An Application to Two-Hop Forwarding of a Model of Buffer Occupancy in ICNs

Marco Cello
DITEN
University of Genoa, Italy
marco.cello@unige.it

Giorgio Gnecco
DIBRIS
University of Genoa, Italy
giorgio.gnecco@dist.unige.it

Mario Marchese
DITEN
University of Genoa, Italy
mario.marchese@unige.it

Marcello Sanguineti
DIBRIS
University of Genoa, Italy
marcello.sanguineti@unige.it

Abstract – *An application of the model proposed in Cello at al., A Model of Buffer Occupancy in ICNs, IEEE Communications Letters, to appear is investigated. Such a model provides a relationship in the z-domain between the discrete probability densities of the buffer state occupancies of the nodes in the network and the sizes of the arriving bulks. Under a class of two-hop forwarding strategies, expressions are obtained for the average buffer occupancy and its standard deviation.*

Keywords: Intermittently-connected networks, congestion control, ad-hoc networks, Markov chains, epidemic routing.

1 Introduction

In the last years various applications emerged, where networks operate under conditions in which the assumptions of "universal connectivity" and "global information" do not hold. Examples are sensor networks [8], social networks or pocket switched networks [6], smart environments, and vehicular ad-hoc networks [18]. A common denomination of such contexts is *Intermittently Connected Networks* (ICNs). As in such contexts the networks may be disconnected most of the time or it may even happen that there is never an end-to-end path available between source and a destination, classical routing and data delivery-approaches (see, e.g., [1]) fail [14].

In [12] it was proved that the expected throughput of reactive protocols (which compute a route only when it is needed) is connected with the average path duration pd, the time to repair a broken path tr, and the source data rate r through the relationship: $throughput = \max(0, r(1 - \frac{tr}{pd}))$. However, node mobility leads to frequent disconnections, thus reducing the average path duration significantly. Consequently, in most cases tr is expected to be larger than the path duration, which implies that the expected throughput is close to zero. Other approaches to deal with routing in ICNs involve the use of additional communications resources (e.g., satellite, UAV, message ferries) forced to follow a given trajectory between disconnected parts of the network, in order to bridge the gap [10, 20] (DataMule, Message Ferries, etc.). In other cases, such as in inter-planetary networks [2], intermittent connectivity is predictable, so classical routing algorithms may be adapted to compute shortest delivery time paths by taking into account future connectivity [7].

Often, neither additional resources with controlled behavior nor predictable trajectories are available. In such cases, one of the most common approaches is *epidemic routing* [17], which is based on the replication and transmission of messages to newly-discovered contacts that do not already possess a copy of the message. In epidemic routing each node maintains a buffer, consisting of messages that it has originated and messages that it is buffering on behalf of other nodes. 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. In the simplest case, epidemic routing is flooding: each time a contact happens, all messages that are not in common between the two nodes are replicated.

In general, however, message replication performed by epidemic routing paradigms imposes a high storage overhead on wireless nodes [19] and very likely node buffers run out of capacity. More sophisticated techniques can be used to limit the number of message transfers. Existing epidemic protocols try to avoid congestion by limiting, either in a deterministic [13] or in a non-deterministic way [11, 16], the number of copies of a message inside the network. So, an analytical framework for congestion control management is needed.

This is the subject of the present contribution, which extends our previous work [3] by applying the model proposed therein to the kind of epidemic routing known as *two-hop forwarding*. First, we describe the analytical framework developed in [3], based on bulk arrival and bulk service queues, to model ICN nodes behavior (Section 2). Then we discuss a relationship between the stationary discrete probability densities of the state occupancies of the ICN node buffers and the discrete probability densities of the sizes of the arriving bulks. As a further step, we investigate a class of two-hop forwarding strategies used by ICN nodes and sometimes exploited in epidemic routing (Section 3). For such a class of forwarding strategies, we derive an expression for the average buffer occupancy (Section 4). Finally, we discuss related literature (Section 5) and draw some conclusions (Section 6).

2 Model description

We consider the following ICN scenario. M nodes, deployed in an area, follow a certain mobility model, for which we impose the following property: for each couple of ICN nodes ($m, n \in \{1, \ldots, M\}, m \neq n$) the number of encounters between them in any given interval of time is a Poisson random variable. This obviously means that the intermeeting time between two generic ICN nodes m and n is an exponentially-distributed random variable. Popular mobility models such as Random Waypoint and Random Direction [5] enjoy such a property.

We denote by $\mathcal{L} \subseteq \{1, \ldots, M\}$ the set of destination nodes. We model each node as a battery of queues (Figure 1). Within a specific node $j \in \{1, \ldots, M\}$, there are $|\mathcal{L}(j)|$ queues, where $\mathcal{L}(j) \triangleq \mathcal{L} \setminus \{j\}$. Each l-queue ($l \in \mathcal{L}(j)$) within the node j receives incoming data for the destination node l in two different modes. Either the data directed to l are internally generated by node j or they have been sent to j by other nodes during previous encounters with j, on the basis of a forwarding strategy. When node $j \in \{1, \ldots, M\}, j \neq l$ encounters node l which is the destination of data it holds in its l-queue, it empties the l-queue completely sending all its data to l. To allow this operation, we assume that the maximum data exchange time between two nodes is much smaller than the average duration of the encounter.

More formally, node j encounters the destination node l with average rate $\mu^{j,l}$ [encounters/s] and sends to l all the packets buffered in its l-queue. Node j generates data in bulks, assigned to l, with average rate $r_s^{j,l}$ [generations/s] and, at each generation, it produces $I_s^{j,l}$ [bulks/generation], set to 1 in this letter. The average rate of bulk generation is $\lambda_s^{j,l} = r_s^{j,l} I_s^{j,l}$ [bulks/s]. We assume an exponentially-distributed time between two consecutive bulk generations. Node j meets any node different from the destination l with average rate $E_e^{j,l} = \sum_{h=1, h\neq j,l}^{M} \mu^{j,h}$ [encounters/s] and, at each encounter, receives $I_e^{j,l}$ [bulks/encounter], set to 1 in this letter. The corresponding bulk generation process has rate $\lambda_e^{j,l} = E_e^{j,l} I_e^{j,l}$ [bulks/s] and is a Poisson process, since it is the sum of independent Poisson processes. The two processes of bulk generation with associated average rates $\lambda_s^{j,l}$ and $\lambda_e^{j,l}$ are assumed to be independent. Due to the assumption on the mobility model and on the generation of bulks, the global process of bulk arrivals in the l-queue is Poisson process. We denote by $\lambda^{j,l} = \lambda_s^{j,l} + \lambda_e^{j,l}$ [bulks/s] its average rate.

The size of each bulk (i.e., the number of packets in the bulk) is also a random variable. We denote by $g_{k,e}^{j,l}$ the probability that the bulk assigned to l and received by j during an encounter is composed of k packets, and by $g_{k,s}^{j,l}$ the probability that the bulk generated by node j and assigned to node l is composed of k packets. The average arrival rate of bulks of k packets in the l-queue, measured in [packets/s], is $\lambda_s^{j,l} g_{k,s}^{j,l} + \lambda_e^{j,l} g_{k,e}^{j,l}$, as indicated in Figure 1. For $k \in \mathbb{N}_0$, we denote by $\{g_{k,s}^{j,l}\}$ and $\{g_{k,e}^{j,l}\}$ the sequences whose components are $g_{k,s}^{j,l}$ and $g_{k,e}^{j,l}$, respectively; $\{g_{k,s}^{j,l}\}$ and $\{g_{k,e}^{j,l}\}$ represent the discrete probability densities of the sizes of the two kinds of bulks. We denote by $p_k^{j,l}$ the stationary probability that the l-queue of node j has k packets and by $\{p_k^{j,l}\}$ the sequence that represents the discrete probability density of the size of the l-queue in 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. The transition rate from a generic state h to the state $h+k$ is $A_k^{j,l} = \lambda_s^{j,l} g_{k,s}^{j,l} + \lambda_e^{j,l} g_{k,e}^{j,l}$, which is the average arrival rate of bulks of length k. On the other hand, if we consider the overall bulk arrival process with average rate $\lambda^{j,l} = \lambda_s^{j,l} + \lambda_e^{j,l}$, then $A_k^{j,l}$ can be expressed as $A_k^{j,l} = \lambda^{j,l} g_k^{j,l}$ where $g_k^{j,l}$ is the probability of a k-length arrival. So, $g_k^{j,l}$ can be simply computed as in (1):

$$g_k^{j,l} = \frac{\lambda_s^{j,l}}{\lambda_s^{j,l} + \lambda_e^{j,l}} g_{k,s}^{j,l} + \frac{\lambda_e^{j,l}}{\lambda_s^{j,l} + \lambda_e^{j,l}} g_{k,e}^{j,l} \, . \tag{1}$$

The quantity $g_{k,s}^{j,l}$ can be interpreted as an endogenous component, since it is associated with the packets generated inside the currently considered node, and $g_{k,e}^{j,l}$ as an exogenous component, since, in general, it depends on the forwarding strategies of the other nodes (see Section 3 for a class of possible models for $\{g_{k,e}^{j,l}\}$). The two terms $\frac{\lambda_s^{j,l}}{\lambda_s^{j,l} + \lambda_e^{j,l}}$ and $\frac{\lambda_e^{j,l}}{\lambda_s^{j,l} + \lambda_e^{j,l}}$ in (1) play the role of weights. We denote by $\{g_k^{j,l}\}$ the sequence composed by the $g_k^{j,l}$ values, which represents the discrete probability density of the size of the bulk (independently from its origin). The complete model of the Markov chain with its transition rates is shown in Figure 2. The model is derived similarly to the ones discussed by Kleinrock in [9, pp.134-139] for different problems, in which only the arrivals or only the services are in bulk form.

To simplify the notation, supposing to refer to node j and queue l, in the remainder of the letter we omit the superscripts j and l. So, (1) becomes

$$g_k = \frac{\lambda_s}{\lambda_s + \lambda_e} g_{k,s} + \frac{\lambda_e}{\lambda_s + \lambda_e} g_{k,e} \, . \tag{2}$$

It can be proved easily that for any choice of the discrete probability density $\{g_k\}$, the continuous-time Markov chain in Figure 2 is irreducible and positive recurrent and that these properties are inherited by its associated embedded Markov chain. For this case, it is known that the stationary discrete probability density $\{p_k\}$ always exists and is unique [4, Theorems 3 and 8, Chapter 5]. The next proposition from [3] provides a relationship between $\{p_k\}$ and

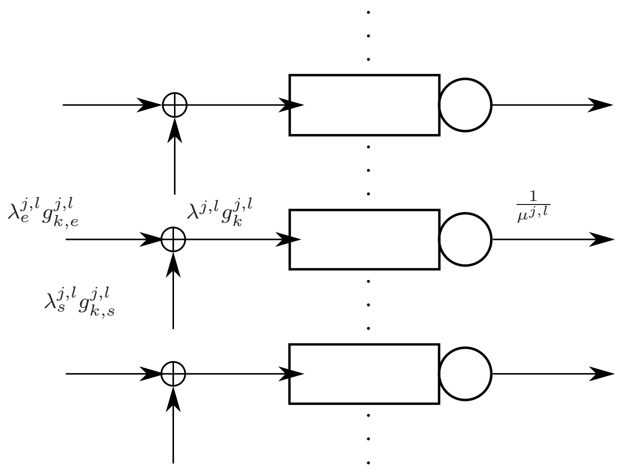

Figure 1: Model of the generic ICN node $j \in \{1, \ldots, M\}$ and its l-queue, where $l \in \mathcal{L}(j)$ ($k \in \mathbb{N}_0$).

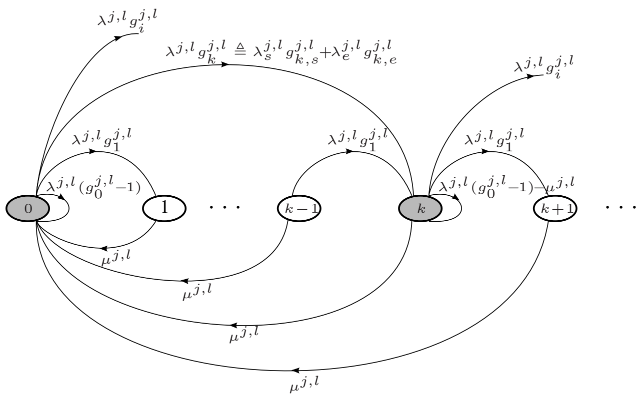

Figure 2: Transition rates for the continuous-time Markov chain related to l-queue inside node j.

$\{g_k\}$ by using their z-transforms $P(z) \triangleq \sum_{k=0}^{\infty} p_k z^{-k}$ and $G(z) \triangleq \sum_{k=0}^{\infty} g_k z^{-k}$.

Proposition 2.1 *$P(z)$ and $G(z)$ satisfy*

$$P(z) = \frac{\mu}{(\lambda + \mu) - \lambda G(z)} \,. \tag{3}$$

Note that such z-transforms have nonempty regions of convergence at least for $|z| > 1$. Indeed, considering for instance the case of the sequence $\{p_k\}$, one has

$$\sum_{k=0}^{\infty} |p_k z^{-k}| \le \sum_{k=0}^{\infty} |z^{-k}| = \frac{|z|}{|z| - 1} < \infty, \text{ for } |z| > 1.$$

3 A class of two-hop forwarding strategies

In two-hop forwarding, a packet can reach the destination only when one of these events occurs: 1) the source node meets the destination node; 2) the destination node meets another node that has previously received the packet from the source node itself. In this section and in the next one, we suppose that all the nodes of the network have the same traffic parameters and follow the same forwarding strategy. A possible forwarding strategy, which is a way to implement two-hop forwarding, is the following: inside each buffer, each node distinguishes between the packets generated by the node itself and the ones coming from the other nodes. When a node meets another one that is different from the destination, the latter sends all the packets generated by itself to the first node with probability q, otherwise no exchange is performed with probability $(1 - q)$. In other words, suppose that the node analyzed j, which contains the l-queue under study, encounters the node $i \neq l$. Node i downloads to j all the packets generated by i and contained in its l-buffer with probability q. We denote by $\{\bar{p}_k\}$ the stationary probability that node i contains k packets generated by i itself in its l-buffer (such a probability does not depend on i, since by assumption all the nodes of the network have the same traffic parameters). The next corollary provides a relationship between the z-transforms $\bar{P}(z)$ and $G_s(z)$ of $\{\bar{p}_k\}$ and $\{g_{k,s}\}$, respectively. We denote by $\{\delta_{k,h}\}$ the Kronecker delta ($\delta_{k,h} \triangleq 1$ for $k = h$ and $\delta_{k,h} \triangleq 0$ otherwise).

Corollary 3.1 *$\bar{P}(z)$ and $G_s(z)$ satisfy*

$$\bar{P}(z) = \frac{\mu}{(\lambda + \mu) - (\lambda_s G_s(z) + \lambda_e)} \,. \tag{4}$$

Proof. The result is obtained by applying Proposition 2.1 neglecting the exogenous component (which does not influence the content of the portion of the buffer made up only of the internally generated packets), i.e., setting $\{g_{k,e}\} = \{\delta_{k,0}\}$, whose z-transform is $G_e(z) = 1$. Then one applies $G(z) = \frac{\lambda_s}{\lambda_s + \lambda_e} G_s(z) + \frac{\lambda_e}{\lambda_s + \lambda_e} G_e(z)$ (which follows by (2)). ■

So, turning back to the model of two-hop forwarding, the size of the portion of the l-buffer in the node i made only by the packets generated by i is k with probability $\bar{p}_k$, and i sends k packets to j with probability $\bar{p}_k q$. On the other hand, node i does not send anything to node j in two cases: the first one happens with probability $\bar{p}_0 q$, i.e., when the portion of the buffer in i used for l and composed only by the packets generated by i is empty; the second one happens with probability $(1 - q)$ because of the forwarding strategy. More formally, $\{g_{k,e}\}$ is given by

$$\{g_{k,e}\} = (1 - q)\{\delta_{k,0}\} + q\{\bar{p}_k\} \,, \tag{5}$$

for $q \in [0, 1]$. Corollary 3.2 provides an expression for the z-transform $P(z)$ of the sequence $\{p_k\}$ under the class of two-hop forwarding strategies (5).

Corollary 3.2 *If $\{g_{k,e}\}$ has the form (5), then*

$$P(z) = \frac{\mu}{(\lambda+\mu) - \left(\lambda_s G_s(z) + \lambda_e\left((1-q) + q\frac{\mu}{(\lambda+\mu) - (\lambda_s G_s(z) + \lambda_e)}\right)\right)} \,. \tag{6}$$

Proof. It is obtained by applying Proposition 2.1 with $\{g_{k,e}\}$ of the form (5) (whose z-transform is $G_s(z) = (1 - q) +$

$q\bar{P}(z)$) and replacing $\bar{P}(z)$ by its expression provided by Corollary 3.1. ■

For the following analysis, the values of $P'(z)$ and $P''(z)$ (the first and the second complex derivatives of $P(z)$, respectively) computed at $z = 1$ are also needed. Starting from the expression of $P(z)$ in Corollary 3.2, simple computations provide the following corollary.

Corollary 3.3 *If $\{g_{k,e}\}$ has the form (5), then*

$$P'(1) = \frac{\lambda_s}{\mu} G'_s(1) + \frac{\lambda_e}{\mu} G'_e(1)\,, \tag{7}$$

$$\begin{aligned} P''(1) \quad = \quad & \frac{\lambda_s}{\mu} G''_s(1) + \frac{\lambda_e}{\mu} G''_e(1) + 2\frac{\lambda_s^2}{\mu^2}(G'_s(1))^2 \\ & +2\frac{\lambda_e^2}{\mu^2}(G'_e(1))^2 + 4\frac{\lambda_s\lambda_e}{\mu^2} G'_s(1) G'_e(1)\,, \end{aligned} \tag{8}$$

where

$$G'_e(1) = q\frac{\lambda_s}{\mu} G'_s(1)\,, \tag{9}$$

$$G''_e(1) = q\frac{\lambda_s}{\mu} G''_s(1) + 2q^2\frac{\lambda_s^2}{\mu^2}(G'_s(1))^2\,. \tag{10}$$

Note that the computations of formulas (7) and (8) do not require inverting z-transforms.

4 Buffer occupancy

The analysis detailed in the previous sections allows us to analyze the average buffer occupancy (11) and its standard deviation (12):

$$\sum_{i=0}^{\infty} i p_i = -P'(1)\,, \tag{11}$$

$$\sqrt{\sum_{i=0}^{\infty}\left(i - \sum_{k=0}^{\infty} k p_k\right)^2 p_i} \quad = \sqrt{P''(1)(P''(1) - 2P'(1))} \tag{12}$$

Formulas (11) and (12) are checked by exchanging the order of differentiation and summation in the definitions of $P'(z)$ and $P''(z)$, then taking $z = 1$. Figure 3 shows the behaviors of the average buffer occupancy (11) and its standard deviation (12) for the class of forwarding strategies (5), by varying the parameter q and the values $\mu, \lambda_e, \lambda_s$. Note from the figures that both expressions are linear in q. For illustrative purposes, we consider for the endogenous component $\{g_{k,s}\}$ a model in which the conditions $G'_s(1) = -1$ and $G''_s(1) = 2$ hold. An example of such a model is

$$\{g_{k,s}\} = \{\delta_{k,1}\}\,, \tag{13}$$

whose z-transform is

$$G_s(z) = z^{-1}\,, \tag{14}$$

i.e. all bulks are composed of 1 packet.

Similar curves can be obtained for more complex models. Figure 4 shows the behaviors of the average buffer occupancy (11) and its standard deviation (12) for a Poisson discrete probability density

$$\{g_{k,s}\} = \left\{\frac{a^k e^{-a}}{k!}\right\}\,, \tag{15}$$

($a > 0$ is a parameter), whose z-transform is

$$G_s(z) = e^{-a(1-z^{-1})}\,. \tag{16}$$

where $a = 3$, $G'_s(1) = -3$ and $G''_s(1) = 15$.

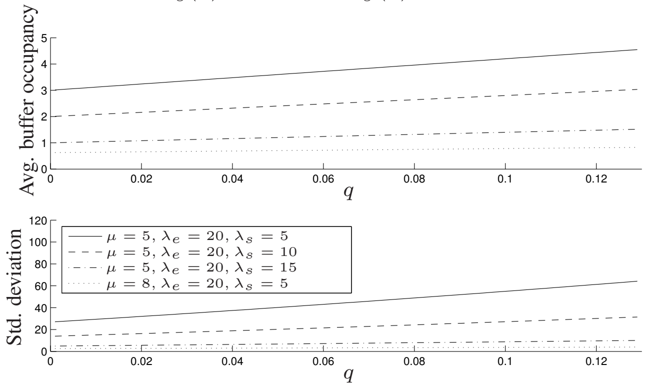

Figure 3: Average buffer occupancy and its standard deviation for the class of forwarding strategies (5), by varying the parameter q and considering a model for the endogenous component $\{g_{k,s}\}$ for which one has $G'_s(1) = -1$ and $G''_s(1) = 2$.

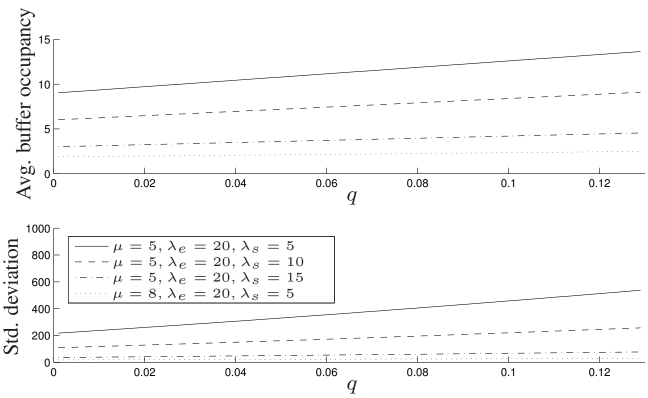

Figure 4: Average buffer occupancy and its standard deviation with a Poisson discrete probability density for the endogenous component $\{g_{k,s}\}$ for which $G'_s(1) = -3$ and $G''_s(1) = 15$.

5 Related Literature

An elegant model was proposed in [11] to analyze the delivery delay and its relative trade-offs with energy consumption and buffer requirements in the so-called (p, q)-*epidemic* *routing*. In [11] p and q represent, respectively, the probability that a node accepts a packet copy from another node when none of them is the source and the probability that a node accepts a packet copy from the packet source node. With a proper tuning of the values of p and q, (p, q)-epidemic routing models flooding, randomized flooding, or two-hops forwarding. The model is based on a continuous-time Markov chain, in which the state represents the number of copies of a specific packet in the system.

In [15], the authors developed a mathematical framework based on a Markov chain to get insights into the global congestion behavior. Their analysis is greatly simplified by replacing some random variables in the model with their expected values.

Differently from [11] and [15], in this paper we have focused on the behavior of a network single node, estimating both the discrete probability density of the size of its l-queue and the exogenous component $\{g_{k,e}\}$ of $\{g_k\}$ for a class of two-hop forwarding strategies. In [3], a similar analysis was done for a different class of forwarding strategies used in epidemic routing.

6 Conclusions

We have applied to a class of two-hop forwarding strategies a relationship between the discrete probability densities of bulk and queue sizes, which, under fixed traffic rates, depends only on the traffic generated by single nodes towards a specific destination. This allows to compute the average buffer occupancy and its standard deviation for a specific queue that contains traffic for a given destination within a node, knowing only the discrete probability density of the size of the bulks generated by that node towards the given destination. This has immediate practical advantages, e.g., in congestion control. Although the results are formulated for a single destination, they can be extended to the case of traffic directed to multiple destinations with possibly different generation rates.

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