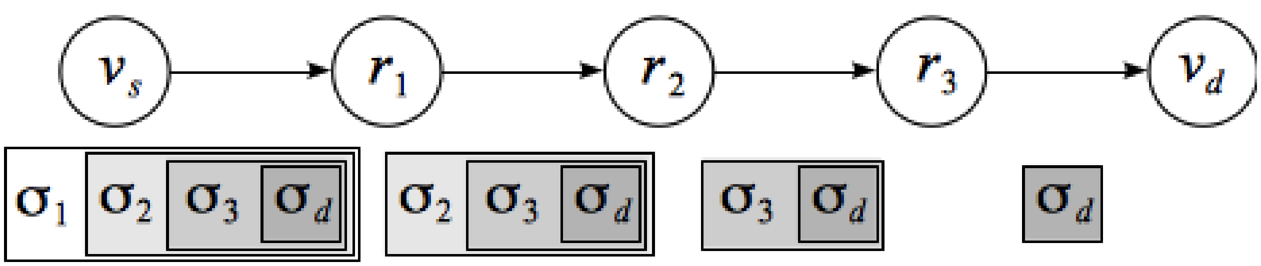


2. Preliminary and Related Works

- Onion Routing, e.g., Tor
  - Layered encryptions are applied to a message



$$\sigma_1 := E(PK_{r_2}, \sigma_2)$$
$$\sigma_2 := E(PK_{r_2}, \sigma_3)$$
$$\sigma_3 := E(PK_{r_2}, \sigma_d)$$
$$\sigma_d := E(PK_s, m)$$



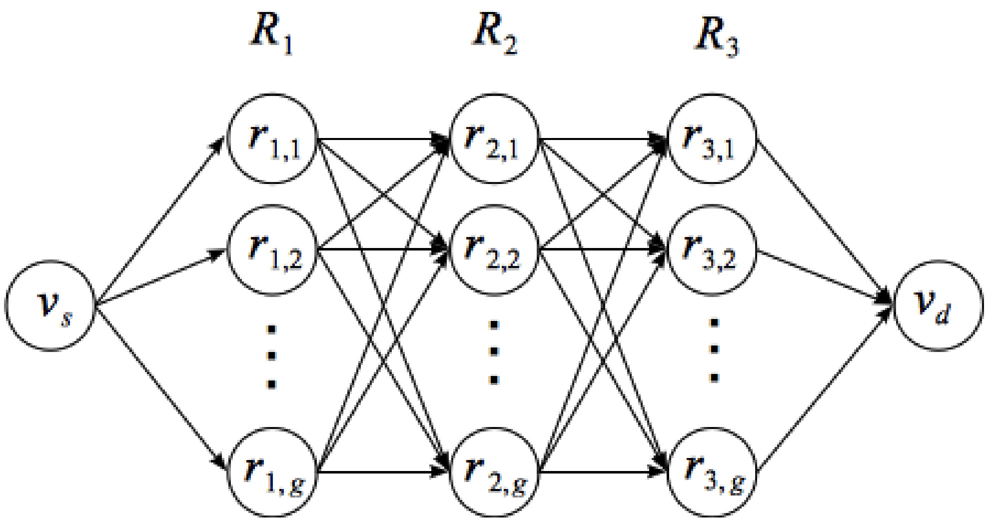
Related Works

- Many anonymous routing protocols have been proposed for ad hoc networks
  - Onion-based, zone-based, and so on
- But, only a few protocols have been designed for DTNs
  - e.g., onion-based [1] and threshold-based
  - No protocol with multi-copy forwarding has been designed
  - No theoretical work has been done

[1] C. Shi, X. Luo, P. Traynor, M. H. Ammar, and E. W. Zegura, "ARDEN: Anonymous Networking in Delay Tolerant Networks," Ad Hoc Netw., vol. 10, no. 6, pp. 918–930, 2012.

3. Abstract Onion-Based Anonymous Routing

- Abstract onion-based anonymous routing protocol
  - Introduction of onion groups
    - A set of nodes consists of an onion group
    - Anycast-lilke forwarding
  - Single-copy and multi-copy forwarding



Multi-Copy Forwarding

- System Initialization:
  - The nodes in the system are divided into $\left\lceil \frac{n}{g} \right\rceil$ groups, where g is the group size
  - Public/private keys initializations
- Input parameters:
  - The number of intermediate onion routers: K
  - The number of message copies: L
  - The message deadline: T
- Multi-Copy Forwarding (v_s, v_d, m, K, L, T)
  - Selects a set of onion groups, $R_1, R_2, \ldots, R_K$
  - Generates an onion
  - Sets $v_s.ticket = L$

Multi-Copy Forwarding (Cont.)

- v_i does the following at contact with v_j at the k-th hop
  - v_i and v_j establishes a secure link
  - If $v_j \in R_k$ and Forward(.)
    - v_i sends m to v_j
    - v_i decrements $v_i.ticket$ by 1
    - If $v_i.ticket = 0$, then v_i deletes m from the buffer
    - v_j sets $v_j.ticket = 1$
- if v_d receives m, routing succeeds
- If m is not delivered to v_d within T, routing fails

Note: the definition of Forward(.) is left to application designers
e.g., intermediate onion relays are allow to have one copy

4. Analyses

- Analyses
  - Performance : delivery rate and message overhead
  - Security : traceable rate and path anonymity
- The attack model
  - The compromise attack: a node is physically compromised, and the transmission of a message is monitored
  - Compromised nodes are randomly chosen by the uniform distribution

Delivery Rate

- One-hop delivery
  - The inter-contact time between v_i and v_j is defined by $1/\lambda_{i,j}$
  - $\lambda_{i,j}$ is assumed to be exponentially distributed
  - $\Pr\left[v_i \text{ contacts with } v_j \text{ within } T\right] = \int_0^T \lambda_{i,j} e^{-\lambda_{i,j} t} dt = 1 - e^{-\lambda_{i,j} T}$
- Multi-hop delivery
  - An opportunistic path is modeled by the hypoexponential distribution [ICDCS'11]
- For the proposed protocol
  - We will define an opportunistic onion path
  - Which incorporates anycast forwarding

[ICDCS'11] W. Gao, G. Cao, A. Iyengar, and M. Srivatsa, "Supporting Cooperative Caching in Disruption Tolerant Networks," in ICDCS, 2011, pp. 151– 161.

Delivery Rate (Cont.)

- The contact frequency for the k-th hop: λ_k
  - $\lambda_k = \begin{cases} \sum_{j=1}^{g} \lambda_{s,r_{k,1}} & \text{for } k = 1 \\ \frac{1}{g} \sum_{i=1}^{g} \sum_{j=1}^{g} \lambda_{r_{k-1,i},r_{k,j}} & \text{for } 2 \leq k \leq K \\ \sum_{j=1}^{g} \lambda_{r_{k-1,j},d} & \text{for } k = K+1 \end{cases}$

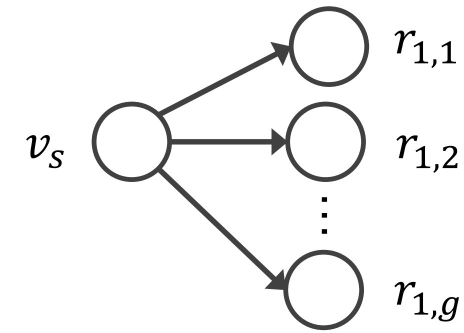


Fig 1. The first hop.

- The delivery rate: $P_{delivery}(T)$
  - The coefficient: $A_k^{(\eta)} = \prod_{j=1,j\neq k}^{(\eta)} \left(\frac{\lambda_j}{\lambda_j - \lambda_k}\right)$
  - $P_{delivery}(T) = \sum_{k=1}^{\eta} A_k^{(\eta)} \left(1 - e^{-\lambda_k T}\right)$
  - $P_{delivery}(T, L) = \sum_{k=1}^{\eta} A_k^{(\eta)} \left(1 - e^{-\lambda_k L T}\right)$

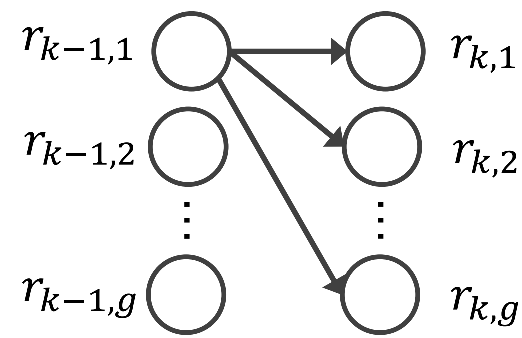


Fig 1. The k-th hop.

Message Forwarding Cost

- The spray-and-wait between two nodes
  - For a connected pair of v_i and v_d, a message is eventually delivered, when $T \to \infty$
  - At most $2L-1$ message transmissions
- Onion-based routing with $L = 1$
  - Num of msg tx is $K+1$
- Onion-based routing with $L \geq 2$
  - The first hop: $2L-1$
  - The k-th hop $(2 \leq k \leq K)$: KL
  - Num of msg tx is $(K+2)L-1$

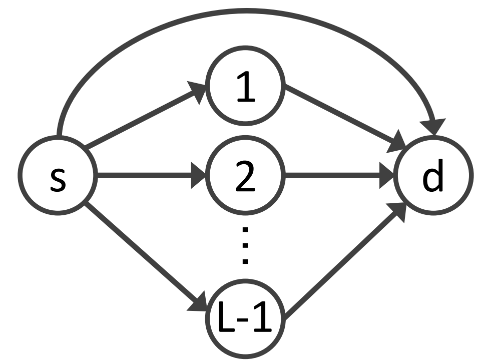


Fig 1. Source spray-and-wait
$2(L-1)+1 = 2L-1$

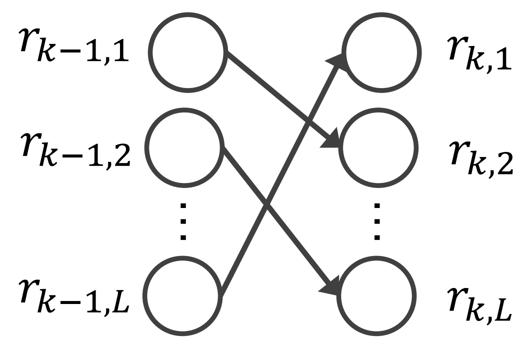


Fig 2. Msg TX btwn 2 groups ($L \leq g$ holds)

The Traceable Rate

- The attack model
  - For path $v_1 \to v_2 \to \ldots \to v_k$, should v_i be compromised, link $v_i \to v_{i+1}$ will be disclosed
- The traceable rate
  - Quantifies how much portion of a path is disclosed
  - $P_{trace} = \frac{1}{\eta^2}\sum_{i=1}^{C_{seg}}\left(c_{seg,i}\right)^2$, where η is the path length

$$v_1 \to v_2 \to v_3 \to v_4 \to v_5$$

Case 1: $P_{trace} = \frac{2^2+1^2}{4^2} = \frac{5}{16}$

$$v_1 \to v_2 \to v_3 \to v_4 \to v_5$$

Case 2: $P_{trace} = \frac{3^2}{4^2} = \frac{9}{16}$

The Traceable Rate (Cont.)

- Our approach
  - The binary rep. of a path is defined by $b = \{b_1, b_2, \ldots,\}$
    - $b_i = 1$ indicates the compromised link
  - The problem is reduced to estimating the run length of 1's
  - The run is the same consecutive 0's or 1's

$$v_1 \rightarrow v_2 \rightarrow v_3 \rightarrow v_4 \rightarrow v_5 \rightarrow v_6$$

$$b = 01101$$

$$P_{trace} = \frac{2^2 + 1^2}{5^2}$$

The Traceable Rate (Cont.)

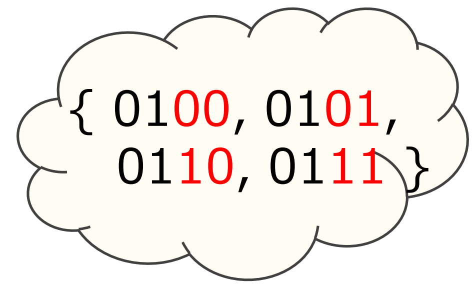
- This can be modeled by the geometric distribution
  - Let X_i be the random variable that represents the run length of the first segment starting from b_i
  - c : # of compromised nodes, n : # of nodes
  - $E[X_i] = \sum_{k=\lceil E[X_i]\rceil+1}^{\eta} k^2 \left(\frac{c}{n}\right)^k \left(1-\frac{c}{n}\right)$
- The traceable rate : $P_{trace}(c)$
  - We have $C_{seg} \leq \lceil \eta/2 \rceil$
  - $P_{trace}(c) = \frac{1}{\eta^2} \sum_{i=1}^{\lceil \eta/2 \rceil} E[X_i^2]$

$$b = \underbrace{10101010\ldots10}_{\eta\text{-bit}}$$

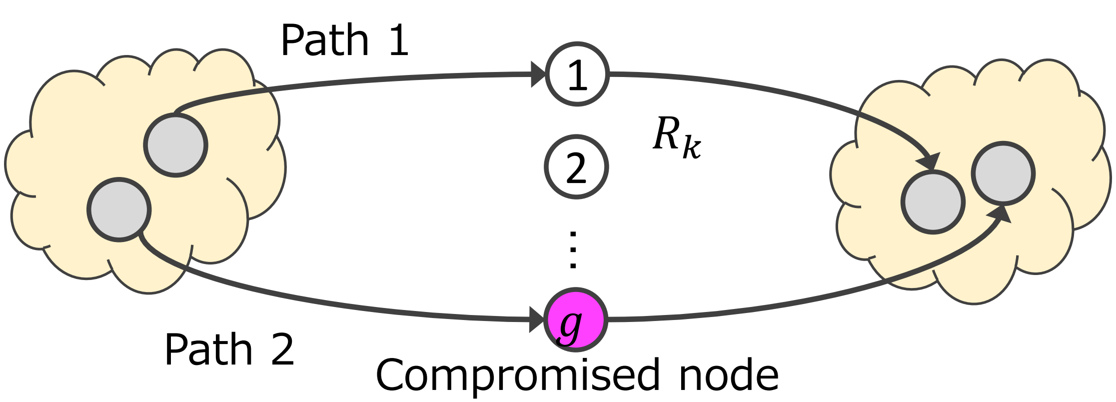
There is 0 between neighboring segments

Path Anonymity

- Anonymity
  - An entropy-based metric, $-\sum_{\forall i \in \phi} p_i \log(p_i)$
  - Application-dependent
  - Example: a bit string 01XX



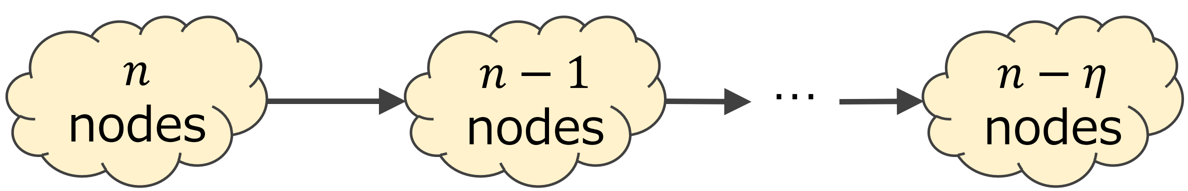
- Path anonymity for DTNs
  - Path anonymity : $D(\phi') = \frac{H(\phi')}{H_{max}}$
  - Note: the copies of a message can be correlated



The k-th onion router in path 1 must be one of the nodes in R_k

Path Anonymity (Cont.)

- The maximal entropy of the system
  - There are $\binom{n}{\eta}$ possible paths, when $c = 0$
  - $H_{max} = -\sum_{\forall \text{path} \in \phi} \frac{(n-\eta)!}{n!} \log\left(\frac{(n-\eta)!}{n!}\right)$
  - $\sum_{\forall \text{path} \in \phi} \frac{(n-\eta)!}{n!}$ equals to 1, since every path in an anonymous set is identified with the same probability



Path Anonymity (Cont.)

- The entropy of the system
  - The joint probability that a node is selected as an onion router and is compromised: $\frac{1}{g} \cdot \frac{cg}{n} = \frac{c}{n}$
  - Let Y be the random variable that represents the number of compromised nodes on a path
  - This follows the Binomial dist.: $E[Y] = \sum_{i}^{\eta} i \binom{\eta}{i} \left(\frac{c}{n}\right)^{i} \left(1 - \frac{c}{n}\right)^{\eta - i}$
  - The probability that an adversary can guess the next node:
  - $P_{guess}(v_i, n, g, k) = \begin{cases} \frac{1}{g} & \text{if } v_i \text{ is compromised} \\ \frac{1}{n-k} & \text{if otherwise} \end{cases}$

Path Anonymity (Cont.)

- Let $c_0 = E[Y]$
- The probability of successfully guessing path i :
  - $p_i = \underbrace{\frac{(n-K+c_0)!}{n!}}_{\text{In the case that a node is NOT compromised}} \cdot \underbrace{\frac{1}{g^{c_0}}}_{\text{In the case that a node is compromised}}$
- The entropy of the system:
  - $H(\phi') = -\sum_{\forall \text{path} \in \phi'} \frac{(n-\eta+c_0)!}{g^{c_0} n!} \log\left(\frac{(n-\eta+c_0)!}{g^{c_0} n!}\right)$
- Path anonymity $D(\phi')$
  - $D(\phi') = \frac{H(\phi')}{H_{max}} = \frac{(\eta-c_0)(\ln(n)-1)+c_0 \ln(g)}{\eta(\ln(n)-1)}$

5. Simulations

- Comparisons between analysis and simulation
  - Delivery rate, message overhead, traceable rate, and path anonymity
- Parameters
  - Group size g, Num of onion routers K, Num of copies L
- Two scenarios
  - Randomly generated graphs
  - Real traces with CRAWDAD dataset

Simulations with Random Graphs

- A contact graphs are randomly generated
- 1000 simulations experiments are conducted

Table. Simulation parameters.

Parameter	Value (default value)
The number of nodes, n	1000
The inter-contact time, λ	0 to 360 minutes
The group size, g	1 – 10 (5)
The number of onion routers, K	1 – 10 (3)
The number of copies, L	1 - 5
The message deadline, T	60 to 1800 minutes
The % of compromised nodes, c/n	0% - 50% (10%)

Delivery Rate and Message Overhead

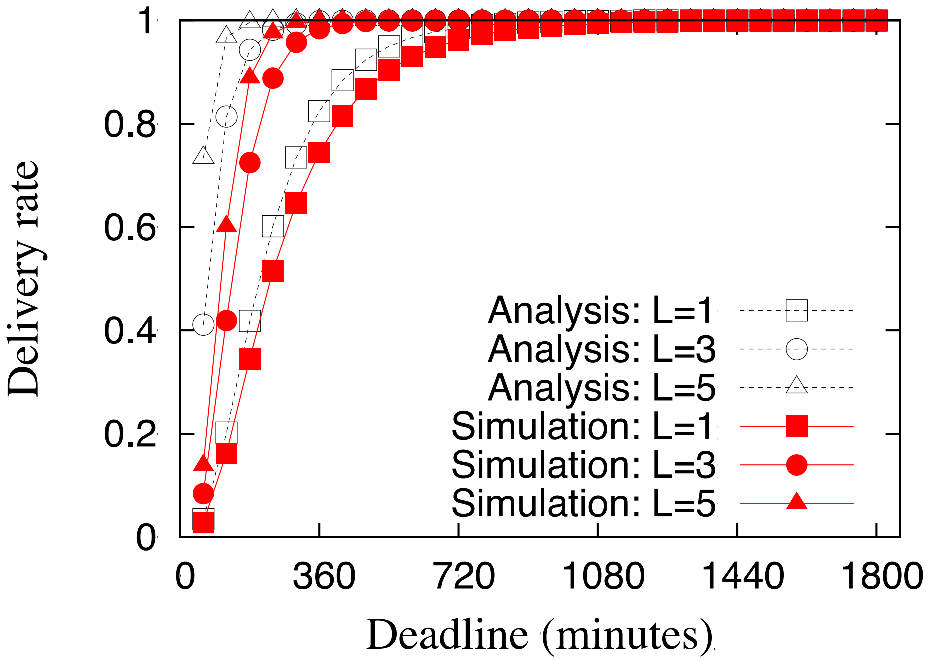


Fig. Delivery rate

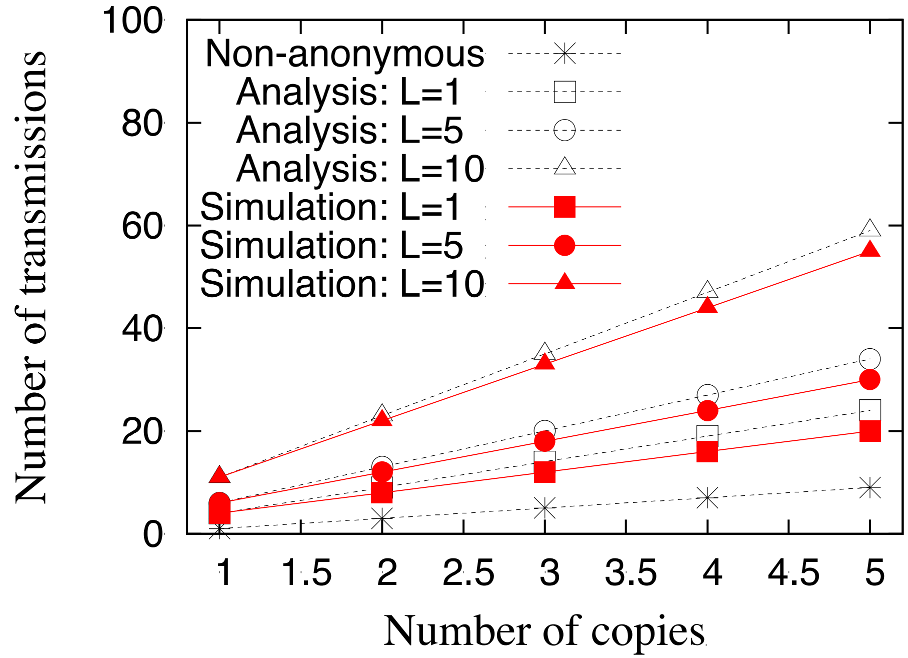


Fig. Message overhead

- The delivery rate increases as the value of L increases
- The # of msg forwarding increases, as the value of L increases

Traceable Rate and Anonymity

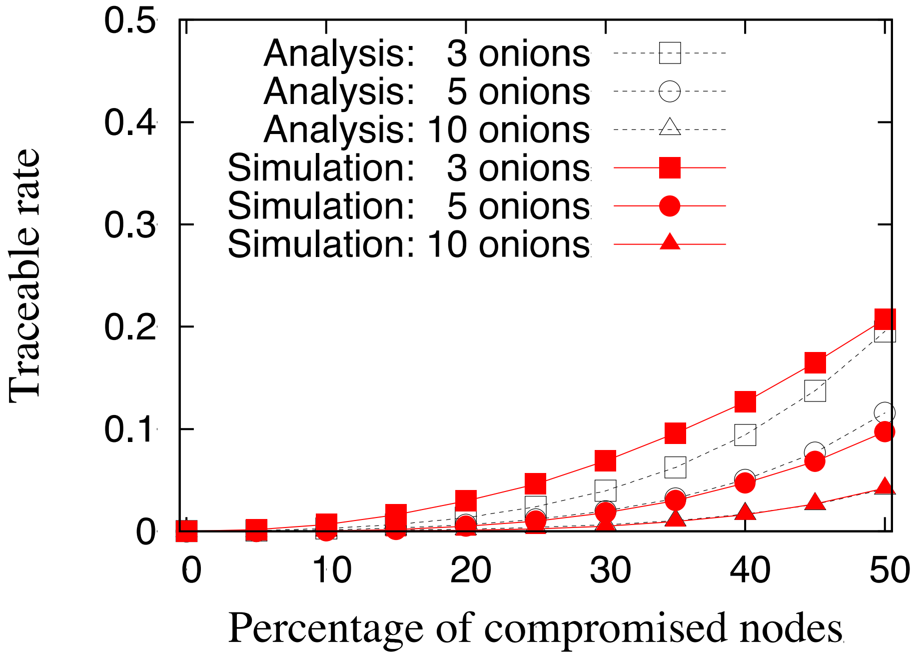


Fig. Traceable rate

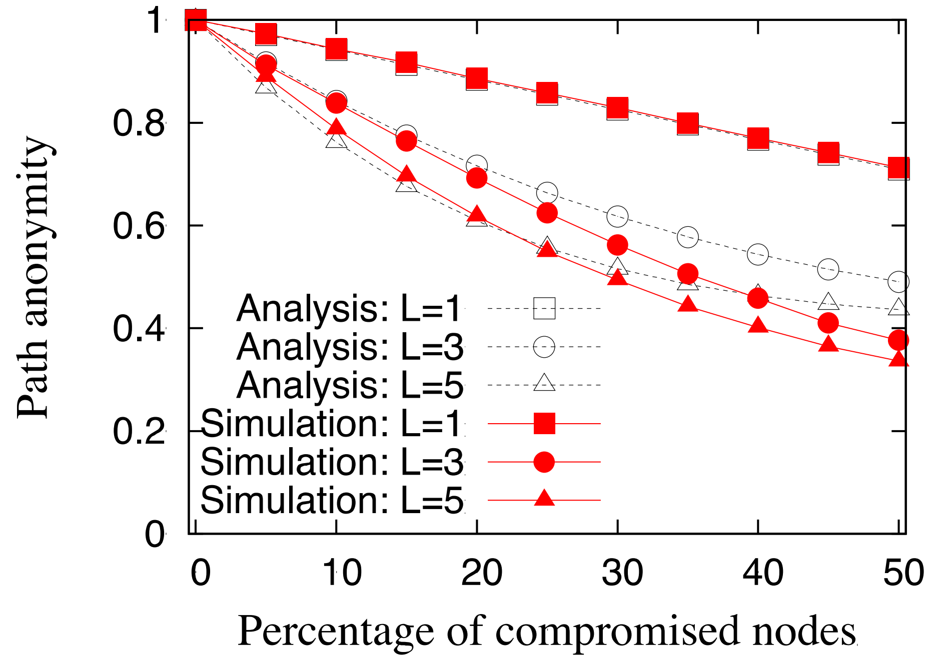


Fig. Path Anonymity

- Note: the traceable rate is independent from the value of L
- The traceable rate decreases, as the onion length increases
- The path anonymity decreases, as the value of L increases

Results with Real Traces

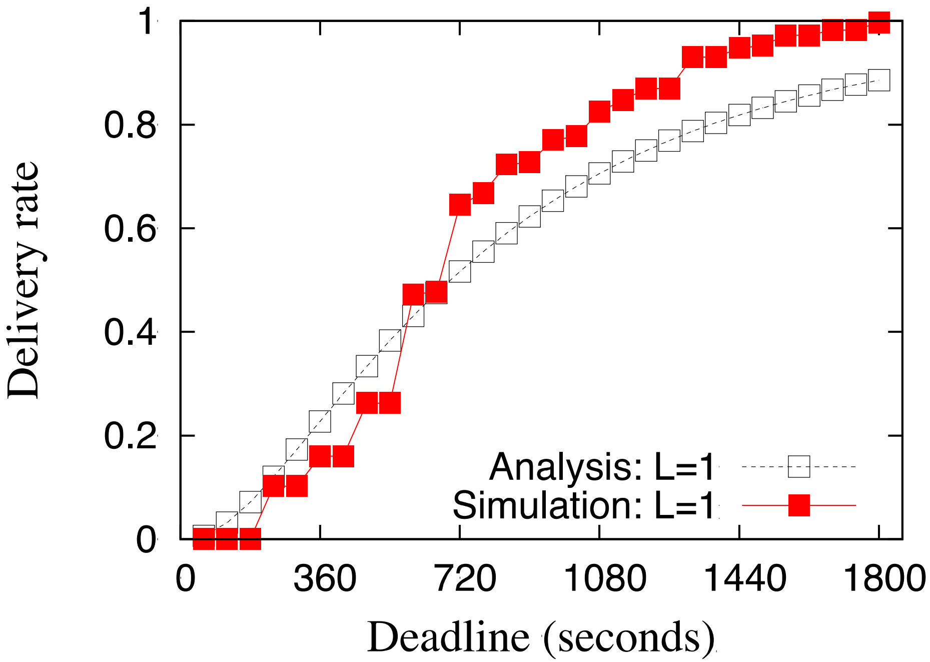


Fig. the delivery rate
Cambridge traces (a small and dense network with 12 iMotes)

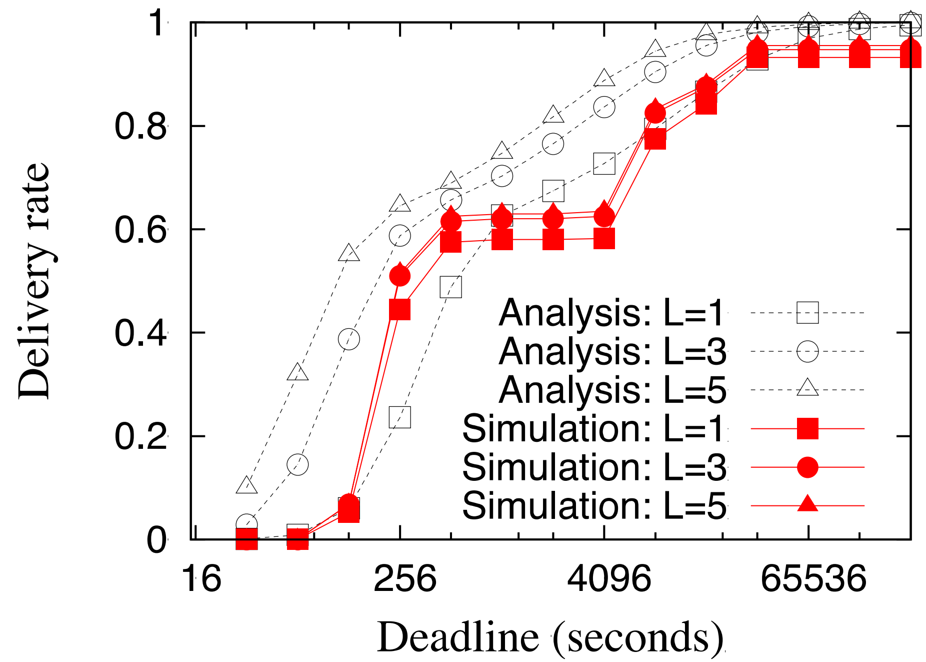


Fig. the delivery rate
Infocom'15 traces (a medium size network with 41 iMotes)

- There exist on and off-business hours

6. Conclusions

- We emphasize the theoretical aspects of onion-based anonymous routing in DTNs
  - An abstract of onion-based anonymous routing protocols
  - The analysis of the delivery rate, message overhead, traceable rate, and path anonymity
  - The analyses provide the closed-form solutions to approximate the simulation results

Thank you

Observations

- Three parameters, g, K, and L
  - Group size g : determined by the administrator
  - The onion length K: flexible setting is not possible
  - The number of copies L : tunable by each message transmission
- Rule of thumb
  - Larger L improve delivery rate, but reduces path anonymity