Online Routing of Stochastically Arriving Bundles in Delay Tolerant Networks

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Delay Tolerant Networks

• Internet is inter-net. Why do we need another architecture to deal with heterogeneity?

• Internet protocol suit was not designed for links with intermittent connectivity or long propagation delay.
Long propagation delay
Intermittent links (link occultation, frequent disconnection)
Implicit assumptions behind internet protocol design

- Small round trip time
- Existence of a contemporaneous path
Delay Tolerant Networks

• Overlay architecture; internet of internets
  – Extreme example: Mars internet, Earth internet, overlay architecture connecting them

• Message-oriented
  – Non-interactive due to disconnection of links

• Hop-by-hop reliability
  – Not end-to-end reliability like IP suit
  – Message (bundle) custody transfer
DTN nodes connecting performance challenging links
Key DTN Concept
DTN Bundles as an application overlay

Bundles: A Store and Forward Application Overlay

A “network of internets” spanning dissimilar environments
Research: Bundle Routing

• Links go **on and off** and **link speed is time-varying**.
  – Randomly
  – Deterministically

• Bundle arrivals may be **random** or **deterministic**

• **Control variables**
  – Joint routing and transmission scheduling
Problem Space of Bundle Routing

Unpredictable connectivity, dynamic traffic, short propagation delays
Probabilistic connectivity, dynamic traffic, short propagation delays
Deterministic connectivity, static traffic, long propagation delays

Sensors go to sleep in random fashion to conserve energy

Static or Quasi-static
Dynamic

ZebraNet

IPN

CONNECTIVITY

PROPAGATION DELAY

TRAFFIC
Layering of Bundle Services, securities and reliabilities of Bundle Transfer
System Model

- DTN nodes and links are modeled by a graph \((V, E)\).
- Time-varying link speed \(r_{ij}(\tau)\) (e.g., bits per second), the maximum transmission rate allowed at time \(\tau\).

- Exogenous bundle arrivals at node \(s\), destined to node \(d\):
  - Poisson process with arrival rate \(\lambda_{sd}\)
- Bundle length: random variable \(L_{sd}\), with pdf \(p_{sd}(l)\)

- A node \(i\)'s online routing and transmission decision upon bundle arrival:
  * The next node \(j\)
  * Transmission rates \(f_{ij}(t)\)
Link delay model

For the model to be more inclusive, we can capture propagation delay and the case of packets arriving out of order.

Suppose that a bundle becomes available for transmission at time \( t \). Bundle transfer delay through link \((i, j)\) is

\[
\max_{0 \leq s \leq L} \left\{ \Delta(s, t, f') + d_{ij}^p \left( t + \Delta(s, t, f) \right) \right\}
\]

where \( \Delta(s, t, f') \) is the time that elapses from \( t \) until the \( s \)th segment is transmitted (i.e., \( \int_t^{t+\Delta(s, t, f')} f(\tau) d\tau = s \) in fluid model), \( d_{ij}^p (\tau) \) is the propagation delay of the segment that is transmitted at time \( \tau \).
In designing a policy

• One must think of the end-to-end bundle delays

• Prevent overflows at the receiving node
  – Limited storage, extreme importance of power
  – Feedback-based flow control is impractical
Suggestion: Online routing based on nominal flows

\( \bar{r}_{ij} \): average link rate, time average of \( r_{ij}(t) \) or \( E[r_{ij}(t)] \) of stationary random process

Feasible set of flows \( \{ f_{ij}^{sd} | i, j, s, d \in V \} \)

\[ f_{ij}^{sd} \geq 0, \forall s, d, i, j \]

\[ \sum_j f_{sj}^{sd} = \lambda_{sd} E[L_{sd}], \forall s, d \]

\[ \sum_i f_{id}^{sd} = \lambda_{sd} E[L_{sd}], \forall s, d \]

\[ \sum_k f_{ki}^{sd} = \sum_j f_{ij}^{sd}, \forall i \neq s, d, \forall s, d \]

\[ \sum_{s,d} f_{ij}^{sd} < \bar{r}_{ij}, \forall i, j \quad \text{Use} \quad \sum_{s,d} f_{ij}^{sd} < \bar{r}_{ij} - \varepsilon_{ij}, \forall i, j \]
Determine nominal flows offline:

Example

M/M/1 approximation of queue length for link \((i, j)\):

\[
\frac{\sum_{sd} f^{sd}_{ij}}{\bar{r}_{ij} - \sum_{sd} f^{sd}_{ij}}
\]

buffer (storage) occupancy at node \(i\):

\[
\sum_{j} \frac{\sum_{sd} f^{sd}_{ij}}{\bar{r}_{ij} - \sum_{sd} f^{sd}_{ij}}
\]

Feasible set of flows that

\[
\max_{\{f^{sd}_{ij} \mid i, j, s, d \in V\}} \min_{i} \left[ B_i - \sum_{j} \frac{\sum_{sd} f^{sd}_{ij}}{\bar{r}_{ij} - \sum_{sd} f^{sd}_{ij}} \right],
\]

where \(B_i\) is the storage capacity at node \(i\).
If we need no discriminate s-d pairs

\[
\max_{\{f_{ij}^d | i, j, d \in V\}} \min_i \left[ B_i - \sum_j \frac{\sum_{sd} f_{ij}^d}{r_{ij} - \sum_d f_{ij}^d} \right]
\]

subject to

\[ f_{ij}^d \geq 0, \ \forall d, i, j \]

\[ \sum_d f_{ij}^d \leq r_{ij} - \varepsilon_{ij}, \ \forall i, j \]

\[ \sum_j f_{ij}^d = \lambda_{id} E[L_{id}] + \sum_k f_{ki}^d, \ \forall i, \forall d \neq i \]

\[ \sum_k f_{kd}^d = \sum_s \lambda_{sd} E[L_{sd}], \ \forall d \]
Suggested Online routing: leaky bucket

Source → Regulator buffer → Token bucket

σ: bucket size

r: token generation rate

Single-queue
Online algorithm

- Run for each link \((i, j)\) and destination \(d\) a leaky bucket with credit rate \(f_{ij}^d\).

  * Credit rate ensures that the average flow rate never exceeds nominal flow \(f_{ij}^d\).

  * Bucket size limits burstiness, so that the buffer overflow at next node \(j\) may not be likely.

- Routing decision: Upon arrival of bundle with size \(L\) destined to node \(d\), choose the next-hop a node from the nodes that have accumulated credit at least \(L\) for destination \(d\).

- If no such neighboring node exists, wait until one of the neighbors accumulate enough credit.