

# Performance of Ad Hoc Networks with Two-Hop Relay Routing and Limited Packet Lifetime

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**Abstract**—Considered is a mobile ad hoc network consisting of three types of nodes (source, destination and relay nodes) and using the two-hop relay routing protocol. Packets at relay nodes are assumed to have a limited lifetime in the network. All nodes are moving inside a bounded region according to some random mobility model. Both closed-form expressions, and asymptotic results are provided for the packet delivery delay and the energy needed to transmit a packet from the source to its destination. Our model is validated through simulations for two mobility models (random waypoint and random direction mobility models), numerical results for the two-hop relay protocols are reported, and the performance of the two-hop routing and of the epidemic routing protocols are compared.

**Keywords:** Ad hoc network; Two-hop relay protocol; Limited packet lifetime; Mobility model; Markovian analysis; QoS metric.

## I. INTRODUCTION

Mobile Ad Hoc networks (MANETs) often experience network disconnectivity, especially when the nodes are moving frequently and the network is sparse. Grossglauser and Tse [3] introduce the *two-hop relay* mechanism, that works as follow: when there is no route between the source node and the destination node, the source node transmits copies of the packets to all neighboring nodes (called *relay* nodes) that it meets for delivery to the destination. A relay node is only allowed to send a packet to its destination node, and it is not allowed to send the packet to another relay node, thereby justifying the name of this protocol. The objective of this paper is to study the packet delivery delay and the overhead induced by the two-hop relay protocol. This will be done under the assumption that packets at relay nodes have a limited lifetime in the network. Another relay protocol closely related to the two-hop relay protocol is the so-called *epidemic routing* protocol [4]. The performance of both the two-hop relay protocol and the epidemic routing protocol will also be compared in this paper. A full version of this paper is available as a technical report [1].

## II. THE MANET MODEL

We consider a network consisting of one source node, one destination node, and  $N - 1$  relay nodes. Following [2] we assume that the *inter-meeting* times between any pair of nodes, defined as the time duration time between two consecutive points in time where these nodes meet (i.e. come

within transmission range of one another), are independent and identically distributed (iid) exponential random variables (rvs) with expected value  $1/\lambda$ . Transmissions between any two nodes only take place at meeting times and are assumed to be instantaneous and always successful. This corresponds to the situation where the transfer time of a packet between two nodes is negligible with respect to their inter-meeting time. In addition to the model in [2], we assume that each *copy* of the packet has a *Time-To-Live* (TTL). When the TTL of a copy expires then the copy is destroyed. TTLs are assumed to be iid rvs with an exponential distribution with rate  $\mu > 0$ . The packet to be sent by the source has no TTL associated with it. Throughout this paper we address the unique scenario where the source wants to send a single packet to the destination node using two-hop relay protocol. This assumption gives the best performance, in term of delivery delay of packets, that the two-hop relay protocol can achieve in the scenario of multiple packets in the network.

At time  $t = 0$ , the source is ready to transmit the packet to the destination. Let  $T_d$  denotes the packet delivery time (or delivery delay), defined as the first time after  $t = 0$  when the destination node receives the packet (or a copy of the packet). Let  $G_d$  denotes the number of copies generated by the source before the delivery time. The state of the system for  $t < T_d$  is represented by the random variable  $I(t) \in \{1, 2, \dots, N\}$ , where  $I(t)$  gives the number of copies. For  $t \geq T_d$ , it is assumed that the state of the system,  $I(t)$ , is  $a$ . Under the assumptions made,  $\{I(t), t \geq 0\}$  is an absorbing, finite-state, continuous-time Markov chain, with transient states  $\{1, 2, \dots, N\}$  and absorbing state  $a$ . Let  $\mathbf{MC}$  denotes the absorbing, finite-state, discrete-time Markov chain *embedded* just before the jump times of the Markov chain  $\{I(t), t \geq 0\}$ . Let  $m(i, j)$  be the  $(i, j)$ -entry of the fundamental matrix of  $\mathbf{MC}$ . Recall that  $m(i, j)$  gives the expected number of visits to transient state  $j$  before absorption (or delivery time) given that  $I(0) = i$ . The following propositions hold.

*Proposition 1:* The expected delivery delay is

$$\overline{T_d} = \sum_{k=1}^N \frac{m(1, k)}{N\lambda + (k-1)\mu} \approx \frac{1}{\lambda} \sqrt{\frac{\pi}{2N}} + \frac{\lambda + \mu}{3\lambda^2 N} + o\left(\frac{1}{N^2}\right),$$

for  $(N \uparrow \infty)$ . See [1] for a closed-form expression of  $m(1, k)$ .

*Proposition 2:* The expected number of copies generated

by the source before the delivery time is

$$\begin{aligned} \overline{G}_d &= \frac{1}{2} \left[ \sum_{k=1}^N \frac{\lambda k^2 + \lambda N + (k-1)\mu}{N\lambda + (k-1)\mu} m(1, k) \right] - 1 \\ &\approx \frac{\lambda + \mu}{3\lambda} + \sqrt{\frac{\pi N}{2}} + o\left(\frac{1}{N}\right), \quad (N \uparrow \infty) \end{aligned}$$

Proofs are given in [1]. From these asymptotic results we derive the Little-like formula  $\overline{G}_d \approx \lambda N \overline{T}_d$  ( $N \uparrow \infty$ ) relating the total expected number of copies generated by the protocol (protocol overhead) to the expected delivery time.

#### A. Model validation

We have simulated the two-hop relay protocol with exponential timeouts for both the Random Waypoint (RWP) and the Random Direction (RD) mobility models. In our simulation settings, for both the RWP and the RD models the area is a square of side-length  $L = 2000m$ , the speed is constant and equals to  $V = 10m/sec.$ , there is no pause time, and the transmission range  $R$  is constant and the same for all nodes. In addition, in the RD model the travel time is constant and equals to  $30sec.$  and the nodes reflect on reaching the boundaries. For different values of  $N$ , Table I reports the relative errors of delivery delay obtained from the exact result and by simulations for the RWP and RD models. We conclude that, for both mobility models, our model is accurate for  $N$  relatively small. Observe that more accurate results are reported for the RD model. In addition, the relative error as a function of  $R/L$  was evaluated and our model shows good results for small value of  $R/L$  especially in the case of RD model, see [1].

$N$	10	20	30	40	100
<b>RWP</b> $ 1 - \frac{E_{Sim}[T_d]}{E_m[T_d]} $ (%)	6	9	14	18	26
<b>RD</b> $ 1 - \frac{E_{Sim}[T_d]}{E_m[T_d]} $ (%)	1	6	9	9	24

TABLE I

RELATIVE ERROR OF DELIVERY DELAY CALCULATED FROM MODEL AND BY SIMULATIONS FOR THE RWP AND RD MODELS:  $\mu = 0.0001$ .

#### B. Comparison of two-hop relaying and epidemic routing

In this section, we compare the expected delivery delay,  $E[T_d]$ , as a function of  $\mu$ , the timeout intensity, for the two-hop relay and the epidemic routing protocols. The computation of the expected delivery delay and the expected number of packets transmitted for the epidemic routing protocol is similar to that carried out for the two-hop relay protocol, except that the fundamental matrix for the epidemic routing protocol cannot be computed in explicit form. This matrix was obtained numerically. As expected, we observe that the epidemic routing protocol induces a smaller expected delivery delay than the two-hop relay protocol see Figure 1, but at the expense of a much more important overhead in terms of the number of copies generated.

#### C. Limited energy consumption

We now evaluate a new two-hop relay scheme that limits the energy consumption by limiting the number of copies

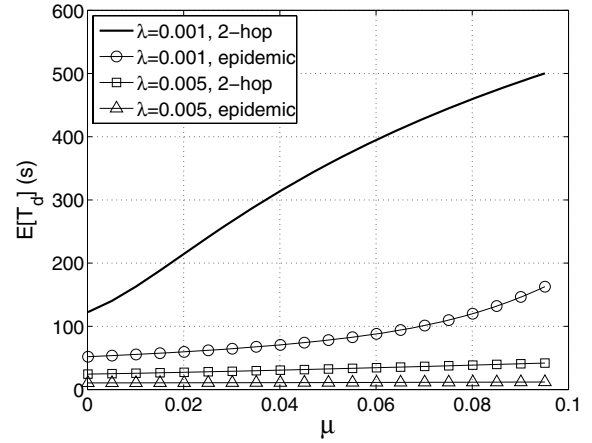


Fig. 1. Expected delivery delay for two-hop relay and epidemic routing protocols as a function of  $\mu$  for  $N = 100$ .

generated by the source before delivery to  $K$  copies. For different values of  $\lambda$ , the inter-meeting time rate, Figure 2 plots the expected delivery time under the  $K$ -limited two-hop relay protocol for different values of  $K$ . For each  $\lambda$ , we observe there exists a threshold  $K_0$  such that the expected delivery delay is almost constant when  $K \geq K_0$  ( $K_0 \sim 20$  for  $\lambda = 0.001$ ).

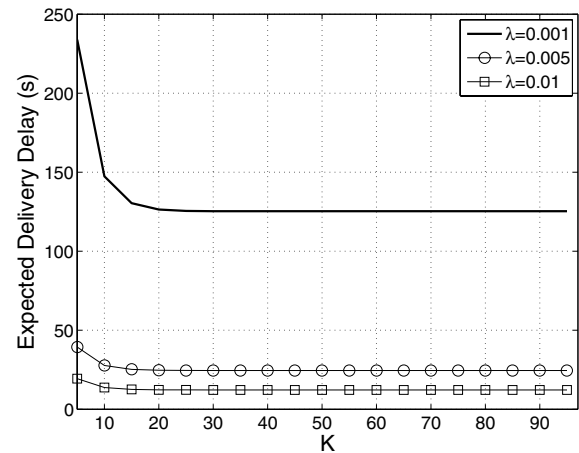


Fig. 2. Expected delivery delay under  $K$ -limited two-hop relay protocol for different values of  $K$  ( $N=100, \mu=0.001$ ).

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