Forwarding Redundancy in Opportunistic Mobile Networks: Investigation, Elimination and Exploitation

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Abstract—Opportunistic mobile networks consist of mobile devices which are intermittently connected via short-range radios. Forwarding in such networks relies on selecting relays to carry and deliver data to destinations upon opportunistic contacts. Due to the intermittent network connectivity, relays in current forwarding schemes are selected separately in a distributed manner. The contact capabilities of relays hence may overlap when they contact the same nodes and cause forwarding redundancy. This redundancy reduces the efficiency of resource utilization in the network, and may impair the forwarding performance if being unconsciously ignored. In this paper, based on investigation results on the characteristics of forwarding redundancy in realistic mobile networks, we propose methods to eliminate unnecessary forwarding redundancy and ensure efficient utilization of network resources. We first develop techniques to eliminate forwarding redundancy with global network information, and then improve these techniques to be operable in a fully distributed manner with limited network information. We furthermore propose adaptive forwarding strategy to intentionally control the amount of forwarding redundancy and satisfy the required forwarding performance with minimum cost. Extensive trace-driven evaluations show that our schemes effectively enhance forwarding performance with much lower cost.

Index Terms—Data Forwarding, Opportunistic Mobile Networks, Redundancy, Relay Selection, Adaptability.

1 INTRODUCTION

Opportunistic Mobile Networks, also known as Delay/Disruption Tolerant Networks (DTNs) [16], consist of hand-held mobile devices such as PDAs, laptops and smartphones. These devices are connected only intermittently when they opportunistically contact each other, i.e., move into the communication range of their short-range radios (e.g., Bluetooth, WiFi). Such intermittent network connectivity can be a result of mobility, device sparsity or power outage. Examples of such networks include groups of individuals moving in disaster recovery areas, urban sensing [13] and Vehicular Ad-hoc Networks (VANETs) [5].

The intermittent network connectivity among mobile devices makes it difficult to maintain end-to-end communication links or global network information. To facilitate communication in opportunistic mobile networks, node mobility is exploited to let nodes physically carry messages as relays, which forward messages when they opportunistically contact other nodes. The key problem is hence how to make effective forwarding decisions, to ensure that the messages are carried by relays with the best chance to contact their destinations.

Forwarding decision in opportunistic mobile networks consists of two stages. First, the utility of a node for forwarding a message is determined. Due to the lack of global information about how to reach the destination, node’s utility is evaluated by predicting the node’s capability of contacting others in the future. Various utility functions evaluating such nodes contact capability have been proposed based on node mobility pattern [9], [40], stochastic node contact process [30], [2] or social network concepts [10], [25], [23]. Second, node utilities are applied to various forwarding strategies for different tradeoffs between forwarding performance and cost. Epidemic [38] and RAPID [2] optimize forwarding performance by utilizing all the nodes and contact opportunities for replicating messages. Most strategies only replicate messages to relays with high utilities and improve forwarding performance with lower cost.

In this paper, we envision that conventional wisdom has been focusing on developing various relay utility functions or forwarding strategies for opportunistic mobile networks, but generally ignore the large amount of forwarding redundancy produced by the current forwarding schemes, i.e., the calculated utility of a relay may not reflect its actual contribution on forwarding a message. The major reason for such redundancy is that the utility of a relay, in current forwarding schemes, is evaluated separately without considering the existence of other relays carrying replicas of the same message, and the contact capabilities of relays hence may overlap with each other. The relays may contact the same node at different times in the future, but only the first relay
having contacted the destination delivers the message. The capabilities of all other relays contacting this node are redundant and wasted.

The existence of forwarding redundancy generally reduces the efficiency of resource utilization in opportunistic mobile networks, because some relays may have only little contribution on forwarding the message if the forwarding redundancy is unconsciously neglected and inappropriately grows. Message replicas carried by these relays ineffectively consume the limited network resources including channel bandwidth and local storage buffer, and further impair the performance of forwarding other messages. On the other hand, in application scenarios with strict performance requirements such as disaster recovery or emergency notification, intentionally maintaining and exploiting such redundancy with specific forwarding strategies helps create a sufficient number of message replicas and satisfy the required performance for forwarding the message.

The major focus of this paper, therefore, is to appropriately address the impact of forwarding redundancy in opportunistic mobile networks, and make forwarding schemes $i)$ being able to correctly identify and eliminate unnecessary forwarding redundancy from relays' utilities, so as to improve the efficiency of resource utilization and forwarding performance in opportunistic mobile networks, and $ii)$ being able to adaptively maintain the amount of forwarding redundancy in the network, so as to exploit such forwarding redundancy for satisfying the specific performance requirements of different mobile applications. Our basic idea is to develop cost-effective methods which identify the nodes that existing relays are likely to contact in the future, so that forwarding redundancy can be eliminated by avoiding these nodes from being contacted again, when the contact capabilities of other relays are later evaluated. Such redundancy hence can be further exploited by adaptively adjusting the criteria of relay selection with respect to the required contact capabilities of relays. More specifically, we made the following contributions:

- **Investigation.** We investigate characteristics of forwarding redundancy from both theoretical and experimental perspectives. We first formulate a theoretical framework about variations of forwarding performance and redundancy when message replicas are created, and then conduct experimental studies using existing forwarding schemes over real-world mobile network traces. We observe that some message replicas contribute little on improving the delivery ratio, and up to 70% of relays' utilities in current forwarding schemes are redundant. This result seriously impairs forwarding effectiveness and highlights the necessity of redundancy elimination.

- **Elimination.** The major challenge of eliminating forwarding redundancy is the lack of global network information. This makes it hard to estimate the cumulative contact capability of existing relays and determine forwarding redundancy. To address this challenge, we first propose a scheme to eliminate forwarding redundancy with global network information, and then make it distributed. We provide formal analysis on the accuracy of distributed redundancy elimination, and propose two alternative methods to correct the possible errors during redundancy elimination due to incompleteness of network information. After redundancy elimination, limited resources at each relay is effectively allocated to messages according to the relay's utilities for forwarding them. Evaluation results show that the forwarding performance after redundancy elimination is improved by 20% with 40% less cost.

- **Exploitation.** The exploitation of forwarding redundancy is based on the relays' utilities after redundancy elimination, which reflect the actual contribution of relays for forwarding messages. We design adaptive forwarding strategy to intentionally control the amount of forwarding redundancy in the network, and achieve the delivery ratio required by specific mobile applications with the minimum cost. This is achieved by adaptively adjusting a message forwarding threshold at individual relays based on the up-to-date network condition.

The rest of this paper is organized as follows. Section 2 describes our network model and motivation of eliminating forwarding redundancy. Based on investigation results in Section 3, our schemes for eliminating and exploiting forwarding redundancy are described in Sections 4 and 5. The performance of our proposed schemes are evaluated by trace-driven simulations in Section 6. Section 7 reviews related work and Section 8 concludes the paper.

2 Overview

2.1 Network Model and Assumptions

Opportunistic contacts among mobile devices are described by network contact graph (NCG) $G(V,E)$, where contact process between nodes $i, j \in V$ is modeled as an edge $e_{ij} \in E$, and $e_{ij}$ only exists if $i$ and $j$ have contacted before.

We focus on effectively forwarding messages to destinations with minimum cost, measured by the average number of replicas created per message$^1$. We consider that each relay has only limited resources of channel bandwidth and local buffer. When replicas of multiple messages are forwarded to the same relay, their priorities are determined to maximize the effectiveness of utilizing the relay's resources. We assume a well-defined communication mechanism at and below the link layer, and the consideration of link quality or channel interference is beyond the scope of this paper.

We assume that each message has a finite lifetime $T$. Letting the forwarding delay be a random variable $X \in$

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$^1$ Each relay only carries one replica of a message, and hence the number of replicas created for a message is equal to the number of relays used for forwarding the message.
2.2 Motivation

Forwarding redundancy in opportunistic mobile networks is illustrated by the example in Figure 1. Figure 1(a) only shows part of NCG near the data source S, and none of the nodes in Figure 1(a) has contacted the destination, which is far away and not shown in the figure. In this case, the node’s capability of contacting other nodes is used as its utility for forwarding decision, and forwarding redundancy occurs when the relays A, B and C contact many nodes in common. In particular, when B receives message replica at time \( t_2 \) from S and becomes a relay, node G contacted by B is also contacted by another existing relay A. Hence, the contact of B to G is redundant. B’s utility without such redundancy, measured in number of nodes that B has contacted, should be 2 instead of 3. Similarly, contacts of relay C to nodes J and K are redundant because of the existence of B, and this redundancy reduces C’s utility from 3 to 1.

This redundancy, if being unconsciously ignored and grows inappropriately, may impair the forwarding effectiveness. For example, with the existence of B, replicating message from A to C at time \( t_3 \) is ineffective because it only increases the cumulative number of nodes that the relays contact by \( (6-5)/5 = 20\% \), but increases the number of message replicas by 33\%. C may also prevent node F with higher utility from being used as relay when forwarding strategy like Delegation [15] is used, due to the “fake” high utility of C.

Elimination of this redundancy is challenging due to the lack of global network information. When \( S \) replicates message to \( B \) at time \( t_2 \), \( A \) may not know the existence of relay \( B \) if \( A \) has disconnected with \( S \). Hence, when \( A \) determines whether to replicate message to \( C \) at time \( t_3 \), the redundancy between \( B \) and \( C \) on nodes \( J \) and \( K \) is hard to be eliminated.

2.3 Metrics

We measure forwarding redundancy as follows:

**Definition 1:** Redundancy percentage \( P_k(t_1, t_2) \) of \( k \) existing relays during time period \([t_1, t_2]\) is defined as

\[
P_k(t_1, t_2) = 1 - \frac{\left| \bigcup_{i=1}^{k} N_i(t_1, t_2) \right|}{\sum_{i=1}^{k} |N_i(t_1, t_2)|},
\]

where node \( j \in N_i(t_1, t_2) \) if it is contacted by the \( i \)-th relay during time period \([t_1, t_2]\). The \( i \)-th relay belongs to \( N_i(t_1, t_2) \).

Forwarding redundancy varies when different utility functions are used for forwarding decision. In general, the utility of node \( i \) is calculated as \( U_i = \sum_{j=1}^{N} c_{ij} \), where \( N \) is number of nodes in the network and \( c_{ij} \) is the capability of node \( i \) contacting \( j \). Utility functions are classified into two categories according to the network information used to measure \( c_{ij} \).

The first category is **observational** utilities, in which \( c_{ij} \) is measured by direct network observations in the past. These observations include pairwise contact frequency (Freq) [14] and elapsed time since last contact (Elapsed-Time) [11]. **Betweenness** [17] is also used in social-aware forwarding schemes [25], and defines \( c_{ij} = \sum_{k=1}^{N} g_{jk}(i) \), where \( g_{jk}(i) \) is the number of shortest paths between node \( j \) and \( k \) on the NCG and \( g_{jk}(i) \) is the number of such paths passing node \( i \). Betweenness hence indicates the relative importance of node \( i \) in facilitating communication among other nodes.

The second category is **probabilistic** utilities, where \( c_{ij} \) indicates pairwise contact probability derived from node contact process. **PROPHET** [30] increases \( c_{ij} \) by \((1 - c_{ij}) \cdot p_{init}\) each time when \( i \) and \( j \) contact, and \( CCP \) [22] defines \( c_{ij} = 1 - e^{-\lambda_{ij} T} \), where \( \lambda_{ij} \) is the pairwise contact rate.

These utilities apply to various forwarding strategies. In **Compare-and-Forward** [11], [14], a relay replicates messages to nodes with higher utility than itself. **Delegation** [15] reduces the number of replicas, such that a relay only replicates message to nodes with higher utility than any existing relay that it is aware of. In **Spray-and-Focus** [36], the maximum number of message replicas is fixed and a relay forwards message to another node without retaining a local copy.

In this paper, we study forwarding redundancy over various combinations of forwarding strategies and utility functions. Note that there are more forwarding strategies and utility functions having been developed than the ones mentioned above. Our goal is not to address forwarding redundancy for each of them, but to demonstrate the general impact of this redundancy on forwarding performance, as well as the universal methodology for practical redundancy elimination.

2. Note that nodes \( i \) and \( j \) are not included in calculating their utilities when \( i \) determines whether to replicate message to \( j \). Existing relays are not included in such calculation either.
### 2.4 Traces

Four sets of opportunistic mobile network traces are used in this paper. They record contacts among mobile devices with Bluetooth or WiFi interfaces moving in suburban areas (DieselNet [3]), conference site (Infocom [25]) and university campus (MIT Reality [12], UCSD [32]). Bluetooth-enabled devices periodically detect their peers nearby, and a contact is recorded when two devices move close. WiFi-enabled devices search for nearby WiFi Access Points (APs) and associate themselves to the APs with the best signal strength. A contact is recorded when two devices are associated to the same AP. As summarized in Table 1, the four traces differ in their contact type, network scale and node contact frequency.

### TABLE 1

<table>
<thead>
<tr>
<th>Trace</th>
<th>DieselNet</th>
<th>Infocom</th>
<th>MIT Reality</th>
<th>UCSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network type</td>
<td>WiFi</td>
<td>Bluetooth</td>
<td>Bluetooth</td>
<td>AP-based</td>
</tr>
<tr>
<td>Contact type</td>
<td>Direct</td>
<td>Direct</td>
<td>Direct</td>
<td>AP-based</td>
</tr>
<tr>
<td>No. devices</td>
<td>40</td>
<td>78</td>
<td>97</td>
<td>275</td>
</tr>
<tr>
<td>Duration (days)</td>
<td>20</td>
<td>4</td>
<td>246</td>
<td>77</td>
</tr>
<tr>
<td>No. contacts</td>
<td>3,268</td>
<td>182,951</td>
<td>114,046</td>
<td>123,225</td>
</tr>
<tr>
<td>No. contacts per pair per day</td>
<td>0.102</td>
<td>7.52</td>
<td>0.049</td>
<td>0.021</td>
</tr>
</tbody>
</table>

### 3 INVESTIGATION

In this section, we investigate the characteristics of forwarding redundancy from both theoretical and experimental aspects. We first provide theoretical insights on variations of delivery ratio and redundancy percentage when the message is being replicated, and then investigate these variations on real-world traces listed in Table 1. Our findings are summarized as follows, and generally highlight the necessity of eliminating forwarding redundancy in opportunistic mobile networks.

- Forwarding redundancy widely exists in current forwarding schemes, and seriously impairs the forwarding effectiveness if not being appropriately eliminated.
- Message delivery ratio and redundancy percentage are closely correlated. Hence, forwarding redundancy can be intentionally controlled for satisfying the required delivery ratio.
- The practical variations of delivery ratio and redundancy percentage accurately match our theoretical expectations.

### 3.1 Theoretical Framework

#### 3.1.1 Delivery Ratio

We assume that a message is generated at time $t_0$ and expires at time $t_e$, with lifetime $T = t_e - t_0$. As a result, the message delivery ratio with $k$ relays is

$$D_k(t_0, t_e) = 1 - \prod_{i=1}^{k} \left(1 - \frac{n_i}{N}\right), \quad (2)$$

where $N$ is the number of nodes in the network, $n_i = |N_i(t_i, t_e)|$ and $t_i$ is the time when the message is replicated to the $i$-th relay. When message is replicated to another relay $R_{k+1}$, $D_k$ increases by $\Delta D_k = (1-D_k) \frac{N_{k+1}}{N}$. If $n_i$ are i.i.d. stationary random variables with $\mathbb{E}(n_i) = \mu_c$, we have

$$\mathbb{E}(D_k) = 1 - (1 - \mu_c/N)^k. \quad (3)$$

In Eq. (2), both the destination and the nodes in $N_i$ are assumed to be uniformly distributed in the network. In social computing applications with community structures, such distribution may be highly skewed. Relays within the same community may contact the same nodes and lead to lower delivery ratio. In contrast, $N_i$ of relays within different communities may not overlap at all.

Comparatively, delivery ratio without considering forwarding redundancy is $D_k(t_0, t_e) = \frac{\sum_{i=1}^{k} n_i}{\sum_{i=1}^{k} n_i}$. When message is replicated to another relay $R_k$, $D_k$ increases by $\Delta D_k = (1-D_k) \frac{N_{k+1}}{N}$. If $n_i$ are i.i.d. stationary random variables with $\mathbb{E}(n_i) = \mu_c$, we have

$$\mathbb{E}(D_k) = 1 - (1 - \mu_c/N)^k. \quad (3)$$

3.1.2 Redundancy Percentage

The redundancy percentage of $k$ relays is

$$P_k = 1 - N \cdot D_k/N_k,$$

where $D_k$ is defined in Eq. (2) and $N_k = \sum_{i=1}^{k} n_i$. Since $\mathbb{E}(\frac{1}{N_k}) \geq \frac{1}{kn_c}$, we have

$$\mathbb{E}(P_k) \leq 1 - N \cdot \mathbb{E}(D_k)/(k\mu_c), \quad (4)$$

and this upper bound is asymptotically tight because $\mathbb{E}(P_N) = 1 - N \cdot \mathbb{E}(D_N)/(N\mu_c)$ when $N$ is sufficiently large. When message is replicated to another relay $R_{k+1}$, $P_k$ increases by

$$\Delta P_k = P_{k+1} - P_k = \frac{N \cdot D_k}{N_k} - \frac{N \cdot D_{k+1}}{N_{k+1}} = \frac{N \cdot n_{k+1}}{N_k} \cdot (D_k - \frac{N_k}{N} (1 - D_k)). \quad (5)$$

### Table 1

Trace summary

<table>
<thead>
<tr>
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<th>Infocom</th>
<th>MIT Reality</th>
<th>UCSD</th>
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<td>0.021</td>
</tr>
</tbody>
</table>
Lemma 1: For ∀k ≥ 1, ΔP_k ≥ 0.

Proof: Consider functions f(n_1, ..., n_k) = \frac{1}{N} \sum_{i=1}^{k} n_i = N_k/N and g(n_1, ..., n_k) = \frac{1}{\prod_{i=1}^{k} (1 - \frac{1}{N})} = \frac{D_k}{D_k(1 - \frac{1}{N})}. For ∀i ∈ [1, k] we have ∂f/∂n_i = \frac{1}{N} and ∂g/∂n_i = \frac{1}{N(1 - \frac{1}{N})} \cdot (1 + g(n_1, ..., n_k)). Since f(0, ..., 0) = g(0, ..., 0) = 0, we have f(n_1, ..., n_k) ≤ g(n_1, ..., n_k) for ∀n_1, ..., n_k ∈ [0, N] and the lemma follows.

Lemma 1 shows that forwarding redundancy does not decrease each time when message is replicated, and this is also illustrated in Figure 2(b) by using its upper bound in Eq. (4). When μ_c increases, a node can be contacted by more relays and hence leads to higher redundancy percentage.

We also notice that replicating message to more relays increases the relay coverage and redundancy percentage simultaneously. The relationship between the two perspectives is described by the following theorem.

Theorem 1: When 1 ≤ n_i < N/2 for ∀i ∈ [1, k], there exists k_0 ∈ [1, N] such that for ∀k ≤ k_0, ΔP_k ≤ ΔD_k, and for ∀k > k_0, ΔP_k > ΔD_k.

Proof: From Eqs. (2) and (5), we have

\[ \Delta P_k - \Delta D_k = \frac{n_{k+1}(D_k(f(k + N) - f(k)))}{N_k(N_k + n_{k+1})}, \tag{6} \]

where f(k) = \frac{N \cdot N_k + n_k \cdot n_{k+1}}{N} and N_k = \sum_{i=1}^{k} n_i.

Eq. (6) shows that the proof of Theorem 1 is equivalent to prove that there exactly exists one k_0 ∈ (0, ∞) such that f(k_0) = \frac{D_{k_0}}{D_{k_0}(1 - \frac{1}{N})} = 0. This is proved in the following steps.

Step 1: Let g(k) = \frac{D_k}{D_k(1 - \frac{1}{N})} and we immediately have f(0) = g(0) = 0. f(1) = \frac{N \cdot n_1 + n_1 \cdot n_2}{N^2}, and g(1) = \frac{N \cdot n_1}{N - n_1}. Since n_i ∈ [1, N/2] for ∀i ∈ [1, k], we also have f(1) ≥ g(1).

Step 2: It is easy to have \frac{∂f(k)}{∂k} > 0 and \frac{∂g(k)}{∂k} > 0 for ∀k.

Step 3: Since n_{k+1} ∈ [1, N/2) and f(k + 1) − f(k) ≥ \frac{N_k}{N}, we have \frac{∂^2 f(k)}{∂k^2} > 0. We also see that \frac{∂^2 g(k)}{∂k^2} ≥ \frac{∂^2 f(k)}{∂k^2} > 0 in the similar way from Eq. (2).

The theorem is proved by combining the three steps above.

3.2 Trace Studies

We investigate the characteristics of forwarding redundancy in the traces listed in Table 1. In each experiment, a message is generated with random source and destination over 100 simulation runs for statistical convergence.

![Delivery ratio and redundancy percentage in different traces when message is replicated to more relays](image)

(a) Delivery ratio (b) Redundancy percentage

Fig. 3. Delivery ratio and redundancy percentage in different traces when message is replicated to more relays

![Delivery ratio and redundancy percentage in the Infocom trace with different utility functions](image)

(a) Delivery ratio (b) Redundancy percentage

Fig. 4. Delivery ratio and redundancy percentage in the Infocom trace with different utility functions

A warm-up period is reserved before message is generated, for nodes to collect necessary network information and calculate their utilities.

3.2.1 Impact of forwarding redundancy

We first vary the number of message replicas using the Spray-and-Focus strategy [36] and the utility function of CCP [22]. Message lifetime T is adaptively determined in different traces to ensure that the designated number of message replicas is created.

As shown in Figure 3, both delivery ratio and redundancy percentage increase when more message replicas are created. This increase is determined by the contact patterns and frequencies of mobile nodes, which are trace-dependent. In the MIT Reality trace, when the number of relays is smaller than 3, redundancy percentage is lower than 40%, and each message replica noticeably improves delivery ratio by 10%. However, the other

<table>
<thead>
<tr>
<th>Trace</th>
<th>D_{max}</th>
<th>m</th>
<th>fitting error</th>
</tr>
</thead>
<tbody>
<tr>
<td>DieselNet</td>
<td>0.5233</td>
<td>0.2728</td>
<td>1.65 × 10^{-3}</td>
</tr>
<tr>
<td>Infocom</td>
<td>0.5021</td>
<td>0.4182</td>
<td>1.307 × 10^{-3}</td>
</tr>
<tr>
<td>MIT Reality</td>
<td>0.5402</td>
<td>0.4549</td>
<td>1.077 × 10^{-3}</td>
</tr>
<tr>
<td>UCSD</td>
<td>0.4893</td>
<td>0.1206</td>
<td>2.48 × 10^{-4}</td>
</tr>
</tbody>
</table>
6 message replicas being created later only improve delivery ratio by another 10%, but increase redundancy percentage to 70%. Similar cases are also found in other traces. These results show that inappropriate growth of forwarding redundancy has only little contribution on forwarding performance but impairs the forwarding effectiveness.

When more message replicas are created, increase of delivery ratio shown in Figure 3(a) is consistent with our theoretical expectations in Section 3.1. To validate this consistency, we perform least-square curve fitting on Figure 3(a) using formula $E\{D_t\} = D_{\text{max}} \cdot (1 - (1 - m)^k)$ where $m = \mu_c / N$, and results in Table 2 show that fitting error is lower than $2 \times 10^{-3}$ in all cases. Similar consistency is also found for redundancy percentage by comparing Figure 3(b) with Figure 2(b).

In Figure 4 we also investigate the impact of different utility functions. Freq and PROPHET lead to lower delivery ratio and higher redundancy because they inaccurately measure nodes’ contact capability. CCP and Betweenness perform better, especially when more message replicas are created.

3.2.2 Correlation Analysis

We are also interested in the correlation between delivery ratio and redundancy percentage. Figure 5 shows that the two metrics are closely correlated and increase simultaneously when message replicas are being created. We notice that there is an inflection point in each curve in Figure 5. Delivery ratio increases faster than redundancy percentage before the inflection point and vice versa. This result also validates our expectation in Theorem 1. As shown in Figure 5(a), the position of inflection point is mainly determined by node contact frequency and is trace-dependent.

The position of inflection point also depends on the forwarding strategy and utility function being used. Figure 5(b) shows that Compare-and-Forward is less effective and Spray-and-Focus performs better, when CCP is used as the utility function. Similarly, Figure 5(c) shows that PROPHET and CCP produce more redundancy than Betweenness does, with the Delegation forwarding strategy.

4 Elimination

In this section, we will eliminate forwarding redundancy from the utilities evaluating relays’ contact capability, so as to prevent this redundancy from affecting forwarding decision and ensure efficient network resource utilization.

Our basic idea is to keep track of Cumulative Relay Information (CRI) for each message, which records the cumulative contact capability of relays used for forwarding the message. The definition of CRI depends on the amount of network information available at individual nodes, and will be described later. When a relay $R$ determines whether to replicate the message to node $A$, $R$ compares the contact capability of $A$ with the current CRI of the message, and checks whether nodes contacted by $A$ have also been contacted by other relays. If so, this redundancy is eliminated from $A$’s utility, so that $A$’s utility reflects its actual contribution on forwarding the message. Moreover, when replicas of multiple messages are forwarded to $A$ with limited resources, their priorities are also determined by $A$’s utility after redundancy elimination.

We first focus on eliminating forwarding redundancy with complete CRI at the global scope, and then extend this scheme to be distributed with incomplete CRI maintained at individual relays. Impact of this incompleteness to redundancy elimination is analyzed and addressed from various perspectives.

4.1 Redundancy Elimination with Global CRI

We first assume that each node knows the global CRI. In practice, this information can be provided via a specific backend server, which maintains CRI and connects to nodes via 3G or satellite links5. The global CRI maintains

5. These communication links are generally expensive and have only limited bandwidth. Hence, they cannot be used for forwarding messages.
a quantity $C_i^{(k)}$ for each node $i$, which indicates the cumulative capability of the current $k$ relays contacting node $i$. $C_i^{(0)} = 0$ for all $i$. Each time when the message is replicated to another relay $R_{k+1}$, $C_i^{(k)}$ for each non-relay node $i$ is updated as

$$C_i^{(k+1)} = f(C_i^{(k)}),$$

(7)

where $C_i^{(k+1)}$ is the capability of $R_{k+1}$ contacting $i$, and is evaluated when the message is replicated to $R_{k+1}$ without being changed in the future. $f(\cdot)$ is a utility-dependent function with the following properties:

- **Monotonicity.** For all $k \in [1, N]$, $C_i^{(k+1)} \geq C_i^{(k)}$.
- **Convexity.** For all $k \in [1, N]$, $C_i^{(k+1)} \leq C_i^{(k)} + e_i^{(k+1)}$.

Forwarding redundancy caused by $R_{k+1}$ on node $i$ is identified as the difference between $C_i^{(k+1)}$ and $C_i^{(k)} + e_i^{(k+1)}$. Hence, after redundancy elimination, the utility of $R_{k+1}$ for forwarding this message is calculated as

$$U_{k+1} = \sum_{i=1}^{N} (C_i^{(k+1)} - C_i^{(k)}),$$

(8)

which indicates the actual contribution of $R_{k+1}$ on forwarding the message instead of $\sum_{i=1}^{N} C_i^{(k+1)}$. We design $f(\cdot)$ for observational and probabilistic utility functions, respectively.

### 4.1.1 Observational Utilities

For observational utilities including Freq, ElapsedTime and Betweenness, the contribution of $C_i^{(k+1)}$ to $C_i^{(k+1)}$ is reduced by the ratio between $e_i^{(k+1)}$ and $C_i^{(k)} + e_i^{(k+1)}$, i.e.,

$$C_i^{(k+1)} = C_i^{(k)} + \frac{e_i^{(k+1)}}{C_i^{(k)} + e_i^{(k+1)}} \cdot C_i^{(k+1)}.$$  

(9)

Eq. (9) can be interpreted in various ways when being applied to different utility functions. For Freq, the chance for $R_{k+1}$ to provide useful contact capability to node $i$ is proportionally reduced due to the existing contact capability $C_i^{(k)}$. This reduction also applies to ElapsedTime, because the reciprocal of elapsed time since last contact equivalently measures contact frequency by assuming stationary contact process. For example, if two relays $A$ and $B$ contact node $i$ with the frequency 2 and 8 respectively, the cumulative $C_i^{(2)} = 2 + \frac{8 \times 8}{2+8} = 8.4$ according to Eq. (9). For the third relay $C$ contacting $i$ with the frequency 6, $C_i^{(3)} = 8.4 + \frac{6 \times 8}{2+8+6} = 10.9$.

For Betweenness, $e_i^{(k+1)}$ measures the number of nodes which can communicate with node $i$ via $R_{k+1}$. Betweenness in opportunistic mobile networks is usually calculated in an ego-centric manner [17]. Forwarding redundancy exists when the neighborhood of $R_{k+1}$ on NCG overlap with that of other relays, and hence can be calculated similarly using Eq. (9).

Fig. 6. The impact of redundancy elimination in Eq. (10) to forwarding decision with Delegation strategy.

### 4.1.2 Probabilistic Utilities

For probabilistic utilities including PROPHET and CCP, $C_i^{(k+1)}$ is the probability for $R_{k+1}$ to contact $i$. We assume that the contact process of each relay is independent, and

$$C_i^{(k+1)} = 1 - \prod_{j=1}^{k+1} (1 - C_i^{(j)}).$$

Hence,

$$C_i^{(k+1)} = 1 - (1 - C_i^{(k)}) \cdot (1 - C_i^{(k+1)}).$$

(10)

The impact of redundancy elimination on forwarding decision is illustrated in Figure 6. The utilities of $B$ and $C$ are reduced by nearly 50% after their redundancy of contacting $G$, $J$ and $K$ is eliminated, and hence will not be used as relays due to their low utilities. Instead, $A$ replicates message to $F$ which is effective to contact more distinct nodes and has more contribution on forwarding the message.

### 4.2 Distributed Elimination

When the global CRI is unavailable, each relay maintains CRI in a distributed manner6, only based on its local information about its neighbors on NCG. Due to the lack of end-to-end network connectivity, the CRI maintained at relays may be incomplete and partially overlap with each other. For example, in the network shown in Figure 6, node $J$ is contacted by three relays $A$, $B$ and $C$. The CRI about node $J$ maintained at $B$ includes capability of $A$ and $B$ contacting $J$, but the CRI maintained at $C$ only includes that of $A$ and $C$.

Due to this possible overlapping, relays need to merge their maintained CRI when they contact, and the quantity $C_i^{(k)}$ is insufficient for maintaining CRI in a distributed manner. In the above example, it is difficult for relays $B$ and $C$ to correctly identify this overlapping and merge their CRI to calculate the cumulative capability of $A$, $B$ and $C$ contacting $J$.

In this case, CRI is maintained in a more fine-grained level. A relay maintains a list for each non-relay node $i$, and the list records the capability $C_i^{(j)}$ of each relay $R_j$ contacting $i$. When relays $B$ and $C$ in Figure 6 contact each other, their lists are merged to correctly calculate
CRI of node J based on Eqs. (9) or (10), and this process is illustrated in Figure 7.

The amount of storage space for maintaining CRI is related to the number of relays, which is much smaller than the number (N) of nodes in the network. For example, the required space is \( O(N \cdot (\log N)^2) \) when Delegation strategy is used.

### 4.3 Accuracy Analysis and Improvement

When CRI is maintained in a distributed manner, accuracy of redundancy elimination may be impaired due to incompleteness of CRI. This incompleteness appears when a relay is unaware of some other existing relays, and is illustrated in Figure 8(a) which describes forwarding process as a Message Replication Tree (MRT). Without loss of generality, we assume that communication links among \( R_1, ..., R_{k-1} \) have broken when message is replicated to relay \( R_k \). In Figure 8(a) when message is replicated from \( R_3 \) to \( R_7 \), \( R_7 \) knows \( R_2 \) because \( R_2 \) receives message replica earlier from \( R_1 \) which is also the parent of \( R_3 \) on MRT, but \( R_7 \) is unaware of the existence of \( R_4 \) and \( R_5 \) because the link between \( R_4 \) and \( R_5 \) has broken. Similarly, neither \( R_4 \) nor \( R_5 \) knows \( R_3 \) and \( R_6 \) and \( R_7 \).

**Definition 2:** The Blind Zone (BZ) \( \mathbb{B}_{R_i}(t) \) of a relay \( R_i \) at time \( t \) is defined as a set of relays which receive message replica before time \( t \), such that a relay \( R_j \in \mathbb{B}_{R_i}(t) \) if \( R_i \) is unaware of the existence of \( R_j \) at time \( t \).

The BZs of relay \( R_5 \) and \( R_7 \) are indicated by dashed circles in Figure 8(a). Based on this definition, incompleteness of CRI at time \( t \) is measured by average size of relays’ BZ as \( I_k = \frac{1}{k} \cdot \sum_{i=1}^{k} |\mathbb{B}_{R_i}(t)| \), where \( k \) is the number of relays.

This incompleteness of CRI may cause false positive and false negative errors to forwarding decision. First, \( R_5 \) and \( R_7 \) in Figure 8(b) contact node \( A \) with probability 0.5 and 0.6, and the actual utility of \( R_7 \) should be 2.2 instead of 2.5 according to Eq. (10). When Delegation strategy is used, \( R_7 \) should not receive message replica from \( R_3 \) because \( R_6 \) becomes relay earlier and 2.3 > 2.2. Hence, \( R_7 \) is a false positive error. Second, \( R_3 \) incorrectly considers that \( R_7 \) has the highest utility of 2.5 among existing relays. This prevents \( R_8 \) from becoming a relay and leads to a false negative error.

We propose two alternative schemes to address these errors and improve the accuracy of redundancy elimination. First, we pre-regulate the forwarding process before message is actually replicated to relays, so as to reduce the chance for errors to occur. Second, we opportunistically adjust relays after they receive message replicas, when the errors are detected.

#### 4.3.1 Pre-regulation of Forwarding Process

A relay \( R_k \) is inevitably blind to relays which receive message replica later and not from \( R_k \) itself. Hence, we focus on ensuring that \( R_k \) knows all the relays \( R_1, ..., R_{k-1} \), i.e., \( |\mathbb{B}_{R_k}(t)| = |\mathbb{B}_{R_k}(t) \cap \{ R_1, ..., R_{k-1} \} | = 0 \) for \( \forall t \geq T_{k_0} \) where \( T_k \) is the time \( R_k \) receives message replica. This is achieved by regulating forwarding process represented by MRT.

\[ |\mathbb{B}_{R_k}(t)| \] is controlled by two parameters \( N_R \) and \( K_R \). \( N_R \) is the maximum number of non-leaf relays at each level of MRT. We let the non-leaf relays at a level of MRT have larger indices than any leaf relay at the same level, and only allow the non-leaf relays to replicate message and produce new relays. \( K_R \) is the maximum number of new relays that a non-leaf relay can produce, and we limit that \( K_R \geq N_R \). MRTs with \( (N_R, K_R) \) from (1,1) to (2,2) are illustrated in Figure 9.

**Lemma 2:** \( |\mathbb{B}_{R_k}(t)| = 0 \) for \( \forall k \geq 1 \) when \( N_R = 1 \).

**Proof:** We prove this lemma by induction over levels of MRT.
Step 1: if $R_k$ is at the first level, $k = 1$ and $R_1$ is the source node. The lemma simply holds.

Step 2: we suppose that the lemma holds for all the relays at the $j$-th level. Since $N_R = 1$, all the relays at the $(j+1)$-th level receive message replica from the same parent $R^{(j)}$ at the $j$-th level. For $R_k$ at the $(j+1)$-th level, $i$) it knows all the relays at the upper levels from $R^{(j)}$ because $|B_{R^{(j)}}(t)| = 0$, ii) it knows all the relays at the $(j+1)$-th level with smaller index because they also receive message replica from by $R^{(j)}$. The lemma hence also holds for $R_k$ at the $(j+1)$-th level.

This lemma is proved by combining Steps 1 and 2. □

From Lemma 2, we immediately have the following theorem considering that $|B_{R_{k-1}}(t)| = |B_{R_k}(t)| = 0$.

**Theorem 2:** When $N_R = 1$, $I_k = \frac{(k-1)(k-2)}{2k^2}$ for any $K_R \geq 1$.

$I_k$ increases with $K_R$ when $N_R > 1$. Non-leaf relays usually have the best capability contacting other nodes and determine which node to be the next non-leaf relay, so to ensure that a sufficient number of message replicas are created.

### 4.3.2 Posterior Adjustment of Relays

The aforementioned pre-regulation may prevent some relays from receiving message replica and affect forwarding performance. Another way is to adjust the relays in a posterior manner, when the false positive and false negative errors are detected. These errors are detected opportunistically when relays contact each other and update their maintained CRI.

A relay $R_k$ autonomously revokes itself by removing its message replica, when it detects itself as false positive. For this detection, $R_k$ memorizes the situation at time $T_k$ when it received message replica. Each time when $R_k$ contacts another relay and updates its CRI, it recalculates its utility at time $T_k$. The false positive error is detected when $R_k$ realizes that it should not be a relay with the new utility. In Figure 8(b), $R_7$ finds that its utility should be 2.2 instead of 2.5 when it contacts $R_6$, and realizes itself as false positive. After $R_7$ revoked itself, $R_5$ is responsible for notifying other relays to remove $R_7$’s information from their maintained CRI.

Figure 8(b) shows that a false negative error only happens after a false positive error. After relay $R_7$ revokes itself, the false negative error on $R_6$ is detected until $R_3$ or $R_8$ is notified about the revocation of $R_7$. Since $R_3$ may not be in contact with $R_6$ by then, $R_3$ spreads the information about this error among existing relays, so that $R_8$ receives message replica if it contacts any relay being aware of this false negative error.

In general, the delay for the errors to be corrected is determined by both the network scale and node contact pattern. Since the selected relays have good capability contacting other nodes, this delay is expected to be much shorter than the inter-contact time among mobile nodes.

### 4.4 Local Allocation of Relay Resources

A relay has only limited local resources. When replicas of multiple messages are forwarded to a relay, its resources should be allocated to the appropriate message replicas. Such problem of local resource allocation has been studied in [2], but with the assumption that each message has equal size. Instead, we propose a generalized solution based on the relays’ utilities after redundancy elimination.

When replicas of $M$ messages with sizes $s_1, \ldots, s_M$ are forwarded from relay $R_1$ to relay $R_2$ with buffer size $B$, the problem of resource allocation at $R_2$ is formulated as

\[
\max \sum_{k=1}^{M} U_2^{(k)} x_k \quad \text{s.t.} \sum_{k=1}^{M} s_k x_k \leq B,
\]

where $x_k \in \{0, 1\}$ indicate whether the $k$-th message replica is forwarded to $R_2$, and $U_2^{(k)}$ is utility of $R_2$ defined in Eq. (8) for forwarding the $k$-th message. Note that the forwarding redundancy between the existing relays (including $R_1$) and $R_2$ for forwarding the $k$-th message has been eliminated from $U_2^{(k)}$. Eq. (11) ensures that $R_2$’s resources are allocated to the appropriate message replicas, such that $R_2$ has the most contributions on forwarding these messages. In practice, since $B$ and $s_k$ in Eq. (11) are usually integers in numbers of bytes, Eq. (11) can be solved in pseudo-polynomial time $O(M \cdot B)$ using a dynamic programming approach [31].

Due to the limited channel bandwidth and contact duration, $R_1$ may not be able to transmit all the message replicas selected by Eq. (11) to $R_2$ before the contact ends. The order for message replicas to be transmitted follows their order being selected when solving Eq. (11) using dynamic programming, due to the property of optimal substructure of Eq. (11).

### 5 Exploitation

Elimination of forwarding redundancy improves the effectiveness of network resource utilization and enhances the cumulative forwarding performance, but the specific performance requirements for forwarding individual messages may not be satisfied due to the reduced number of message replicas being created. The examples of such applications include emergency notification, which require reliable and timely message delivery and have strict requirement on delivery ratio.

In this section, based on the capability of eliminating forwarding redundancy, we develop adaptive forwarding strategy to exploit such redundancy and satisfy the delivery ratio required by each message with the minimum number of message replicas. We replicates messages based on relays’ utilities after redundancy elimination, and adaptively controls the amount of forwarding redundancy according to the required delivery ratio and up-to-date network condition.
Fig. 10. Exploitation of forwarding redundancy

5.1 Basic Methodology

When a relay $R$ determines whether to replicate a message to another node $A$, most of current forwarding strategies can be summarized as a uniform comparison-based framework shown in Figure 10(a). $R$ compares a local quantity $Q_R$ which is called “forwarding threshold” with $A$’s utility $U_A$ for forwarding the message, and only replicates the message to $A$ if $Q_R < U_A$. Different strategies vary in $Q_R$ they use. Compare-and-Forward maintains $Q_R$ as utility of $R$, and in Delegation $Q_R$ is the highest utility among all the relays that $R$ is aware of. In all the strategies, the method of calculating and updating $Q_R$ is fixed during forwarding process.

Our basic idea for controlling the amount of forwarding redundancy is to adaptively adjust $Q_R$ at each relay $R$ by multiplying $Q_R$ with a parameter $\alpha$, as illustrated in Figure 10(a). We assume that message is generated at time 0 and expires at time $T$. As a result, $\alpha$ at time $t_c \leq T$ is determined by the estimated delivery ratio $\tilde{D}(t_c)$ that relays at $t_c$ can achieve at $T$, and the remaining time $T - t_c$ for forwarding the message.

This exploitation is illustrated in Figure 10(b). Ideally, more relays receive message replicas when $t_c$ elapses and gradually improve $\tilde{D}(t_c)$ to the required delivery ratio $D$ before $T$, so that $\alpha \equiv 1$. However, in practice the increase of $\tilde{D}(t_c)$ may be different due to the specific network contact pattern, and we adjust $\alpha$ accordingly to approximate $\tilde{D}(t_c)$ to the ideal case. In Case 1 shown in Figure 10(b) where $\tilde{D}(t_c)$ at time $t_c < T/2$ is already close to $D$, $\alpha$ increases to avoid redundant relays. In Case 2 where $\tilde{D}(t_c)$ is too low, $\alpha$ decreases to ensure that there is a sufficient number of relays to achieve $D$.

Note that we minimize the number of relays used to achieve $D$ based on relays’ utilities after redundancy elimination. Otherwise, without redundancy elimination in Section 4, $D$ can still be achieved by reducing $\alpha$ but the number of relays increases due to forwarding redundancy among relays. Moreover, increasing $\alpha$ or using fewer relays does not necessarily reduce the amount of forwarding redundancy in the network.

The value of $\alpha$ is calculated based on the CRI maintained at time $t_c$ and is used to estimate $\tilde{D}(t_c)$. We calculate $\alpha$ as $\tilde{N}_{R}/N_{R}$, where $N_R$ is additional number of relays needed at time $t_c$ for achieving $D$ and $\tilde{N}_{R}$ is the estimated number of relays that can receive message replica during time period $(t_c, T)$. We propose effective heuristics to estimate both $N_R$ and $\tilde{N}_{R}$ at individual relays, and also exploit periodicity of relays’ contact capability for more accurate control of $\alpha$.

5.2 Heuristics

5.2.1 Estimating $N_R$

$N_R$ is determined by CRI maintained at time $t_c$. Suppose there are $k$ relays a time $t_c$, $\tilde{D}(t_c) = \frac{1}{\sum_{i=1}^{N} C_i^{(k)}}$ where $C_i^{(k)}$ is the cumulative capability of the $k$ relays contacting node $i$. From Section 3 we know that the increase of actual delivery ratio over $k$ can be modeled as $\mathbb{E}D_k = D_{\max} \cdot (1 - (1 - m)^k)$. Each time when we have a new relay $R_k$, we update the parameters $D_{\max}$ and $m$ by least-square curve fitting over the estimated $\tilde{D}(t_c)$, and $N_R$ is calculated as

$$N_R = \frac{\ln(1 - \frac{D}{D_{\max}})}{-k}.$$  

5.2.2 Estimating $\tilde{N}_{R}$

We estimate $\tilde{N}_{R}$ based on the intervals $T_i$ between the times that the $i$-th and $(i+1)$-th relays receive message replica, and we propose two alternatives of heuristics for such estimation.

The first heuristic is based on the observation in Figure 13(b) that $T_i$ generally increases with $i$. We estimate the next time interval $T_{k+1} = \max_{1 \leq i \leq k} T_i$ and $\tilde{N}_{R} = (T - t_c)/T_{k+1}$.

Another alternative is to model the variation of $T_i$ as an Auto-Regressive (AR) process with the order of $p$ ($p < k$). A $p$-order AR process is defined as

$$T_k = \sum_{i=1}^{p} \phi_i T_{k-i} + \epsilon_k,$$  

where $\phi_1, \ldots, \phi_p$ are the parameters and $\epsilon_k$ is white noise. Based on $T_i$ in the past, these parameters can be estimated either via least-square regression or using Yule-Walker equations [4]. $\tilde{N}_{R}$ can be estimated by recursively calculating these time intervals in the future, until $\sum_{i=k+1}^{N_R} T_i \geq T - t_c$.

$\tilde{N}_{R}$ estimated by AR process is generally more accurate, but also requires more information of $T_i$ to estimate parameters in Eq. (12). In practice, the first alternative is used for estimating $\tilde{N}_{R}$ during initial stage of forwarding, and is switched to AR process after there are at least $p + 1$ relays.

5.3 Exploitation of Periodicity

The contact patterns among mobile devices are related to human behaviors, and lead to periodicity of forwarding performance and redundancy at various time scales. We
exploit such periodicity for more accurate control of forwarding redundancy.

We first investigate such periodicity in real-world traces. We divide each trace into 100 pieces with equal time length, generate message at the beginning of each piece, and investigate delivery ratio and redundancy percentage at the end of each piece. This periodicity is shown in Figure 11, with Delegation and Betweenness used for forwarding decision. Periodicity of delivery ratio is approximated by periodic function \( \tilde{G}(t) = G(t \mod T_p) \), where \( T_p \) is its period and \( G(t) = A \cdot e^{-\frac{(t-\mu)^2}{2\sigma^2}} \) is Gaussian function. Parameters of \( \tilde{G}(t) \) are listed in Table 3, where \( T_p \) and \( \mu \) are in number of days.

Table 3 exhibits periodicity of relays’ contact capability and motivates us to adjust \( Q_R \) according to transient contact capability of relays during time period \([t_c, T] \). For example, in the DieselNet and Infocom traces, nodes contact each other more often during daytime and have higher chances to be used as relays. \( Q_R \) should be increased accordingly to reduce the amount of forwarding redundancy. In contrast, \( Q_R \) should decrease during nighttime when node contact capability is low.

Our basic idea is to apply an additional coefficient \( \beta \) being multiplied to parameter \( \alpha \), and \( \beta \) is calculated by comparing the transient contact capability of relays during \([t_c, T] \) with their cumulative contact capability. Based on the Gaussian formulation of periodicity described above, \( \beta \) is calculated as

\[
\beta = \frac{2T_p}{A\sigma\sqrt{\pi}} \cdot \frac{1}{T-t_c} \int_{t_c}^{T} \tilde{G}(t)dt, \tag{13}
\]

where \( A\sigma\sqrt{\pi}/(2T_p) \) indicates cumulative contact capability of relays, because \( \int_{0}^{T_p} \tilde{G}(t)dt = A\sigma\sqrt{\pi}/2 \) when \( \tilde{G}(k \cdot T_p) = 0 \) for \( \forall k \geq 0 \). In practice, parameters of \( \tilde{G}(t) \) are estimated based on \( \hat{D}(t_c) \), which is calculated from the maintained CRI.

## 6 Performance Evaluation

In this section, we evaluate the performance of our redundancy elimination schemes, using the realistic mobile network traces listed in Table 1. The first half of each trace is used for nodes to collect network information and all the messages are generated at randomized times afterwards. We assume that the channel bandwidth is 1 Mbps (Bluetooth v1.2), and the message size is uniformly distributed in \([10Mb, 50Mb]\). As reported in [18], most of contacts in the traces we use last long enough to transmit at least one message replica. The buffer size of nodes is uniformly distributed in \([50Mb, 500Mb]\) so that each node can carry at least one message replica.

### 6.1 Performance of Redundancy Elimination

We first evaluate the performance of redundancy elimination with global and distributed CRI. We generate a message every hour with random source and destination, and the evaluation results over all the messages are shown in Figure 12, where Betweenness and CCP are used to represent observational and probabilistic utility functions, respectively.

Figure 12(b) shows that our schemes effectively eliminate forwarding redundancy by more than 50%. This elimination enables effective utilization of the relays’ resources, and hence leads to 20% improvement of the cumulative delivery ratio and 40% reduction on the forwarding cost\(^7\). Note that the contact capabilities of selected relays after redundancy elimination may still overlap, but this remaining redundancy is very limited compared to the useful contact capability provided by relays. Figure 12 also shows the impact of CRI incompleteness to redundancy elimination and forwarding performance. When CRI is maintained in a distributed

---

### Table 3: Parameters of periodicity of delivery ratio

<table>
<thead>
<tr>
<th>Trace</th>
<th>( T_p )</th>
<th>( A )</th>
<th>( \mu )</th>
<th>( \sigma )</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>DieselNet</td>
<td>1.171</td>
<td>0.390</td>
<td>0.568</td>
<td>0.248</td>
<td>0.0082</td>
</tr>
<tr>
<td>Infocom</td>
<td>1.064</td>
<td>0.574</td>
<td>0.6398</td>
<td>0.552</td>
<td>0.0359</td>
</tr>
<tr>
<td>MIT Reality</td>
<td>7.036</td>
<td>0.498</td>
<td>4.106</td>
<td>2.891</td>
<td>0.0351</td>
</tr>
<tr>
<td>UCSD</td>
<td>6.894</td>
<td>0.2696</td>
<td>3.211</td>
<td>1.597</td>
<td>0.0229</td>
</tr>
</tbody>
</table>

---

\(^7\) We consider the overhead of maintaining CRI as negligible because it only happens when relays contact and the size of CRI metadata is very small compared with the messages being forwarded.
6.2 Effectiveness of Accuracy Improvement

As discussed in Section 4.3, the accuracy of redundancy elimination may be impaired due to CRI incompleteness at individual relays. Various techniques have been proposed in Section 4.3 to detect and correct the possible errors during redundancy elimination. Such CRI incompleteness, which is measured by average size of relays’ BZ, is shown in Figure 14 with Compare-and-Forward and CCP used for forwarding decision. Figure 14(a) shows that the average BZ size can be up to 35%. We also evaluate the effects of pre-regulation of forwarding process on reducing the average BZ size, and the results are shown in Figure 14(b). As expected by Lemma 2, the average BZ size is reduced by up to 50% when $N_R = 1$, but increases when $N_R$ or $K_R$ increases.

The performance of error detection and correction schemes proposed in Section 4.3 are evaluated in Figure 15. Figure 15(a) shows that the majority of errors is false positive, and false negative errors are only noticeable when many message replicas are created. Our schemes can effectively detect both types of errors, and limit the cumulative error percentage lower than 10%. Figure 15(b) also evaluates the delay of error detection. Obviously this delay is closely related with data lifetime. When data lifetime is set as 1 week for the MIT Reality trace, Figure 15(b) shows that both types of errors can be detected and corrected within 20% of the data lifetime.

Using the same strategy and utility function, the performance of schemes proposed in Section 4.3 for improving the accuracy of distributed redundancy elimination is evaluated in Figure 16. First, by comparing Figure 12 and Figure 16, we see that posterior adjustment of relays effectively corrects errors during distributed redundancy elimination, and improves forwarding performance to the level of global elimination. Second, Figure 16(b)
shows that pre-regulation of forwarding process further-
mores reduces forwarding redundancy over 10%, but it
also prevents some relays from receiving message replica
and reduces delivery ratio by 3%. Figure 16 indicates
that the two schemes have different tradeoff between
forwarding performance and redundancy, and should be
used according to the specific application scenario and
requirements.

6.3 Performance of Redundancy Exploitation
We first evaluate values of $\alpha$ in practice, and the results
in Figure 17 show that values of $\alpha$ are proportional to
$T$. When $T$ increases to 48 hours, the average value of
$\alpha$ increases over 100%. We notice that values of $\alpha$
generally lower than 1 when $T \leq 12$ hours, which means
that more relays are needed to achieve $D$ during the
short message lifetime. In contrast, when $T = 48$ hours,$\alpha$
quickly increases to avoid redundant relays. Similarly,
Figure 17(b) shows that higher $D$ reduces $\alpha$ so that more
relays can be used for forwarding the message.

For evaluating the performance of our proposed for-
warding strategy, we use the same experiment settings
as in Section 6.1. The required delivery ratio for each
message is uniformly distributed in $[0.5D_{avg}, 1.5D_{avg}]$, and
$D_{avg}$ varies in our experiments. The evaluation
results are shown in Figure 18 where Delegation and
CCP are used for forwarding decision. When $D_{avg} = 40%$
and $T \leq 12$ hours, our strategy creates more message
replicas to ensure that the required $D$ can be achieved.
When $T$ increases, our strategy avoids redundant relays
and achieves $D$ with 40% less relays.

Comparatively, when $D_{avg} = 70%$, redundancy percent-
age increases to create more message replicas. Figure
18(a) shows that the actual delivery ratio only achieves
65% due to limited node contact capability. In this case,
our strategy ensures that best-effort forwarding perfor-
mance is provided.

7 RELATED WORK
The research on data forwarding in DTNs originates
from Epidemic routing [38] which floods the entire net-
work. Later studies develop data forwarding strategies
to approach the performance of Epidemic routing with
lower forwarding cost, which is measured by the number
of data copies created in the network. While the most
conservative approach always keeps a single data copy
and Spray-and-Wait [35] holds a fixed number of data
copies, most schemes leave such numbers as dynamic
and make data forwarding decision by comparing the
nodes’ utility functions. Representative strategies include Compare-and-Forward [11], [14], Delegation [15] and Spray-and-Focus [36], which were exploited when studying forwarding redundancy in this paper. Other forwarding strategies [37], [39], [8], [29] also aim to achieve various tradeoffs between the data forwarding performance and cost.

The utility functions of mobile nodes, which measure the nodes’ contact capabilities, are generally independent from the data forwarding strategies mentioned above [20]. Various utility functions can be applied to the same forwarding strategy for different performance requirements. Some schemes predict node contact capability by estimating their co-location probabilities in different ways, such as the Kalman filter [9] and semi-Markov chains [40]. In some other schemes, node contact pattern is exploited as abstraction of node mobility pattern for better prediction accuracy, based on the experimental [7], [27] and theoretical [6] analysis on the node contact characteristics. Such node contacts are detected via energy-efficient periodic probing methods [1], [21], [24], and the detected contact history is then used to predict the nodes’ capability of contacting others in the future. MaxProp [5] estimates the node contact likelihood based on the contact counts in the past, and PodNet [28] forwards data to nodes based on their received data queries in the past.

Social properties of human mobility including centrality and community structures are also exploited for forwarding messages [25], [22]. SimBet [10] uses ego-centric betweenness as relay selection metric, and BUBBLE Rap [25] considers node centrality hierarchically in social community structures. [22] exploited both centrality and social communities for multicasting, and proposed Cumulative Contact Probability (CCP) as the utility function for data forwarding based on the cumulative node contact rates and the assumption of exponential distribution of pairwise node inter-contact time. Such CCP metric was also used in this paper. [19] furthermore extends CCP to the multi-hop network scope.

Social community structure in opportunistic mobile networks, on the other hand, is usually used to determine the network scope for evaluating node centrality, and can be detected in a fully distributed manner in various ways [26]. k-clique-based [34] method enables the detection of overlapping communities, and modularity-based method [33] works on weighted network contact graph. Based on such community detection techniques, BUBBLE Rap [25] exploited social community structures for data forwarding in opportunistic mobile networks based on the cumulative node contact characteristics. Node centrality is evaluated at various network scopes according to the community boundary of the destination, and data is hence forwarded in a hierarchical manner.

8 CONCLUSIONS

In this paper, we study forwarding redundancy in opportunistic mobile networks, which may seriously impair the forwarding performance. We investigate its characteristics from both theoretical and experimental perspectives, and propose effective schemes to eliminate this redundancy with limited network information. We furthermore exploit this redundancy adaptively to satisfy specific performance requirements of mobile applications. Extensive trace-driven simulations show that our schemes effectively improve forwarding performance with much lower cost.

REFERENCES


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