Forwarding in Opportunistic Networks with Resource Constraints

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Abstract

Effective forwarding in mobile opportunistic networks is a challenge, given the unpredictable mobility of nodes, short contact durations between nodes, wireless interference and limited buffer sizes.

Most forwarding algorithms aim at decreasing costs (relative to flooding the network) by forwarding only to nodes which are likely to be good relays. While it is non-trivial to decide if an encountered node is a good relay or not at the moment of encounter, it is harder still to prioritize which messages to *transmit* under the presence of short contact durations and which messages to *drop* when buffers become full.

The main objective of this paper is to study different message prioritization schemes using real measurements. Such schemes can be broadly divided into two categories - schemes which do not use any network information, and schemes which do. Examples of the former set of schemes include FIFO/LIFO etc. For the latter set of schemes, there is a key design choice: On one hand, we have the following scheme: when a forwarding opportunity presents itself, assign high priorities to messages which are relatively close to their intended destination. On the other hand, we can assign high priorities to messages which are farther away from their destination than closer messages. In order to decide if messages are close to their destination or not, we have to rely on a forwarding algorithm. For this, we use delegation forwarding schemes which have been shown to be efficient in terms of cost incurred in the network. We develop a new set of prioritization schemes based on delegation schemes. We consider these schemes in our empirical study.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Store and forward networks*

General Terms

Algorithms, Measurement, Performance

Keywords

Mobile Opportunistic Networks, Delay-Tolerant Networks, Forwarding Algorithms, Pocket Switched Networks

1. INTRODUCTION

Forwarding in mobile opportunistic networks is a hard problem because of two key challenges: the unpredictable mobility of the underlying nodes, and the resource constraints which include limited battery life, short contact durations and small buffers.

While there has been work [7, 6, 17, 4, 8] that addresses the first challenge, little work has been done to address the second challenge. For a mobile network operating under such constraints, the joint question of which messages to transmit and which messages to drop becomes important. As with a forwarding algorithm, every node should be able to decide which messages are transmitted and which messages are dropped based on the information the node has, all the while balancing the trade-offs that exist between success rate, delay and cost. Hence there is a need to develop and study prioritization schemes for messages such that nodes can forward high priority messages and drop low priority messages.

Message prioritization can be performed independent of the underlying forwarding algorithm. Such schemes include FIFO [18], LIFO and ttl-based algorithms [17]. While such schemes are easy to implement, the fact that they do not take into account network information can lead to poor performance and suboptimal use of the scarce resources.

For the schemes which do use network information to make informed decisions there is a crucial question: on the one hand, one can assign high priorities to messages which are close to their intended destination. A node following such a scheme, will upon an encounter, drop the message farthest from its destination and transmit the message closest to its destination. Proposed schemes which share this philosophy include PREP [15] and DLE [5].

On the other hand, one can decide to assign high priorities to messages which are farthest away from their destination [2]. Following such a scheme, the first message which will get dropped will be the message which is closest to its destination, and the first message which will get transmitted (after delivering the those messages destined to the encountered node) will be the message farthest from the destination. Clearly the notion of ‘ distance’ to a destination is extremely important in such schemes that use network information.

This paper starts with the observation that in order to develop an effective prioritization scheme, it is useful to study dropping schemes and transmission schemes independently of each other. In order to facilitate our study, we develop and study a message prioritization scheme based on delegation forwarding algorithms [8].

In previous work we have shown that delegation schemes reduce costs by relying on principles of optimal stopping theory to decide when to forward messages [8]. These schemes rely on a forwarding metric assigned to every node, that is generically referred to as ‘quality’ for that node. This metric determines the probability of successful delivery of messages to their intended destination, and hence convey the notion of 'distance' to a destination. For the purposes of this study, the choice of delegation forwarding is not essential. However the combination of low cost and the use of a generic metric to convey distance make delegation schemes appealing for basing our study. We augment the delegation algorithms with a replication-count number, which we refer to as *delegation number*. This number is then used to assign priorities to messages.

In this paper we study a variety of schemes using real encounter traces. The most significant result of our paper is the scheme which assigns high priorities to messages with low delegation number performs the best in terms of success rate, delay and cost. We interpret this result in light of the path explosion phenomenon observed before [7].

2. RELATED WORK

Most of the work done in mobile opportunistic networks [3, 7, 12] is on the design of forwarding algorithms which aim at maximizing performance while reducing cost [13, 7, 8, 11, 17, 4, 6]. Our focus here is to explore different message priority schemes given that we already have a forwarding algorithm. In particular we use the delegation schemes developed in [8].

There has been prior work done in designing message priority schemes. Epidemic routing [18] uses FIFO scheme, while the main idea behind Drop Least Encountered (DLE) (developed in [5] and subsequently used with different forwarding proposals [13, 16, 9]) is to drop the message with least likelihood of delivery. A similar idea has been proposed in PREP [15] where messages which are farthest from their destination are assigned low priorities. These proposals primarily differ in how they define the notion of distance to the destination. In our work, we take the probability of successful delivery to the intended destination as the distance; higher the probability, lower the distance. We rely on frequency (contact rate) and destination frequency (contact rate with a given destination) [8] as indicators of the probability.

Our study is aimed at networks which consist of mobile devices carried by humans in conference/social settings [3, 7]. There has been similar work in message prioritization in other similar networks, like vehicular DTNs, most notably MaxProp [2] where a node assigns high priorities to messages which are relatively new in the network.

Our work is different(and indeed harder) as we have to consider short contact durations as well as ensure low overall cost in the network given that energy is a precious resource unlike in vehicular DTNs [2, 1].

3. ASSIGNING PRIORITIES TO MESSAGES

In this section we first describe the setting we are working with. We then discuss the schemes which we study as well as the potential implications of using these schemes. We then describe the a prioritization scheme which is based on delegation forwarding.

3.1 Formulation

Building on the formulation given in [8] we assume a set of mobile nodes $\mathcal{N}_i \in \mathbb{M}$ with $|\mathbb{M}| = N$. Nodes generate messages over time; each message has a particular source and destination. We define M_i as the set of messages held by a given node $\mathcal{N}_i$. When nodes come into contact; have encounters, they are capable of exchanging messages. Messages are transmitted in whole from node to node during node contact intervals, after which both nodes hold message *replicas*. Nodes hold on to the message replicas until their respective buffers are full, at which time the nodes have to decide which message to drop. Nodes do not possess any *a priori* knowledge of the number of nodes in the system or knowledge of any properties of the other nodes. We are working in a setting where all nodes are mobile; we do not consider settings where some nodes may be stationary and are gateway nodes to the Internet.

We consider the following metrics: (1) *cost,* which is the number of replicas per generated message in the network; (2) *success rate*, which is the fraction of generated messages for which at least one replica is eventually delivered; and (3) *average delay,* which is the average duration between a message's generation and the first arrival of one of its replicas at the destination. By "high performance" we mean high success rate and low average delay.

When a node $\mathcal{N}_i$ encounters another node $\mathcal{N}_j$, the basic question that a forwarding algorithm addresses is which subset of messages m_i in the set M_i should node $\mathcal{N}_i$ forward to node $\mathcal{N}_j$ to maximize performance and minimize cost. Many of the proposed solutions differ in the type of network information used, as well as how they use it to answer the above question (refer to [8] for a detailed discussion on this point). However some of these schemes are designed and evaluated under the assumptions of infinite buffer capacity and infinite bandwidth [8, 17, 12, 10]. With no resource constraints there is no need for prioritization of messages.

However under the presence of finite contact durations and finite buffers, the questions of prioritizing the transmission and dropping of messages becomes equally important. The question then becomes which messages in the subset m_i should node $\mathcal{N}_i$ transmit first and which messages in the subset should node $\mathcal{N}_j$ drop first to minimize cost and maximize performance?

We start with the observation that it is important to study message dropping schemes independently of message transmission schemes. This will let us identify a consistent prioritization scheme if it exists. From a node's perspective, message prioritization schemes can either be independent of the forwarding algorithm or use the information provided by the forwarding algorithm to decide on the priorities.

Examples of the former include **FIFO**, **LIFO** and **Random**. These schemes do not use any extra information of the network - a node merely inspects its buffer and drop/transmits a message in FIFO/LIFO manner. Else the node will pick a random message to drop or transmit. We consider these schemes in our study. More details are provided in the next section.

When message prioritization schemes incorporate network information, one can think of two diametrically opposite schemes. On one hand we have the following scheme: upon an encounter, assign high priority to messages that are closest to their destination, and low priority to messages that are further away from their respective destination. The rationale for such a scheme is fairly intuitive — the network expends some energy in replicating and forwarding a message close to its destination. Given a choice between spending energy on a message that will get closer still to its destination, or a message which is not certain to reach its destination, choose the former. Example schemes include PREP [15] and DLE [5].

The main problem with such schemes is that some messages might suffer from 'under-replication'; a node might only replicate and forward messages which are close to a destination, never giving a chance to relatively new messages to propagate in the network (Although PREP [15] does use a hop-count value to ensure under-replication does not occur).

On the other hand a node can adopt the following scheme: assign high priority to messages which are farthest from their destination and low priority to messages which are closest to their respective destinations. This scheme is less-intuitive — given that we rely on multi-hop forwarding, favoring a message that is far from its intended destination over a message close to its destination would entail spending more resources which are scarce in the first place. Besides, dropping a message which is close to its destination, with the hope that another replica of the message makes it to the destination may increase delays for that message. However a potential benefit of such a scheme is that it may address the ‘under-replication’ problem. As a message makes its way thru the network to get closer to its destination, multiple replicas of the message might propagate, increasing the probability of successful delivery.

We explore these tradeoffs using empirical measurements in the next section. However before we do so, we need to address the question of which metrics should we use that give a good indication of distance to the destination.

Algorithm 1 Augmented Delegation Forwarding

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

We use the delegation forwarding scheme[8] which have been to shown to be efficient in terms of cost and deliver high performance.

3.2 Delegation Number based Priorities

To recap, the main idea of delegation forwarding is as follows. Every node has a ‘quality’ associated with it, which is a generic metric that gives the likelihood of the node successfully delivering messages to a destination. The **key idea** of delegation forwarding is that a given node will forward a message only if the encountered node has *quality higher than all seen so far by the message*. Delegation forwarding has been shown to reduce average cost by a factor of O($\sqrt{N}$) [8]. We augment the delegation scheme by including a simple replication-count. We refer to this number as *delegation number* (d_m) of the message. The delegation number is incremented in the message, it is then replicated and forwarded.

A formal statement of the augmented delegation forwarding is given in Algorithm 1. Consider a node holding a message with a high delegation number. This would mean : (i) this node is one of the best candidate nodes to forward the message to its intended destination, and hence is close to the destination, else it would not be holding the message; (ii) even if the node itself is not a good candidate to carry the message to the destination, a high number signifies that the message has been passed to candidates that *are* good candidate nodes to carry the message. Likewise consider a message with a low delegation number: the message has not been replicated enough because the message is relatively young.

An example is given in Fig. 1. In this example, consider node A which has two messages in its buffer ($\mathcal{M}_1$, $\mathcal{M}_2$), both with $d_1, d_2 = 1$. Node A encounters node B which is turns out to be a better candidate for message $\mathcal{M}_1$. d_1 is increased, the message is then replicated and forwarded to node B. Node A has another encounter say, with node C and forwards $\mathcal{M}_1$ again. d_1 is therefore

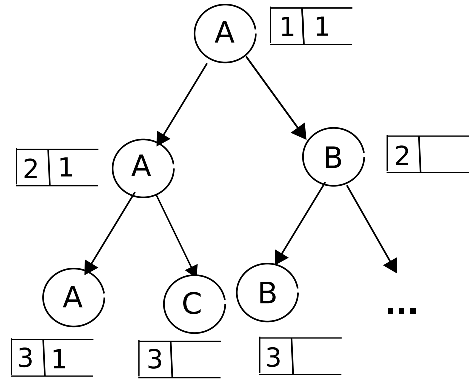

Figure 1: Delegation Tree for node A

3, while d_2, which has not been forwarded, remains 1. Clearly, the high delegation number for $\mathcal{M}_1$ in node A tells us that $\mathcal{M}_1$ has been forwarded to nodes which are good or better candidates to carry the message. Likewise the high delegation number for $\mathcal{M}_1$ in node C tells us that node C belongs to the set of good candidate nodes to carry the message. The low delegation number on $\mathcal{M}_2$ signifies that it has not been replicated enough, because it is relatively new in the network.

We formulate the two prioritization schemes and study them empirically using real encounter traces. The details are given in the next section.

4. EVALUATION

In this section we evaluate various message drop and transmission schemes using real encounter traces.

4.1 Data Details

In order to evaluate various schemes in realistic settings, we rely on real encounter traces collected in conference settings. These data sets comprise of contact traces between short-range Bluetooth enabled devices (iMotes [3]) carried by individuals in conference environments, specifically Infocom 2006 and Conext 2006. More details about the devices and the datasets, including synchronization issues can be found in [14]. We isolated two 3-hour periods Tuesday, 9AM-12PM from both the data sets for our study. We selected the 3-hour periods such that the total contact rate of nodes is fairly stable. In addition, most participants are present in the first day of the conference. These are the same data sets used in [7], and more details can be found in that paper and the references therein. We present results from one dataset (Infocom 2006, 9AM-12PM) due to space constraints, however we note that our results are similar across both data sets.

4.2 Experiments

As mentioned earlier, we study message dropping and message transmission schemes independently of each other.

In order to capture a diverse set of conditions, we choose a stateless algorithm epidemic [18], a destination agnostic algorithm (“frequency” [8]) and a destination based algorithm (“destination frequency” [8]) as the underlying forwarding algorithms. While epidemic algorithm relies on always forwarding messages on every contact, frequency relies on using contact rates of nodes to make forwarding decisions. Destination frequency uses contact rate with the destination to make decisions. Therefore, the frequency algorithm will operate as follows. A node upon an encounter with

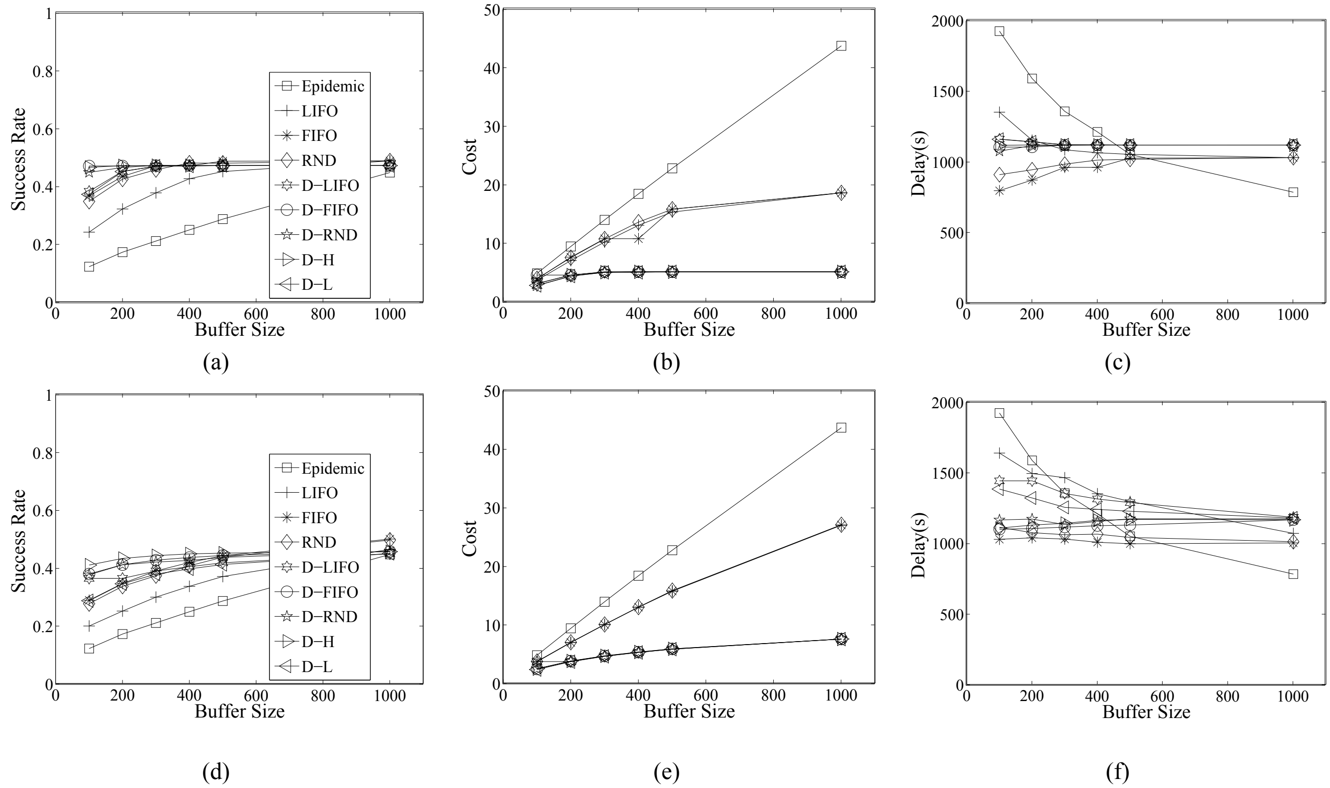

Figure 2: Message Dropping Schemes Info 06 9-12 (a,b,c) Destination Frequency (d,e,f) Frequency; (a,d) Success Rate, (b,e) Cost and (c,f) Delay

another node, forwards messages only if the the encountered node has a higher contact rate than itself. Destination frequency operates similarly but the information used is contact rate with the destination instead.

The latter two have been shown to give good performance while reducing cost in the network. Delegation schemes can be applied to any generic metric which gives the likelihood of successful delivery of a message to its intended destination. We therefore also consider delegation versions of frequency and destination frequency for comparison. The delegation version of frequency would then be: a node, upon an encounter, forwards messages if the encountered node has contact rate higher than the rate of all nodes seen so far. A similar scheme can be designed with destination frequency. Refer to [8] for more details.

We implemented a variety of forwarding algorithms in a trace-driven simulator. For each trace and forwarding algorithm we study, we generate a set of messages with sources and destinations chosen uniformly at random, and generation times from a Poisson process averaging one message per 4 seconds. All our results are averaged over 10 simulation runs. Our metrics are success rate, average delay, and cost (as defined in Section 3). Each simulation run was therefore 3 hours long; to avoid end-effects, no messages were generated in the last hour of each trace.

4.3 Message Dropping Policies

We limit and vary the size of buffers per node and choose to study the following set of policies which span a spectrum of possible design choices. Ties are broken randomly. We make the assumption that all messages are inserted in arrival order in a buffer. Given this, we have:

FIFO: Upon a buffer overflow condition, node $\mathcal{N}_i$ drops the oldest message in the buffer.

LIFO: Upon a buffer overflow condition, drop the newest message in the buffer.

Random: Upon a buffer overflow condition, drop a random message from the buffer. This scheme is between the FIFO and LIFO schemes mentioned above.

As mentioned in Section 3, these schemes are independent of the forwarding algorithm. We consider these policies in conjunction with our algorithms defined earlier(Frequency, Destination Frequency and their delegation versions). In addition, we also focus on the two schemes we developed which exploit the information provided to them by the forwarding algorithm.

High (H): Upon a buffer overflow, drop the message which has the highest delegation number $d_i = \max_{\forall\ j}(d_j)$. This is analogous to dropping the message which is closest to the destination as well the message which has been forwarded many times.

Low (L) Upon a buffer overflow, drop the message which has the smallest delegation number $d_i = \min_{\forall}\ j(d_j)$. This is analogous to dropping the message which is relatively young in the network or the message which is farthest from the destination.

We vary the buffer size (100, 200, 300,400, 500 and 1000) messages on every node. We study drop policies independently of bandwidth constraints, hence we assume unbounded contact duration in these experiments.

The results are shown in Fig. 2. The plots show success rate, cost and delay versus increasing buffer size. The top plot shows results for destination frequency and the bottom set of plots correspond to frequency. Figs.2 (a,d) show success rate versus buffer size. We first note that the all schemes perform similarly at high buffer sizes. Presumably, epidemic forwarding which does not do well under the

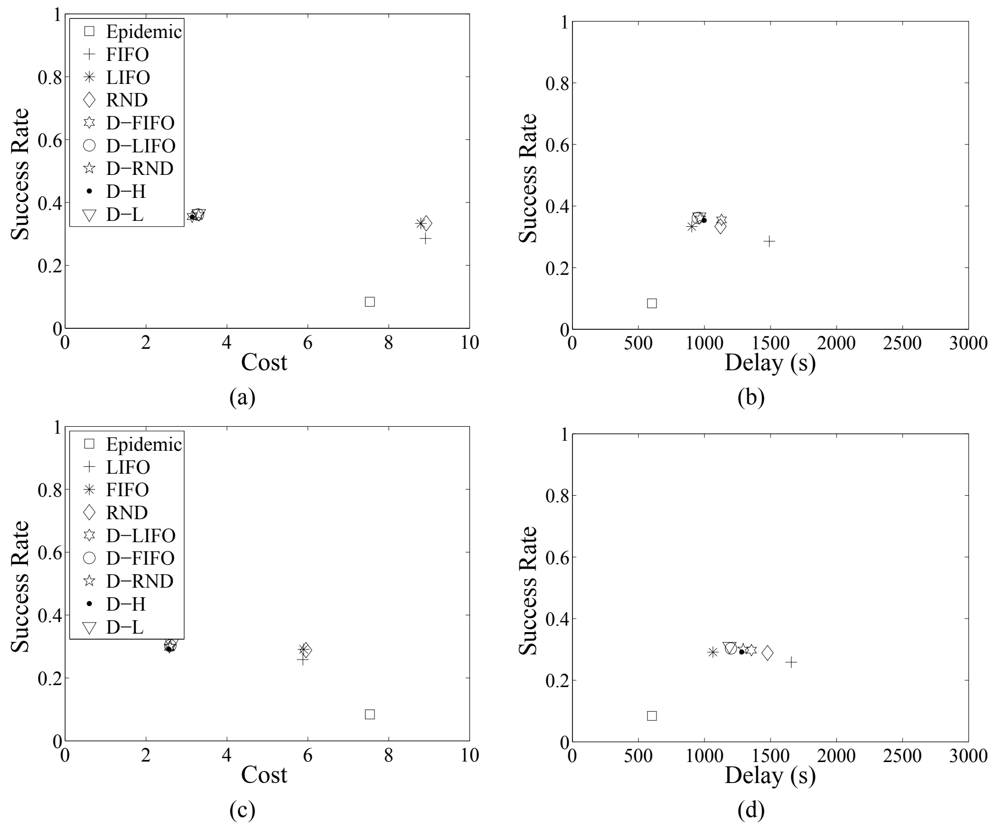

Figure 3: Message Transmission Schemes Info 06 9-12 (a,b) Destination Frequency (c,d) Frequency; (a,c) Success Rate vs Cost, (b,d) Success Rate vs Delay

presence of small buffers (as has been reported before [15]), will perform the best with higher buffer sizes. All delegation schemes have a higher success rate than the non-delegation versions. This is because delegation schemes have been shown to reduce overall cost [8] in the network, so they utilize the scarce resources more efficiently. Figs. 2 (b,e) show cost versus increasing buffer sizes. Clearly the cost will increase as buffer sizes increase, but for all algorithms (excluding once again, epidemic), large buffers do not help in increasing the success rate. All the delegation schemes achieve a very low cost; similar results have been reported before [8]. Figs. 2 (c,f) show average delays as a function of message buffer sizes. The average delays decrease for epidemic as buffer sizes increase. However for the other schemes, the increase in buffer sizes do not have a large effect on delay. Across different schemes, however we note that while LIFO does the best, delegation schemes have higher delays - though they are not prohibitively high. The surprising result is that delegation-H policy(drop the message with the highest delegation number) gives the best success rate(with low cost) amongst all policies; for low buffer sizes it is an improvement by a factor of almost 2 over LIFO. The delegation-H policy is opposite of the policy employed by PREP and DLE in that we drop the message which is closest to its respective destination.

As discussed before, dropping a message close to its destination might increase delays. However we see from the results that the delays do increase, but they are not prohibitive. Overall it would appear that delegation schemes (H,RND) perform well under small buffer sizes, and the policy of dropping the message which is closest to its intended destination offers the best trade-off between performance and cost.

4.4 Message Transmission Policies

In order to impose constraints on message transmission, we limit the number of messages which a node can transmit during an encounter to at-most 1. We study transmission policies independent of buffer constraints, therefore we assume infinite buffers on nodes.

The schemes we study are the same as the ones dropping schemes studied above. We briefly describe the schemes:

FIFO: Upon a node encounter, node $\mathcal{N}_i$ forwards the oldest message in the buffer. Once the message has been forwarded it is reinserted to the back of the buffer.

LIFO: Upon a node encounter, forward the youngest message in the buffer. We reinsert the message to the beginning of the buffer after it has been forwarded.

Random: Forward a random packet from the buffer. This scheme is between the FIFO and LIFO schemes mentioned above.

We consider these policies in conjunction with our algorithms (Frequency, Destination Frequency and their delegation versions). In addition we consider two additional schemes which make use of the delegation number:

High (H): Upon a node encounter, forward the message which has the highest delegation number $d_i = \max_\forall\ j(d_j)$. This is analogous to forwarding the message which is closest to the destination as well the message which has been forwarded many times.

Low (L) Upon a node encounter, forward the message which has the smallest delegation number $d_i = \min_\forall\ j(d_j)$. This is analogous to forwarding the message which is relatively young in the network.

The results are presented in Fig. 3. The results for destination frequency are presented on top, and the results for frequency are presented below. Fig. 3 (a,c) display success rate versus cost. All delegation based schemes perform similarly. Epidemic does not perform well. We can therefore conclude that the epidemic algorithm does not perform well under resource constraints, as also observed before[15]. It would appear that dropping policies have more impact than transmission policies.

4.5 Relation to Path Explosion

Taken as a whole, it would appear that the delegation schemes perform much better under resource constraints. This is primarily because they reduce overall cost in the network, thereby reducing contention.

In addition, the augmented delegation schemes which use the delegation number to prioritize message dropping/transmission perform better as they use the extra information available to them. In particular it would appear that the joint policy of dropping the message with the highest delegation number performs better than all schemes.

We interpret this result in light of the path explosion phenomenon[7]. The basic observation is that there is an exponential increase in the number of temporal paths between nodes in such networks. This means that for a given node pair, finding the optimal delay path is hard, but finding one of the many sub-optimal paths is a relatively easier task. This has implications on the performance of forwarding algorithms. However the question is how does one initiate a path explosion? While a comprehensive study of the necessary and sufficient conditions for the explosion to take place is beyond the scope of this work (some factors have been identified in [7]), we posit that prioritization of messages play an important role for such a phenomenon to take hold.

By assigning higher priority to messages with a low delegation number, we are in essence ensuring that such messages do not get dropped, and have a chance to be replicated and propagate in the network. Therefore by prioritizing transmission of messages with a low delegation number, this increases the likelihood that explosion takes place for those messages. The use of delegation schemes further ensure that the message is replicated and forwarded to the best nodes at the minimum cost.

Likewise, when a message with a high delegation number is dropped, more likely than not path explosion for that message has occurred; there are other replicas of the message which can potentially be delivered to the intended destination. In addition, dropping a message which is ostensibly close to its destination does not increase the delay by a large factor, as due to the path explosion phenomenon, many near-optimal (in terms of delay) paths to the destination exist.

5. CONCLUSIONS

Efficient forwarding in mobile opportunistic networks is a challenging problem. While a lot of work has been done in the design of forwarding algorithms, little work has been done on studying forwarding under the presence of short contact durations and finite buffers. Under such circumstances, the problem of prioritizing messages for transmission or dropping becomes important.

In this paper, we provide an empirical study of different schemes. In order to facilitate our study, we design a scheme based on earlier results of delegation forwarding. The main idea is to add a replication-count to delegation schemes. We design a message prioritization scheme based on this number.

We evaluate different schemes using real encounter traces. For ease of analysis we study forwarding and dropping policies seperately. This allows us to isolate the effects of the two policies. Since our results show that forwarding policies have much less effect than dropping policies, we are able to conclude that careful selection of dropping policy is of primary importance. More specifically, we find that the scheme which assigns high priority to messages with low delegation number and lower priority for high delegation number performs best in terms of balancing success rate, delay and cost. We interpret this result in light of previous results related to path explosion phenomenon found in the same traces we use in this study.

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