Average packet delivery delay in intermittently-connected networks

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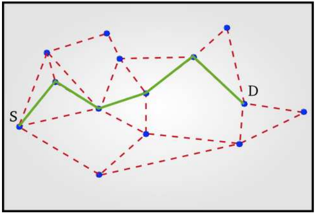
AIRO 2014 - Como, September 2-5, 2014

Outline

1. Intermittently-Connected Networks (ICNs)
   - Networking paradigms: IP-like and DTN (Delay-Tolerant Networking)
2. ICN model
3. Average packet delivery delay
   - IP-like paradigm
   - DTN paradigm
4. Comparison of the two approaches
5. Extensions

Intermittently-Connected Networks (ICNs)

- Intermittently-Connected Networks (ICNs)
  - Characterized by:
    - intermittent connectivity (the existence of end-to-end paths between source (S) and destination (D) nodes is not always guaranteed);
    - long and variable delays;
    - asymmetric data rates;
    - high error rates.



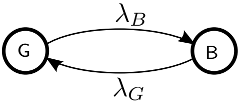
Networking paradigms for ICNs

- Two networking paradigms for ICNs.
  - In the IP-like paradigm, incoming packets are stored in routers for a few milliseconds/seconds (short-term storage).
    - In order to transmit the data, the IP-like paradigm requires the availability of a permanently available end-to-end path during the entire transmission.
  - In the Delay-Tolerant Networking (DTN) paradigm, the storage places can hold for a long time messages with no delay constraints (persistent storage).
    - The DTN approach, by adopting a store-and-forward mechanism with longer-term storage, is able to cope with intermittent connectivity and link disruptions.

Mobility model

- Inter-meeting time and contact time between two generic nodes: exponentially distributed random variables.
  - Typical of node mobility models, such Random Waypoint and Random Direction.
- Behaviour of the communication link between each pair of nodes: described by a continuous-time Markov chain (CTMC).
  - Two configurations.
    - G (Good): the two nodes are in contact and are able to transmit the data (i.e., the link is operating).
    - B (Bad): the two nodes are not in contact (i.e., the link is disrupted and there is no connection. at all).

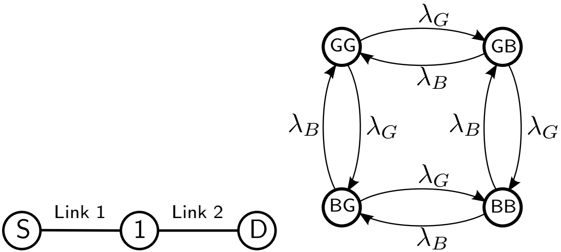
Model of each communication link



- $\lambda_G > 0$: transition rate of each link from G to B;
- $\lambda_B > 0$: transition rate of each link from B to G;
- $\tau_G = \frac{1}{\lambda_G}$: average lifetime of the state G;
- $\tau_B = \frac{1}{\lambda_B}$: average lifetime of the state B;
- $\pi_G = \frac{\tau_G}{\tau_G+\tau_B} = \frac{\lambda_B}{\lambda_G+\lambda_B}$: stationary probability of the state G;
- $\pi_B = \frac{\tau_B}{\tau_G+\tau_B} = \frac{\lambda_G}{\lambda_G+\lambda_B}$: stationary probability of the state B.

Network topology

- L-hop network topology, modeling a single path source-destination.
  - L independent links.
  - State of the network represented by the ordered L-tuple of the states (either G or B) of its links.
- For $L = 2$:



(a) Network topology (b) The associated CTMC

Average packet delivery delay

- t_{IP} and t_{DTN} : average packet delivery delays experienced by a packet transmitted under the IP-like and DTN paradigms, resp.
  - Packet generation process: Poisson process.
    - One can use in the analysis the Poisson Arrivals See Time Averages (PASTA) property.
  - the Sum of the transmission and propagation delays along each link is modeled by a constant $\Delta \geq 0$.
    - The limit case in which $\Delta = 0$ models the situation in which both are considered negligible delays.

IP-like versus DTN paradigm

Differences between the two paradigms.

- In the IP-like paradigm, incoming packets are stored in routers for a few milliseconds/seconds (short-term storage).
    - In order to transmit the data, the IP-like paradigm requires the availability of a permanently available end-to-end path during the entire transmission.
        - All the L links have to be in the good state, for a sufficiently long time interval.
- In the Delay-Tolerant Networking (DTN) paradigm, the storage places can hold for a long time messages with no delay constraints (persistent storage).
    - The DTN approach, by adopting a store-and-forward mechanism with longer-term storage, is able to cope with intermittent connectivity and link disruptions.
        - Communication can be successful even if at any time there is only one link in the good state, for a much shorter time interval.

Goals

In this talk:

comparing the average packet-delivery delays of IP-like and DTN paradigms.

- M. Cello, G. Gnecco, M. Marchese, M. Sanguineti, "Evaluation of the Average Packet Delivery Delay in Highly-Disruptive Networks: the "IP-like" and DTN protocol cases", IEEE Communications Letters, vol. 18, pp. 519-522, 2014.
- M. Cello, G. Gnecco, M. Marchese, M. Sanguineti, "Congestion-Aware Forwarding Strategies for Intermittently Connected Networks", submitted.

This is a preliminary step towards the following goal:

optimizing the trade-off between the average buffer occupancy and the average packet delivery delay.

Notations

- 2^L states of the CTMC associated with the L-hop network topology: ordered in decreasing lexicographical order, starting from the state 1 in which all the L links are in the configuration G, and ending in the state 2^L in which all the L links are in the configuration B.
    - For example, with $L = 3$ one gets $\{GGG, GGB, GBG, GBB, BGG, BGB, BBG, BBB\}$
- π_i: stationary probability of the i-th state of the CTMC.
    - By the link-independence assumption, $\pi_i = \pi_G^{g(i)} \pi_B^{L-g(i)}$, where $g(i)$ is the number of links in the configuration G for the state i.

- q_{ij}: transition rate from the state i to the state j.
  - For each pair of different states i and j of the CTMC, $q_{ij} \neq 0$ if and only if i and j differ in the state of one link only. More specifically, $q_{ij} = \lambda_B$ if that specific link moves from the configuration B in the state i to the configuration G in the state j, otherwise $q_{ij} = \lambda_G$.
  - For $i = j$, we set (by definition)

$$q_{ii} := - \sum_{l \in \{1,\ldots,2^L\} \setminus \{i\}} q_{il} \,.$$

- Expected first hitting time k_i of the state 1 in which all the links are in the configuration G: expectation of the first time at which the CTMC, starting from the state i, “hits” or visits the state 1.
  - Vector of k_i's: minimal non-negative solution of the linear system

$$\begin{cases} k_i = 0, & \text{for } i = 1\,, \\ -\displaystyle\sum_{j=1}^{2^L} q_{ij} k_j = 1, & \text{for } i = 2, \dots, 2^L \end{cases}$$

  - Simplifications, thanks to symmetry arguments.

Average packet delivery delay for the IP-like paradigm

Proposition

Given an L-hop network topology whose independent links have the same values of λ_G and λ_B and a constant value Δ for the sum of transmission and propagation delays, the average packet delivery delay in the IP-like scenario is given by

$$t_{IP} = L\Delta + \frac{1 - p(L\lambda_G, L\Delta)}{p(L\lambda_G, L\Delta)}\left(\tau(L\lambda_G, L\Delta) + k_{2^L-1}\right) + \sum_{j=1}^{2^L} \pi_j k_j\ , \qquad (1)$$

where $p(L\lambda_G, L\Delta) := \int_{L\Delta}^{\infty} (L\lambda_G) e^{-(L\lambda_G)x} dx$ *and* $\tau(L\lambda_G, L\Delta) := \int_0^{L\Delta} x \frac{(L\lambda_G)e^{-(L\lambda_G)x}}{1-e^{-(L\lambda_G)(L\Delta)}} dx$. *For* $L\Delta \simeq 0$, *(1) simplifies to*

$$t_{IP} \simeq \sum_{j=1}^{2^L} \pi_j k_j \qquad (2)$$

Average packet delivery delay for the DTN paradigm

Proposition

Given an L-hop network topology whose independent links have the same values of λ_G and λ_B and a constant value Δ for the sum of the transmission and propagation delays, the average packet delivery delay in the DTN scenario is given by

$$t_{DTN} = L\left[\Delta + \frac{1-p(\lambda_G,\Delta)}{p(\lambda_G,\Delta)}(\tau(\lambda_G,\Delta)+\tau_B) + \pi_B\tau_B\right], \tag{3}$$

where $p(\lambda_G,\Delta) := \int_\Delta^\infty \lambda_G e^{-\lambda_G x} dx$ *and* $\tau(\lambda_G,\Delta) := \int_0^\Delta x\frac{\lambda_G e^{-\lambda_G x}}{1-e^{-\lambda_G\Delta}} dx$. *For* $\Delta \simeq 0$, *(3) simplifies to*

$$t_{DTN} \simeq L\pi_B\tau_B \tag{4}$$

Comparison of the two approaches

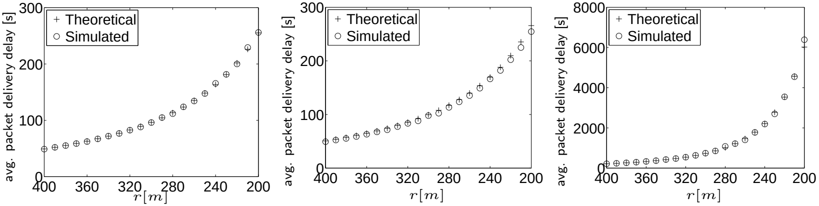
- Comparison of the performances of the IP-like and DTN approaches carried out
  - both numerically, via formulas (1) and (3) provided by Propositions 1 and 2, resp.,
  - and by using an event-driven ad-hoc simulator written in C++,

under various levels of network disruption.

Scenarios

- Random Waypoint mobility model on a square of size $1km^2$ with speed chosen uniformly in $[14.5, 36]m/s$.
- Transmission radius r of the nodes (i.e., the largest inter-node distance under which the associated link is in the configuration G): from $400m$ to $200m$.
    - Associated values of λ_G: from $0.0478s^{-1}$ to $0.0955s^{-1}$.
    - Associated values of λ_B: from $0.0328s^{-1}$ to $0.0164s^{-1}$.
- We have varied also the number L of hops and the value Δ of the sum of the transmission and propagation delays.

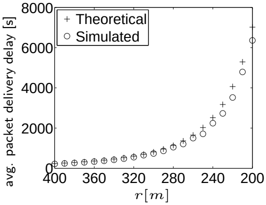
Results for the IP-like paradigm



(c) $L = 2,\ \Delta = 0s$

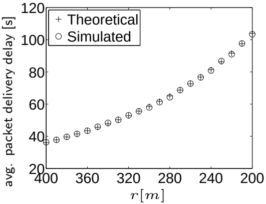
(d) $L = 2,\ \Delta = 0.1s$

(e) $L = 4,\ \Delta = 0s$

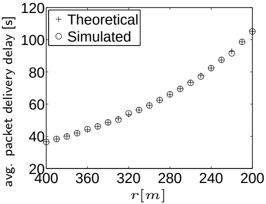


(f) $L = 4,\ \Delta = 0.1s$

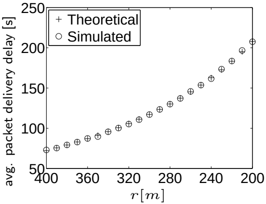
Results for the DTN paradigm



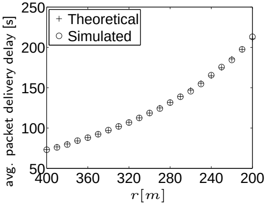
(g) $L = 2,\ \Delta = 0s$



(h) $L = 2,\ \Delta = 0.1s$



(i) $L = 4,\ \Delta = 0s$



(j) $L = 4,\ \Delta = 0.1s$

Comments

- For an increasing number L of hops and a decreasing value of the transmission radius r, in the considered ICN scenarios the DTN approach dramatically outperforms the IP-like one.
- In most cases, the simulated curves are practically overlapped to the theoretical ones.
  - This is due to the ergodicity of the underlying continuous-time Markov chain of the two models.
  - The maximum relative error in the results presented is referred to the IP-like case for $L = 2$, $\Delta = 0.1s$ and $r = 200m$, and is below 6.5%.
- The results confirm and address quantitatively the fact (realized experimentally in various works) that, when the network experiences a high degree of disruption, DTN outperforms the IP-like paradigm in terms of a smaller average packet delivery delay.

Extensions

- We have focused on the case of an L-hop network topology modeling a single source-destination path.
- Possible extensions of the model to the case of multiple paths (e.g., nodes organized in layers).
- Simplest extension to the case of a more complex topology and multiple paths: interpreting L - for the DTN paradigm - as the average number of hops in the first path that delivers the packet to the destination.
  - In this case, L being the same, the comparison is still in favour of DTN. The model overestimates t_{DTN}, since the path under consideration is not generic, but the one that minimizes the packet delivery delay with respect to several paths.

- Investigating the dependencies of the obtained expressions t_{IP} and t_{DTN} on their parameters $(L, \lambda_G, \lambda_B, \Delta)$.
- Evaluating and optimizing the trade-off between the average buffer occupancy and the average packet delivery delay.
  - DTN paradigm: larger average buffer occupancy, smaller average packet delivery delay.
  - IP-like paradigm: smaller average buffer occupancy, larger average packet delivery delay.
- Case of many source/destination pairs: possible analysis through noncooperative game theory.
  - Congestion avoidance through transmission rate adaptation.

Thank you for your attention

References

1. M. Cello, G. Gnecco, M. Marchese, M. Sanguineti, "Evaluation of the Average Packet Delivery Delay in Highly-Disruptive Networks: the "IP-like" and DTN protocol cases", IEEE Communications Letters, vol. 18, pp. 519-522, 2014.
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