Probability Delegation Forwarding in Delay Tolerant Networks

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***Abstract*—**

I. Introduction

Delay Tolerant Network (DTN) is a type of wireless mobile networks that do not guarantee the existence of a path between a source and a destination at any time. When two nodes move within each other's transmission range during a period of time, they *contact* or *meet* each other. When they are out of each other's transmission range, the connection is lost. The message to be delivered needs to be stored in the local buffer. Examples include people carrying handy devices moving in conferences, university campuses and in social settings. The message delivery in this kind of network is multi-hop and the connection between nodes is *non-predictable*. Furthermore, there is limited knowledge of each node about the network.

In such a DTN, the most important metric is the *delivery ratio*, because the network must be able to reliably deliver data. The second metric is the *delivery latency* [11]. And the third one that attempts to minimize resource consumption such as buffer space or power is the number of *copies* duplicated.

In this paper, the challenge is to reduce the number of copies without affecting too much delivery ratio and delivery latency as in Delegation Forwarding.

II. Related Work

Due to the uncertainty and time-varying nature of DTNs, routing poses unique challenges. In the literature, some routing approaches are based on deterministic mobility [9], [10], [12]–[16], [18], [19], [21] while some others are based on general mobility where nodes mobility cannot be predicted [2], [5], [20]. In this paper, we discuss the situation of general mobility: nodes move dynamically in different directions with different speeds and thus the connection between nodes is non-predictable.

If the general mobility model is used, when a source node wants to find a route to a destination, since it does not know where the destination lies, one rudimental approach is to perform a flooding-based route discovery as in [20] where whenever a host receives a message, it will pass it to all those nodes it can reach directly at that time so that the spread of the message is like the epidemic of a disease. Epidemic routing has the highest performance. However, it has non-neglectable drawbacks [17]: it consumes a high amount of bandwidth and energy; may result in poor performance because of high contention for shared resources. As the average node degree increases, it is not scalable in terms of memory size needed and number of transmissions performed.

In [7], a strategy called *delegation forwarding* has been put forward. The main idea of delegation forwarding is that each node has an associated quality metric. A node will forward a message only if it encounters another node whose quality metric is greater than any seen by the message so far. The authors show that despite the simplicity of the strategy, it works surprisingly well. Analysis shows that in a N-node network, delegation forwarding has expected cost $O(\sqrt{N})$ while the naive scheme of forwarding to any higher quality node has expected cost $O(N)$. Simulation on real traces shows performance as good as other schemes at a much lower cost.

The message is *only* forwarded to *highest*-quality nodes. To make the forwarding decision, the system should be observed for a sequence of samples. Conceptually, a small number of replica copies are selected which are the very best candidates to deliver the message to the destination eventually.

The key element in delegation forwarding is the existence of a quality metric with the property that nodes with higher quality are better candidates as intermediate message carriers than lower quality nodes. The quality can be destination dependent and destination independent. FRESH [8] uses the time elapsed since the last contact with the destination node as a metric. This is destination dependent. [6] uses the total contacts of a node with all other nodes as a metric and hence is destination independent.

The delegation forwarding is presented in Algorithm DF.

III. Probability Delegation Forwarding (PDF)

We believe that we can reduce costs even more by involving probability in the routing process. Our approach seeks to forward the message to the *highest* quality nodes in the system with a probability. That is, if the probability is set as p, and if a node $\mathscr{N}_i$ meets a node $\mathscr{N}_j$ with a higher quality than itself, $\mathscr{N}_i$ will forward the message to $\mathscr{N}_j$ with a probability of p. On the other hand, it is also possible that $\mathscr{N}_i$ will not

Algorithm DF: Delegation Forwarding

Let $\mathscr{N}_1, \cdots, \mathscr{N}_N$ be nodes
Let $\mathscr{M}_1, \cdots, \mathscr{M}_M$ be messages
Node $\mathscr{N}_i$ has quality x_{im} and threshold τ_{im} for $\mathscr{M}_m$.
INITIALIZE $\forall i, m : \tau_{im} \leftarrow x_{im}$
On contact between $\mathscr{N}_i$ and node $\mathscr{N}_j$:
for m in $1, \cdots, M$ **do**
  if $\mathscr{M}_m$ is currently held by $\mathscr{N}_i$ **then**
    if $\tau_{im} < x_{jm}$ **then**
      $\tau_{im} \leftarrow x_{jm}$
      if $\mathscr{N}_j$ does not have $\mathscr{M}_m$ **then**
        forward $\mathscr{M}_m$ from $\mathscr{N}_i$ to $\mathscr{N}_j$
      end if
    end if
  end if
end if

Algorithm PDF: Probability Delegation Forwarding

Let $\mathscr{N}_1, \cdots, \mathscr{N}_N$ be nodes
Let $\mathscr{M}_1, \cdots, \mathscr{M}_M$ be messages
Node $\mathscr{N}_i$ has quality x_{im} and threshold τ_{im} for $\mathscr{M}_m$.
INITIALIZE $\forall i, m : \tau_{im} \leftarrow x_{im}$
On contact between $\mathscr{N}_i$ and node $\mathscr{N}_j$:
for m in $1, \cdots, M$ **do**
  if $\mathscr{N}_i$ is chosen by probability $p : (p < 1)$ **then**
    if $\mathscr{M}_m$ is currently held by $\mathscr{N}_i$ **then**
      if $\tau_{im} < x_{jm}$ **then**
        $\tau_{im} \leftarrow x_{jm}$
        if $\mathscr{N}_j$ does not have $\mathscr{M}_m$ **then**
          forward $\mathscr{M}_m$ from $\mathscr{N}_i$ to $\mathscr{N}_j$
        end if
      end if
    end if
  end if
end if

forward the message to $\mathscr{N}_j$ with a probability of $1-p$. Since $p \in [0, 1)$, in each forwarding, the number of copies will be further reduced. Therefore, the total costs in routing will be reduced.

In the process, no global knowledge is needed. Each node decides whether to forward the message or not by itself.

The complete algorithm is shown in Algorithm PDF.

IV. Analysis

In this section, we compare the costs of the two algorithms. We consider a single message and calculate the upperbound on the number of copies created for each message.

A. Cost of DF

The cost of DF is given in [7]. To make the paper inclusive, we include the idea here. For any node i maintaining a quality metric x_i $(0 < x_i \leq 1)$ and a threshold value τ_i, we focus on the gap $g_i = 1 - \tau_i$ between the current threshold and 1. The node that generates the message has an initial threshold $\tau_i = x_i$. The initial gap $g = 1 - x_i$.

Consider a node that updated its gap value n times. The node's current gap is denoted as the random variable G_n. Since nodes meet according to rates that are independent of node quality, the node is equally likely to meet a node with any particular quality value. The next update of the gap occurs when it meets a node with a quality greater than G_n, and all values above this threshold are equally likely.

Hence, we can write

$$G_{n+1} = G_n \times U, \tag{1}$$

where U is independent of G_n and follows a uniform distribution on $(0, 1]$. By induction we then find:

$$E[G_{n+1}|G_n] = \frac{G_n}{2}, \text{hence } E[G_n] = \frac{g}{2^n}. \tag{2}$$

Moreover, from Eq.(1), we see that G_n approximately follows a lognormal distribution (see section 2.2 in [3]), with median $\frac{g}{e^n}$. Hence the distribution is highly skewed with most of the probability mass below the mean, and so with large probability we have $G_n \leq \frac{g}{2^n}$.

The replication process can be described by a dynamic binary tree T, which contains all the nodes that have a copy of the message. Initially T contains a single node with associated gap g. Each time a node with a copy of the message meets another node having higher quality than any node seen so far, two child nodes are created for the node. Both have updated gap value. Some branch of the tree will grow faster than others. The total size of the tree represents the upperbound on the number of copies created. We wish to bound the total size of the tree.

We define the set $B = \{i | x_i \geq 1 - \frac{g}{\sqrt{N}}\}$, which we call the *target set*. We will also identify a subtree of the tree T in which children are excluded for nodes having a threshold above $1 - \frac{g}{\sqrt{N}}$. In other word, all the nodes in the subtree have a gap $< \frac{g}{\sqrt{N}}$. This subtree is called the *target-stopped tree*.

The essential observation is the following: if n is close to $\log_2(\sqrt{N})$, then except with a small probability, a node at generation n in the tree has a gap at most $\frac{g}{2^n} \leq \frac{g}{\sqrt{N}}$. This is because of the highly skewed nature of the distribution of G_n, as described above. Hence, we can safely assume that the target-stopped tree has depth at most n. Note that the total number nodes of appearing at generations $0, 1, \cdots, n-1$ is at most $2^n = \sqrt{N}$.

Now we can bound the total size of the tree. The total size of the tree which is also the upperbound of the number of copies is:

$$C_{DF} = 2^n + \frac{N}{2^n}. \tag{3}$$

The minimum value of this result is obtained by making the two items 2^n and $\frac{N}{2^n}$ equal. That is, $2^n = \frac{N}{2^n}$. Thus, $n = \frac{1}{2}\log_2 N$. So,

$$C_{DF}(n) = 2\sqrt{N}. \tag{4}$$

B. Cost of PDF

In the PDF algorithm, node i has a $p : (p < 1)$ probability to forward the message. For example, if $p = \frac{3}{4}$, then the node has 75% of the chance to forward the message. If the node is not chosen by the probability, it is equivalent to the truncating the subtree from this node in the binary tree. Since the nodes are randomly chosen by the probability p, $E[G_n] = \frac{g}{2^n}$ still holds.

We define the set $B = \{i | x_i \geq 1 - \frac{g}{2^n}\}$ as the target set, and the subtree with all the node whose gap $< \frac{g}{2^n}$ as the target-stopped tree.

Now we bound the total size of the tree which is also the upperbound of the number of copies as:

$$C_{PDF}(n) = (2p)^n + \frac{N}{2^n}.$$

$C_{PDF}(n)$ is minimized when

$$\begin{aligned} C'_{PDF}(n) &= (2p)^n ln2p - N \cdot 2^{-n} ln2 = 0 \\ So, (4p)^n &= \frac{N ln2}{ln2p}. \end{aligned}$$

Then,

$$\begin{aligned} n &= log_{4p} \frac{N ln2}{ln2p} \\ &= log_{4p} N + log_{4p} ln2 - log_{4p} ln2p \\ &\approx log_{4p} N. \end{aligned}$$

Thus,

$$\begin{aligned} C_{PDF}(n) &= (2p)^n + \frac{N}{2^n} = 2 \cdot (2p)^n \\ &= 2 \cdot (2p)^{log_{4p} N} = 2 \cdot N^{log_{4p} 2p} \end{aligned}$$

So,

$$C_{PDF}(n) = 2 \cdot N^{log_{4p} 2p}. \quad (5)$$

Since $p < 1$, $C_{PDF}(n) < 2\sqrt{N} = C_{DF}(n)$.

Hence we see that probability delegation forwarding narrows the set of targeted nodes as additional message copies get created.

V. Simulations

Next we conduct simulations to compare DF and PDF. Actually DF can be treated as a special case of PDF with a probability of 100%. So in the simulations, the results for probability 100% are for algorithm DF and the results for probabilities less than 100% are for PDF algorithm with different probabilities.

In our simulations, we use real traces posted on [**?**]. The data sets consist of contact traces between short-range Bluetooth enabled devices (iMotes [4]) carried by individuals in conference environments, namely Infocom 2006 and Content 2006.

In the simulations, we use three metrics as follows.

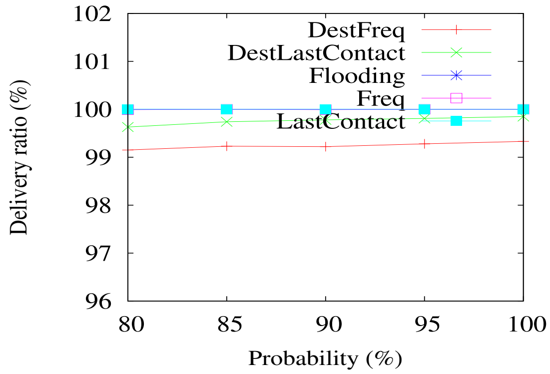
- Delivery Ratio: it is the most important network performance metric in DTNs. It is defined as the fraction of generated messages that are correctly delivered to the final destination within a given time period.
- Latency: it is the time between when a message is generated and when it is received. This metric is important because minimizing latency lowers the time messages spend in the network, reducing contention for resources. Therefore, lowering latency indirectly improves delivery ratio. Many applications can benefit from a short delivery latency.
- Copies: it is the number of copies of a message that a protocol generates in routing. It is an approximate measure of the computational resources required, as there is some processing required for each message. Also it is also an approximate measure of power consumption, and bandwidth and buffer usages as more copies will use more of these resources.

The quality of each node in DF and PDF can be decided using different forwarding algorithms as follows:

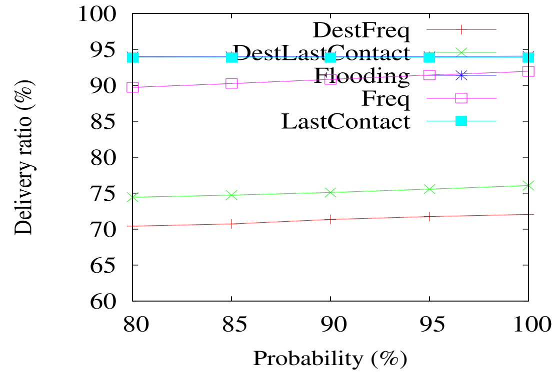
- Flooding [20]: Node $\mathscr{N}_i$ forwards $\mathscr{M}_m$ to $\mathscr{N}_j$ unless $\mathscr{N}_j$ already has a copy of the message. Flooding achieves the highest possible delivery ratio and lowest latency. However, it has the highest cost.
- Frequency (**Freq**) [6]: Node $\mathscr{N}_i$ forwards $\mathscr{M}_m$ to node $\mathscr{N}_j$ if $\mathscr{N}_j$ has more total contacts with all other nodes than does $\mathscr{N}_i$. This algorithm is destination independent.
- Last Contact (**LastContact**): Node $\mathscr{N}_i$ forwards $\mathscr{M}_m$ to node $\mathscr{N}_j$ if $\mathscr{N}_j$ has contacted any node more recently than has $\mathscr{N}_i$. This algorithm is destination independent.
- Destination Frequency (**DestFreq**): Node $\mathscr{N}_i$ forwards $\mathscr{M}_m$ to node $\mathscr{N}_j$ if $\mathscr{N}_j$ has contacted $\mathscr{M}_m$'s destination more often than has $\mathscr{N}_i$.
- Destination Last Contact (**DestLastContact**) [8]: Node $\mathscr{N}_i$ forwards $\mathscr{M}_m$ to node $\mathscr{N}_j$ if $\mathscr{N}_j$ has contacted $\mathscr{M}_m$'s destination more recently than has $\mathscr{N}_i$. This algorithm is FRESH [8].

We randomly generate a source and a destination. We try different probabilities starting from 80% to 100% with an increase step of 5%. For each source and destination pair, under a certain probability, we use all the forwarding algorithms we consider. We record delivery ratio, latency and the number of copies used for each set of data. The process is repeated for $10,000$ pairs of randomly generated source and destination pairs. The results are averaged and shown in the figures.

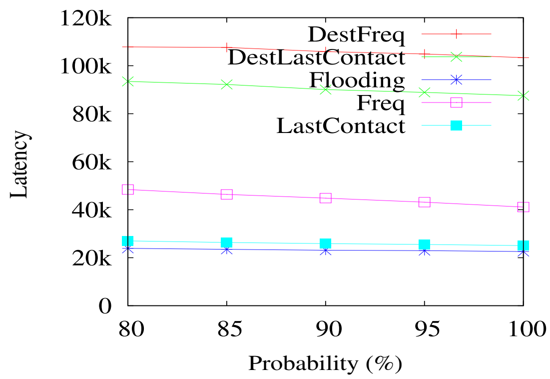
From the results in both traces, we can see that if we use a probability above 80%, the curves in figures are almost flat. That is, the effects to delivery ratio and latency are not much, especially if the probability is above 90%. For the number of copies (costs), we know that DF (probability 100%) uses the least number of copies. So we use that as a baseline and against which calculate the increased copy percentages with the decrease of the probabilities. As the results in both traces show, the number of copies will increase more and more folds as the probability becomes smaller and smaller. These justify our idea that PDF can achieve the same performance as DF



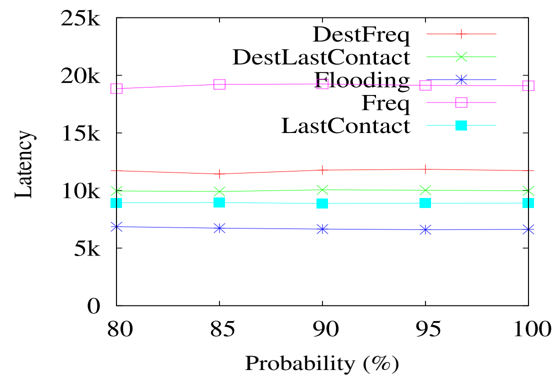
(a) Delivery ratio



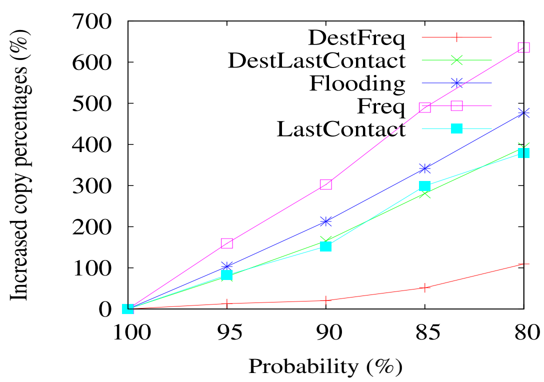
(b) Delivery ratio



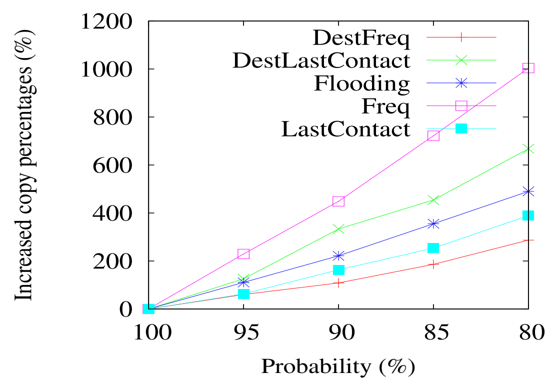
(c) Delivery latency



(d) Delivery latency



(e) Increased copy percentages



(f) Increased copy percentages

Fig. 1. Results using Content trace

but with fewer copies if probability is not too small.

VI. Conclusion

Acknowledgments

This research was supported in part by NSF grant CNS 0835834.

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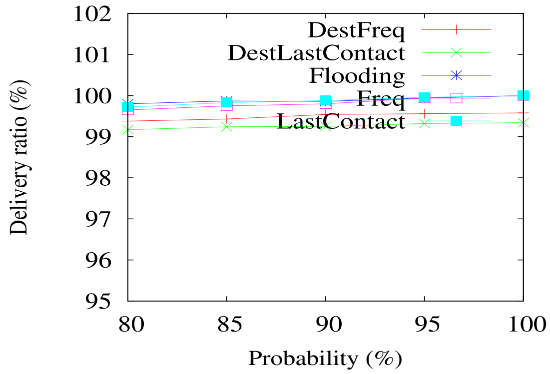
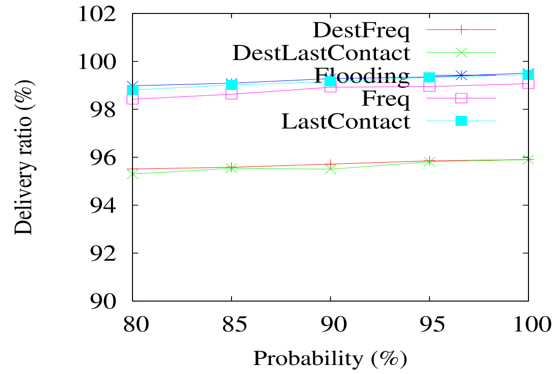
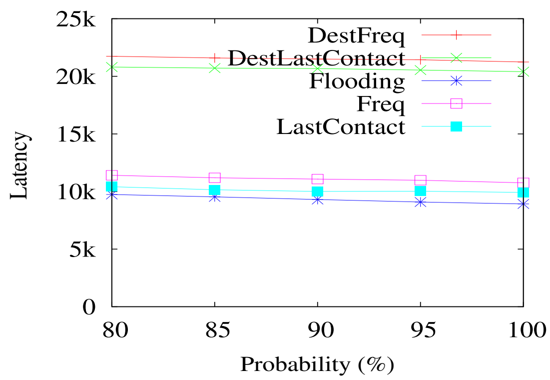


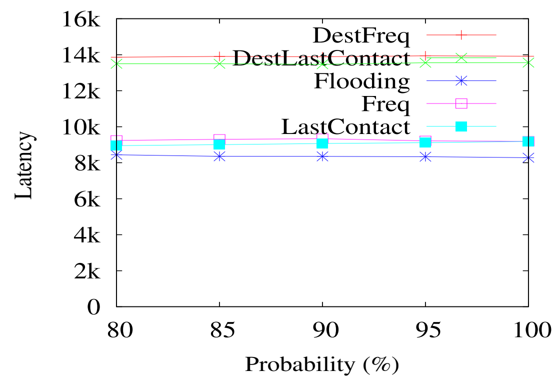
(a) Delivery ratio



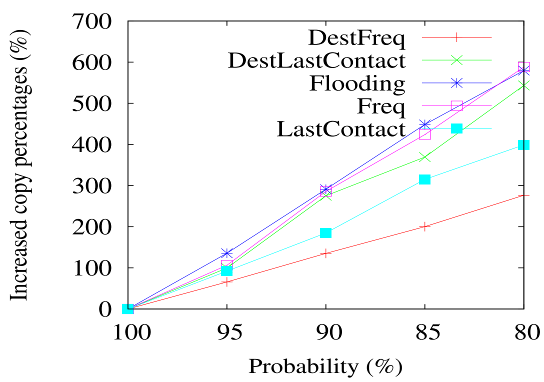
(b) Delivery ratio



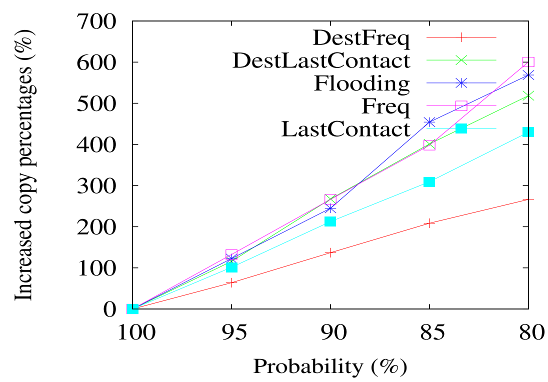
(c) Delivery latency



(d) Delivery latency



(e) Increased copy percentages



(f) Increased copy percentages

Fig. 2. Results using Infocom trace

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