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The Effects of Node Cooperation Level on Routing Performance in Delay Tolerant Networks

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Abstract— **In this paper, we analyze the effect of different degrees of node cooperation on the performance of routing protocols for delay tolerant networks. We first present an accurate analytical characterization of the performance of epidemic and two-hops routing in terms of expected packet delivery rate under the standard assumption of fully cooperative node behavior. This characterization is itself an interesting result, since it requires accurately approximating the *distribution* of the packet delivery delay. We then use the results derived in the first part of the paper to analytically characterize epidemic routing protocol performance in presence of different degrees of node cooperation. We also performed extensive simulations for a broader set of routing protocols and cooperation scenarios. The results of our simulations show that, while epidemic routing provides the better PDR performance under all investigated degrees of network cooperation, binary SW routing can achieve comparable performance, while significantly reducing message overhead. Binary SW routing shows also the better resilience to lower node cooperation levels amongst the considered routing protocols. Finally, our results suggest that even a modest level of node cooperation is sufficient to achieve 3-4–fold performance improvement with respect to the most pessimistic scenario in which all potential forwarders drop messages.**

I. Introduction

The delay tolerant network paradigm has attracted increased attention in the research and industrial community in recent years. Differently from other types of wireless multi-hop networks, DTNs are characterized by a very sparse node population, and by the lack of full network connectivity at virtually every time. Given these features, eventual message delivery to the destination can be achieved only through node mobility, which is indeed the main communication mean in the network.

Node cooperation is fundamental to ensure acceptable performance in DTNs: in fact, differently to more traditional (fully connected) types of wireless multi-hop networks, nodes are typically requested not only to act as message forwarders, but also to store in their own buffer other nodes' messages for a very long time interval (store-and-forward communication). Thus, both energy and memory resources, which are very limited in a typical mobile node, has to be sacrificed for the other nodes' good.

Despite the relatively higher degree of node cooperation typically assumed in DTN protocols as compared to protocols designed for other types of wireless multi-hop networks, little attention has been devoted to investigate the effects of reduced degrees of node cooperation on the performance of typical DTN protocols. Since routing is the most important network functionality, in this paper we focus our attention on evaluating routing protocol performance when the degree of node cooperation is not necessarily the highest possible.

To the best of our knowledge, only a few recent papers [5], [9] deals with cooperation issues in DTNs. In [5], the authors assume selfish node behavior, and present a mechanism to discourage selfish node behavior during message exchange based on the principles of barter. In [9], the authors consider three well-known routing protocols for DTNs, and evaluate their performance through simulation under different levels of node cooperation. The main finding of their study is that two-hops routing in general appears more resilient to less cooperative node behavior amongst the considered routing protocols.

Differently from previous work, we present a *theoretical* framework for studying the effects of different degrees of node cooperation: we assume that each message is considered as successfully delivered to destination only if delivery occurs within a certain time TTL since its generation, and we aim at estimating the packet delivery rate (PDR) under different routing protocols and degrees of node cooperation. More specifically, we consider three common DTN routing protocols, and four different cooperation scenarios, ranging from fully non-cooperative to fully cooperative scenario, including intermediate cooperation scenarios where node cooperation level might be either pre-determined or adaptive to network conditions.

Formal analysis of expected PDR is not trivial, since estimating the *expected* packet delivery delay, as it has extensively been done in the literature [2], [8], [10], [11], [14], is not sufficient, and an accurate characterization of the *distribution* of packet delivery delay has to be provided. To the best of our knowledge, only a few papers [2], [14] attempted to characterize the packet delivery delay distribution (in fully cooperative scenarios). However, the authors of [2] consider a network model in which the TTL is associated with each single message replica, and thus their results cannot be used to provide bounds on the delivery time since initial message generation. On the other hand, the results of [14] are based on ordinary differential equations and are asymptotic in nature; as shown in this paper, the approach of [14] when applied to networks of reasonable size considerably *overestimates* network performance.

The specific novel theoretical contributions of this paper are:

$i)$ an accurate analytical characterization of epidemic [13] and two-hops [7] routing performance in the fully cooperative scenario. Our bounds are very accurate and, most importantly, *lower bound* PDR performance, thus they can be used to provide *minimal performance guarantee in a DTN*.
$ii)$ for epidemic routing, we analytically characterize performance also in a scenario in which node cooperation level is expressed in terms of a parameter p, namely the probability that a potential forwarder node actually stores and relays the message. The derived bound can be used also to accurately estimate stationary network operational points of a cooperation scenario in which nodes' cooperation level is adaptive to network conditions.

All the derived bounds are shown to be significantly more accurate than those derived from the asymptotic analysis of [14].

We also perform an extensive simulation-based performance evaluation to cover those cases where theoretical analysis is not provided. The main findings of this evaluation are: $i)$ binary SW routing [10] provides the best compromise between PDR performance and message overhead also in presence of reduced node cooperation levels; and $ii)$ even a modest level of node cooperation is sufficient to achieve a considerable performance improvement over the fully non-cooperative scenarios.

II. Preliminaries

We consider the following DTN routing protocols:
$i)$ *Epidemic* [13]: the source node generates a new copy of the message each time it encounters a new node; when two relay nodes meet, they exchange each other message copies, till the message is eventually delivered to the destination node.
$ii)$ *Two-hops* [7]: the source node generates up to L copies of the message, and delivers $L-1$ copies of it to the first $L-1$ encountered new nodes; any node holding a single copy of the message, can deliver it only to the destination. This routing algorithm is equivalent to Spray and Wait routing with source spraying [10].
$ii)$ *Binary Spray and Wait* [10]: the source node initially holds L copies of the message; when a node holding $K \leq L$ copies of the message encounters a new node, it delivers to the new node $\left\lfloor \frac{K}{2} \right\rfloor$ copies of the message, and keeps the remaining $\left\lceil \frac{K}{2} \right\rceil$ with it. When a node remains with a single copy of the message, it can deliver the message only to the destination node.

In the analysis presented in the next sections, we assume the following:
1) *low load*: network traffic is low, so that buffer capacity on the nodes is not an issue (i.e., it can be considered as virtually infinite).
2) *node mobility*: nodes move according to an arbitrary mobility model with exponentially distributed meeting time with rate $\frac{1}{emt}$ between arbitrary node pairs, where emt is the expected meeting time between arbitrary node pairs. The fact that meeting times are exponentially distributed has been formally proved for some mobility models (e.g., random walks [1]), and confirmed through simulation-based analysis for common mobility models such as random waypoint, random direction, and so on [12]. We recall that the meeting time of a mobility model is defined as the time elapsed between a random time instant (after node spatial distribution has reached the stationary state) and the first "meeting" of an arbitrary node pair, where a "meeting" occurs when two nodes come into each other transmission range.
3) *transmission range*: two nodes can communicate iff they are within distance r, where r is the transmission range; this is equivalent to assuming isotropic, deterministic propagation of the radio signal with distance.
4) *no contention*: any communicating pair of nodes does not interfere with any other pair communicating at the same time. This assumption is justified by the very low node density in a typical DTN scenario, and by the relatively low network load scenario considered in this paper.
5) *fast transmissions*: relative speed between arbitrary node pairs is very low compared to transmission time; in other words, we assume that the duration of node "meetings" is always sufficient for the two nodes to exchange the content of their buffers.
6) *TimeToLive*: a message is correctly delivered to the destination iff it is received within a certain time, denoted TTL, since its generation.
7) *traffic model*: message source/destination pairs are chosen uniformly at random amongst the M network nodes. For obvious reasons, we assume source and destination are distinct nodes.

In the following, we will consider four different node behaviors, ranging from fully cooperative to fully defective:
$a)$ *Coop*: behave according to the routing protocol specifications.
$b)$ *Def*: discard messages received by other nodes (unless the node itself is the destination), and correctly send own messages.
$c)$ *Rand*: forward a message received by other nodes with fixed probability p.
$d)$ *TfT*: forward a message received by other nodes with probability p, where p depends on network conditions; for definiteness, in the following we assume that p equals the observed Packet Delivery Rate (PDR) for own messages.

III. Analysis of fully cooperative scenario

A. Epidemic Routing

Our goal is to characterize the expected PDR of epidemic routing under different degrees of cooperation between nodes in stationary conditions. We start by considering the fully cooperative scenario, i.e., all nodes behave according to $Coop$ strategy.

Before presenting the analysis, we introduce the following notation. We use notation $f(\lambda, x)$ and $F(\lambda, x)$ to denote the pdf and cdf of an exponential random variable of parameter λ, namely $f(\lambda, x) = \lambda e^{-\lambda x}$ and $F(\lambda, x) = 1 - e^{-\lambda x}$.

In the following, we repeatedly use the fact that the distribution of the minimum of a set of n independent exponential random variables of parameter λ is exponential of parameter $n\lambda$.

Let M denote the number of network nodes. By the law of large numbers, evaluating the expected PDR is equivalent to computing the probability of the event "a message generated at an arbitrary node i is delivered to an arbitrary destination node j within time TTL", denoted Rec. We have

$$P_{EC}(Rec) = \sum_{i=1}^{M-1} P(Rec|D_i) \cdot P(D_i) \ , \qquad (1)$$

where D_i denotes the event "destination is the i-th node receiving a copy of the message", and subscript EC stands for EpidemicCooperative.

Since the destination is chosen uniformly at random amongst $M-1$ nodes, we have $P(D_i) = \frac{1}{M-1}$ for each i, and (1) can be rewritten as follows:

$$P_{EC}(Rec) = \frac{1}{M-1} \sum_{i=1}^{M-1} P(Rec|D_i) \ . \qquad (2)$$

Let us now consider $P(Rec|D_i) = P(Rec_i)$. We treat separately the case $i = 1$ and $i \geq 2$. If $i = 1$, the destination node is the first node encountered by the source, and $P(Rec_i)$ equals the probability that the two nodes meet within time TTL. Given that the meeting time between an arbitrary pair of nodes is exponentially distributed with rate $\frac{1}{emt}$, and observing that conditioning on D_1 implies that the distribution of the meeting time between the source and the destination (which is the first node met by the source amongst the $M-1$ nodes) is exponential with rate $(M-1)/emt$, we have:

$$P(Rec_1) = F\left(\frac{M-1}{emt}, TTL\right) \ . \qquad (3)$$

Let us now consider the case $i \geq 2$. For the sake of clarity, in the following we say that a node is *colored* if it holds a copy of the message (note that initially only the source is colored). Let T_{i-1} denote the time at which the $(i-1)$-th node is colored by any of the $(i-1)$ nodes (including the source) currently holding the message. Starting from that time, there are i colored nodes in the network. Let $MT_{D,i}$ denote the meeting time between the destination and an arbitrary colored node, conditioned on the event that destination is the i-th colored node. Given the conditioning event, the destination is the *first* node among the remaining $(M-i)$ nodes meeting one of the i nodes with a copy of the message. Hence, $MT_{D,i}$ can be expressed as the minimum of a set of i exponential random variables with the same rate $\frac{(M-i)}{emt}$, whose distribution is exponential with rate $\frac{i(M-i)}{emt}$. We can then write, for $i \geq 2$:

$$\begin{aligned} P(Rec_i) &= \int_0^{TTL} P(Rec_i|T_{i-1} = t) f_{T_{i-1}}(t) dt = \\ &= \int_0^{TTL} F\left(\frac{i(M-i)}{emt}, TTL - t\right) f_{T_{i-1}}(t) dt, \end{aligned}$$

where $f_{T_{i-1}}$ is the pdf of random variable T_{i-1}. In order to compute $f_{T_{i-1}}$, we observe that $T_{i-1} = \sum_{j=1}^{i-1} MT_j$, where MT_j is the random variable corresponding to the meeting time between any of the j colored nodes and one of the remaining $(M-j)$ nodes. Similarly to above, we have that each of the MT_js is an exponential random variable with rate $\frac{j(M-j)}{emt}$, and that T_{i-1} is a sum of exponentially distributed random variables with different rates, where the rate λ_j of the j-th variable is $\frac{j(M-j)}{emt}$.

We now use the following lemma from [3]:

Lemma 1: Let $(X_i)_{i=1\ldots n}$, $n \geq 2$, be independent exponential random variables with pairwise distinct respective parameters λ_i. Then the pdf of their sum is

$$f_{X_1+X_2+\cdots+X_n}(x) = \left[\prod_{i=1}^{n} \lambda_i\right] \sum_{j=1}^{n} \frac{\mathrm{e}^{-\lambda_j x}}{\prod\limits_{\substack{k \neq j \\ k=1}}^{n} (\lambda_k - \lambda_j)}, \qquad x > 0.$$

Note that in our case the parameters of the exponential random variables *are not* distinct (in fact, the rate of MT_j equals the rate of MT_{M-j}, for $j = 1, \ldots, \lfloor M/2 \rfloor$), hence we cannot directly use the lemma above. To circumvent this problem, we artificially decrease the rate λ_{MT_j} of the MT_js random variables with $j > \lfloor M/2 \rfloor$ by multiplying them by $(1-\epsilon)$, for a small enough $\epsilon > 0$[1].

Hence, the rates MT_js are defined as:

$$\lambda_{MT_j} = \begin{cases} \frac{j(M-j)}{emt} & \text{if } j \leq \left\lfloor \frac{M}{2} \right\rfloor \\ (1-\epsilon) \cdot \frac{j(M-j)}{emt} & \text{if } \left\lfloor \frac{M}{2} \right\rfloor < j \leq M-2 \end{cases} ,$$

and Lemma 1 can be applied to compute $f_{T_{i-1}}(t)$.

To validate our analysis, we have performed a set of simulations, in which M nodes are initially distributed uniformly at random in a square area of $10km$ side. Nodes have a transmission range of $250m$, and move according to the random waypoint (RWP) mobility model with no pause time and fixed speed v. Since the stationary node spatial distribution generated by the RWP model is not uniform [4], we let the nodes initially move in order to reach the stationary distribution. After stabilization, a randomly selected node generates a message directed towards a randomly selected destination, and a binary value 0/1 is computed depending on whether the message is delivered to the destination within time $TTL = 3600s$ (value 1) or not (value 0). We performed a large set of such experiments (more than 20000 for each parameter setting), and experimentally estimated $P_{EC}(Rec)$ as the number of successful experiments (i.e., experiments returning value 1) over the total number of experiments.

The results of this experimental estimation of $P_{EC}(Rec)$ when $M = 30$ and nodes' speed v is varied between 2 and $15m/sec$ are reported in Figure 1. The figure reports also the analytical estimation computed (using Mathematica$^{\text{TM}}$) according to the analysis reported above, where ϵ is set to 0.1 in the definition of the λ_{MT_j} terms. The values of the emt for the random waypoint mobility model has been computed according to the formula reported in [12]. For the sake of comparison, we report also the asymptotical bound for the PDR derived in [14] (ZNKT curve). As seen from the figure,

[1]Our choice of decreasing, instead of increasing, the actual rate of the MT_js goes in the direction of providing a *lower bound* to the actual PDR, which is more useful than an upper bound for, e.g., QoS estimation.

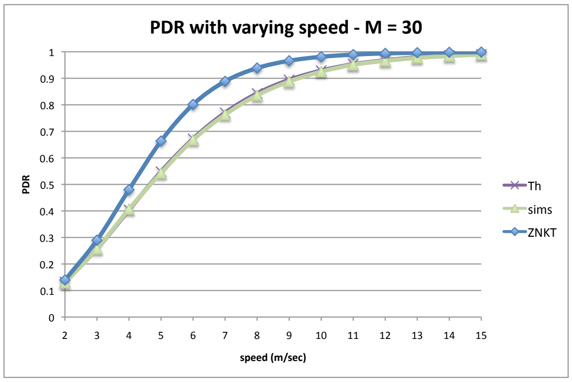

Fig. 1. Probability of correctly delivering a message within time $TTL = 3600s$ with epidemic routing for RWP mobile networks with $M = 30$ nodes and increasing node velocity. Fully cooperative scenario.

our analytical estimation is very accurate for all the range of speed considered, while the bound of [14] is accurate only when the experimental PDR is either very low or very high.

B. Two-hops routing

The analysis of two-hops routing is much more involved than the case of epidemic routing, since the process of spreading the message in the network is asymmetric. The process of coloring nodes under two-hops routing can be logically divided into two phases, called *spraying* and *wait* phase (see [11]). In the spraying phase, up to $L-1$ copies of the message are delivered to up to $L-1$ distinct relay nodes; during this phase, the coloring process is asymmetric, since the source colors every new encountered node, while relay nodes can color only the destination. In the wait phase, the coloring process becomes symmetric, since all colored nodes (including the source, which now holds only the last copy of the message) can deliver the message only to the final destination. As we shall see, the difficulty in analyzing the probability of message delivery within time TTL with two-hops routing lies in the asymmetry of coloring during the spraying phase.

Before presenting the analysis, we need some preliminary notions and definitions. Consider n i.i.d. continuous random variables $X_1, \ldots, X_n$, and let $\overline{X}_1, \ldots, \overline{X}_n$ be a realization of the n random variables. We now order the values of the realization in increasing order, starting from the smallest, and denote with $\overline{X}_{(1)}, \ldots, \overline{X}_{(n)}$ the ordered values. Each of the $\overline{X}_{(i)}$, for $i = 1, \ldots, n$, can be considered as a realization of a random variable $X_{(i)}$, which is known as the *i-th order statistic* of random variables $X_1, \ldots, X_n$ (note that $X_{(1)} = \min\{X_1, \ldots, X_n\}$ and $X_{(n)} = \max\{X_1, \ldots, X_n\}$). Denoting by $\psi(x)$ and $\Psi(x)$ the pdf and cdf, respectively, of each of the X_i, the pdf of the i-th order statistic of random variables $X_1, \ldots, X_n$ is [6]:

$$Ord(n, i, x) = \frac{n!}{(i-1)!(n-i)!} \Psi(x)^{i-1} (1 - \Psi(x))^{n-i} \psi(x) \ .$$

In the following, we denote by $Ord(n, i, \lambda, x)$ the pdf of the i-th order statistic of a set of n i.i.d. exponential random variables of parameter λ.

Similarly to the case of epidemic routing, we compute the probability $P_{2HC}(Rec)$ of delivering the message to destination within time TTL as follows:

$$P_{2HC}(Rec) = \sum_{i=1}^{L} P(Rec|D_i) \cdot P(D_i) \ , \qquad (4)$$

where D_i denotes the event "destination is the i-th colored node", and subscript 2HC stands for 2HopsCooperative. Note that the summation ends at L, since at most $L-1$ relay nodes are colored before the destination.

When $i = 1$, the destination is the first colored node, and the spraying phase does not even start. We are then in the same conditions as in the case of epidemic routing, and we can write:

$$P(Rec|D_1) \cdot P(D_1) = F\left(\frac{M-1}{emt}, TTL\right) \cdot \frac{1}{(M-1)} \qquad (5)$$

The case $i = L$ is also easy to handle. When $i = L$, the spraying process is finished (i.e., $(L-1)$ relay nodes have been colored by the source), and coloring of the destination occurs during the wait phase. Note that in the wait phase the coloring process is symmetric, hence any of the L nodes currently holding a copy of the message can color the destination. Denote by $S_1, \ldots, S_{M-1}$ the random variables corresponding to the first time source node S meets node i after message generation, for $i = 1, \ldots, M-1$ (see Figure 2). It is easy to see that the starting time of the wait phase is random variable $S_{(L-1)}$, i.e., the $(L-1)-th$ order statistic of random variables $S_1, \ldots, S_{M-1}$, whose pdf is $Ord(M-1, L-1, 1/emt, x)$. Furthermore, conditioned on $S_{(L-1)} = t$, the probability of delivering the message to destination within time TTL is given by the cdf at time $(TTL-t)$ of an exponential random variable with rate L/emt, which represents the time at which the first amongst the L colored nodes meets the destination. We can then write:

$$P(Rec|D_L) = \\ = \int_0^{TTL} F\left(\frac{L}{emt}, TTL - t\right) Ord(M-1, L-1, 1/emt, t) dt \ . \qquad (6)$$

The value of $P(D_L)$ is computed as follows:

$$P(D_L) = 1 - \sum_{i=1}^{L-1} P(D_i) \ , \qquad (7)$$

where the $P(D_i)$s when $i = 2, \ldots, L-1$ are computed below.

When $1 < i < L$, we divide event D_i into mutually disjoint events D_i^S and $D_i^{\overline{S}}$, corresponding to the situation in which the destination is colored by S or by a relay node. Conditioned on event D_i^S, the probability of delivering the message to the destination can be computed observing that the destination is the i-th node encountered by S, and that the random time of this encounter corresponds to the i-th order statistic of random variables $S_1, \ldots, S_{M-1}$. We can then write:

$$P(Rec|D_i^S) = \int_0^{TTL} Ord(M-1, i, 1/emt, t) \ dt \ . \qquad (8)$$

We now compute $P(D_i^{\overline{S}})$, from which $P(D_i^S)$ can be trivially derived. We need to introduce some further notation

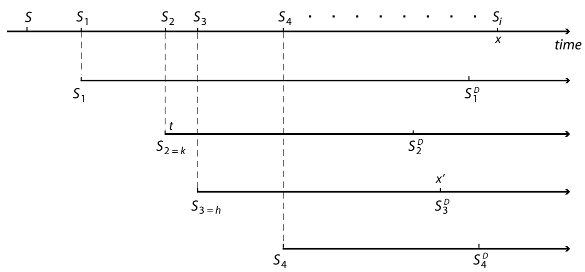

Fig. 2. The destination coloring stochastic process during the spraying phase.

(see Figure 2). We use random variables S_h^D to denote the time at which relay node h (which has been colored at time S_h) first meets the destination. Note that, conditioned on a specific value of $S_h = t$, $S_h^D - t$ has exponential distribution of rate $1/emt$, for $h = 1, \ldots, i-1$. In order to compute $P(D_i^{\overline{S}})$, we further subdivide $D_i^{\overline{S}}$ into disjoint events $D_{i,k}^{\overline{S}}$, $k = 1, \ldots, i-1$, where $D_{i,k}^{\overline{S}}$ is the event "the destination is colored by the k-th relay node"[2]. Note that the above occurs if and only if $S_k^D < S_h^D$ for each $h = 1, \ldots, i-1$ (with $h \neq k$) *and* $S_k^D < S_i$ (see Figure 2).

Let us first compute the probability that $S_k^D < S_h^D$, for arbitrary distinct k, h, with $1 < k, h < i$. Conditioned on $S_h^D = x'$ and $S_k = t$, the pdf of event $S_k^D < S_h^D$ equals the probability that random variable $\hat{S}_k = S_k^D - S_k$, which is exponential of parameter $1/emt$, is below $(x' - t)$ (see Figure 2). We further observe that the pdf of variable S_k is $Ord(M-1, k, 1/emt, t)$. We can then write:

$$P(S_k^D < S_h^D) = \int_0^\infty G(x') f_{S_h^D}(x') dx' \ , \qquad (9)$$

where $f_{S_h^D}(x')$ is the pdf of random variable S_h^D and

$$G(x') = \int_0^{x'} F\left(\frac{1}{emt}, x' - t\right) Ord(M-1, k, \frac{1}{emt}, t) dt \, .$$

In order to derive $f_{S_h^D}(x')$, we observe that, by setting $\hat{S}_h = S_h^D - S_h$, we can write $S_h^D = S_h + \hat{S}_h$. Random variable S_h is the h-th order statistic of random variables $S_1, \ldots, S_{M-1}$, and $\hat{S}_h$ is an exponential random variable of parameter $1/emt$. Hence, $f_{S_h^D}(x)$ is the pdf of a random variable which is the sum of two independent random variables with different (and non-trivial) distributions, which is not easy to derive. To circumvent this problem, we approximate the pdf of S_h with that of S_1 (i.e., of the first order statistic), which is exponential with rate $(M-1)/emt$. Now, S_h^D can be considered as the sum of two independent exponential random variables with different rates, whose distribution is given by Lemma 1. Summarizing, we have

$$f_{S_h^D}(x') \approx f_{S_1 + \hat{S}_h}(x') \ , \qquad (10)$$

where $f_{S_1 + \hat{S}_h}(x')$ is defined as in Lemma 1.

Note that the probability mass of variable S_h is skewed to the right in the time axis with respect to that of variable S_1, with an increasing skewness for increasing h. Hence, our approximation of $f_{S_h^D}(x')$ becomes less and less accurate as h increases. However, the simulation results presented in the following show that the above approximation is very accurate as long as the ratio L/M is around 0.1 or below. Deriving a better approximation of $f_{S_h^D}(x')$ is left for future work.

We now compute the probability that $S_k^D < S_i$, for any $1 < k < i$. Similarly to above, we observe that, conditioned on $S_i = x$ and $S_k = t$, the pdf of event $S_k^D < S_i$ equals the probability that $\hat{S}_k = S_k^D - S_k$ is below $(x - t)$ (see Figure 2). Furthermore, we observe that the pdf of S_i is $Ord(M-1, i, 1/emt, x)$, and that of S_k is $Ord(M-1, k, 1/emt, t)$. We can thus write:

$$P(S_k^D < S_i) = \int_0^\infty H(x) Ord(M-1, i, \frac{1}{emt}, x) \, dx \ , \qquad (11)$$

where

$$H(x) = \int_0^x F\left(\frac{1}{emt}, x - t\right) Ord(M-1, k, \frac{1}{emt}, t) \, dt \, .$$

We can now compute $P(D_i^{\overline{S}})$ as follows:

$$P(D_i^{\overline{S}}) = \sum_{k=1}^{i-1} \left(P(S_k^D < S_i) \prod_{\substack{h=1 \\ h \neq k}}^{i-1} P(S_k^D < S_h^D) \right) \ . \qquad (12)$$

Note that in the above equation we assume that pairs of events ($S_k^D < S_h^D$,$S_k^D < S_{h'}^D$), with $h \neq h'$, are mutually independent, which is not true in general.

We can now compute $P(D_i^S)$ by observing that the probability that the i-th node met by the source is the destination is $1/(M - (i-1))$, implying:

$$P(D_i^S) = \left(1 - P(D_i^{\overline{S}})\right) \cdot \frac{1}{M - (i-1)} \ . \qquad (13)$$

In order to complete the analysis, we are left to compute the probability $P(Rec|D_{i,k}^{\overline{S}})$, i.e., the probability that the message is delivered to the destination within time TTL conditioned on the event that the destination is colored by the k-th relay node, for some $1 < k < i$. Since under such conditioning the destination is colored at time S_k^D (see Figure 2), we have:

$$P(Rec|D_{i,k}^{\overline{S}}) =$$
$$= \int_0^{TTL} F(\frac{M-i}{emt}, TTL - t) Ord(M-1, k, \frac{1}{emt}, t) \ dt \ . \qquad (14)$$

In the above equation, we have used the fact that, conditioned on event $D_{i,k}^{\overline{S}}$, the pdf of random variable S_k^D is closely approximated by the pdf of an exponential random variable of parameter $(M-i)/emt$, corresponding to the first encounter (which, conditioned on $D_{i,k}^{\overline{S}}$, we know is with the k-th relay node) between the destination and one of the i nodes (including the source) currently holding a copy of the message.

Summarizing, we can compute any of the terms $P(Rec|D_i) \cdot P(D_i)$ in the summation of (4) as follows:

[2]Implicit here is the assumption that relay nodes are ordered according to their meeting time with the source.

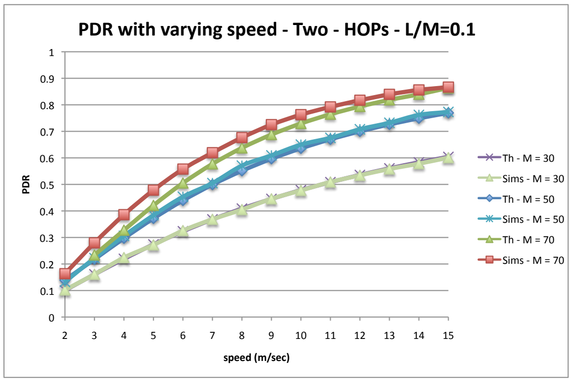

Fig. 3. Probability of correctly delivering a message within time $TTL = 3600s$ with two-hops routing for RWP mobile networks with different number of nodes, $L = M/10$, and increasing node velocity. Fully cooperative scenario.

$$P(Rec|D_i) \cdot P(D_i) = P(Rec|D_i^S)P(D_i^S) + + \sum_{k=1}^{i-1} P(Rec|D_{i,k}^{\overline{S}})P(D_{i,k}^{\overline{S}}) \ ,$$

where $P(D_{i,k}^{\overline{S}})$ is defined as follows:

$$P(D_{i,k}^{\overline{S}}) = P(S_k^D < S_i) \cdot \left(\prod_{\substack{h=1 \\ h \neq k}}^{i-1} P(S_k^D < S_h^D) \right) \ .$$

In order to estimate the impact of the several approximations made in our analysis on the accuracy of the analytical estimation of $P_{2HC}(Rec)$, we have done extensive simulations, using the same setting as in the experiments with epidemic routing. Figure 3 reports the results of the simulation experiments, along with our analytical estimation, for varying node speed and different values of M, where L is set to $M/10$.[3] As seen from the figure, the accuracy of our formula is extremely good for $M = 30$ and $M = 50$, while it becomes relatively worse for $M = 70$. As mentioned above, the increasingly lower inaccuracy of our analytical estimate of $P_{2HC}(Rec)$ as L increases is due to the fact that the accuracy of our estimation of pdf $f_{S_h^D}(x')$ in equation (9) worsens as L increases. This is confirmed by a second set of experiments, in which we have fixed $M = 70$ and velocity to $15m/sec$, and varied L from 2 to 12. The results of this second set of experiments, reported in Figure 4, fully confirm the above observation.

C. Binary SW routing

The node coloring process is very difficult to accurately analyze in case of Binary SW routing. The difficulty lies in modeling the stochastic process of spraying, which is more complex than in the case of two-hops routing. More specifically, with Binary SW every colored node with at least two copies of the message (not only the source) can color a non-destination node during spraying. Hence, we can logically divide nodes during the spraying phase into three categories: non-colored, colored active, and colored inactive. Colored active nodes have at least two copies of the message, and color the first uncolored node they meet independently of whether it is the final destination of the message. On the contrary, colored inactive nodes, which have only one copy of the message, can color only the destination. Note that colored active nodes can become inactive upon coloring of a new node, while the opposite transition is not possible. This ensures the eventual termination of the spraying phase, which happens when all colored nodes become inactive. When the last active colored node becomes inactive, the waiting phase starts, during which all colored nodes can color only the destination.

[3]ZNKT bound for this case is not available, since two-hops routing is analyzed in [14] only when $L = M$.

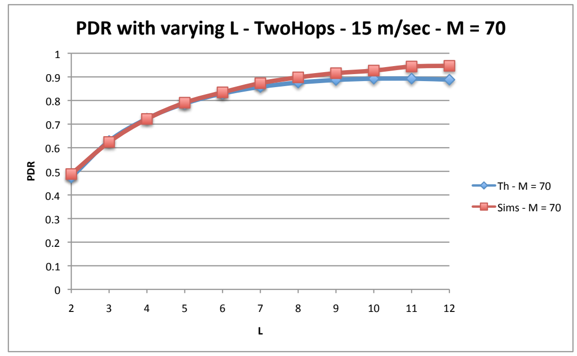

Fig. 4. Probability of correctly delivering a message within time $TTL = 3600s$ with two-hops routing for RWP mobile networks with $M = 70$, speed set to $15m/sec$, and varying values of L. Fully cooperative scenario.

As seen from the above description, the coloring process with Binary SW is quite complex, and characterizing its relevant stochastic properties (e.g., number of colored active nodes at a given time, pdf of the duration of the spraying phase, and so on) is a highly non-trivial task. For this reason, we defer this analysis to future work, and use simulations to estimate Binary SW performance with different degrees of node cooperation.

IV. Analysis of non-cooperative scenarios

A. All defective scenario

In case all nodes are defective, the protocol used to route messages between nodes is irrelevant, since the only possible way to deliver a message to destination is through direct transmission between source and destionation. Under our working assumption of exponentially distributed meeting times, the probability that source and destination come into each other transmission range within time TTL is given by:

$$P_{AD}(Rec) = \left(1 - e^{-\frac{TTL}{emt}}\right) \ ,$$

where AD stands for AllDefective.

The above characterization has been validated through simulation, which has shown an almost perfect overlapping between simulation results and analytical estimate.

B. Rand scenario

We recall that in case of *Rand* cooperation, a node which is not the final destination forwards the message with a given fixed probability p. The relevant cases are when $0 < p < 1$, since otherwise we are either in the fully defective ($p = 0$) or fully cooperative ($p = 1$) scenario.

We start with a characterization of protocol performance under *Rand* cooperation, which will be used in the next subsection to estimate stationary points of operation under *TfT* cooperation.

In the following, we provide an accurate analytical bound of the performance of epidemic routing under *Rand* cooperation, while we will estimate performance of two-hops and binary SW routing only through simulations.

The node coloring process under epidemic routing and *Rand* cooperation is more complex than in the fully cooperative scenario, due to one additional source of randomness in message propagation, namely, the probability p of forwarding the message when a colored node meets an uncolored one. Since node coloring is no longer deterministic, not only the expected meeting time, but also the expected inter-meeting time[4] of the underlying mobility model comes into play. To better understand this point, let us analyze the process of coloring the first non-source node. When the source meets the first (uncolored) node – which occurs according to an exponential random variable with rate $(M-1)/emt$ –, the new node is colored with probability $p<1$. So, with probability p, the rate of the first coloring is the same as in the fully cooperative scenario. However, with probability $1-p$, the new node (call it u) remains uncolored, and the rate of first coloring is determined not only by the rate of encounter of the source with the second uncolored node – which is a random variable with distribution equal to the pdf of the second order statistics of random variables S_is defined in the previous section –, but also by the rate of re-encounter of the source with node u. More specifically, denoting by $S_{(i)}$ the i-th order statistic of the S_is, and by S_u the time between the first and second encounter between the source and node u, we have that the second encounter between the source and an uncolored node is given by $\min\{S_{(2)}, S_{(1)}+S_u\}$. At the time of the second encounter, we again have a node coloring with probability p, and the above reasoning is re-iterated.

As seen from the above description, the characterization of relevant stochastic properties of epidemic routing under *Rand* cooperation is very complex, as it involves mixing estimation of expected meeting and inter-meeting times between different groups of nodes. For this reason, we consider a related stochastic coloring process, in which potential relay nodes are apriori divided into cooperative and non-cooperative nodes. More specifically, we assume that a *fixed* fraction p of the $M-2$ potential forwarders are cooperative (i.e., forward a message with probability 1), while the remaining $(1-p)(M-2)$ nodes are non-cooperative (i.e, forward a message with probability 0). The analysis of this second coloring process is straightforward, since it is equivalent to performing epidemic routing in a fully cooperative network with $p(M-2)+1$ – the $p(M-2)$ cooperative relays plus the destination – (instead of $(M-1)$) nodes.

We have verified the accuracy of our analytical estimation of PDR with epidemic routing under *Rand* cooperation through extensive simulation. The simulation setting is the same as in the previous section. Figure 5 shows the PDR resulting from simulations and the one resulting from our analytical estimation for different values of the forwarding probability p. Note that we have chosen settings for p such that $p(M-2)$ is an integer. For reference, the figure reports also the analytical bound computed according to [14]. As seen from the figure, our estimation turns out to be a relatively accurate *lower bound* to the actual PDR, in contrast to the ZNKT bound, which considerably *overestimates* performance. Hence, differently from the estimation of [14], our bound can be used to provide *minimal performance guarantees* of epidemic routing under *Rand* cooperation. It is also worth observing that while ZNKT characterization turns out to be relatively accurate only for relatively low or high PDR values, our characterization is relatively accurate for the whole range of PDR values, and it is indeed very accurate for $p=0.75$.

C. TfT scenario

The characterization of epidemic routing performance under *Rand* cooperation presented in the previous sub-section can be used to predict stationary operational points of a network under the *TfT* scenario. We recall that with *TfT* cooperation, the packet forwarding probability is adaptive to network conditions: more specifically, the packet forwarding probability p_u for node u equals the long-term observed PDR of the messages sent by u.

Stationary network operational points can be estimated by characterizing the PDR under *Rand* cooperation with different values of the parameter p, and finding the value(s) $\bar{p}$ of p such that the resulting PDR equals $\bar{p}$. To see that these are stationary operational points of a network under *TfT* cooperation, assume all nodes are currently observing a PDR of $\bar{p}$; given *TfT* cooperation, all nodes will forward messages with probability $\bar{p}$, i.e., they behave like a network with *Rand* cooperation of parameter $\bar{p}$, which will keep the observed PDR (and, hence, the cooperation level) at $\bar{p}$.

The characterization of stationary operational points under *TfT* cooperation by means of simulation, and using our analytical bound and the one of [14], are reported in Figure 6–left. We first observe the existence of stationary operational points for all considered speed values; operational points can be very bad (below 0.1 at $2m/s$), relatively good (around 0.7 at $8m/s$), or even close to optimal performance (at $15m/s$). This indicates that the effect of *TfT* cooperation on epidemic routing performance is highly dependent on network conditions:*the better the network conditions, the lesser the effect of the reduced cooperation level*. To be more specific, when the underlying network performance is bad (lowest speed), the performance drop due to *TfT* cooperation w.r.t. fully cooperative scenario is in the order of 50% (PDR drops from 0.13 to 0.06); in the average speed case, the performance drop is in the order of 16% (PDR drops from 0.83 to 0.7); finally, in case of very good network performance (highest speed), the performance drop is negligible.

Concerning the accuracy of the analytical bounds, we observe that while the ZNKT bound can be used to accurately estimate stationary operational points only when epidemic routing performance under full cooperation is either very bad of very good, it considerably overestimates the stationary op-

[4]The expected inter-meeting time is defined as the expected time between two successive meetings between an arbitrary node pair.

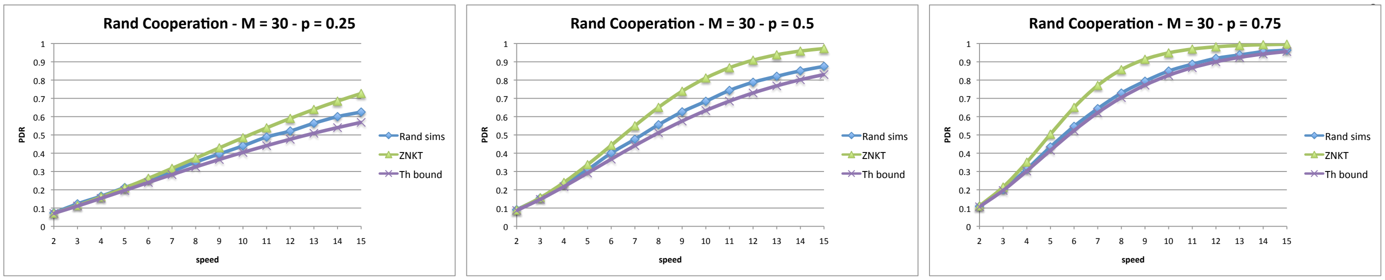

Fig. 5. Probability of correctly delivering a message within time $TTL = 3600s$ with epidemic routing for RWP mobile networks with $M = 30$, $Rand$ cooperation, and varying node velocity.

erational point for the intermediate speed value. In particular, according to ZNKT bound the stationary operational point when the speed is $8m/s$ is around 0.9, while it is around 0.7 according to the simulation results. On the other hand, our analytical bound is able to provide an accurate estimate of stationary operational points for the entire range of considered speeds (the estimate is around 0.6 when speed is $8m/s$).

We have also estimated through simulations the network stationary operational point under *TfT* cooperation with two-hops and binary SW routing (Figure 6–center, –right), using two different values for the number L of message copies to forward. While in case of bad performance of the underlying network (lowest speed) the routing algorithm has little influence on the stationary operational point (which is around 0.06), in case of medium or good network performance the routing algorithm does have an impact on the stationary operational point. More specifically, with medium speed, the operational point is around 0.33 with two-hops routing (for both values of L), while it is around 0.35 (resp., 0.66) with binary SW routing and $L = 4$ (resp., $L = 8$). These values should be compared with the 0.7 operational point in case of epidemic routing. In case of the highest speed value, the situation is worse, with stationary operational points at 0.63 (resp., 0.72) in case of two-hops routing with $L = 4$ (resp., $L = 8$), and at 0.45 (resp., 0.83) in case of binary SW routing with $L = 4$ (resp., $L = 8$), which should be compared with the 0.99 stationary operational point achieved with epidemic routing. Hence, performance drop under the *TfT* scenario when "lightweight" routing protocols are used instead of epidemic routing is considerable (varying in the range 30–50%) in case the underlying network performance (determined by the mobility pattern) is medium to very good. Of course, this performance drop should be carefully traded off with the lesser message overhead under two-hops and binary SW routing, which can be tuned through parameter L. It is worth noting that in some cases, by suitably tuning L binary SW routing provides performance under TfT close to that of epidemic routing, with a much less message overhead (e.g., $8m/s$ speed and $L = 8$). It is also worth observing the relative performance drop between the fully cooperative and *TfT* scenario for i) two-hops and ii) binary SW routing. In case i), it is in the order of 30% (resp., 38%) when $L = 4$ (resp., $L = 8$) for the medium speed, and in the order of 9% (resp., 11%) when $L = 4$ (resp., $L = 8$) for the highest speed. In case ii), it is in the order of 27% (resp., 5%) when $L = 4$ (resp., $L = 8$) for the medium speed, and in the order of 30% (resp., 4%) when $L = 4$ (resp., $L = 8$) for the highest speed. Hence, binary SW shows the better resilience to less cooperative node behavior with respect to the other routing protocols. These results partially contradict the findings of [9], which instead identified two-hops routing as the more resilient to lower node cooperation level. However, the evaluation of [9] was done only for the case $L = M$, and, as we have seen, the setting of L has a considerable impact on a protocol resilience to lower node cooperation levels.

V. Effects of Node Cooperation Level on Routing

In this section we compare the relative performance of the three routing protocols considered in this paper under different levels of node cooperation. Since analytical bounds are available only for a subset of the considered protocols, we consistently use simulations to estimate performance.

The simulation setting is similar to the one described in Section III-A, except that we consider a larger network with $M = 80$ nodes. For two-hops and binarySW routing, we consider two values of parameter L, namely 8 and 16. For each of the considered protocol, we estimate PDR through extensive simulation under the *Rand* scenarios with different values of p. We consider both $p = 0$ and $p = 1$ (equivalent, respectively, to the *Def* and *Coop* scenario), as well as intermediate values of p (0.25, 0.5, and 0.75). The results of this set of simulations are reported in Figure 7. The results for the case $p = 0.75$, which are qualitatively similar to the ones with $p = 1$, are not reported for lack of space. The following observations are in order:

i) Epidemic routing is always the best performing protocol. This is not surprising, considering the higher number of message copies spread under epidemic routing.

ii) Binary SW routing performance is highly dependent on the choice of L, especially when the node cooperation level is medium/high; if L is sufficiently high (in the order of $0.2M$), binary SW performance is close to that of epidemic routing, and message overhead is significantly reduced.

iii) Two-hops routing performance is less dependent on the choice of L, especially when the node cooperation levels is low (the two curves are virtually overlapping when $p = 0.25$); in general, two-hops routing provides the worst performance among the considered protocols, although in some cases performs very close to binary SW routing ($L = 8$ and $p = 1$).

Overall, the results of our simulation suggest that, even in presence of reduced node cooperation level, binary SW routing (with properly set parameter L) provides the best compromise between PDR performance and message overhead. Our results also suggest that even when node cooperation level is close to

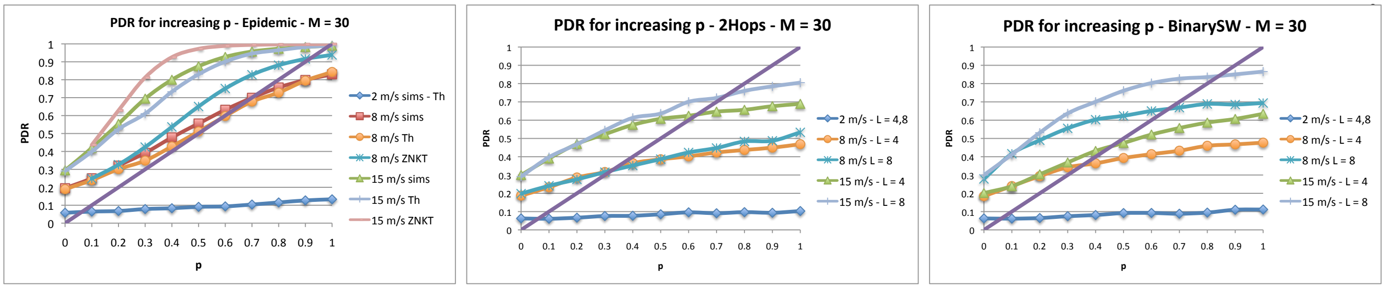

Fig. 6. Probability of correctly delivering a message within time $TTL = 3600s$ with epidemic (left), two-hops (center), and binary SW (right) routing for RWP mobile networks with $M = 30$, and *Rand* cooperation with various values of p. In case of epidemic routing, the $2m/s$ curves for both analytical bounds are overlapped with simulation results, and are not shown.

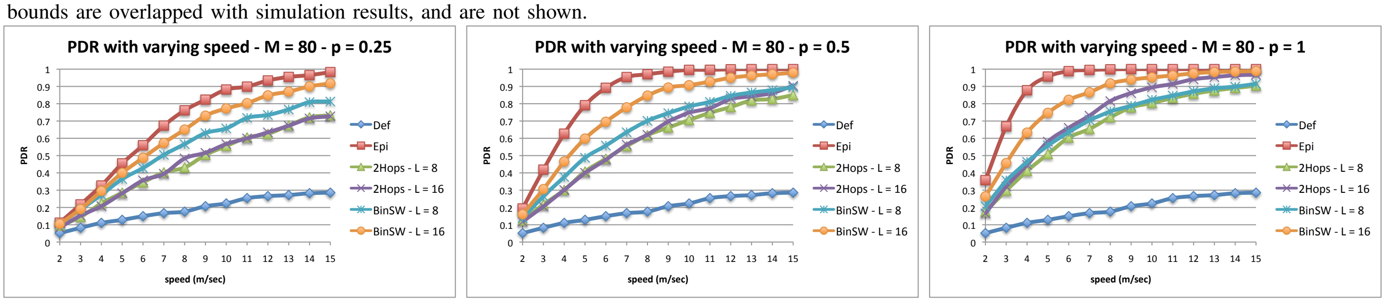

Fig. 7. Probability of correctly delivering a message within time $TTL = 3600s$ with *Rand* cooperation for RWP mobile networks with $M = 80$, with $p = 0.25$ (left), $p = 0.5$ (center), and $p = 1$ (right). For reference, the curve relative to the *Def* scenario is reported in all graphics.

minimum ($p = 0.25$), routing performance can be considerably increased with respect to the most pessimistic *Def* scenario. In particular, performance improvement is as high as 430% with epidemic routing, as high as 275% with two-hops routing, and as high as 370% with binary SW routing.

VI. Conclusions and Future Work

In this paper, we have characterized the performance of common DTN routing protocols under different levels of node cooperation. The analytical bounds presented in this paper allow deriving minimal performance guarantees for epidemic and two-hops routing. To the best of our knowledge, these are the first similar results presented in the literature. Finally, we have performed extensive simulations, and found that: i) binary SW provides the best compromise between PDR performance and message overhead also in presence of reduced node cooperation levels; and ii) even a modest level of node cooperation is sufficient to achieve a considerable performance improvement over the fully non-cooperative scenarios.

We remark that the results presented in this paper can be considered only as a first step towards a better understanding of DTN routing protocol performance in non-cooperative (or partially cooperative) scenarios. Several avenues for further research are open, such as deriving an analytical characterization of binary SW performance, evaluating the effect of limited buffer size when network traffic is medium/high, including more sophisticated node behaviors in the analysis, and so on. We believe the tools and techniques presented in this paper will be helpful for those purposes.

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