Average packet delivery delay in intermittently-connected networks

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1. Intermittently-Connected Networks (ICNs)
   - Networking paradigms: IP-like and DTN (Delay-Tolerant Networking)

2. ICN model

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   - IP-like paradigm
   - DTN paradigm

4. Comparison of the two approaches

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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 as 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 $L = 2$:

![Diagram](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.


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

1. \(2^L\) 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 \(\{GGG, GGB, GBG, GBB, BGG, BGB, BBG, BBB\}\)

2. \(\pi_i\): 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

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

- 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 \(\lambda_G\) and \(\lambda_B\) and a constant value \(\Delta\) for the sum of transmission and propagation delays, the average packet delivery delay in the IP-like scenario is given by

\[
t_{IP} = L\Delta + \frac{1 - p(L\lambda_G, L\Delta)}{p(L\lambda_G, L\Delta)}(\tau(L\lambda_G, L\Delta) + k_2(L - 1)) + \sum_{j=1}^{2L} \pi_j k_j, \quad (1)
\]

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

\[
t_{IP} \simeq \sum_{j=1}^{2L} \pi_j k_j, \quad (2)
\]
Average packet delivery delay for the DTN paradigm

**Proposition**

*Given an $L$-hop network topology whose independent links have the same values of $\lambda_G$ and $\lambda_B$ and a constant value $\Delta$ for the sum of the transmission and propagation delays, the average packet delivery delay in the DTN scenario is given by*

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

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 $\Delta \approx 0$, (3) simplifies to

$$
t_{DTN} \approx L \pi_B \tau_B
$$
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 $1 km^2$ 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 $400 m$ to $200 m$.
  - Associated values of $\lambda_G$: from $0.0478 s^{-1}$ to $0.0955 s^{-1}$.
  - Associated values of $\lambda_B$: from $0.0328 s^{-1}$ to $0.0164 s^{-1}$.

- We have varied also the number $L$ of hops and the value $\Delta$ of the sum of the transmission and propagation delays.
Results for the IP-like paradigm

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

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

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

(f) $L = 4, \Delta = 0.1 \, s$
Results for the DTN paradigm

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

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

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

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