Modeling Restrained Epidemic Routing on Complex Networks

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July 16, 2019

Outline

Background: DTN Routing and Approaches for Realizing Efficiency Delivery

- DTN (Delay/Disruption Tolerant Networking) routing
  - **Store-carry-and-forward** message routing
  - Common performance metrics
    - Message delivery delay, delivery ratio, throughput
- Approaches for realizing efficient delivery
  - Increase the chance of delivery
    - **Message replication**
    - Message coding
  - Avoid congestion/resource starvation
    - (Utility-based) selection of relaying node
    - Message replication suppression with ACK
    - Data compression
    - Message expiration with TTL (Time-To-Live)

Background: Issues in Concurrent Message Transfer and Broadcasting ACK

- **Epidemic routing**
  - Disseminate message replicas through network
  - A large number of message replicas generated
- When the amount of workload is **small**. . .
  - Can achieve **near-optimal** performance
- When the amount of workload is **large**. . .
  - May result in performance degradation due to many message replicas

Related Works: Modeling (Biological) Virus Dissemination (1/2)

- **Biological virus** dissemination modeling (1920's–)
  - Node states
    - SI (Susceptible Infected) model
    - SIS (Susceptible Infected Susceptible) model
    - SIR (Susceptible Infected Recovered/Revmoved) model
  - Contact among nodes
    - **Fully-fixed** (identical nodes, identical contact rates)
    - Graph (**contact relationship** graph)

Related Works: Modeling (Biological) Virus Dissemination (2/2)

- **Biological virus** dissemination modeling (1920's–)
  - Model state
    - Macro model: the number of nodes in every state (e.g., N_S, N_I)
    - Micro model: state of every node (e.g., $s_1, \ldots, s_N$)
  - Model description
    - Discrete (Markov chain): exact but for small systems
    - Continuous (differential equations): approximate but can be **large-scale**

Related Works: Epidemic Routing Modeling

- Mapping from **virus epidemic** to **epidemic routing**
  - What to be infected
    - Human being, animals
      → Nodes (terminals)
  - What infects
    - Biological (single) virus
      → (**Multiple**) messages
  - Recovery from infection
    - Natural recovery
      → **Message discard by TTL or ACK**
  - Objective
    - Virus elimination
      → **Rapid/reliable/low-cost message delivery**

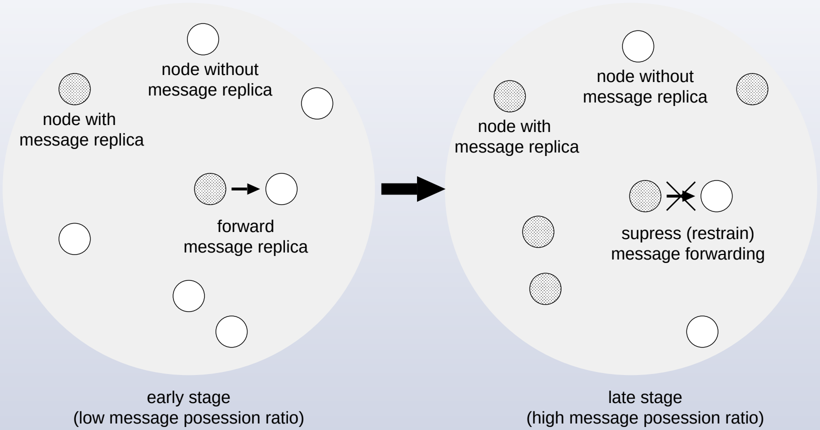
Related Works: Epidemic Routing Modeling

- Restrained epidemic routing
  - Objective: Fast message delivery under concurrent messages routing
  - Idea: **Intentionally refrain** message replication at a later stage
- Development of epidemic modeling on complex networks
  - Describe dynamics of all nodes
    $\rightarrow$ State space explosion
  - Homogeneous node assumption
    $\rightarrow$ Loss of graph structure
  - **Describe dynamics of node classes**
    $\rightarrow$ Reduction in state space
    - **DBMF (Degree-Based Mean Field)** approximation (2002)

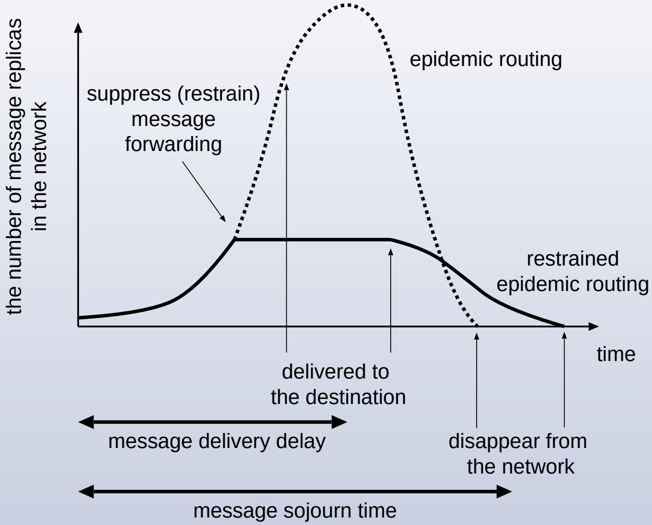
Objective: Modeling Epidemic Routing in Complex Networks

- Describe the dynamics of **restrained epidemic routing**
- Using **DBMF (Degree-Based Mean Field)** approximation
  - Clarify the impact of node contact relationship (complex network) on message delivery

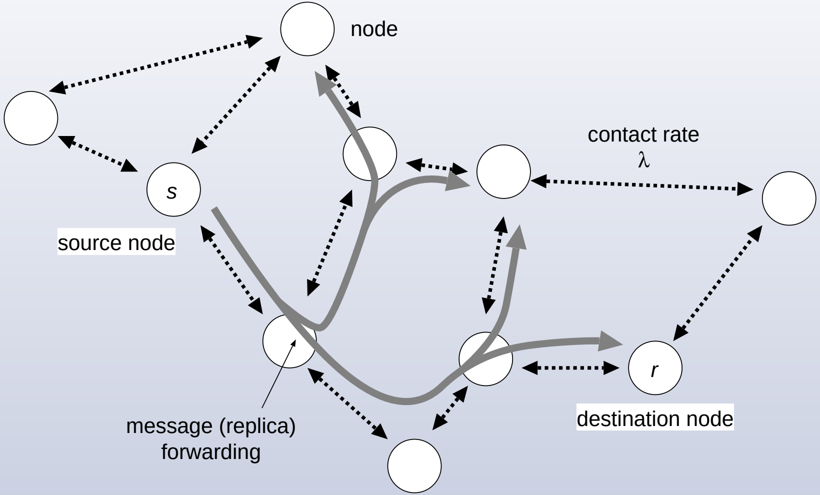
Restrained Epidemic Routing: Overview



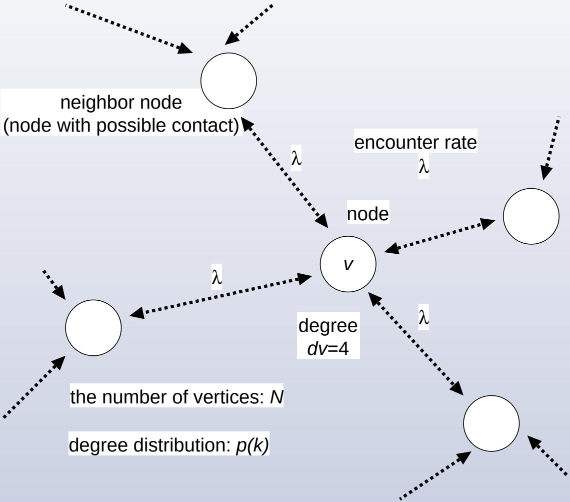
Restrained Epidemic Routing: Comparison with Normal Epidemic Routing



Analytic Model: Message Delivery from Source Node to Destination Node



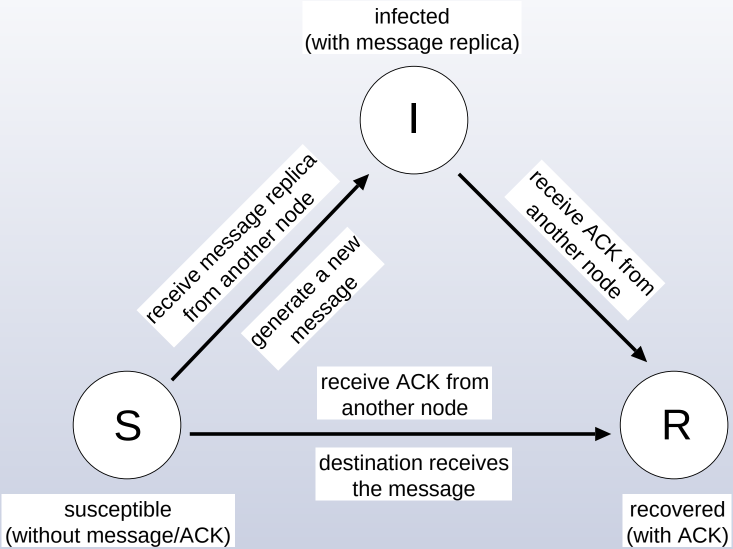
Analytic Model: Representing Node Contacts as Undirected Graph



Assumptions

- Restrained epidemic routing with broadcast ACK
- N nodes
- Message is generated at a source node at $t = 0$
- Contact duration follows Poisson distribution with mean λ
- Degree distribution of contact relationship: $P(k)$

Analytic Model: Mapping to SIR Model



Analysis: Initial State to Message Restraint

- Initial state

$$\rho_k^I(0) = \begin{cases} \frac{1}{N\,P(k)} & k = d_s \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

$$\rho_k^R(0) = 0 \tag{2}$$

$$\rho_k^S(0) = 0 \tag{3}$$

- Dynamics of the number of infected nodes in class k

$$\frac{d\rho_k^I(t)}{dt} = \lambda\, k\, \rho_k^S(t)\, \Gamma_k(t) \tag{4}$$

$$\Gamma_k(t) = \sum_{k'} P(k'|k)\, \rho_{k'}^I(t) \tag{5}$$

Analysis: Message Restraint to Message Delivery

- The number of infected nodes does not change until delivery completion

$$\frac{d\rho_k^I(t)}{dt} = 0 \tag{6}$$

$$\frac{d\rho_k^R(t)}{dt} = 0 \tag{7}$$

$$\frac{d\rho_k^S(t)}{dt} = 0 \tag{8}$$

- From message restraint to message delivery

$$t_2 - t_1 = \frac{1}{\lambda\, d_r\, \Gamma_{d_r}(t_1)} \tag{9}$$

Analysis: Message Delivery to Broadcast ACK Dissemination

- When message is delivered

$$\rho_k^I(t_2) = \rho_k^I(t_1) \tag{10}$$

$$\rho_k^R(t_2) = \begin{cases} \frac{1}{N\,P(d_r)} & k = d_r \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

$$\rho_k^S(t_2) = 1 - \left(\rho_k^I(t_2) + \rho_k^R(t_2)\right) \tag{12}$$

- Message replica reduction with broadcast ACK

$$\frac{d\rho_k^R(t)}{dt} = \lambda\, k\, (1 - \rho_k^R(t))\, \Omega_k(t) \tag{13}$$

$$\Omega_k(t) = \sum_{k'} P(k'|k)\, \rho_{k'}^R(t) \tag{14}$$

Numerical Examples: Three Types of Degree Distributions

- Poisson

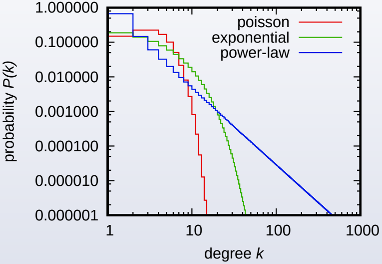
$$P(k) = e^{-\bar{k}} \frac{\bar{k}^k}{k!} \quad (15)$$

- Exponential

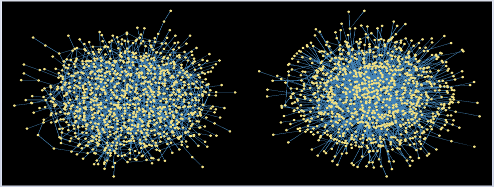
$$P(k) = (1 - e^{-\mu}) e^{-\mu k} \quad (16)$$

- Power-law

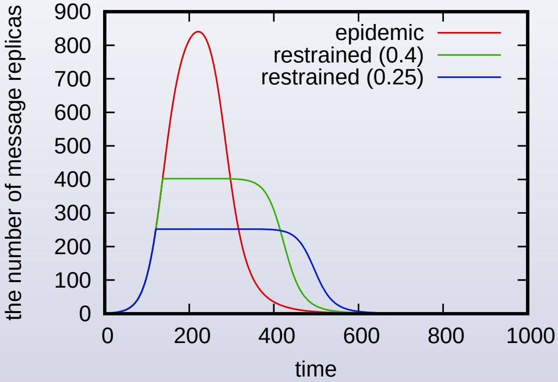
$$P(k) = \frac{k^{-\alpha}}{\zeta(\alpha)} \quad (17)$$



average degree $\bar{k} = 3$

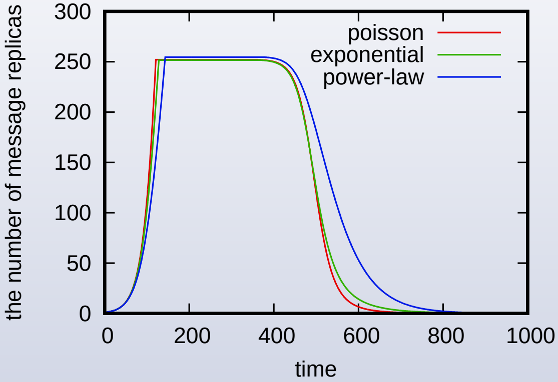


Numerical Example: Evolution of the Number of Message Replicas



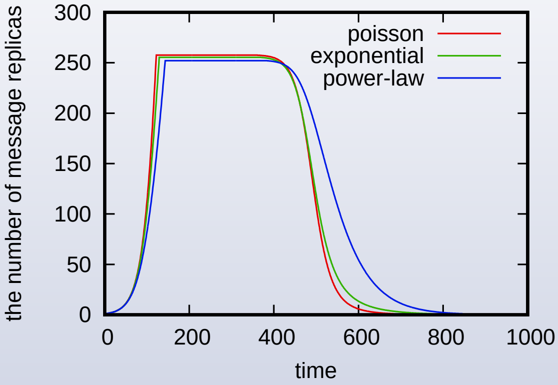
1,000 nodes, degree distribution: Poisson, source and destination degree: 1, contact rate: 1/60

Numerical Examples: Effect of Contact Rate on Message Delivery



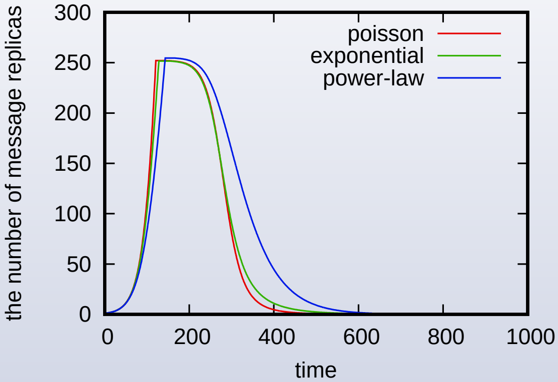
1,000 nodes, source and destination node degree: 1, contact rate: 1/60, p_T: 0.25

Numerical Examples: Effect of Contact Relationship on Message Delivery



1,000 nodes, source node degree: 10, destination node degree: 1, contact rate: 1/60, p_T: 0.25

Numerical Examples: Effect of Contact Relationship on Message Delivery



1,000 nodes, source node degree: 1, destination node degree: 10, contact rate: 1/60, p_T: 0.25

Conclusion

- Model **restrained epidemic routing**
  - Contact relationship is given by **a complex network**
  - Describe the dynamics of a single message routig
- Derive **average message delivery delay** and **average message sojourn time**
- Investigate the impact of contact relationship on message delivery
  - When contact relationship graph is **power-law**
    - **Message delivery delay is larger** than non-power-law cases

Future Works

- Derive exact solutions of average message delivery/sojourn times under **specific** degree distributions
- Modeling resource contention under **multiple concurrent messages routing**
- Designing a DTN routing mechanism utilizing our analysis