Online Routing of Stochastically Arriving Bundles in Delay Tolerant Networks

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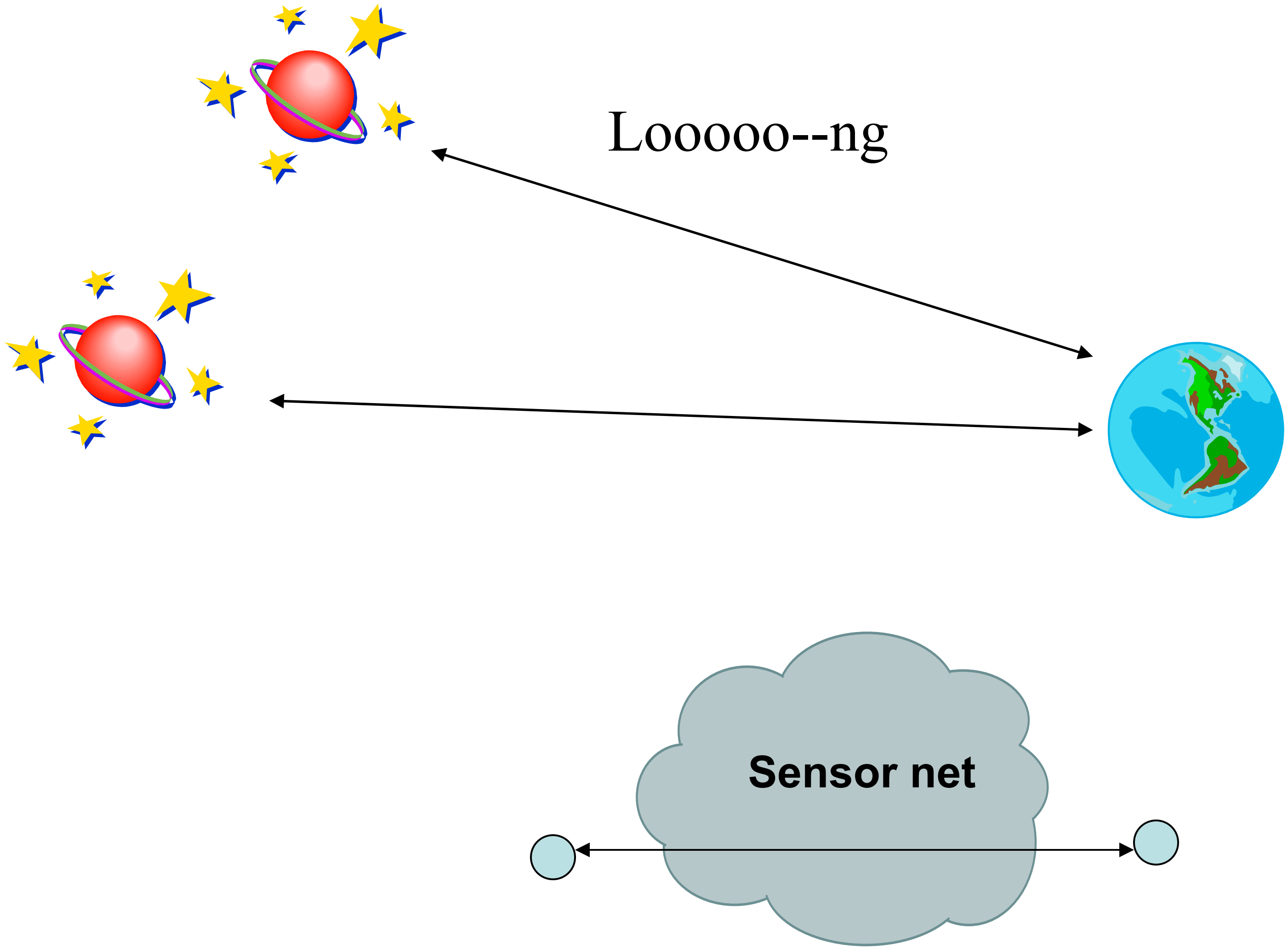
Delay Tolerant Networks

- 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)

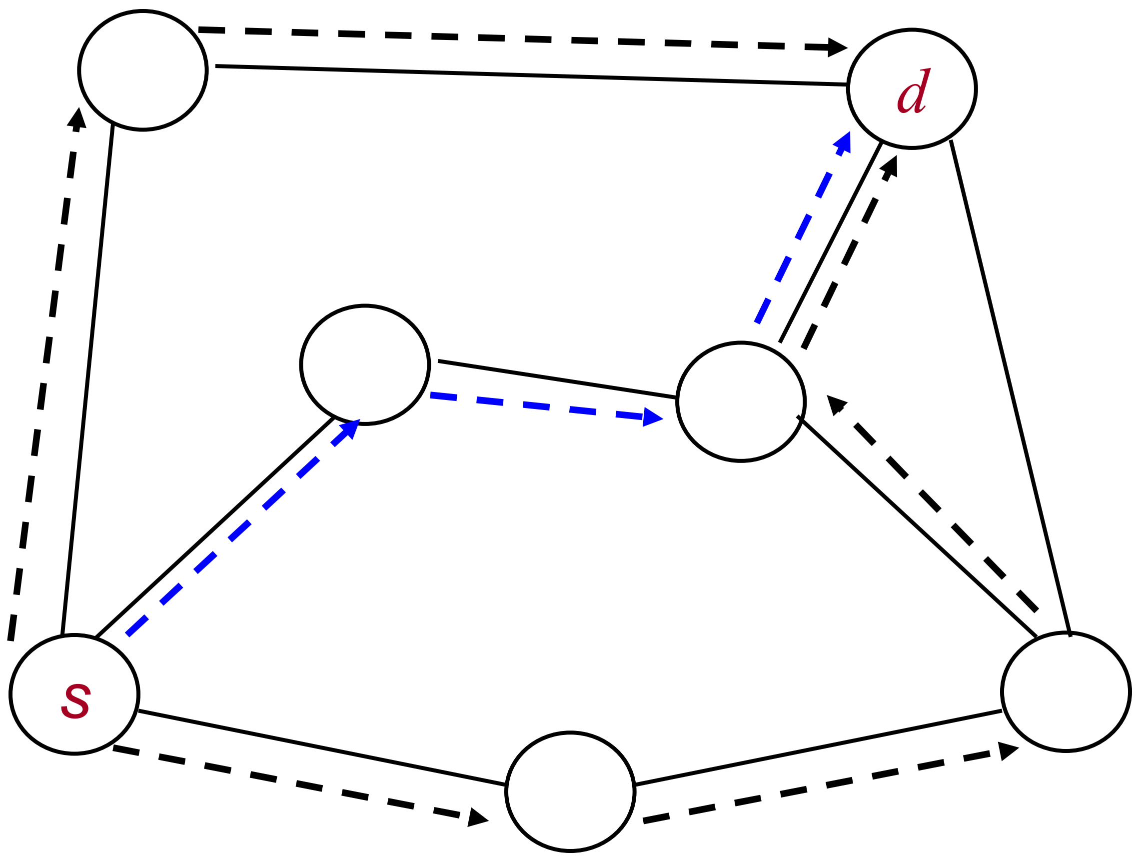
Implicit assumptions behind internet protocol design

- Small round trip time
- Existence of a contemporaneous path

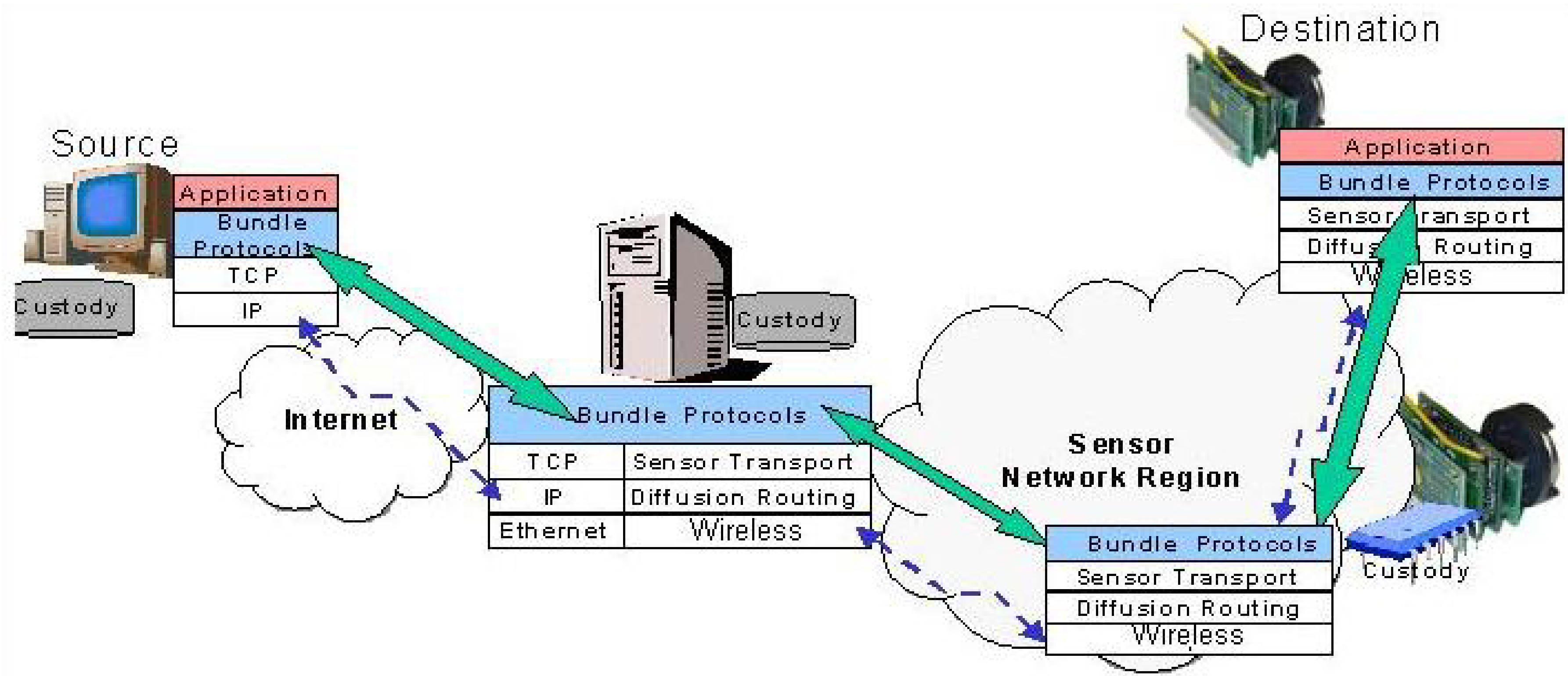
Delay Tolerant Networks

- 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

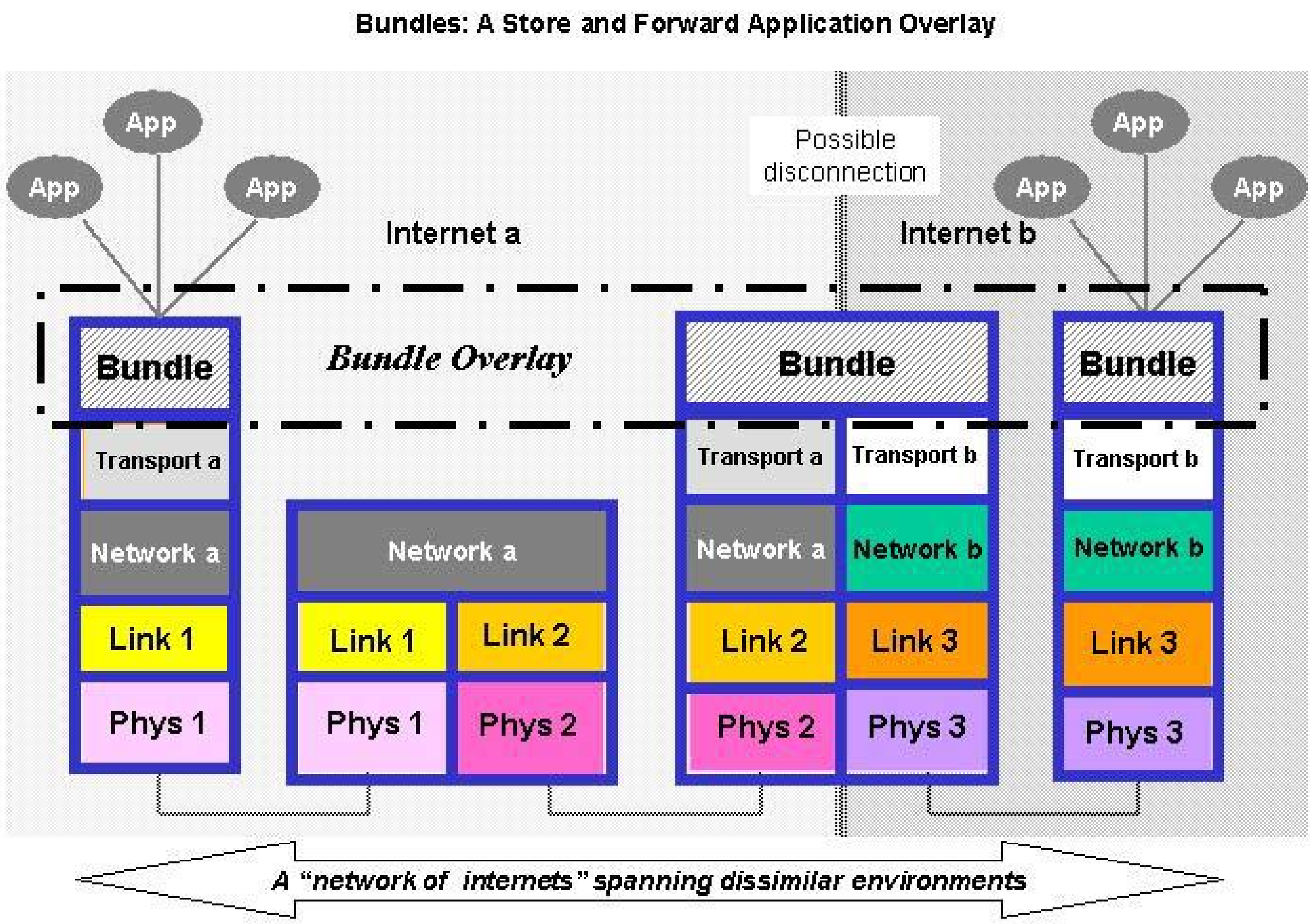
DTN nodes connecting performance challenging links



Key DTN Concept



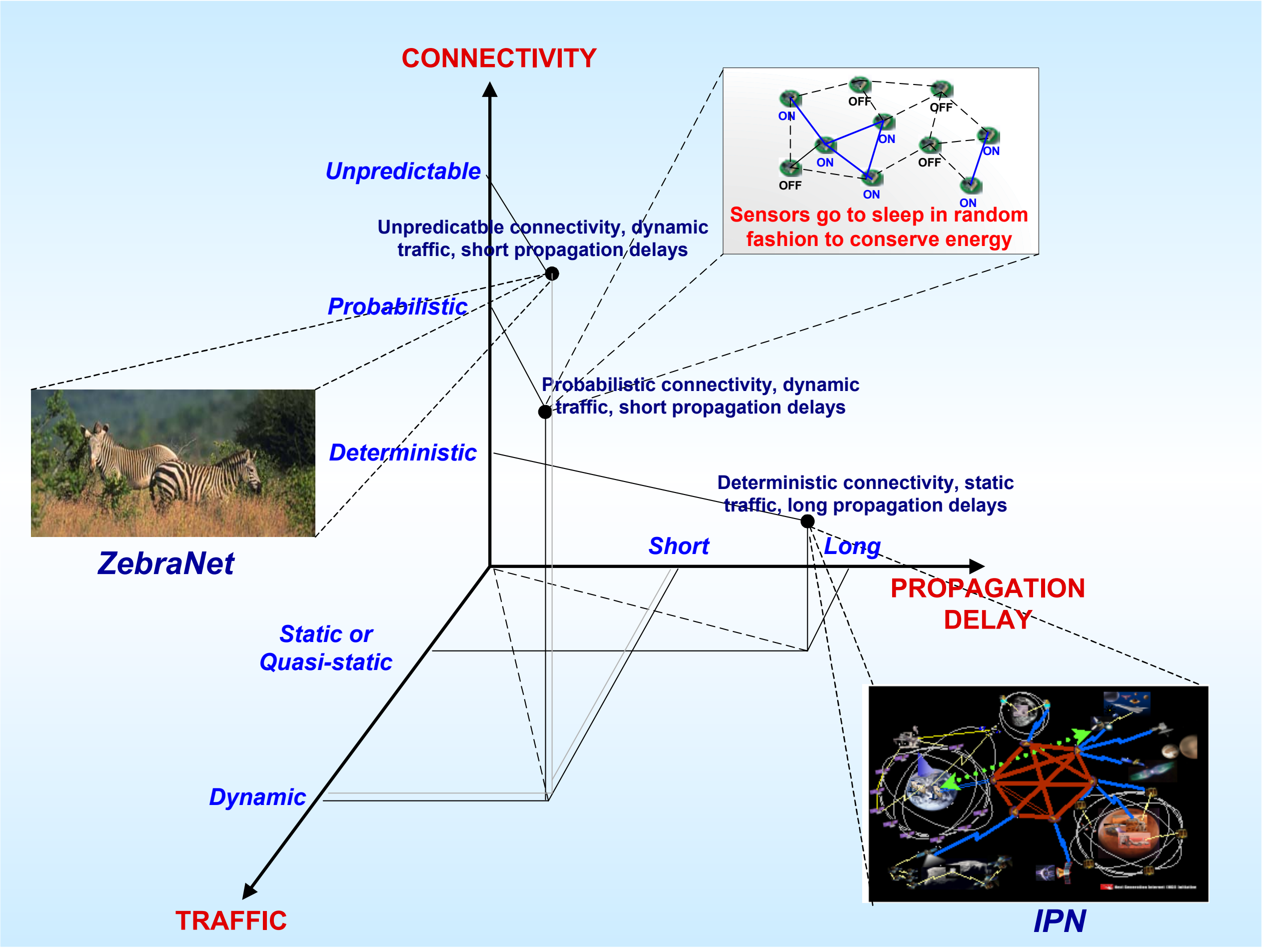
DTN Bundles as an application overlay



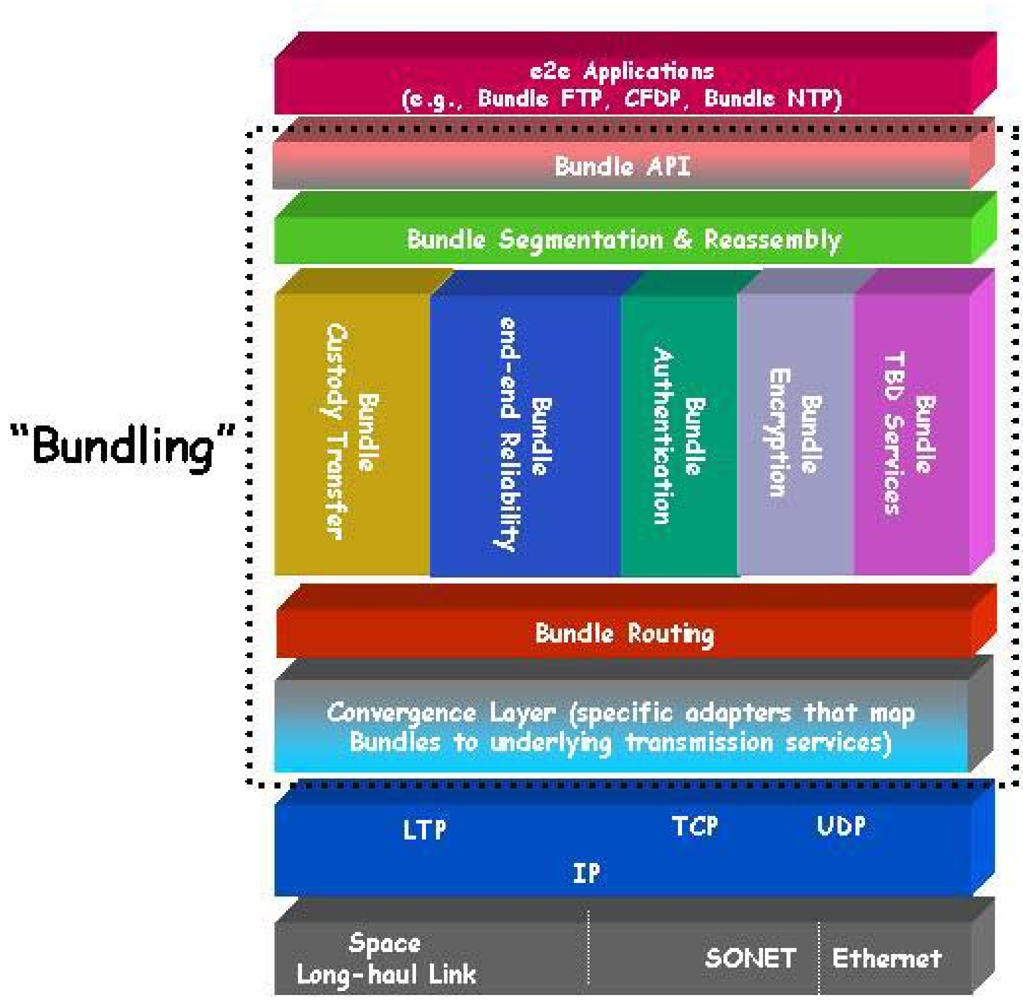
Research: Bundle Routing

- 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



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 τ.

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

- A node i's online routing and trasmission decision upons a 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 our of order.

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

$$\max_{0\le s\le L}\left\{\Delta(s,t,f)+d_{ij}^{p}\left(t+\Delta(s,t,f)\right)\right\}$$

where $\Delta(s,t,f)$ is the time that elapses from t until the sth segment is transmitted (i.e., $\int_t^{t+\Delta(s,t,f)} f(\tau)d\tau = s$ in fluiod model),

$d_{ij}^{p}(\tau)$ is the propagation delay of the segment that is transmitted at time τ.

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

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

Feasible set of flows $\left\{f_{ij}^{sd} \mid i,j,s,d \in V\right\}$

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

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

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

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

$$\sum_{s,d} f_{ij}^{sd} < \overline{r}_{ij},\ \forall i,j \qquad \text{Use } \sum_{s,d} f_{ij}^{sd} < \overline{r}_{ij} - \varepsilon_{ij},\ \forall i,j$$

Determine nominal flows offline: Example

M/M/1 approximation of queue length for link (i, j): $\dfrac{\sum_{sd} f_{ij}^{sd}}{\overline{r}_{ij} - \sum_{sd} f_{ij}^{sd}}$

buffer (storage) occupancy at node *i*: $\sum_j \dfrac{\sum_{sd} f_{ij}^{sd}}{\overline{r}_{ij} - \sum_{sd} f_{ij}^{sd}}$

Feasible set of flows that

$$\max_{\left\{f_{ij}^{sd} | i,j,s,d \in V\right\}} \min_i \left[B_i - \sum_j \frac{\sum_{sd} f_{ij}^{sd}}{\overline{r}_{ij} - \sum_{sd} f_{ij}^{sd}} \right],$$

where B_i is the stirage capcity at node *i*.

If we need no discriminate s-d pairs

$$\max_{\left\{f_{ij}^{d} \mid i,j,d \in V\right\}} \ \min_i \left[B_i - \sum_j \frac{\sum_{sd} f_{ij}^{d}}{\overline{r}_{ij} - \sum_d f_{ij}^{d}} \right]$$

subject to

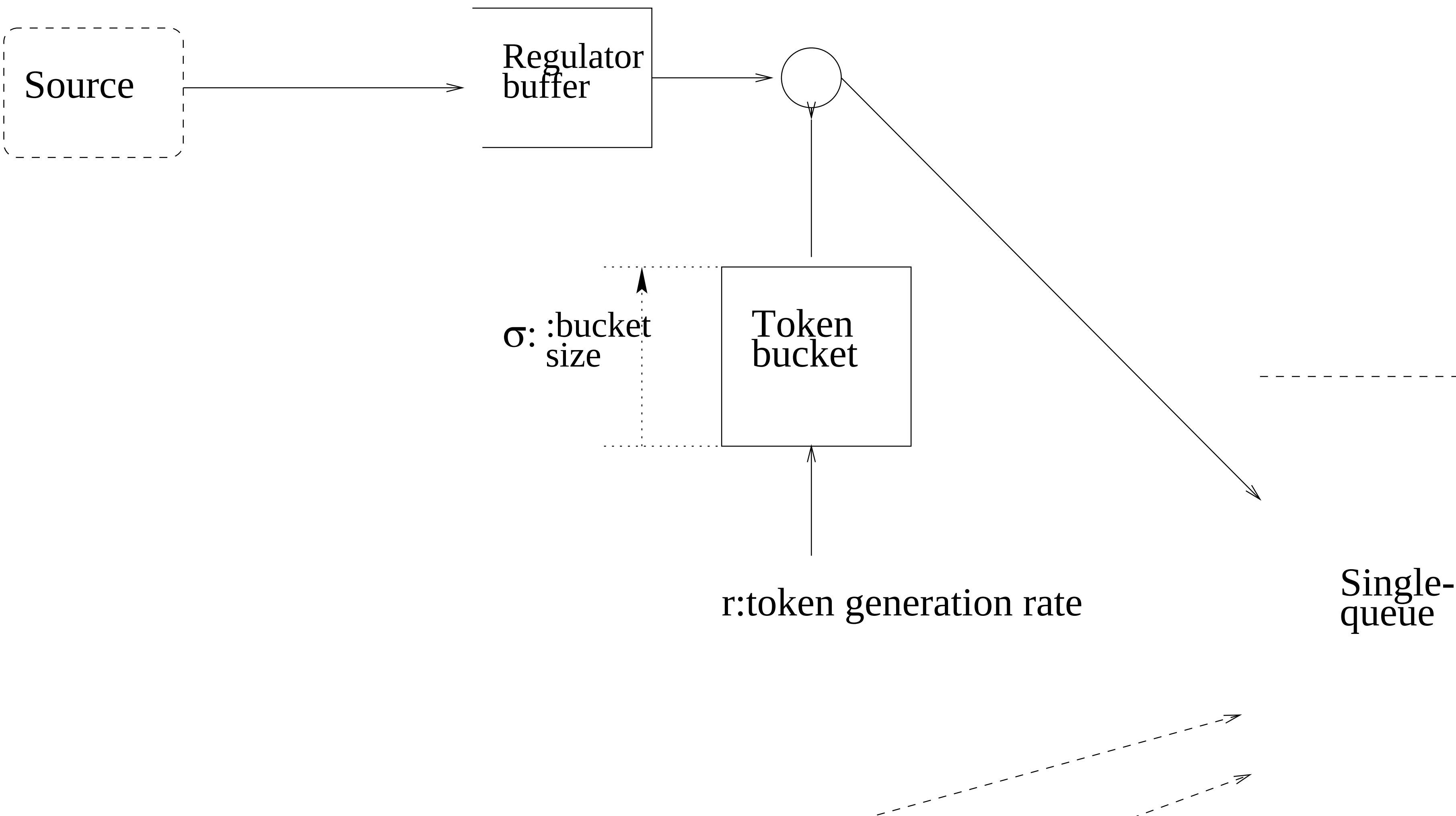
$$f_{ij}^{d} \geq 0, \ \forall d, i, j$$

$$\sum_d f_{ij}^{d} \leq \overline{r}_{ij} - \varepsilon_{ij}, \ \forall i, j$$

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

$$\sum_k f_{kd}^{d} = \sum_s \lambda_{sd} E\left[L_{sd}\right], \ \ \forall d$$

Suggested Online routing: leaky bucket



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.
  * Bucekt 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 accumuate enough credit.