Contention-Aware Analysis of Routing Schemes for Mobile Opportunistic Networks

Apoorva Jindal
Department of Electrical Engineering
University of Southern California
Los Angeles, CA 90089
apoorvaj@usc.edu

Konstantinos Psounis
Department of Electrical Engineering
University of Southern California
Los Angeles, CA 90089
kpsounis@usc.edu

ABSTRACT

A large body of work has theoretically analyzed the performance of routing schemes for mobile opportunistic networks. But a vast majority of these prior studies have ignored wireless contention. Recent papers have shown through simulations that ignoring contention leads to inaccurate and misleading results, even when studying sparse networks.

In this paper, we analyze the performance of routing schemes under contention. To model contention we use our recently-proposed analytical framework which is applicable to any multi-hop wireless network. Then, we take into consideration the special characteristics of mobile opportunistic networks and compute the delays for four representative routing schemes for these networks. Finally, we use these delay expressions to answer practical questions in the context of designing more efficient routing schemes for mobile opportunistic networks.

Categories and Subject Descriptors: C.2.2 [Computer-Communication Networks]: Network Protocols-Routing Protocols.

General Terms: Performance.

Keywords: Delay Tolerant Networks, Performance Analysis, Wireless Contention.

1. INTRODUCTION

Mobile opportunistic networks (also referred to as intermittently connected mobile networks) are networks where most of the time, there does not exist a complete end-to-end path from the source to the destination. Even if such a path exists, it may be highly unstable because of topology changes due to mobility. Examples of such networks include sensor networks for wildlife tracking and habitat monitoring [12], military networks [1], deep-space inter-planetary networks [3], nomadic communities networks [4], networks of mobile robots [25], vehicular ad hoc networks [26] etc.

Recently, a number of routing protocols have been proposed for these networks [6,11,13,17,19–21,23,24,28]. There has been some effort to theoretically characterize the performance of these routing schemes [5,8,14,16,18,19,27]. But, most of these analytical works do not take contention into account. They justify the assumption of no contention by arguing that since the network is pretty sparse, there won't be any contention in the first place and hence, nothing much is lost by ignoring contention in the analysis. [19,22] have shown through simulations that this argument is not valid and contention has a significant impact on performance, even in sparse networks. To demonstrate the inaccuracies which arise when contention is ignored, we use simulations to compare the delay of three different routing schemes in a sparse network with and without contention in Figure 1. The plot shows that ignoring contention not only grossly underestimates the delay, but also predicts incorrect trends and leads to incorrect conclusions. For example, without contention, the spraying based scheme has the worst delay, while with contention, spraying based scheme has the best delay.

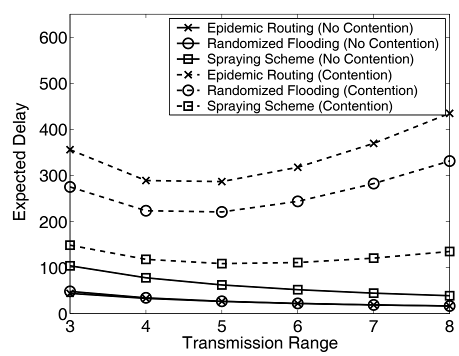

Figure 1: Comparison of delay with and without contention for three different routing schemes in sparse networks. The simulations without contention ensure that there is only one packet in the network at a given time. The simulations with contention use the scheduling mechanism and interference model described in Section 2.2. The routing schemes compared are: epidemic routing [23], randomized flooding [22] and spraying based routing [17].

In general, incorporating wireless contention makes the analysis intractable because it is a very complicated phenomenon manifesting itself in three ways: (i) finite bandwidth which limits the number of packets two nodes can exchange while they are within range, (ii) scheduling of transmissions between nearby nodes which is needed to avoid

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excessive interference, and (iii) interference from transmissions outside the scheduling area, which may be significant due to multipath fading [2]. Recently, [10] has proposed a general analytical framework to incorporate contention in a mobile wireless multi-hop network. This framework incorporates all the three manifestations of contention, and can be used with any mobility and channel model. Loss due to contention is modeled by a loss probability. Note that previous papers (see for example [15, 16]) have also proposed modeling loss due to contention with a loss probability. The difference between the framework in [10] and other papers is that [10] gives an analytical methodology to find the exact expression for this loss probability in terms of the network parameters for any given routing and scheduling scheme. We will use this framework to model contention. [8] is a preliminary effort of ours to use a detailed contention model, and then analyze routing performance, where we cover the special case of epidemic routing under the random walk mobility model.

This paper derives the expected delay for four representative routing schemes for mobile opportunistic networks with contention in the network. Specifically, we analyze direct transmission [20], epidemic routing [23], randomized flooding (or gossiping) [14, 22, 27] and spraying based routing schemes [14, 16, 17, 24]. For each of these schemes, we will find the loss probability due to contention using the framework proposed in [10] and then find the expected end-to-end delay expressions. Then we use these expressions to answer practical questions in the context of designing more efficient routing schemes for mobile opportunistic networks. First, we compare the performance of randomized flooding and a spraying scheme to conclude that spraying schemes outperform gossip schemes. So, we study spraying based schemes in more detail and discuss how to spray copies in the spraying phase so as to reduce the overall end-to-end delay.

The outline of this paper is as follows: Section 2 presents our notation and assumption, summarizes the contention framework and defines some properties of the mobility model which we will use during the course of the analysis. Then, Section 3 finds the expected delay expressions for the four routing schemes. We compare randomized flooding and a spraying based scheme in Section 4.1, and then study strategies to spread copies in spraying based routing schemes in Section 4.2. Finally, Section 5 concludes the paper.

2. PRELIMINARIES

2.1 Notation and Assumptions

We first introduce our notation and state the assumptions we will be making throughout the remainder of the paper.

1. M nodes move in a two dimensional torus of area N.

2. Each node acts as a source sending packets to a randomly selected destination.

3. We assume a Rayleigh-Rayleigh fading model for the channel (both the desired and the interfering signals are Rayleigh distributed).

4. The signal to interference ratio should be greater than a desired threshold, which we call Θ, for the transmission to be successful. For ease of analysis, we assume that two nodes will try to transmit to each other only if the link between them is in the connected region. [2,29] show that this is equivalent to assuming that the nodes will transmit to each other when the distance between them is less than K. (The value of K depends on the transmit power.) Note that this does not imply that transmissions from nodes at a distance greater than K are not going to interfere with the ongoing transmission or that the ongoing transmission will always be successful.

N	Area of the 2D torus
M	Number of nodes in the network
K	The transmission range
Θ	The desirable SIR ratio
s_{BW}	Bandwidth of links in units of packets per time slot

Table 1: Notation used throughout the paper.

2.2 Contention Model

This section briefly summarizes the contention model introduced in [10].

2.2.1 Three Manifestations of Contention

Finite Bandwidth: When two nodes meet, they might have more than one packet to exchange. Say two nodes can exchange s_{BW} packets during a unit of time. If they move out of each other's range, they will have to wait until they meet again to transfer more packets. The number of packets which can be exchanged in a unit of time is a function of the packet size and the bandwidth of the links.
Scheduling: We assume that a CSMA-CA like scheduling mechanism which ensures no simultaneous transmission occurs within the scheduling area of the transmitter and the receiver, is in place to avoid excessive interference. For ease of analysis, we also assume that time is slotted. At the start of the time slot, all node pairs contend for the channel and once a node pair captures the medium, it retains the medium for the entire time slot.
Interference: Even though the scheduling mechanism is ensuring that no simultaneous transmissions are taking place within each other's scheduling area, there is no restriction on simultaneous transmissions taking place outside the scheduling area. These transmissions act as noise for each other and hence can lead to packet corruption.

In the absence of contention, two nodes would exchange all the packets they want to exchange whenever they come within range of each other. Contention will result in a loss of such transmission opportunities. This loss can be caused by either of the three manifestations of contention. The next section summarizes the framework proposed in [10] to find this loss probability.

2.2.2 The Framework

Lets look at a particular packet, label it packet A. Suppose two nodes i and j are within range of each other at the start of a time slot and they want to exchange this packet. Let p^R_{txS} denote the probability that they will successfully exchange the packet during that time slot. (The value of p^R_{txS} depends on the routing mechanism R.) Note that $1-p^R_{txS}$ denotes the loss probability due to contention.

Let E_{bw} denote the event that finite link bandwidth allows nodes i and j to exchange packet A, let E_{sch} denote the event that the scheduling mechanism allows nodes i and j to exchange packets. and, let E_{inter} denote the event that the transmission of packet A is not corrupted due to interference given that nodes i and j exchanged this packet. Packet A will be successfully exchanged by nodes i and j only if the following three events occur: (i) the scheduling mechanism allows these nodes to exchange packets, (ii) nodes i and j decide to exchange packet A from amongst the other packets they want to exchange, and (iii) this transmission does not get corrupted due to interference from transmissions outside the scheduling area. Thus,

$$p_{txS}^{R} = P(E_{bw}) \times P(E_{sch}) \times P(E_{inter}). \quad (1)$$

[10] shows how to compute the three unknown probabilities in Equation (1).

The derivation of these unknown probabilities in [10] shows that p_{txS}^{R} depends on the routing mechanism R only through the probability p_{ex}^{R}, which is the probability that two nodes i and j want to exchange a particular packet. In other words, to apply this framework to a given routing mechanism, the only variable whose value needs to be determined is p_{ex}^{R}. The value of all the three probabilities depend on p_{ex}^{R}. For example, to find $P(E_{sch})$, one has to figure out the number of transmitter-receiver pairs within the scheduling area of the i-j pair which have a packet to exchange (transmitter-receiver pairs which do not have any packet to exchange will not contend for the channel). The probability that two nodes have at least one packet to exchange is a function of p_{ex}^{R}.

We will find the value of p_{ex}^{R} for each routing mechanism we analyze. Given the value of p_{ex}^{R}, the value of p_{txS}^{R} can be derived using the analytical methodology of [10]. We skip the derivation of p_{txS}^{R} given p_{ex}^{R} in this paper. (The interested reader is referred to [10] for details.)

2.3 Mobility Properties

In this section, we define three properties of a mobility model. We will use the statistics of these three properties in the analysis.

(i) Meeting Time: Let nodes i and j move according to a mobility model 'mm' and start from their stationary distribution at time 0. Let $X_i(t)$ and $X_j(t)$ denote the positions of nodes i and j at time t. The meeting time (M_{mm}) between the two nodes is defined as $min_t\{t : \|X_i(t) - X_j(t)\| \le K\}$.

(ii) Inter-Meeting Time: Let nodes i and j start from within range of each other at time 0 and then move out of range of each other at time t_1, that is $t_1 = min_t\{t : \|X_i(t) - X_j(t)\| > K\}$. The inter-meeting time (M_{mm}^{+}) of the two nodes is defined as $min_t\{t - t_1 : \|X_i(t) - X_j(t)\| \le K\}$.

(iii) Contact Time: Assume that nodes i and j come within range of each other at time 0. The contact time τ_{mm} is defined as $min_t\{t - 1 : \|X_i(t) - X_j(t)\| > K\}$.

The statistics of these properties for the random waypoint and the random direction mobility models were studied by [9] and [18]. The two important properties satisfied by both the mobility models, which we use during the course of the analysis are as follows: (i) The expected inter-meeting time is approximately equal to the expected meeting time and (ii) The tail of the distribution of the meeting and the inter-meeting times are exponential. Section 3 finds the delay of routing schemes while assuming the mobility model to be random waypoint, but the results can be easily modified if the nodes move around according to the random direction mobility model instead of random waypoint[1].

3. DELAY ANALYSIS OF ROUTING SCHEMES

In this section, we find the expected end-to-end delay of four different routing schemes for mobile opportunistic networks with nodes moving around according to the random waypoint mobility model. For each routing scheme, we first define the routing algorithm and then derive the end-to-end delay.

3.1 Direct Transmission

Direct transmission is one of the simplest possible routing schemes. Node A forwards a message to another node B it encounters, only if B is the message's destination. [18] studied the performance of direct transmission for mobile opportunistic networks without contention in the network. We now analyze its performance with contention.

First, we find the value of p_{ex}^{dt} (the probability that two nodes i and j want to exchange a particular packet) for direct transmission[2] and then find the expected end-to-end delay.

LEMMA 3.1. $p_{ex}^{dt} = \frac{2}{M(M-1)}$.

Proof: In direct transmission, each packet undergoes only one transmission, from the source to the destination. A packet has node i as its source with probability $\frac{1}{M}$. The probability that j is the destination given i is the source is $\frac{1}{M-1}$ (the destination is chosen uniformly at random from amongst the other $M-1$ nodes). Thus, the probability that i and j want to exchange a particular packet is equal to $\frac{2}{M(M-1)}$ (i is the source and j is the destination or vice versa). □

THEOREM 3.1. *Let $E[D_{dt}]$ denote the expected delay of direct transmission. Then, $ED_{dt} = \frac{E[M_{rwp}]}{p_{success}^{dt}}$, where $E[M_{rwp}]$ is the expected meeting time of the random waypoint mobility model, $p_{success}^{dt}$ is the probability that when two nodes come within range of each other, they successfully exchange the packet before going out of each other's range (within the contact time τ_{rwp}) and is equal to $1 - \left(1 - p_{txS}^{dt}\right)^{E[\tau_{rwp}]}$.*

Proof: The expected time it takes for the source to meet the destination for the first time is $E[M_{rwp}]$ (the expected meeting time). $1 - p_{txS}^{dt}$ is the probability of loss of a transmission opportunity due to contention. Thus, with probability $1 - p_{txS}^{dt}$, the source and the destination are unable to exchange the packet in one time slot. They are within range of each other for $E[\tau_{rwp}]$ number of time slots. (We are making an approximation here by replacing τ_{rwp} by its expected value.) Then $\left(1 - p_{txS}^{dt}\right)^{E[\tau_{rwp}]}$ is the probability that the source fails to deliver the packet to the destination when they came within range of each other. Thus, $p_{success}^{dt} = 1 - \left(1 - p_{txS}^{dt}\right)^{E[\tau_{rwp}]}$.

[1]Note that the analysis presented in Section 3 can be easily modified for any mobility model which satisfies these two properties.

[2]Note that the value of p_{txS}^{R} depends on the routing mechanism through p_{ex}^{R} only. Given the value of p_{ex}^{R}, one can derive the value of p_{txS}^{R} in terms of the network parameters using the framework proposed in [10].

If the two nodes fail to exchange the packet when they were within range, then they will have to wait for one inter-meeting time to come within range of each other again. If they fail yet again, they will have to wait another inter-meeting time to come within range. Thus, $ED_{dt} = E[M_{rwp}] + p_{success}^{dt} \left((1-p_{success}^{dt})E[M_{rwp}^{+}] + 2(1-p_{success}^{dt})^2 E[M_{rwp}^{+}] + \ldots\right) = E[M_{rwp}] + \frac{(1-p_{success}^{dt})E[M_{rwp}^{+}]}{p_{success}^{dt}}$. Since $E[M_{rwp}^{+}] = E[M_{rwp}]$ for the random waypoint mobility model, ED_{dt} evaluates to $\frac{E[M_{rwp}]}{p_{success}^{dt}}$. □

3.2 Epidemic Routing

Epidemic routing [23] extends the concept of flooding to mobile opportunistic networks. It is one of the first schemes proposed to enable message delivery in such networks. Each node maintains a list of all messages it carries, whose delivery is pending. Whenever it encounters another node, the two nodes exchange all messages that they don't have in common. This way, all messages are eventually spread to all nodes. The packet is delivered when the first node carrying a copy of the packet meets the destination. The packet will keep on getting copied from one node to the other node till its Time-To-Live (TTL) expires. For ease of analysis, we assume that as soon as the packet is delivered to the destination, no further copies of the packet are spread.

[5, 18, 27] studied the performance of epidemic routing without contention. [8] analyzed the performance of epidemic routing with contention under a random walk mobility model. We now analyze its performance with contention using the contention framework for the random waypoint mobility model.

To find the expected end-to-end delay for epidemic routing, we first find $E[D_{epidemic}(m)]$ which is the expected time it takes for the number of nodes having a copy of the packet to increase from m to $m+1$.

Lemma 3.2. *$E[D_{epidemic}(m)] = \frac{E[M_{rwp}]}{m(M-m)p_{success}^{epidemic}}$, where $p_{success}^{epidemic} = 1 - \left(1 - p_{txS}^{epidemic}\right)^{E[\tau_{rwp}]}$.*

Proof: $E[D_{epidemic}(m)]$ is the expected time it takes for the copies of a packet to increase from m to $m+1$. When there are m copies of a packet in the network, if one of the m nodes having a copy meets one of the other $M-m$ nodes not having a copy, there is a transmission opportunity to increase the number of copies by one. Since mobile opportunistic networks are sparse networks, we look at the tail of the distribution of the meeting time which is exponential for the random waypoint mobility model. The time it takes for one of the m nodes to meet one of the other $M-m$ nodes is equal to the minimum of $m(M-m)$ exponentials, which is again an exponential random variable with mean $\frac{E[M_{rwp}]}{m(M-m)}$. Now when they meet, the probability that the two nodes are able to successfully exchange the packet is $p_{success}^{epidemic}$. If they fail to exchange the packet, they will have to wait one inter-meeting time to meet again. But, since $E[M_{rwp}] = E[M_{rwp}^{+}]$ for the random waypoint mobility model, and both meeting and inter-meeting times have memoryless tails, the expected time it takes for one of the m nodes to meet one of the other $M-m$ nodes again is still equal to $\frac{E[M_{rwp}]}{m(M-m)}$. Hence, $E[D_{epidemic}(m)] = p_{success}^{epidemic}\frac{E[M_{rwp}]}{m(M-m)} + 2p_{success}^{epidemic}(1-p_{success}^{epidemic})\frac{E[M_{rwp}]}{m(M-m)} + \ldots = \frac{E[M_{rwp}]}{m(M-m)p_{success}^{epidemic}}$. The value of $p_{success}^{epidemic}$ can be derived in a manner similar to the derivation of $p_{success}^{dt}$ in Theorem 3.1. □

Now, we find the values of $p_{ex}^{epidemic}$ for epidemic routing and then find the expected end-to-end delay.

Lemma 3.3. *$p_{ex}^{epidemic} = \sum_{m=1}^{M-1} \frac{2m(M-m)}{M(M-1)} \sum_{i=m}^{M-1} \frac{1}{M-1} \frac{\frac{1}{m(M-m)}}{\sum_{j=1}^{i}\frac{1}{j(M-j)}}$.*

Proof: Given that only m nodes have a copy of the packet, the probability that one of the nodes has it and the other one doesn't, follows from elementary combinatorics. To complete the proof, we have to find the probability that only m nodes have a copy of the packet. Then, applying the law of total probability over the random variable m will yield the result. Please see the Appendix for proof details. □

Theorem 3.2. *Let $E[D_{epidemic}]$ denote the expected delay of epidemic routing. Then,*

$$E[D_{epidemic}] = \sum_{i=1}^{M-1} \frac{1}{M-1} \sum_{m=1}^{i} \frac{E[M_{rwp}]}{m(M-m)p_{success}^{epidemic}} \quad (2)$$

Proof: The probability that the destination is the i^{th} node to receive a copy of the packet is equal to $\frac{1}{M-1}$ for $2 \le i \le M$. The amount of time it takes for the i^{th} copy to be delivered is equal to $\sum_{m=1}^{i} E[D_{epidemic}(m)]$. Applying the law of total probability over the random variable i and substituting the value of $E[D_{epidemic}(m)]$ from Lemma 3.2 gives Equation (2). □

3.3 Randomized Flooding

Randomized flooding [22,27] has been proposed to reduce the overhead and improve the performance of epidemic routing. Under this scheme, a message is forwarded to another node with some probability p smaller than one (that is data is gossiped instead of flooded). When $p = 0$, the scheme reduces to direct transmission, while when $p = 1$, it reduces to standard epidemic routing. [14,16,27] have evaluated the performance of randomized flooding without contention in the network. We now analyze its performance with contention.

First we find the value of $E[D_{rf}(m)]$ which is the expected time it takes for the number of nodes having a copy of the packet to increase from m to $m+1$. Then, we find p_{ex}^{rf} and finally, we find the expected end-to-end delay for randomized flooding.

Lemma 3.4. *$E[D_{rf}(m)] = \frac{E[M_{rwp}]}{\left(m(M-m-1)p_{success}^{1}\right) + \left(mp_{success}^{2}\right)}$, where $p_{success}^{1} = 1 - \left(1 - pp_{txS}^{rf}\right)^{E[\tau_{rwp}]}$ and $p_{success}^{2} = 1 - \left(1 - p_{txS}^{rf}\right)^{E[\tau_{rwp}]}$.*

Proof: The proof runs along similar lines as the proof of Lemma 3.2. The only difference is that whenever one of the m nodes having a copy of the packet meet one of the $(M-m-1)$ non-destination nodes which don't have a copy of the packet, they will try to exchange the packet with probability p only. □

Lemma 3.5. *$p_{ex}^{rf} \approx p\sum_{m=1}^{M-1} \frac{2m(M-m)}{M(M-1)} \sum_{i=m}^{M-1} \frac{1}{M-1} \frac{\frac{1}{m(M-m)}}{\sum_{j=1}^{i}\frac{1}{j(M-j)}}$.*

Proof: See Appendix. □

THEOREM 3.3. *Let $E[D_{rf}]$ denote the expected delay of randomized flooding. Then,*

$$E[D_{rf}] = \sum_{i=1}^{M-1} p_{dest}(i) \sum_{m=1}^{i} E[D_{rf}(m)], \qquad (3)$$

where $p_{dest(i)} = \frac{ip^2_{success}}{\left(i(M-i-1)p^1_{success}\right)+\left(ip^2_{success}\right)} \prod_{m=1}^{i-1} \frac{m(M-m-1)p^1_{success}}{\left(m(M-m-1)p^1_{success}\right)+\left(mp^2_{success}\right)}$ *is the probability that the destination is the $(i+1)^{th}$ node to receive a copy of the packet.*

Proof: The proof runs along similar lines as the proof of Theorem 3.2. □

3.4 Spraying a small fixed number of copies

Another approach to route packets in sparse networks is that of controlled replication or *spraying* [14, 16, 17, 24]. A small, fixed number of copies are distributed to a number of distinct relays. Then, each relay carries its copy until it encounters the destination or until the TTL of the packet expires. By having multiple relays looking independently and in parallel for the destination, these protocols create enough diversity to explore the sparse network more efficiently while keeping the resource usage per message low.

Different spraying schemes may differ in how they distribute the copies and, or how they route each copy. Source spray and wait is one of the simplest spraying schemes proposed in the literature [17]. For this scheme, the source node forwards all the copies (lets label the number of copies being sprayed as L) to the first L distinct nodes it encounters. (In other words, no other node except the source node can forward a copy of the packet.) And, once these copies get distributed, each copy performs direct transmission. [19] analyzed source spray and wait without incorporating contention in the network. We now derive its expected end-to-end delay with contention.

First, we find the value $E[D_{spray}(m)]$ which is the expected time it takes for the number of nodes carrying a copy of the packet to increase from m to $m+1$. Then, we find p^{spray}_{ex} and finally, we find the expected end-to-end delay for source spray and wait.

LEMMA 3.6. $E[D_{spray}(m)] = \begin{cases} \frac{E[M_{mm}]}{(M-1)p^{spray}_{success}} & 1 \le m < L \\ \frac{E[M_{mm}]}{Lp^{spray}_{success}} & m = L \end{cases}$
where $p^{spray}_{success} = 1 - (1 - p^{spray}_{txS})^{E[\tau_{mm}]}$.

Proof: See Appendix. □

LEMMA 3.7. $p^{spray}_{ex} = \left(\frac{2Lp_{dest}(L)}{M(M-1)} \frac{E[D_{spray}(L)]}{\sum_{k=1}^{L} E[D_{spray}(k)]}\right) + \left(\frac{2}{M-1} \sum_{m=1}^{L-1} \sum_{i=m}^{L} p_{dest}(i) \frac{E[D_{spray}(m)]}{\sum_{k=1}^{i} E[D_{spray}(k)]}\right),$
where $p_{dest}(i) = \begin{cases} \left(\prod_{j=1}^{i-1} \frac{M-j-1}{M-1}\right) \frac{i}{M-1} & 1 \le i < L \\ \left(\prod_{j=1}^{i-1} \frac{M-j-1}{M-1}\right) & i = L \end{cases}$ *is the probability that the destination is the $(i+1)^{th}$ node to receive a copy of the packet.*

Proof: The proof runs along the same lines as the proof of Lemma 3.3. □

THEOREM 3.4. *Let $E[D_{spray}]$ denote the expected delay of source spray and wait. Then,*

$$E[D_{spray}] = \sum_{i=1}^{L} p_{dest}(i) \sum_{m=1}^{i} E[D_{spray}(m)]. \qquad (4)$$

Proof: The proof runs along similar lines as the proof of Theorem 3.2. □

3.5 Simulation Results

We use simulations to verify that the approximations made during the course of the analysis do not have a significant impact on the accuracy of the analysis. We use a custom simulator written in C++ for simulations. The simulator avoids excessive interference by implementing a scheduling scheme which prohibits simultaneous transmissions within two hops of each other. It incorporates interference by adding the received signal from other simultaneous transmissions (outside the scheduling area) and comparing the signal to interference ratio to the desired threshold. The simulator allows the user to choose from different physical layer, mobility and traffic models. We choose the Rayleigh-Rayleigh fading model for the channel, random waypoint model for node mobility and Poisson arrivals in our simulations.

We made the following three approximations during the delay analysis: (i) we replace the contact time by its expected value in the expression of $p^R_{success}$ in the delay analysis of all routing schemes, (ii) while analyzing epidemic routing, randomized flooding and source spray and wait, we assume the entire meeting and inter-meeting time distribution to be exponential, and (iii) while analyzing randomized flooding, we use an approximate value of p^{rf}_{ex} to substitute in the expression for p^{rf}_{txS}. The effect of all the three approximations can be studied by varying K and M. Figures 2(a)-2(f) compare the expected end-to-end delay of direct transmission, epidemic routing, randomized flooding and source spray and wait obtained through analysis and simulations for different values of K and M. We have compared the analytical and simulation results for a large number of scenarios, but due to limitations of space, we present some representative results for each routing scheme. Since both the simulation and the analytical curves are close to each other in all the scenarios, we conclude that the analysis is fairly accurate.

4. APPLICATIONS

This section uses the analysis in the previous section to answer some pertinent questions in the context of designing more efficient routing schemes for sparse networks.

4.1 Randomized Flooding vs Source Spray and Wait

Both gossip based and spraying based routing techniques were proposed to achieve good delay performance with a lower resource usage than epidemic routing. So, first we compare which of the two performs better. [19,21] have compared these two approaches with simulations, but having an analytical expression allows us to first find the optimal parameters for both the schemes (p for randomized flooding and L for spraying schemes) and then comparing them, which ensures a fair comparison. [14] compared these two schemes analytically, but their analysis ignored contention.

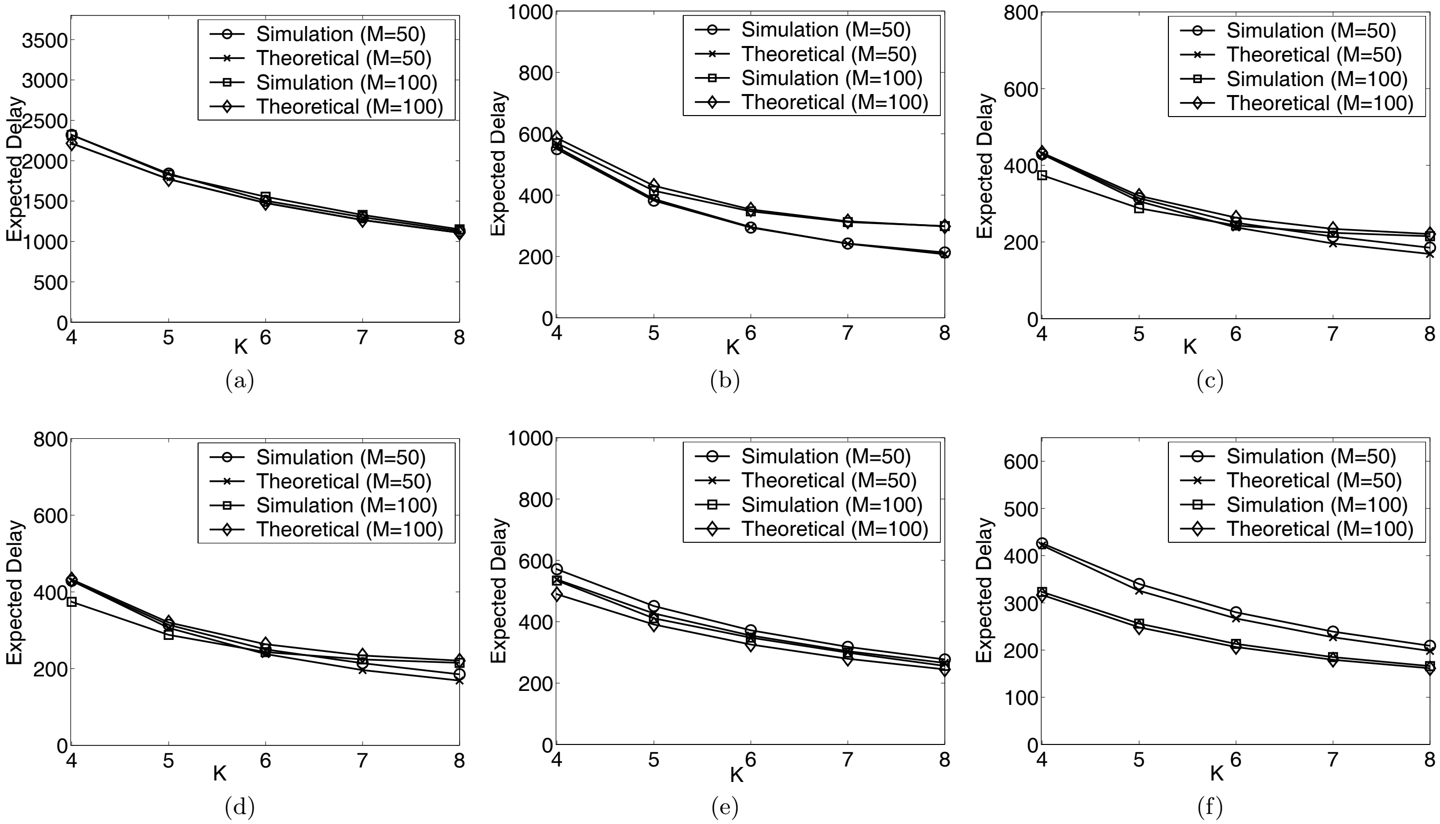

Figure 2: Simulation and analytical results for the expected delay. Network parameters: $N = 150 \times 150$ square units, $\Theta = 5, s_{BW} = 1$ packet/time slot. The transmission range, K, is expressed in the same distance units as $\sqrt{N}$. The delay is expressed in time slots. (a) Direct transmission. (b) Epidemic routing. (c) Randomized flooding with $p = 0.3$. (d) Randomized flooding with $p = 0.7$. (e) Source spray and wait with $L = 5$. (f) Source spray and wait with $L = 15$. (Note that the number of instances for which each Monte Carlo simulation is run is chosen so as to ensure that the 90% confidence interval is within 5% of the simulation value.)

The performance of flooding based schemes degrades significantly due to contention, hence ignoring contention when comparing a flooding based scheme to another scheme will lead to an unfair comparison.

To compare the two schemes, we study how much resource does each scheme use to achieve a given target expected delay. We measure resource consumption in terms of the average number of transmissions required to reach the destination. Larger the number of transmissions, higher is the buffer usage and energy consumption.

We will choose the least value of p and L which will achieve a specific target expected delay because lower the value of p and L, lower will be the resource consumption. We numerically solve Equations (3) and (4) to find the minimum value of p and L which achieve the target delay. The average number of transmissions required to deliver the packet to the destination is equal to $\sum_{i=1}^{M-1} i p_{dest}(i)$, where $p_{dest}(i)$ is the probability that the destination is the $(i+1)^{th}$ node to receive a copy of the packet. We derived the value of $p_{dest}(i)$ in Theorem 3.3 and Lemma 3.7 for randomized flooding and source spray and wait respectively. Figure 3 plots the average number of transmissions required to reach the destination versus the required target delay for both the schemes for two different network densities. We make the following two observations from this figure: (i) source spray and wait is able to achieve lower values of target expected delay than randomized flooding, and (ii) for a target expected delay which can be achieved by both the schemes, source spray and wait uses less resources to achieve it than randomized flooding. The superiority of source spray and wait becomes more prominent as the network density increases.

4.2 Source Spray and Wait vs Fast Spray and Wait

Since spraying based techniques outperform gossip based schemes, we now study the spraying schemes in more detail. Specifically, we discuss how to spray copies in the spraying phase so as to reduce the overall end-to-end delay. Intuitively, spraying copies as fast as possible should minimize the delay as once the copies are spread, the expected amount of time it takes to deliver the packet will be the same for all schemes. So, is trying to spray the copies as fast as possible the optimal way. To answer this question, we compare two different spraying schemes. The first scheme is source spray and wait which was introduced in Section 3.4 and the second scheme is fast spray and wait. In fast spray and wait, every relay node can forward a copy of the packet to a non-destination node which it encounters. (Recall that in source

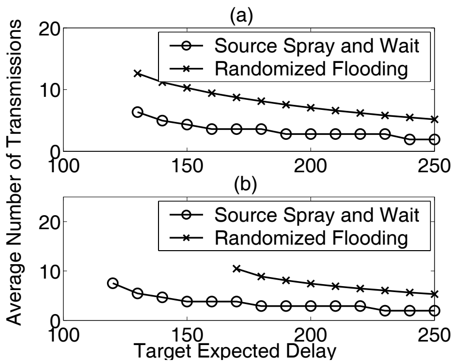

Figure 3: Comparison of source spray and wait and randomized flooding: Average number of transmissions required to deliver the packet to the destination vs target expected delay. Network parameters: $N = 100 \times 100$ **square units,** $K = 6, \Theta = 5, s_{BW} = 1$ **packet/time slot. Delay is expressed in time slots. (a)** $M = 50$. **Note that target delays below** 130 **time units are not achievable by either routing scheme. (b)** $M = 100$. **Note that target delays below** 170 **time units for randomized flooding and** 120 **time units for source spray and wait are not achievable.**

spray and wait, only the source node can forward copies to non-destination nodes.) There is a centralized mechanism which ensures that after L copies of the packet have been spread, no more copies get transmitted to non-destination nodes. Since fast spray and wait spreads copies whenever there is any opportunity to do so, it has the minimum spraying time when there is no contention in the network. On the other hand, since source spray and wait does not use relays to forward copies, without contention, it is one of the slower spraying mechanisms.

We have already analyzed the performance of source spray and wait with contention in the network in Section 3.4. Fast spray and wait can be analyzed in a similar manner. The main difference in the analysis of fast spray and wait is that, when the number of copies of a packet is less than L, the number of copies can increase whenever one of the nodes carrying a copy meets any one of the nodes not carrying a copy.

Now we study how fast do the two schemes spread copies of a packet when there is contention in the network. Figure 4 plots the number of copies spread as a function of the time elapsed since the packet was generated. Somewhat surprisingly, depending on the density of the network, source spray and wait can spray copies faster than fast spray and wait. This occurs because fast spray and wait generates more contention as it tries to transmit at every possible transmission opportunity. In general, unless the network is very sparse, strategies which spray copies slower yield better performance than more aggressive schemes thanks to reducing contention. In ongoing work, we are trying to find the optimal spraying algorithm and design practical and implementable heuristics which achieve performance very close to the optimal. [7] is a first step in this direction. It derives the optimal spraying scheme and a simple heuristic which performs very close to the optimal, but it assumes that there is no contention in the network. Currently, we are merging

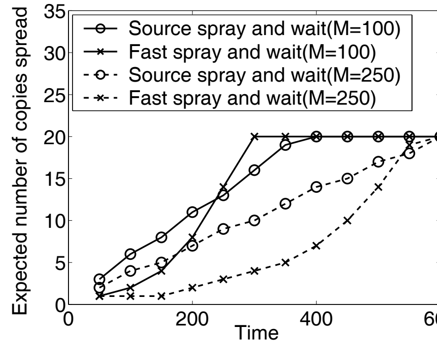

Figure 4: Comparison of fast spray and wait and source spray and wait: Expected number of copies spread vs time elapsed since the packet was generated. Network parameters: $N = 100 \times 100$ **square units,** $K = 5, \Theta = 5, s_{BW} = 1$ **packet/time slot,** $L = 20$. **Time is expressed in time slots.**

this work with the contention framework proposed in [10] to find the optimal spraying scheme with contention in the network.

5. CONCLUSIONS

This paper finds the expected delay for four representative routing schemes for mobile opportunistic networks: direct transmission, epidemic routing, randomized flooding and spraying based schemes, with contention in the network. This paper uses a recently proposed framework to model wireless contention. We use these expressions to conclude that spraying based schemes outperform randomized flooding. So, we study spraying based schemes in more detail and analyze how to spread the copies in a spraying scheme. We conclude that strategies which spray copies as fast as possible generate more contention and are not the best way to spread copies.

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APPENDIX

Proof: (**Lemma 3.3**) Let there be m copies of a particular packet in the network. Then the probability that node i has a copy is equal to $\frac{m}{M}$ and the probability that node j does not have a copy given that node i has one is equal to $\frac{(M-m)}{M-1}$. Thus, the probability that nodes i and j want to exchange the packet given that there are m copies of the packet in the network is equal to $\frac{2m(M-m)}{M(M-1)}$. Now, we find the probability that there are m copies of the packet in the network. The copies of a packet keep on increasing till the packet is delivered to the destination. The probability that the destination is the k^{th} node to receive a copy of the packet is equal to $\frac{1}{M-1}$ for $2 \leq k \leq M$. A packet will have m copies in the network only if the destination wasn't amongst the first $m-1$ nodes to receive a copy. The amount of time a packet has m copies in the network is equal to $E[D_{epidemic}(m)]$. Hence, the probability that there are m copies of a packet in the network equals $\sum_{i=m}^{M-1} \frac{1}{M-1} \frac{E[D_{epidemic}(m)]}{\sum_{j=1}^{i} E[D_{epidemic}(j)]}$. Applying the law of total probability over the random variable m and substituting the value of $E[D_{epidemic}(m)]$ from Lemma 3.2 gives $p_{ex}^{epidemic}$. □

Proof: (**Lemma 3.5**) The proof runs along similar lines as the proof of Lemma 3.3. Given that there are m copies of the packet in the network, the probability that nodes i and j want to exchange a particular packet is equal to $p\frac{2m(M-m)}{M(M-1)}$. The probability that there are m copies of a packet in the network equals $\sum_{i=m}^{M-1} \frac{1}{M-1} \frac{E[D_{epidemic}(m)]}{\sum_{j=1}^{i} E[D_{epidemic}(j)]}$. To simplify the exposition, we make an approximation here by replacing $\left(m(M-m-1)p^1_{success}\right) + \left(mp^2_{success}\right)$ in the denominator of the expression for $E[D_{epidemic}(m)$ by $m(M-m)p^1_{success}$. We use simulations to verify that this approximation does not have a significant effect on the accuracy of the analysis. Note that this approximation is made only during the derivation of p_{ex}^{rf}. □

Proof: (**Lemma 3.6**) The proof runs along the same lines as the proof of Lemma 3.2. When there are $1 \leq m < L$ copies of a packet in the network, there are m nodes which can deliver a copy to the destination only, and there is one source node which can deliver a copy to any of the $M-m-1$ other nodes which do not have a copy of the packet. Hence, there are a total of $m+M-m-1 = M-1$ node pairs, which when meet, have an opportunity to increase the number of copies from m to $m+1$. The expected time it takes for one of these $M-1$ node pairs to meet is $\frac{E[M_{mm}]}{M-1}$. Using the same argument as in the proof of Lemma 3.2, $E[D_{spray}(m)]$ can be derived to be $\frac{E[M_{mm}]}{(M-1)p^{spray}_{success}}$.

When there are L copies of a packet in the network, there are L nodes which can deliver a copy to the destination but even if the source meets some other node which does not have a copy, it cannot attempt to transmit a copy to the other node. The expression for $E[D_{spray}(L)]$ is derived in a manner similar to the derivation of Lemma 3.2 to be $\frac{E[M_{mm}]}{Lp^{spray}_{success}}$. □