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], [38], stochastic node contact process [2], [28] or social network concepts [10], [23], [21]. Second, node utilities are applied to various forwarding strategies for different tradeoffs between forwarding performance and cost. Epidemic [36] 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

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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 percent 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 percent 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.

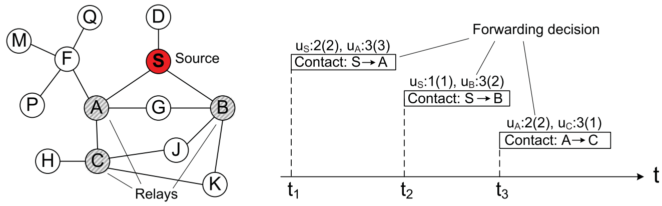
We focus on effectively forwarding messages to destinations with minimum cost, measured by the average number of replicas created per message.[1] We consider that each relay has only limited resources of channel bandwidth and local buffer. When replicas of multiple messages are forwarded to the same 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 $X \in (0,+\infty]$, the expected delay is measured as $\mathbb{E}\{X|X \le T\}$ and the delivery ratio is $\mathbb{P}(X \le T)$. Since the delivery ratio and expected delay are correlated and increase simultaneously when T increases, in this paper we measure forwarding performance using delivery ratio and will not evaluate delay separately.

2.2 Motivation

Forwarding redundancy in opportunistic mobile networks is illustrated by the example in Fig. 1. Fig. 1a only shows

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.



(a) Network contact graph (b) Forwarding decisions

Fig. 1. Illustration of forwarding redundancy. Utility u_i indicates the number of nodes that i contacts, and the value within brackets is the value of u_i after redundancy elimination. Message is replicated from i to j if $u_i < u_j$.

part of NCG near the data source S, and none of the nodes in Fig. 1a 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,[2] 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 percent. 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

$$P_k(t_1, t_2) = 1 - \left| \bigcup\nolimits_{i=1}^{k} \mathbb{N}_i(t_1, t_2) \right| \Big/ \sum_{i=1}^{k} |\mathbb{N}_i(t_1, t_2)|, \qquad (1)$$

where node $j \in \mathbb{N}_i(t_1, t_2)$ if it is contacted by the ith relay during time period $[t_1, t_2]$. The ith relay belongs to $\mathbb{N}_i(t_1, t_2)$.

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.

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 (*ElapsedTime*) [11]. *Betweenness* [17] is also used in social-aware forwarding schemes [23], and defines $c_{ij} = \sum_{k=1}^{j-1} \frac{g_{jk}(i)}{g_{jk}}$, where g_{jk} 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* [28] increases c_{ij} by $(1 - c_{ij}) \cdot p_{init}$ each time when i and j contact,[3] and *CCP* [21] defines $c_{ij} = 1 - e^{-\lambda_{ij} T}$ where λ_{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* [34], 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.

2.4 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 [23]) and university campus (MIT Reality [12], UCSD [30]). 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.

3 Investigation

In this section, we investigate the characteristics of forwarding redundancy from both theoretical and experimental

3. PROPHET proposed in [28] was only used between a relay and the destination. In this paper we extend it to an arbitrary pair of nodes.

TABLE 1
Trace Summary

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

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[4] with k relays is

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

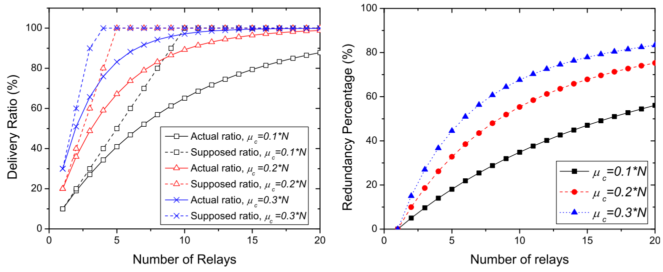
where N is the number of nodes in the network, $n_i = |\mathbb{N}_i(t_i, t_e)|$ and t_i is the time when the message is replicated to the ith relay. When message is replicated to another relay R_{k+1}, D_k increases by $\Delta D_k = (1 - D_k) \cdot \frac{n_{k+1}}{N}$. If n_i are i.i.d. stationary random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

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

In Eq. (2), both the destination and the nodes in $\mathbb{N}_i$ 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, $\mathbb{N}_i$ of relays within different communities may not overlap at all.

Comparatively, delivery ratio without considering forwarding redundancy is $\widetilde{D}_k = \frac{1}{N} \cdot \sum_{i=1}^{k} n_i$ with $\sum_{i=1}^{k} n_i \leq N$, and $\mathbb{E}\{\widetilde{D}_k\} = k\mu_c/N$. Fig. 2a illustrates the difference

4. The delivery ratio of a single message equals to its probability to be delivered to the destination before expiration.



(a) Comparing $\mathbb{E}\{D_k\}$ and $\mathbb{E}\{\widetilde{D}_k\}$ (b) Redundancy percentage

Fig. 2. Theoretical variation of delivery ratio and redundancy percentage.

between $\mathbb{E}\{D_k\}$ and $\mathbb{E}\{\widetilde{D}_k\}$ when k increases. While $\mathbb{E}\{\widetilde{D}_k\}$ linearly increases with k, $\mathbb{E}\{D_k\}$ increases slower. This difference is larger when k increases or μ_c is smaller. Since the distribution of node contact capability is highly skewed in reality [23], value of μ_c is low and the actual delivery ratio is much lower than that indicated by relays' utilities.

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 $\mathbb{E}\{\frac{1}{N_k}\} \geq \frac{1}{k\mu_c}$, we have

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

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

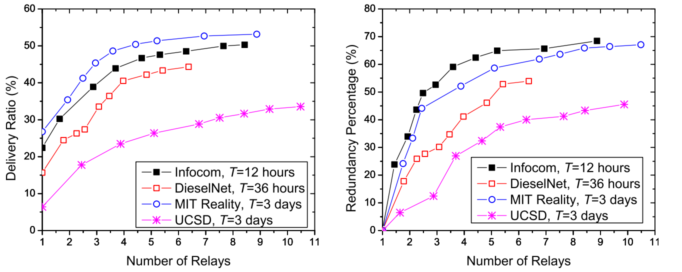
$$\begin{aligned}\Delta P_k = P_{k+1} - P_k &= \frac{N \cdot D_k}{N_k} - \frac{N \cdot D_{k+1}}{N_k + n_{k+1}} \\ &= \frac{N \cdot n_{k+1}}{N_k(N_k + n_{k+1})} \cdot \left(D_k - \frac{N_k}{N}(1 - D_k)\right).\end{aligned} \tag{5}$$

Lemma 1. *For* $\forall k \geq 1$, $\Delta P_k \geq 0$.

Proof. Consider functions $f(n_1, \ldots, n_k) = \frac{1}{N}\sum_{i=1}^{k} n_i = N_k/N$ and $g(n_1, \ldots, n_k) = \frac{1 - \prod_{i=1}^{k}(1 - \frac{n_i}{N})}{\prod_{i=1}^{k}(1 - \frac{n_i}{N})} = \frac{D_k}{1 - D_k}$. For $\forall i \in [1, k]$ we have $\frac{\partial f}{\partial n_i} = \frac{1}{N}$ and $\frac{\partial g}{\partial n_i} = \frac{1}{N(1 - \frac{n_i}{N})} \cdot (1 + g(n_1, \ldots, n_k))$. Since $f(0, \ldots, 0) = g(0, \ldots, 0) = 0$, we have $f(n_1, \ldots, n_k) \leq g(n_1, \ldots, n_k)$ for $\forall n_1, \ldots, n_k \in (0, N]$ 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 Fig. 2b 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.



(a) Delivery ratio (b) Redundancy percentage

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

Theorem 1. *When* $1 \leq n_i < N/2$ *for* $\forall i \in [1, k]$, *there exists* $k_0 \in [1, N]$, *such that for* $\forall k \leq k_0$, $\Delta P_k \leq \Delta D_k$, *and for* $\forall k > k_0$, $\Delta P_k > \Delta D_k$.

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 $f(k) = \frac{N \cdot N_k + N_k^2 + N_k n_{k+1}}{N}$ 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 $k_0 \in (0, \infty)$ such that $f(k_0) - \frac{D_{k_0} \cdot N}{1 - D_{k_0}} = 0$. This is proved in the following steps.

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

Step 2. It is easy to have $\frac{\partial f(k)}{\partial k} > 0$ and $\frac{\partial g(k)}{\partial k} > 0$ for $\forall k$.

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

The theorem is proved by combining the three steps above. □

Theorem 1 shows that, when the number of message replicas is small, each replica has limited forwarding redundancy but considerably increases delivery ratio. However, when message is replicated to more relays, the newly created replicas gradually become redundant and only contribute little to the forwarding performance.

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. 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 [34] and the utility function of CCP [21]. Message lifetime T is adaptively determined in different traces to ensure that the designated number of message replicas is created.

TABLE 2
Curve Fitting on Delivery Ratio

Trace	$D_{\max}$	m	fitting error
DieselNet	0.5233	0.2728	1.65×10^{-3}
Infocom	0.5021	0.4182	1.307×10^{-3}
MIT Reality	0.5402	0.4549	1.077×10^{-3}
UCSD	0.4893	0.1206	2.48×10^{-4}

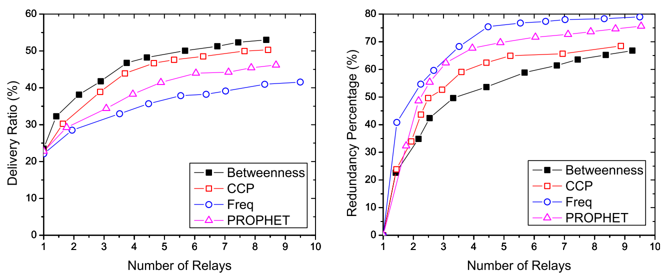
As shown in Fig. 3, both delivery ratio and redundancy percentage increase when more message replicas are created. This increase is determined by the contact patterns and frequencies of mobile nodes, which are trace-dependent. In the MIT Reality trace, when the number of relays is smaller than 3, redundancy percentage is lower than 40 percent, and each message replica noticably improves delivery ratio by 10 percent. However, the other six message replicas being created later only improve delivery ratio by another 10 percent, but increase redundancy percentage to 70 percent. 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 Fig. 3 a is consistent with our theoretical expectations in Section 3.1. To validate this consistency, we perform least-square curve fitting on Fig. 3a using formula $\mathbb{E}\{D_k\} = D_{\max} \cdot (1 - (1 - m)^k)$ where $m = \mu_c / N$, and results in Table 2 show that fitting error is lower than 2×10^{-3} in all cases. Similar consistency is also found for redundancy percentage by comparing Figs. 3b with 2b.

In Fig. 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.

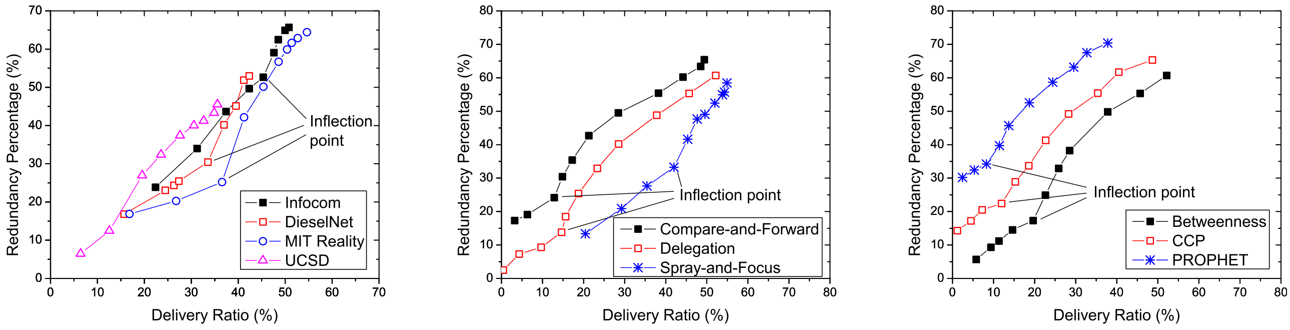
3.2.2 *Correlation Analysis*

We are also interested in the correlation between delivery ratio and redundancy percentage. Fig. 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 Fig. 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 Fig. 5a, the



(a) Delivery ratio (b) Redundancy percentage

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



(a) Correlation in different traces (b) Correlation with different forwarding strategies (c) Correlation with different utilities

Fig. 5. Correlation between delivery ratio and redundancy percentage. An inflection point is found in all cases.

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. Fig. 5b shows that Compare-and-Forward is less effective and Spray-and-Focus performs better, when CCP is used as the utility function. Similarly, Fig. 5c 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 links.[5] The global CRI maintains 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 $\forall i$. 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

$$C_i^{(k+1)} = f\big(C_i^{(k)}, c_i^{(k+1)}\big), \tag{7}$$

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

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

$$U_{k+1} = \sum_{i=1}^{N} \big(C_i^{(k+1)} - C_i^{(k)}\big), \tag{8}$$

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.

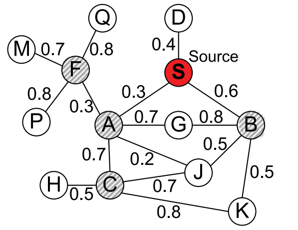
4.1.1 Observational Utilities

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 $c_i^{(k+1)}$ and $C_i^{(k)} + c_i^{(k+1)}$, i.e.,

$$C_i^{(k+1)} = C_i^{(k)} + \frac{c_i^{(k+1)}}{C_i^{(k)} + c_i^{(k+1)}} \cdot c_i^{(k+1)}. \tag{9}$$

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

5. These communication links are generally expensive and have only limited bandwidth. Hence, they cannot be used for forwarding messages.



(a) Network contact graph. Numbers on the edges are the pairwise contact probabilities.

With redundancy	Without redundancy
S(1.3)⟶A(2.2)	S(1.3)⟶A(2.2)
S(2.2)⟶B(2.4)	S(2.2)⟶B(1.14)
A(2.2)⟶C(2.7)	A(2.2)⟶C(1.18)
A(2.7)⟶F(2.6)	A(2.2)⟶F(2.3)

(b) Message replication. Numbers in the brackets indicate nodes' probabilistic utilities

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

Information at B

Cumulative	A	B
F:0.3	0.3	
G:0.94	0.7	0.8
J:0.6	0.2	0.5
K:0.5		0.5

Information at C

Cumulative	A	C
F:0.3	0.3	
G:0.7	0.7	
H:0.5		0.5
J:0.76	0.2	0.7
K:0.8		0.8

Merge

Cumulative	A	B	C
F:0.3	0.3		
G:0.94	0.7	0.8	
H:0.5			0.5
J:0.88	0.2	0.5	0.7
K:0.9		0.5	0.8

Fig. 7. Distributed maintenance of CRI based on the network in Fig. 6.

$C_i^{(2)} = 2 + \frac{8\times 8}{2+8} = 8.4$ according to Eq. (9). For the third relay C contacting i with the frequency 6, $C_i^{(3)} = 8.4 + \frac{6\times 6}{8.4+6} = 10.9$.

For Betweenness, $c_i^{(k+1)}$ 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).

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,

$$C_i^{(k+1)} = 1 - (1 - C_i^{(k)}) \cdot (1 - c_i^{(k+1)}). \tag{10}$$

The impact of redundancy elimination on forwarding decision is illustrated in Fig. 6. The utilities of B and C are reduced by nearly 50 percent after their redundancy of contacting G, J and K has been 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 manner,[6] 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 Fig. 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.

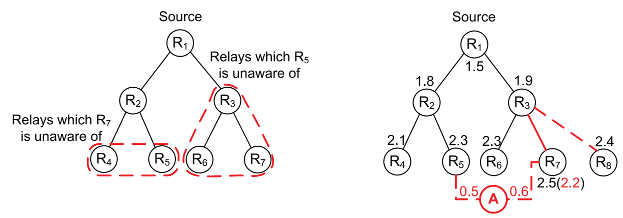
In this case, CRI is maintained in a more fine-grained level. A relay maintains a list for each non-relay node i, and the list records the capability $c_i^{(j)}$ of each relay R_j contacting i. When relays B and C in Fig. 6 contact each other, their lists are merged to correctly calculate CRI of node J based on Eqs. (9) or (10), and this process is illustrated in Fig. 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 Fig. 8a which describes forwarding process as a *Message Replication Tree (MRT)*. Without loss of generality, we assume that communication links among $R_1, \ldots, R_{k-1}$ have broken when message is replicated to relay R_k. In Fig. 8a 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_1 and R_2 has broken. Similarly, neither R_4 nor R_5 knows R_3, 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*



(a) Incomplete CRI at relays. Relays receive message replicas from their parents, and are indexed by their time receiving message replica.

(b) R_7: false positive error, R_8: false negative error. Numbers at the nodes indicate relays' probabilistic utilities.

Fig. 8. Incompleteness of CRI and its impact on forwarding decision. Delegation strategy is used.

6. A relay initializes its CRI as its own contact capability.

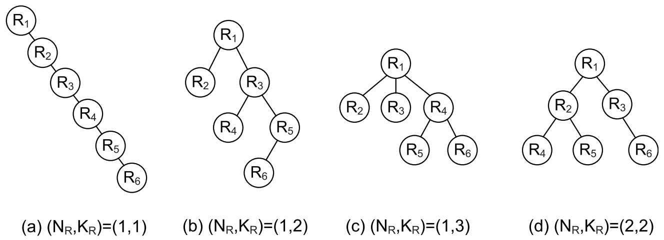


Fig. 9. MRTs with six relays and different combinations of (N_R, K_R).

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 Fig. 8a. 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 Fig. 8b 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 $R_1, \ldots, R_{k-1}$, i.e., $|\widetilde{\mathbb{B}}_{R_k}(t)| = |\mathbb{B}_{R_k}(t) \cap \{R_1, \ldots, R_{k-1}\}| = 0$ for $\forall t \geq T_k$, where T_k is the time R_k receives message replica. This is achieved by regulating forwarding process represented by MRT.

$|\widetilde{\mathbb{B}}_{R_k}(t)|$ 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 Fig. 9.

Lemma 2. $|\widetilde{\mathbb{B}}_{R_k}(t)| = 0$ *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 jth 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 jth level. For R_k at the $(j+1)$th level, i) it knows all the relays at the upper levels from $R^{(j)}$ because $|\widetilde{\mathbb{B}}_{R^{(j)}}(t)| = 0$, 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 $|\mathbb{B}_{R_{k-1}}(t)| = |\mathbb{B}_{R_k}(t)| = 0$.

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 Fig. 8b, R_7 finds that its utility should be 2.2 instead of 2.5 when it contacts R_5, 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.

Fig. 8b 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_8 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_8 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

$$\max \sum_{k=1}^{M} U_2^{(k)} x_k \quad \text{s.t.} \sum_{k=1}^{M} s_k x_k \leq B, \tag{11}$$

where $x_k \in \{0, 1\}$ indicate whether the kth message replica is forwarded to R_2, and $U_2^{(k)}$ is utility of R_2 defined in Eq. (8) for forwarding the kth message. Note that the forwarding redundancy between the existing relays (including R_1) and R_2 for forwarding the kth 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 [29].

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).

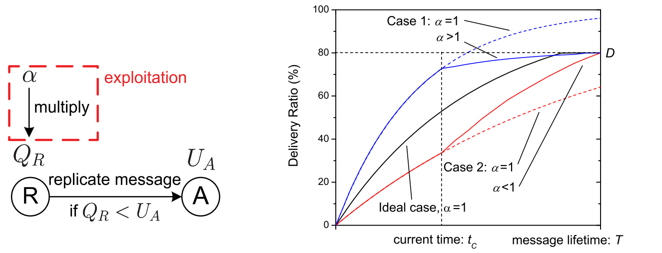
5 Exploitation

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.

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 Fig. 10a. 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.



(a) Comparison-based forwarding strategy

(b) Dynamic values of α with required delivery ratio $D = 80\%$

Fig. 10. Exploitation of forwarding redundancy.

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 α, as illustrated in Fig. 10a. We assume that message is generated at time 0 and expires at time T. As a result, α at time $t_c \leq T$ is determined by the estimated delivery ratio $\widetilde{D}(t_c)$ 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 Fig. 10b. Ideally, more relays receive message replicas when t_c elapses and gradually improve $\widetilde{D}(t_c)$ to the required delivery ratio D before T, so that $\alpha \equiv 1$. However, in practice the increase of $\widetilde{D}(t_c)$ may be different due to the specific network contact pattern, and we adjust α accordingly to approximate $\widetilde{D}(t_c)$ to the ideal case. In Case 1 shown in Fig. 10b where $\widetilde{D}(t_c)$ at time $t_c < T/2$ is already close to D, α increases to avoid redundant relays. In Case 2 where $\widetilde{D}(t_c)$ is too low, α decreases to ensure that there is a sufficient number of relays to achieve D.

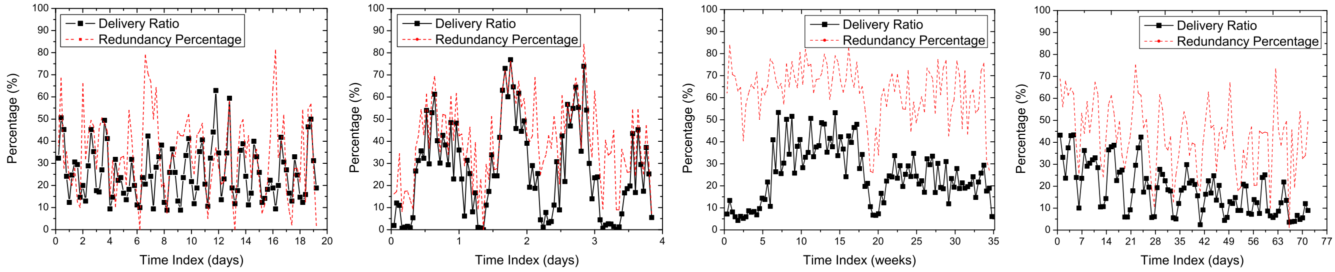
Note that we minimize the number of relays used to achieve D based on relays' utilities after redundancy elimination. Otherwise, without redundancy elimination in Section 4, D can still be achieved by reducing α but the number of relays increases due to forwarding redundancy among relays. Moreover, increasing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

The value of α is calculated based on the CRI maintained at time t_c and is used to estimate $\widetilde{D}(t_c)$. We calculate α as $\widetilde{N}_R/N_R$, where N_R is additional number of relays needed at time t_c for achieving D and $\widetilde{N}_R$ 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 $\widetilde{N}_R$ at individual relays, and also exploit periodicity of relays' contact capability for more accurate control of α.

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, $\widetilde{D}(t_c) = \frac{1}{N} \cdot \sum_{i=1}^{N} C_i^{(k)}$ 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



(a) DieselNet (b) Infocom (c) MIT Reality (d) UCSD

Fig. 11. Periodicity of delivery ratio and redundancy percentage. The periodicity in the DieselNet and Infocom traces is at daily scale, and that in the MIT Reality and UCSD traces is at weekly scale.

least-square curve fitting over the estimated $\widetilde{D}(t_c)$, and N_R is calculated as

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

5.2.2 Estimating $\widetilde{N}_R$

We estimate $\widetilde{N}_R$ based on the intervals T_i between the times that the ith 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 Fig. 13b that T_i generally increases with i. We estimate the next time interval $T_{k+1} = \max_{1 \le i \le k} T_i$, and $\widetilde{N}_R = (T - t_c)/T_{k+1}$.

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

$$T_k = \sum_{i=1}^{p} \phi_i T_{k-i} + \epsilon_k, \tag{12}$$

where $\phi_1, \ldots, \phi_p$ are the parameters and ϵ_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]. $\widetilde{N}_R$ can be estimated by recursively calculating these time intervals in the future, until $\sum_{i=k+1}^{\widetilde{N}_R} T_i \ge T - t_c$.

$\widetilde{N}_R$ 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 $\widetilde{N}_R$ 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 piece. This periodicity is shown in Fig. 11, with Delegation and Betweenness used for forwarding decision. Periodicity of delivery ratio is approximated by periodic function $\widetilde{G}(t) = G(t \bmod T_p)$, where T_p is its period and $G(t) = A \cdot e^{-\frac{(t-\mu)^2}{\sigma^2}}$ is Gaussian function. Parameters of $\widetilde{G}(t)$ are listed in Table 3, where T_p and μ 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 β being multiplied to parameter α, and β 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, β is calculated as

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

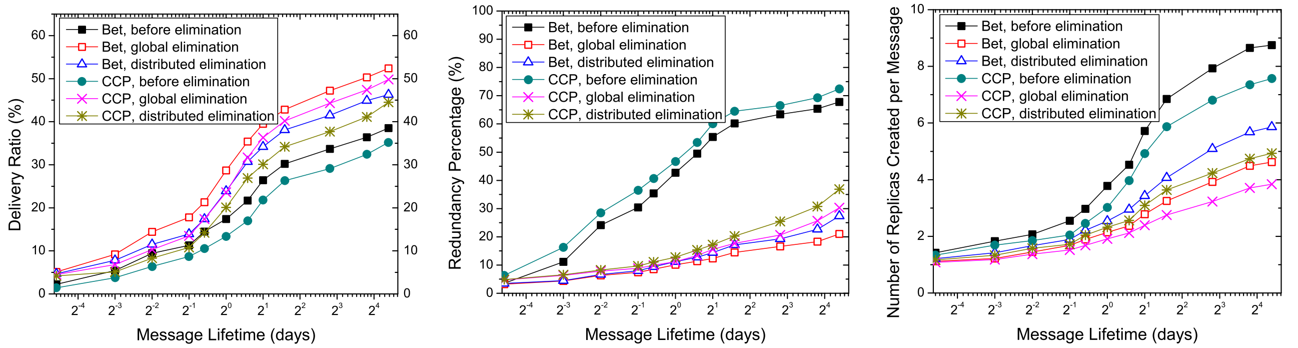
where $A\sigma\sqrt{\pi}/(2T_p)$ indicates cumulative contact capability of relays, because $\int_0^{T_p} \widetilde{G}(t)\, dt \doteq A\sigma\sqrt{\pi}/2$ when $\widetilde{G}(k \cdot T_p) \doteq 0$ for $\forall k \ge 0$. In practice, parameters of $\widetilde{G}(t)$ are estimated based on $\widetilde{D}(t_c)$, 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 $[10\ Mb, 50\ Mb]$. As reported in [18], most of contacts in the traces we use last long enough to transmit at least one

TABLE 3
Parameters of Periodicity of Delivery Ratio

Trace	T_p	A	μ	σ	error
DieselNet	1.117	0.390	0.663	0.248	0.0082
Infocom	1.064	0.574	0.6398	0.552	0.0359
MIT Reality	7.036	0.498	4.106	2.891	0.0031
UCSD	6.894	0.2696	3.211	1.597	0.0229



(a) Delivery ratio (b) Redundancy Percentage (c) Number of replicas created per message

Fig. 12. Performance of redundancy elimination with global and distributed CRI. Compare-and-Forward strategy is used in the MIT Reality trace. Our schemes eliminate forwarding redundancy by more than 50 percent, and improve the cumulative delivery ratio by 20 with 40 percent less cost in number of replicas created per message.

message replica. The buffer size of nodes is uniformly distributed in $[50\ Mb, 500\ Mb]$ 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 Fig. 12, where Betweenness and CCP are used to represent observational and probabilistic utility functions, respectively.

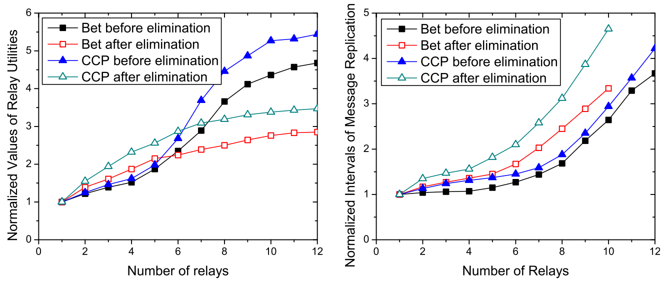
Fig. 12b shows that our schemes effectively eliminate forwarding redundancy by more than 50 percent. This elimination enables effective utilization of the relays' resources, and hence leads to 20 improvement of the cumulative delivery ratio and 40 percent reduction on the forwarding cost.[7] Note that 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. Fig. 12 also shows the impact of CRI incompleteness to redundancy elimination and forwarding performance. When CRI is maintained in a distributed manner at individual relays, the CRI incompleteness increases redundancy percentage by 10 percent, and leads to 20 percent increase of forwarding cost.

We also evaluated values of relays' utilities and intervals of message replication after redundancy elimination, as shown in Fig. 13. For each message, we use the utility and replication interval of the first relay for normalization. We observe that relays' utilities after redundancy elimination are reduced by up to 40 percent, and this is the major reason for reduction of forwarding cost shown in Fig. 12c. It also takes longer time for each message to be replicated.

6.2 Effectiveness of Accuracy Improvement

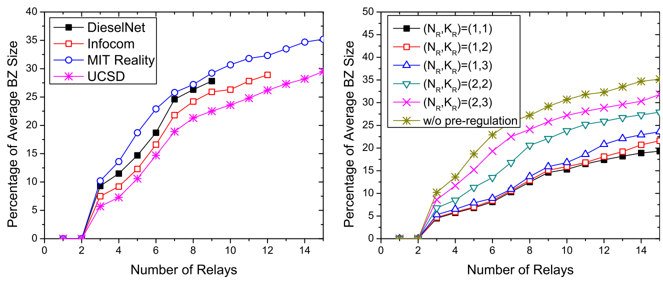
As discussed in Section 4.3, the accuracy of redundancy elimination may be impaired due to CRI incompleteness at individual relays. Various techniques have been proposed in Section 4.3 to detect and correct the possible errors during redundancy elimination. Such CRI incompleteness, which is measured by average size of relays' BZ, is shown in Fig. 14 with Compare-and-Forward and CCP used for forwarding decision. Fig. 14a shows that the average BZ size can be up to 35 percent. We also evaluate the effects of pre-regulation of forwarding process on reducing the average BZ size, and the results are shown in Fig. 14b. As expected by Lemma 2, the average BZ size is reduced by up to 50 percent 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 Fig. 15. Fig. 15a 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 percent. Fig. 15b also evaluates the delay of error detection. Obviously this delay is closely related with data lifetime. When data lifetime is set as 1



(a) Change of relays' utilities (b) Intervals of message replication

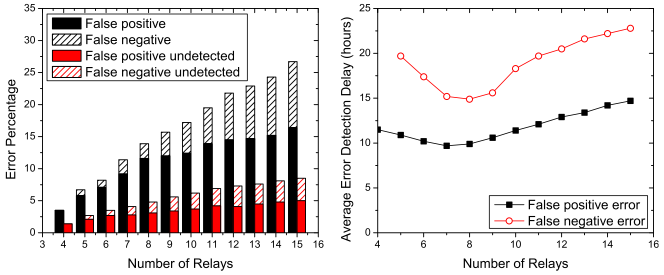
Fig. 13. Detailed effects of redundancy elimination.



(a) BZ sizes in different traces (b) BZ sizes in MIT Reality trace

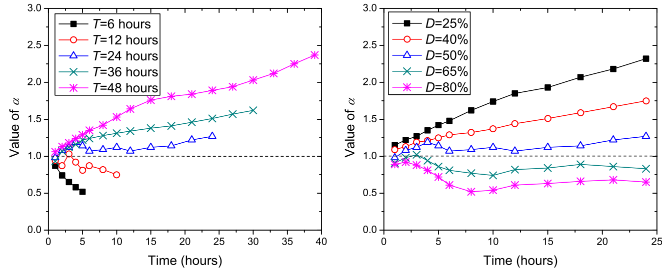
Fig. 14. Average BZ size of relays.

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.



(a) Performance of error detection (b) Error detection delay

Fig. 15. Performance of error detection in MIT Reality trace. Data lifetime is set as 1 week (168 hours).



(a) Different T with $D = 50\%$ (b) Different D with $T = 24$ hours

Fig. 17. Values of α for achieving the required delivery ratio D in Infocom trace. Delegation and CCP are used for forwarding decision.

week for the *MIT Reality* trace, Fig. 15b shows that both types of errors can be detected and corrected within 20 percent 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 Fig. 16. First, by comparing Figs. 12 and 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, Fig. 16b shows that pre-regulation of forwarding process furthermore reduces forwarding redundancy over 10 percent, but it also prevents some relays from receiving message replica and reduces delivery ratio by 3 percent. Fig. 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

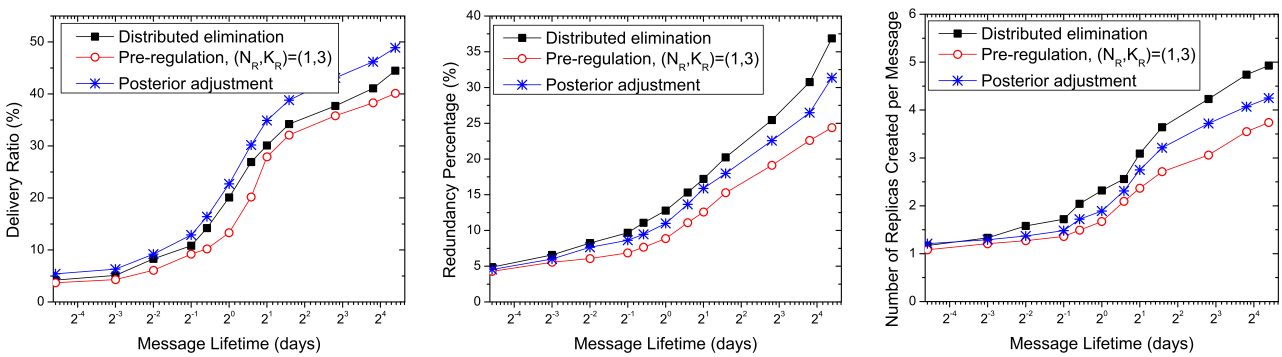
We first evaluate values of α in practice, and the results in Fig. 17 show that values of α are proportional to T. When T increases to 48 hours, the average value of α increases over 100 percent. We notice that values of α are generally lower than 1 when $T \leq 12$ hours, which means that more relays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

For evaluating the performance of our proposed forwarding 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 Fig. 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 percent less relays.

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

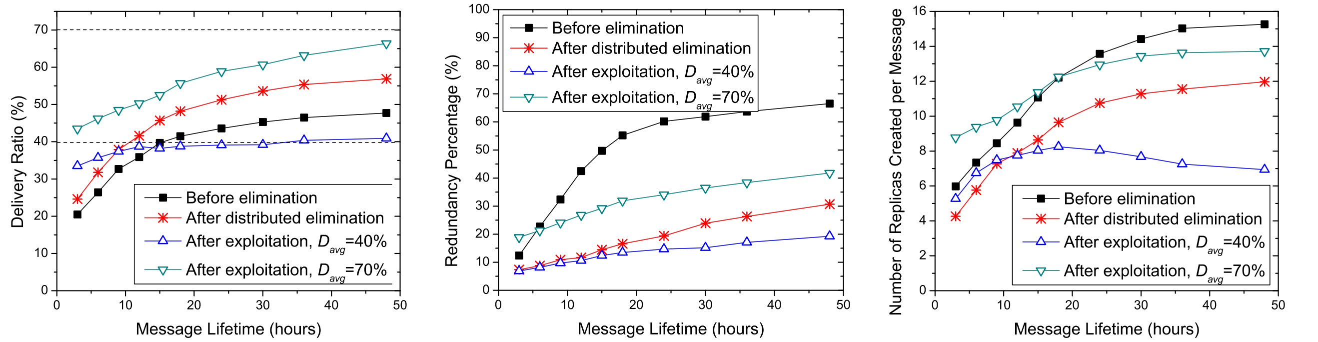
7 Related Work

The research on data forwarding in DTNs originates from Epidemic routing [36] which floods the entire network. 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 [33] 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 [34], which were exploited when studying forwarding redundancy in this paper. Other forwarding strategies [8], [27], [35], [37] also aim to achieve various tradeoffs between the data forwarding performance and cost.



(a) Delivery ratio (b) Redundancy Percentage (c) Number of replicas created per message

Fig. 16. Performance of improving the accuracy of distributed redundancy elimination in the MIT Reality trace.



(a) Delivery ratio (b) Redundancy Percentage (c) Number of replicas created per message

Fig. 18. Performance of exploiting forwarding redundancy in the Infocom trace. When $D_{avg} = 40\%$, we furthermore reduce the amount of forwarding redundancy as well as the forwarding cost. When $D_{avg} = 70\%$, the amount of forwarding redundancy increases to create more message replicas and provides best-effort forwarding performance.

The utility functions of mobile nodes, which measure the nodes' contact capabilities, are generally independent from the data forwarding strategies mentioned above. 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 [38]. In some other schemes, node contact pattern is exploited as abstraction of node mobility pattern for better prediction accuracy, based on the experimental [7], [25] and theoretical [6] analysis on the node contact characteristics. Such node contacts are detected via energy-efficient periodic probing methods [1], [20], [22], 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 [26] 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 [21], [23]. SimBet [10] uses ego-centric betweenness as relay selection metric, and BUBBLE Rap [23] considers node centrality hierarchically in social community structures. [21] 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. Gao and Cao [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 [24]. k-clique-based [32] method enables the detection of overlapping communities, and modularity-based method [31] works on weighted network contact graph. Based on such community detection techniques, BUBBLE Rap [23] 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.

Acknowledgments

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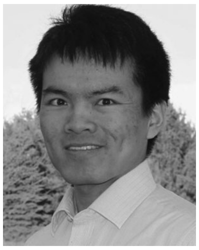

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