Forwarding strategies for congestion control in intermittently connected networks

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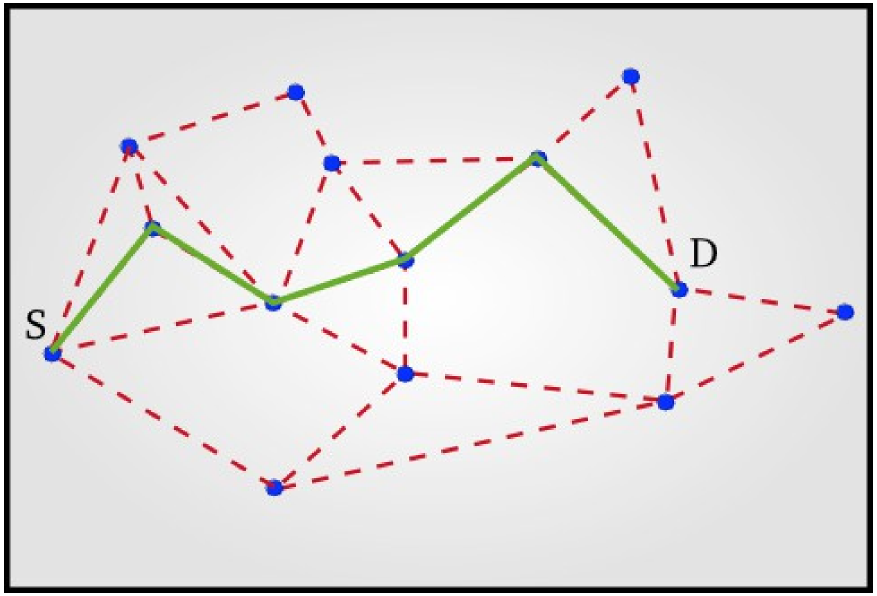
Implicit **Internet analysis** assumptions

- In Internet analysis, although often not explicitly stated, **a number of key assumptions are made** regarding the characteristics of the network:
  - **an end-to-end path always exists**;
    - *routing finds (single) "best" existing route*
  - ***any link*** *is assumed to be bidirectional, with symmetric data rates,* ***low bit error rate*** *and* ***low latency****;*
    - *window-based flow/congestion control works*
    - *end-to-end reliability using ARQ (Automatic Repeat Request) works well (enough)*
  - *network* ***nodes*** *remain* ***completely functional most of the time***



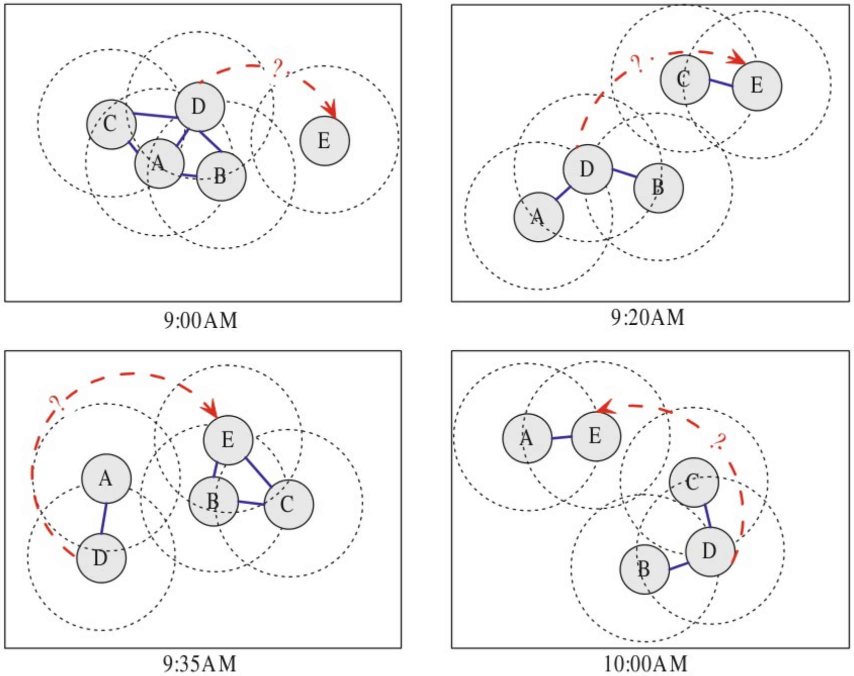
New challenges...

- In last years, a class of challenging networks, which violate one or more of the previous assumptions and may not be well served by the current TCP/IP model, have become important. Examples:
  - **interplanetary networks** ----> long delay (e.g., minutes), high bit error rates (e.g. 10^{-2}), scheduled contacts;
  - **vehicular networks, ad-Hoc networks** ----> intermittent links due to mobility or changes in signal strength;
  - **sensor/actuator networks** ----> intermittent links due to extremely limited end-node power, memory, and CPU capability;
  - **military ad-Hoc networks** ----> disconnections due to mobility, environmental factors, or intentional jamming

These networks are called in the literature “Intermittently Connected Networks (ICNs)”

Issues in ICN

- Disconnected most of the time;
- there is seldom an end-to-end path available;
- due to the high latencies, control packets are often old



- **classical routing and data delivery-approaches usually fail** [Sadagopan03], [Durst99]

Forwarding approaches in ICN

two different models of intermittence in ICN

- intermittent and no predictable links;
- low latency links and relatively small error rates;
- **scenario**: sensor networks, vehicular networks, etc..

- predictable connections;
- high latency links and high bit error rates;
- **scenario**: interplanetary networks

Forwarding: in general, there is **no coordinated process of selection of the path followed by a message** from the source to the destination

Routing/Forwarding approaches in ICN (first model)

- The most common approaches are based on **epidemic routing** [Vahdat00]. When two nodes meet each other:
  - they decide how many and which stored messages are exchanged;
  - in turn, each node requests copies of messages from the other one;
  - in the simplest case, epidemic routing is “flooding”: each time a contact occurs, all messages that are not in common between the two nodes are replicated
- message replication in **epidemic routing** paradigms **imposes a high storage overhead** on nodes and very likely node buffers run out of capacity

Routing/Forwarding approaches in ICN (first model)

- More sophisticated techniques used to **limit the number of message copies in the network** include:
    - spraying algorithms [Spyropoulos05];
    - replications of a copy with some probability [Small05], [Tseng02], [Matsuda08];
    - intelligent filtering replication strategies using history-based or utility-based routing [Chen01], [Juang02], [Lindgren03], [Burgess06], [Spyropoulos07], [Balasubramanian07], [Erramilli08];
- in the literature there are very few works ([Matsuda08], [Thompson10]) devoted to an analytical study of buffer node behaviour (useful for congestion analysis and control)

What we have done

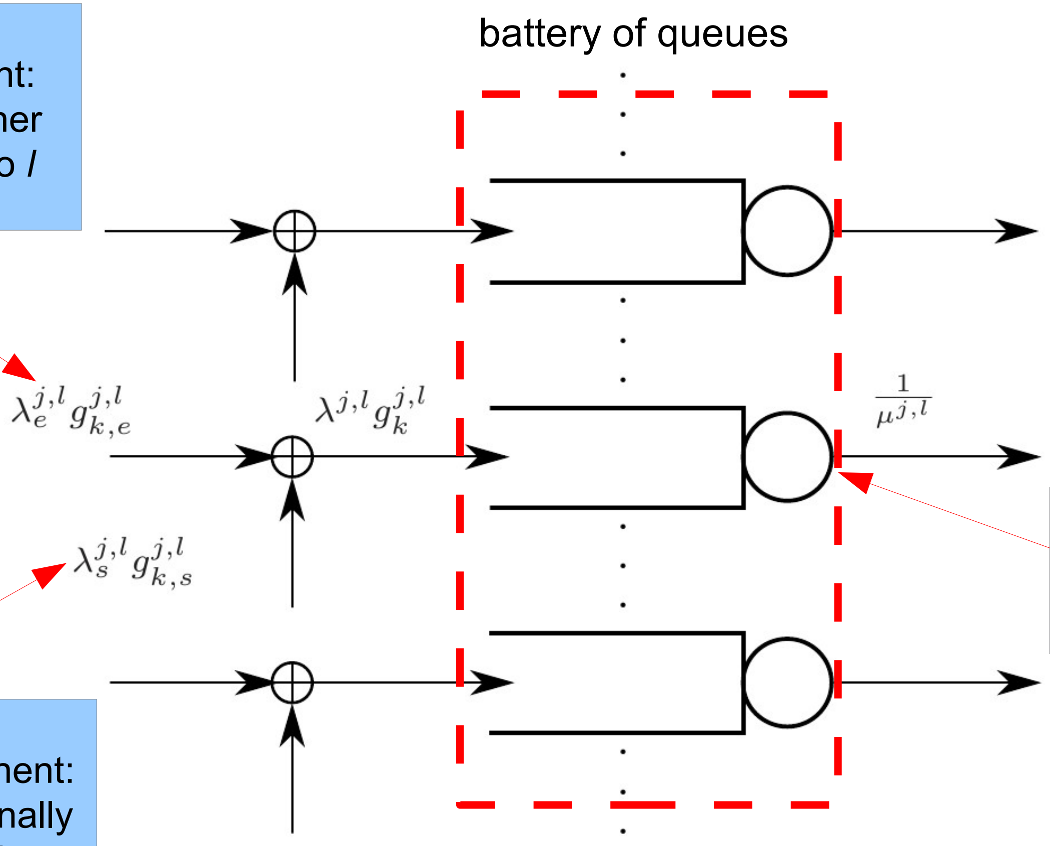
- In [Cello12] **we proposed a model** for the analysis of the behaviour of buffers inside ICN nodes, based on a continuous-time Markov chain with bulk arrivals and bulk services;
- in this talk, **we apply that model to** two kinds of epidemic routing known as **q-forwarding** and **two-hop forwarding**

Our model

- Useful to represent epidemic routing and its variations: each time two nodes are in communication, they exchange each other a bulk of data packets;
- all the **packets** have the **same size**;
- mobility model assumption: the **process of encounter** among nodes is a **Poisson process**;
- **a generic node *j* receives data from other nodes and from itself (internally generated data)**: the **process of bulk arrivals** is a **Poisson process**; the two processes are **independent**;
- the **data received** are organized in **different queues**, each queue is dedicated to a specific destination *l*;
- a generic *l*-queue is emptied completely when the node *j* encounters the destination node *l*

Model of the generic ICN node j

each *l*-queue within the node *j* receives incoming data for the destination node *l*



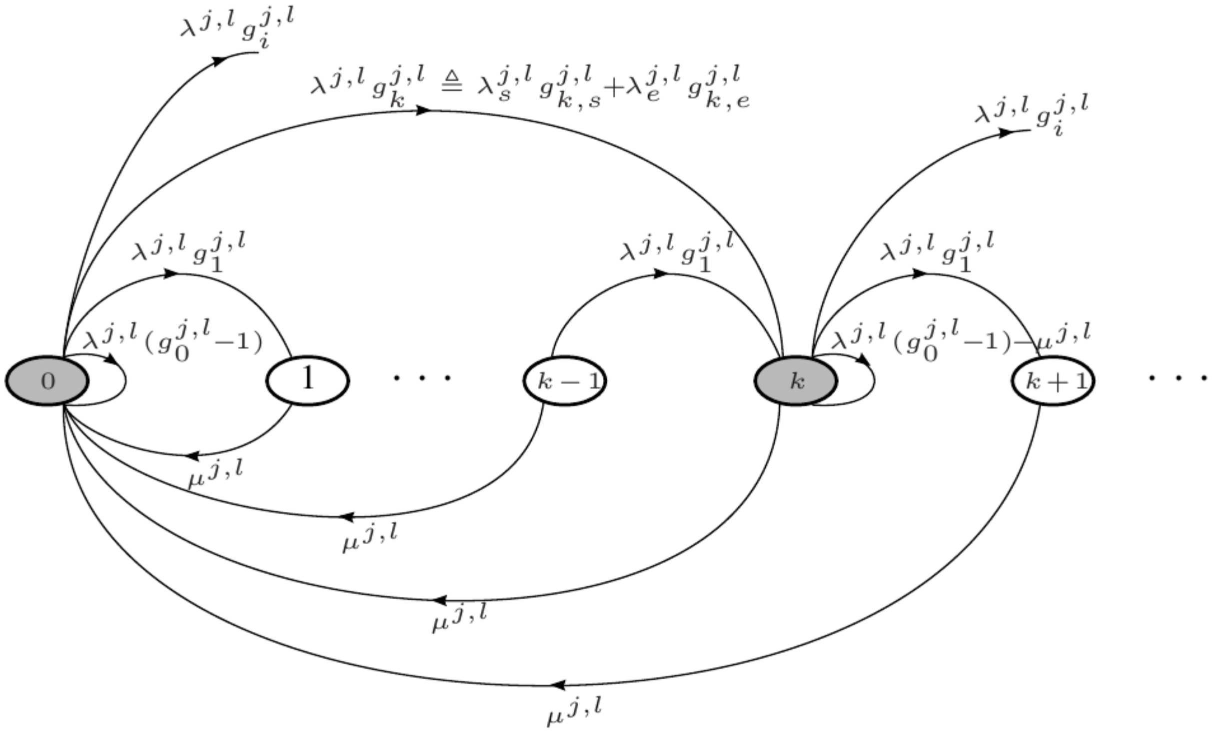
Exogenous component: data received from other nodes and directed to *l*

the buffer is emptied when node *j* encounters destination *l*

Endogenous component: data generated internally and directed to *l*

Transition rates for the continuous-time Markov chain related to *l*-queue inside node *j*

- The model introduced above allows us to model the evolution of each *l*-queue as a **continuous-time Markov chain with bulk arrivals and bulk services**



Relation

- The model described before allows us to find a relationship between:
  - *g*: discrete probability density of the size of a bulk received by the *l*-queue of node j, with *z-transform G(z)*;
  - *p*: discrete stationary probability density of the size of the *l*-queue of node *j*, with *z-transform P(z)*;
  - for simplicity, we have omitted here the possible dependency on *l* and *q*, assuming identical nodes;
- In [Cello12] we provided a **relation between *G(z)* and *P(z)* in the *z-domain***:

$$P(z) = \frac{\mu}{(\lambda + \mu) - \lambda G(z)}$$

Q-forwarding and two-hop forwarding

- We apply the previous result to two versions of epidemic routing called **q-forwarding** and **two-hop forwarding**
- In **q-forwarding**,
  - when a node meets another one that is different from the destination, it exchanges the whole content of its buffer with probability *q*, whereas, with probability *(1-q),* no exchange is performed;
  - the packet reaches the destination when any of the nodes containing it and different from the destination meets the destination
- In **two-hop forwarding**, a packet can reach the destination when:
  - the source node meets the destination node;
  - the destination node meets another node that has previously received the packet from the source;
  - here, the parameter $0<q<1$ represents the probability of transmitting an internally-generated bulk during a contact
- In **two-hop forwarding**, no other ways to reach the destination are possible (at most *two hops* can occur)

Decomposition of G(z)

- We decompose *G(z)* as

$$G(z) = \frac{\lambda_s}{\lambda_s + \lambda_e} G_s(z) + \frac{\lambda_e}{\lambda_s + \lambda_e} G_e(z)$$

  where $G_s(z)$ and $G_e(z)$ represent *endogeneous* and *exogeneous* components, respectively, whereas λ_s and λ_e are rates of endogenous bulk generation and exogeneous bulk arrival, respectively
- The rates satisfy $\lambda=\lambda_s+\lambda_e$
- The **model of $G_s(z)$** is taken as **given**, whereas **$G_e(z)$ depends on the protocol that models the interaction between two nodes in contact** (forwarding strategy)

P(z) for q-forwarding

- In **q-forwarding**, for a buffer of infinite capacity,
  - for $q=0$, one obtains

$$P(z) = \frac{\mu}{(\lambda+\mu) - (\lambda_s G_s(z) + \lambda_e)}$$

  - for $0<q<1$ and $q<\mu/\lambda_e$ (to avoid congestion), one obtains

$$P(z) = \frac{\lambda+\mu-\lambda_s G_s(z) - \lambda_e(1-q)}{2\lambda_e q} - \frac{\sqrt{(\lambda+\mu-\lambda_s G_s(z)-\lambda_e(1-q))^2 - 4\lambda_e \mu q}}{2\lambda_e q}$$

P(z) for two-hop forwarding

- In **two-hop forwarding**, for a buffer of infinite capacity, one has

$$P(z) = \frac{\mu}{(\lambda+\mu) - \left(\lambda_s G_s(z) + \lambda_e \left((1-q) + q\frac{\mu}{(\lambda+\mu)-(\lambda_s G_s(z)+\lambda_e)}\right)\right)}$$

Buffer analysis

- The analysis allows to express, for a buffer of infinite capacity:
  - **the average buffer occupancy:**

$$\sum_{i=0}^{\infty} i p_i = -P'(1)$$

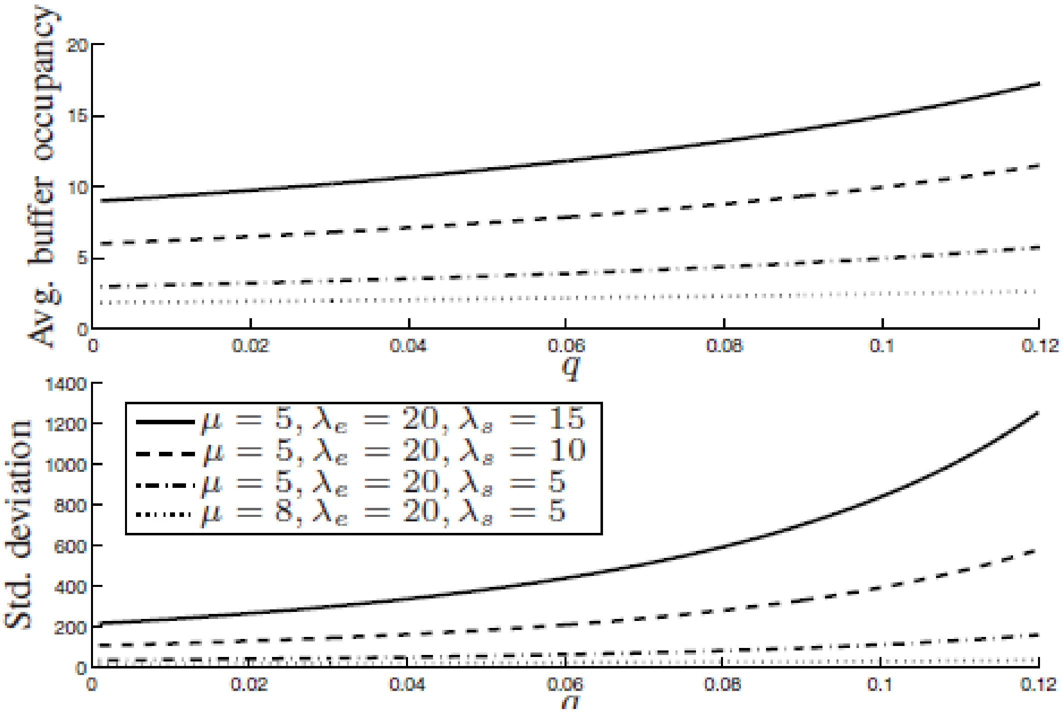
one needs only to know *P(z)*

  - **its standard deviation:**

$$\sqrt{\sum_{i=0}^{\infty}\left(i-\sum_{k=0}^{\infty} k p_k\right)^2 p_i} = \sqrt{P''(1)(P''(1)-2P'(1))}$$

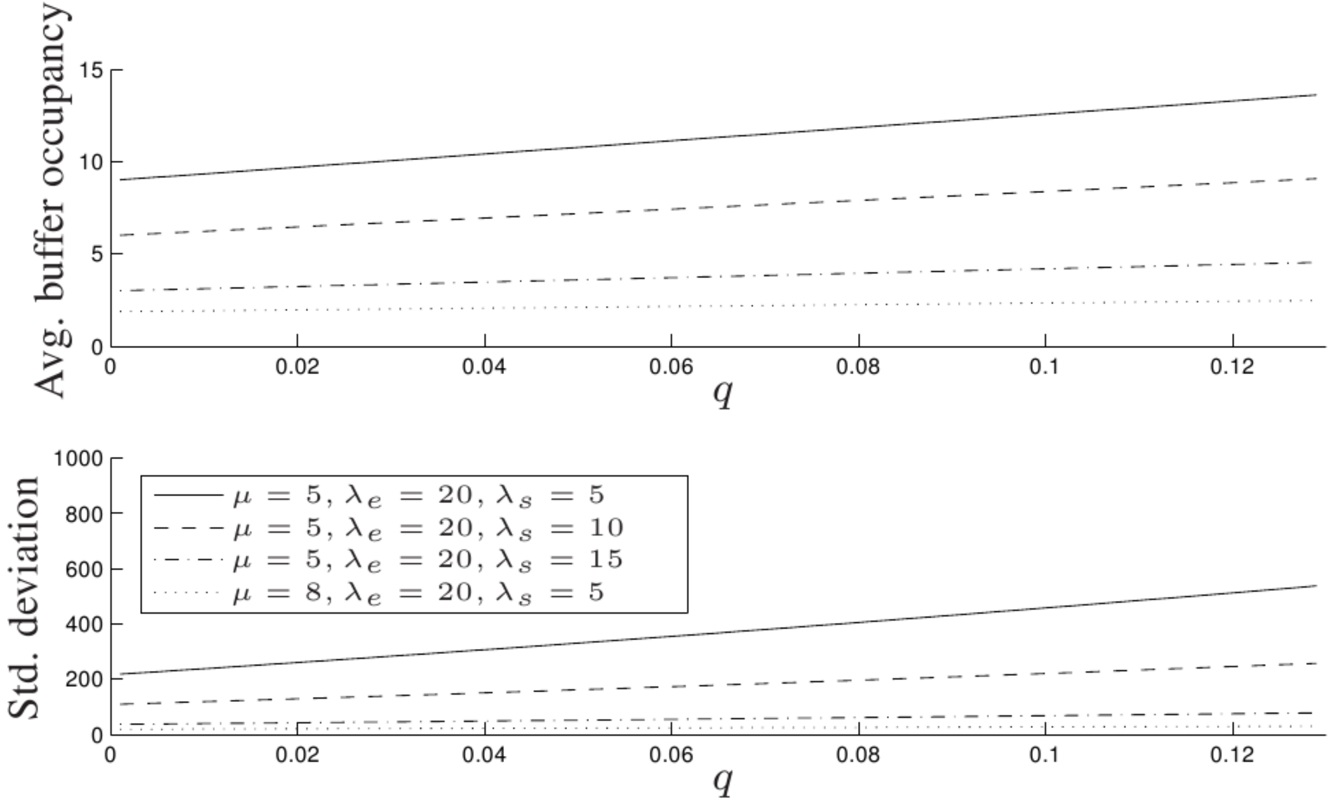
Simulation 1 (q-forwarding)

- Average buffer occupancy and its standard deviation for a generic *l*-queue;
- when a node meets another node that is different from the destination, it exchanges the whole content of its buffer with probability *q*, whereas, with probability *(1-q)*, no exchange is performed;
- the node generates a bulk whose size is a Poisson random variable



Simulation 2 (two-hop forwarding)

- Average buffer occupancy and its standard deviation for a generic *l*-queue;
- the parameter 0<*q*<*1* represents the probability of transmitting an internally-generated bulk during a contact;
- the node generates a bulk whose size is a Poisson random variable



Extensions

- expression for the **average latency**, similar to the one obtained in [Matsuda2008]
- extension to a buffer with **finite capacity** (**upper bounds** on **loss probability**);
- possible extensions to other classes of forwarding strategies;
- possible extension to different classes of nodes, each one associated with its own bulk generation rate;
- **optimization of the model parameters** to reach a good **trade-off**, e.g., **between average buffer occupancy and average latency**

Optimization problem

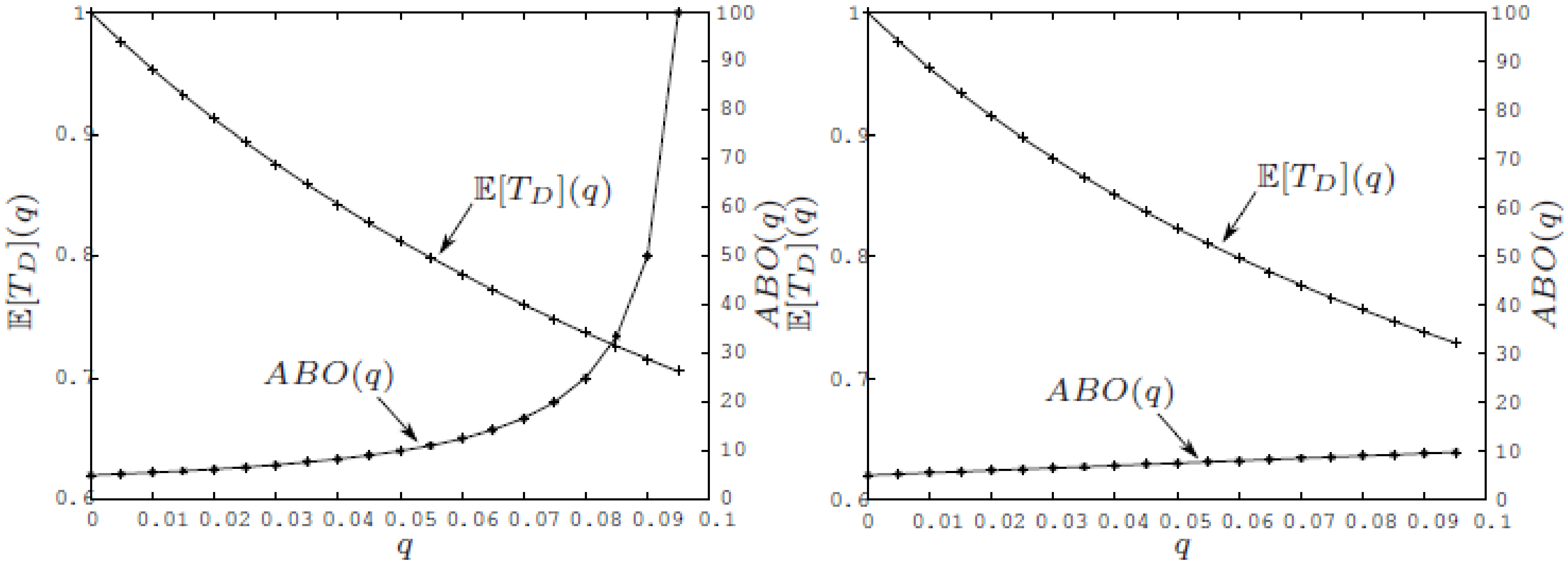
- *ABO(q)*: **average buffer occupancy**
- *E[T_D](q)*: **average time to destination** (average latency)

$$C(q,\alpha) \triangleq ABO(q) + \alpha \mathbb{E}[T_D](q)$$

- For a fixed value of the weight parameter, find

$$\min_{0 \le q < \mu/\lambda_e} C(q,\alpha)$$

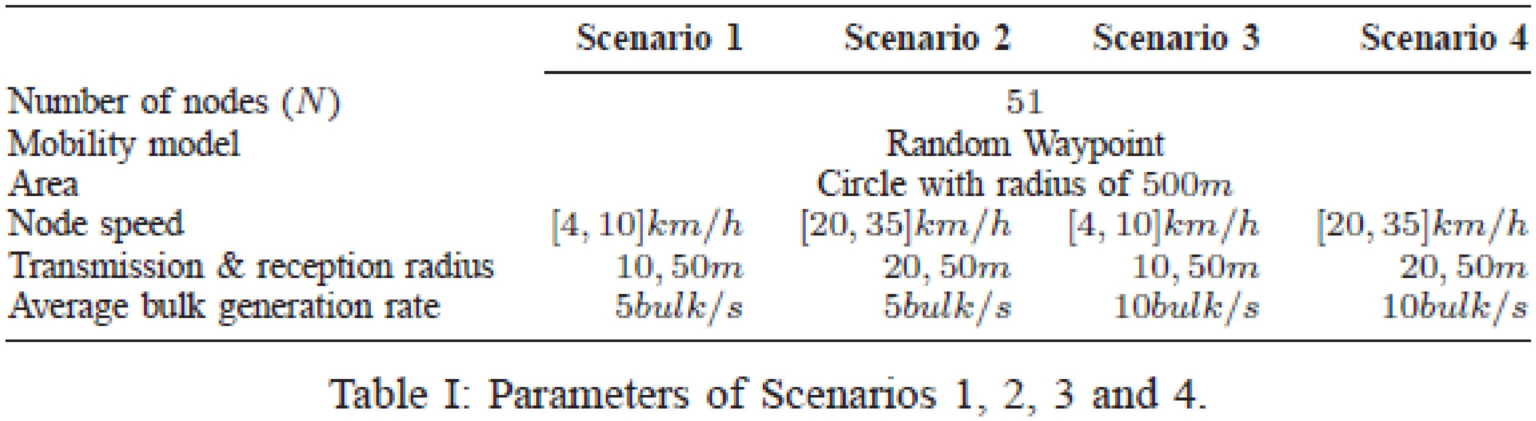
Numerical results



(a) q-forwarding strategies.

(b) Two-hop forwarding strategies.

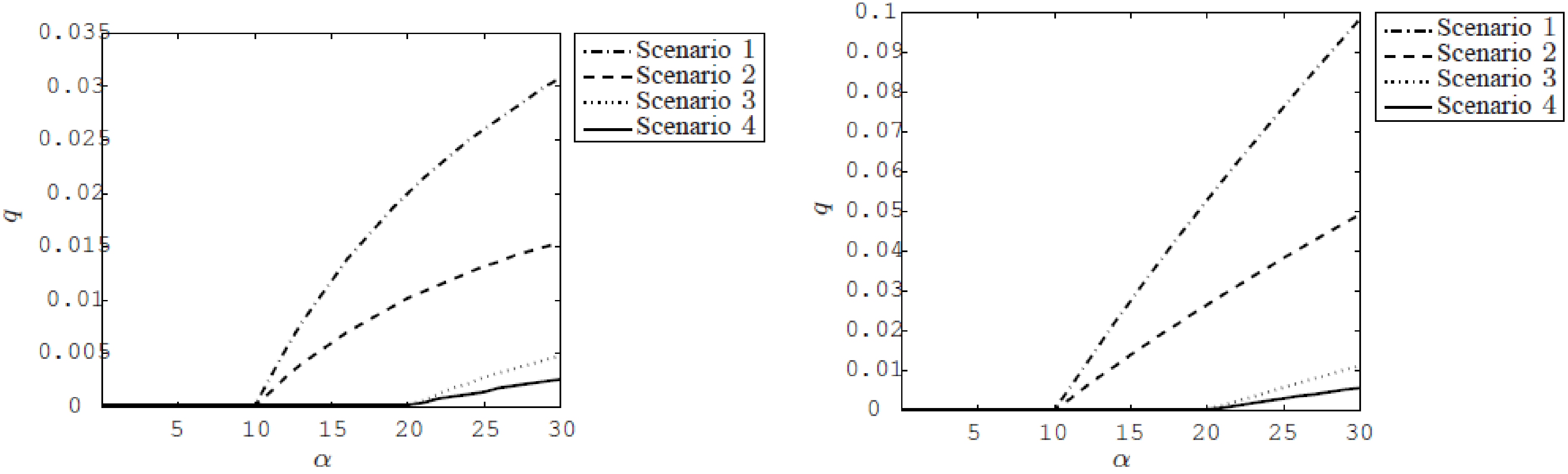
Scenarios



	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Number of nodes (N)	51			
Mobility model	Random Waypoint			
Area	Circle with radius of $500m$			
Node speed	$[4, 10]km/h$	$[20, 35]km/h$	$[4, 10]km/h$	$[20, 35]km/h$
Transmission & reception radius	$10, 50m$	$20, 50m$	$10, 50m$	$20, 50m$
Average bulk generation rate	$5bulk/s$	$5bulk/s$	$10bulk/s$	$10bulk/s$

Table I: Parameters of Scenarios 1, 2, 3 and 4.

Optimal values of the parameter q



(a) *q*-forwarding strategies.

(b) Two-hop strategies.

Conclusion

- **Epidemic routing** is a viable technique to cope with the forwarding problem in an ICN;
- BUT epidemic routing, in its **basic version**, imposes a **high storage overhead** on wireless nodes and very likely node buffers run out of capacity;
- in the literature there exist many **variations of the basic epidemic routing**, but **very few works** are devoted to the **analytical study of buffer node behaviour**, which is **useful for congestion analysis and control**;
- we have proposed a **theoretical framework** based on a continuous-time Markov chain with bulk arrivals and bulk services;
- this framework allows us to **compute several performance parameters** (average buffer occupancy, its std deviation, average latency) and **optimize their trade-offs**

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Thank you