GAR: Group aware cooperative routing protocol for resource-constraint opportunistic networks

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ABSTRACT

Opportunistic networks are a new evolution of mobile ad hoc networks composed of intermittently connected nodes, in which the routing based on the dynamic topology is a challenging issue. In opportunistic networks, the mobile nodes with common interest or close relationship may form into groups and move together, which brings us a good feature to employ when designing the routing protocol for the resource-constraint opportunistic networks. Our main idea in this paper is to maximize the message delivery probability with the consideration of the group feature in the opportunistic network under the constraints of bandwidth and buffer space. Embedded this idea, we propose a cooperative routing protocol called GAR, which includes a cooperative message transfer scheme and a buffer management strategy. In the cooperative message transfer scheme, the limited bandwidth is considered and the message transfer priorities are designed to maximize the improved delivery probability. In the buffer management strategy, by considering the constraint of buffer space, we propose a cooperative message caching scheme and the dropping order of the messages is designed to minimize the reduced delivery probability. We also propose an improved strategy to utilize the extra contact duration between each pair of encountering nodes to further improve the performance. Finally, we conduct the simulations to demonstrate the effectiveness of our proposed GAR protocol under different network parameters.

1. Introduction

As one type of Delay Tolerant Networks (DTNs), opportunistic networks are composed mainly by mobile nodes that do not have persistent connections among them. In opportunistic networks, routing is a challenging issue since the path from a source to a destination is intermittently connected. The conventional routing protocols are generally not applicable, and the store-carry-and-forward mechanism is therefore adopted to deliver messages in such kind of networks. In most of the routing protocols used for opportunistic networks, each node decides the message transfer order independently when it meets its encounter. Due to the sporadic node density and unpredictable node mobility, the contact duration between each pair of nodes may not last long enough for them to transfer all the messages. It is desirable if the two encountering nodes can cooperate with each other to build the message transfer order which can efficiently make use of the limited contact duration [1].

Opportunistic networks can be formed by mobile nodes such as the portable devices carried by the human beings [2]. In this scenario, the mobile nodes with common interest or close relationship may form into groups and move together. One typical application scenario is the disaster recovery system [3]: imagine an intense earthquake that devastates most infrastructures of cellular networks, leading to the collapse of cellular network services for a long time. In this post-earthquake scenario, the survivors would tend to move in groups to assist each other in case of secondary disasters. The mobile phones carried by the survivors can construct an opportunistic network with the group feature. Under such a critical scenario, the survivors would try to communicate with their relatives or friends to enquire their safety as early as possible, which will trigger a huge traffic burst that may overburden the limited bandwidth and buffer space of mobile nodes.

Such critical scenario motivates us to design a routing protocol for the resource-constraint opportunistic network. As the nodes within a group likely encounter each other more frequently and the intra-group links are relatively stable, a source node can leverage the group feature by first delivering the message to the
destination group, and then letting the message be routed to the destination via the intra-group links. Moreover, the nodes within the same group can cooperatively share their limited buffers in caching the messages. Therefore, we can integrate the group feature into the design of efficient routing and buffer management strategies for opportunistic networks.

Fig. 1 shows a sample opportunistic network, in which the nodes form into four groups, G1, G2, G3 and G4. Suppose that the source node S wants to send a message mS to node D at time t1 (Fig. 1(a)), it can adopt the following routing procedure: when node S encounters node A at time t2 (Fig. 1(b)), node S can forward mS to node A. After node A receives many messages from its encounter node S, its buffer may be full. As nodes A and B are in the same group and currently connected, node A can transfer mS to node B and drop mS from its local buffer space to make more room for receiving other messages from node S. At time t3 (Fig. 1(c)), node B meets node C. As node C can predict that the probability it will meet the destination group G4 is larger than that of node B, node B will forward mS to node C. Finally at time t4 (Fig. 1(d)), node C encounters D and delivers mS to node D successfully. We can see that, by using the group feature, the message can be delivered in the opportunistic network more efficiently.

In this paper, we propose a group aware cooperative routing protocol for opportunistic networks called GAR, which aims to maximize the message delivery probability under the resource constraints of both bandwidth and buffer space. The proposed GAR protocol includes a cooperative message transfer scheme and a buffer management strategy. In the cooperative message transfer scheme, the limited bandwidth available for mobile nodes is considered and two encountering nodes will exchange messages cooperatively to maximize the delivery probability. In the buffer management strategy, we further consider the constraint of mobile nodes’ buffer space, and propose the cooperative message caching scheme, in which the message dropping priorities are set to minimize the reduced delivery probability. We also propose an improved strategy to utilize the extra contact duration of the encountering nodes to further improve the performance.

The main contributions of this paper are summarized as follows:

- We propose the cooperative message transfer scheme for opportunistic networks using the group feature, in which the limited bandwidth is considered and the message transfer priorities are set to maximize the improved delivery probability;
- By considering the constraint of mobile nodes’ buffer space, we propose the buffer management strategy in which the cooperative message caching scheme is proposed and the message dropping priorities are set to minimize the reduced delivery probability;
- We propose an improved strategy to utilize the extra contact duration of the encountering nodes to further improve the performance;
- We implement our proposed GAR protocol in the ONE simulator and conduct the simulations to illustrate its effectiveness under different network parameters.

The rest of this paper is organized as follows. In Section 2, we discuss the existing opportunistic network routing protocols and the buffer management schemes. The system model is presented in Section 3. Section 4 describes our proposed cooperative routing protocol using the group feature. The performance evaluation is briefly presented in Section 5. Section 6 concludes this paper and puts forward our future work.

2. Related work

Routing and buffer management issues in opportunistic networks have been well studied in recent years [4–7].

The routing protocols in opportunistic networks can be classified into three categories: epidemic-based, forwarding-based and quota-based routing protocols. Epidemic routing [8] is the earliest proposed routing scheme to deliver message in the opportunistic networks, in which each message is replicated and flooded to the entire network resulting in greatly consuming the limited bandwidth and buffer space. Some other epidemic-based routing schemes [4][9][10] are proposed to reduce the overhead. In Prophet [4], the likelihood of meeting the destination is used as the metric to determine whether a node will replicate and forward a message to its encounter. In MaxProp [9], each node schedules both the messages to be replicated to its encounter and the message to be dropped in case of buffer insufficiency. In the delegation forwarding [10], the message is replicated and forwarded by a node to its encounter only if its encounter has a better quality metric such as the delivery rate, average delay, and cost. BUBBLE Rap [11] is a social-based forwarding algorithm using the properties of social network and it is designed for pocket switched networks. In BUBBLE Rap, the node, which has a message destined for another node, will first forward this message to its encounter with a higher global ranking until the message reaches a node in the same community as the destination. After that, the message will be forwarded to the node with a higher local ranking until it reaches the destination.

Some forwarding-based routing schemes [12–17], in which each message only has one single replica in the network, are proposed to reduce the overhead. In [12], the delay tolerant network routing problem is formulated, and several routing algorithms corresponding to the percentage of knowledge are proposed. Jones et al. [13] design a practical single copy routing mechanism based on the minimum estimated expected delay, which is calculated based on the average meeting interval between each pair of nodes in the network using the Dijkstra’s algorithm. The predict and relay (PER) [14] scheme relies on predicting the future contacts based on the semi-markov process. CREST [15] is a DTN routing protocol that uses the conditional residual time to opportunistically forward messages between pairs of encountering nodes. In CREST, the residual time between a pair of nodes is proved to be dependent on their previous time of contact. Based on CREST, CSRP [16] is proposed which routes the messages over conditional shortest paths by defining the cost of links as the conditional inter-meeting times rather than the conventional inter-meeting times. Gao et al. [17]
propose a forwarding approach by exploiting the transient node contact patterns, based on which each node can make a more accurate prediction for data forwarding decision.

The quota-based routing protocols [18–21] are the tradeoff between the epidemic-based routing and the forwarding-based routing with single copy. As the number of replicas of each message in the network is predefined, the quota-based routing protocols can control the overhead while maintaining a high delivery ratio. Spray-and-Wait [18] disseminates the replicas of each message in the spray phase. When the node has only one replica of the message, it will be in the wait phase, in which the message will be delivered only when the node meets the destination. Spray-and-Focus [19] adopts the spray phase in [18], and when the node has only one replica of the message, it will be in the focus phase, in which the message can be forwarded to its encounter with a higher utility to improve the performance. Liu and Wu propose an optimal probabilistic forwarding protocol [20] in which they assume each node knows the mean inter-meeting times of all pairs of nodes in the network. An encounter based routing scheme called EBR is proposed in [21], which distributes the replicas of a message between two encounters according to the proportion of their estimated encounter values. Chen and Lou propose the EER and CR routing protocols [22] which take the residual time-to-live of each message into consideration.

Buffer management is also studied in opportunistic networks as replicas of all messages generated for routing can easily exhaust nodes’ limited buffer space. In MaxProp [9], the messages to be dropped are scheduled according to their hop counts. In [23,24], the efficient buffer management policies for opportunistic networks which can be tuned to minimize the average delivery delay or to maximize the average delivery ratio are proposed. Li et al. [25] propose the adaptive optimal buffer management policies for realistic opportunistic networks in which the mobility model is adjusted according to the nodes’ historical meeting information, and it can optimize certain network performance metrics, such as maximizing the average delivery ratio or minimizing the average delivery delay. In [26], a routing scheme for socially selfish opportunistic networks is proposed which takes the size of each message into consideration. However, this scheme is a bit unfair because it prefers to transfer the messages with smaller size and drop the messages with larger size while the delivery ratio is calculated in term of the number of delivered messages.

3. System model

We consider an opportunistic network with \(n\) nodes moving within a rectangular region. The nodes are composed of \(m\) groups in advance due to their close relationships. We denote \(v_i\) as node \(i\) and \(G_j\) as group \(j\). For a message \(m_k\), we call the group as the destination group which the destination node of \(m_k\) belongs to. Within a group, the nodes have a close geographical relationship, so they likely encounter relatively more frequently and their connections are also relatively stable compared with those among the nodes from different groups.

We assume that the transmission range of each node is \(R\). Two nodes \(v_i\) and \(v_j\) can communicate with each other at time \(t\) only if their geographical locations are within the transmission range of each other at time \(t\), i.e., \(X_i(t) - X_j(t) \leq R\), where \(X_i(t)\) and \(X_j(t)\) represent the positions of \(v_i\) and \(v_j\) at time \(t\) respectively. If a node has more than one neighbor within its transmission range, its communication with any neighbor will be overhead by all the other neighbors. We define the meeting time between two nodes as the time when they first come within the transmission range of each other and the leaving time between two nodes as the time when they first depart outside the transmission range of each other.

Thus, the \(s^{th}\) meeting time between nodes \(v_i\) and \(v_j\), which is denoted as \(t_{ij}^s\), refers to the meeting time since their \((s-1)^{th}\) leaving time, which is denoted as \(t_{ij}^{s-1}\), i.e., \(t_{ij}^s = \min\{t > t_{ij}^{s-1}, |X_i(t) - X_j(t)| \leq R\}\); and the \(s^{th}\) leaving time between nodes \(v_i\) and \(v_j\), denoted as \(t_{ij}^s\), is the leaving time since their \(s^{th}\) meeting time \(t_{ij}^s\), i.e., \(t_{ij}^s = \min\{t > t_{ij}^s, |X_i(t) - X_j(t)| > R\}\). Initially, if nodes \(v_i\) and \(v_j\) can communicate with each other at time \(t_0\), then \(t_{ij}^0 = t_0\) and \(t_{ij}^0 = \min\{t > t_0, |X_i(t) - X_j(t)| > R\}\). Otherwise, \(t_{ij}^0 = t_{ij}^0 = t_0\). For a node \(v_i\) that has a message with the size of \(S_m\) bytes and the data transmitting rate is \(T\), bytes per second, node \(v_i\) can transmit the message to node \(v_j\) successfully at time \(t_{ij}^0\) only if \(t_{ij}^0 > t_0\) or \(t_{ij}^0 = t_0\).

We assume that each generated message, when first generated, has a time-to-live (TTL) to limit its lifetime. The TTL value is measured in the scale of time unit. The message has to be delivered to the destination within its TTL; otherwise, it will be discarded when its TTL expires.

4. Group aware cooperative routing protocol

In this section, we describe the group aware cooperative routing (GAR) protocol in details. Our principle in designing the routing protocol is to maximize the message delivery probability, that is, to maximize the improved delivery probability of the message transfer within the limited contact duration and to minimize the miss probability of the message drop-off in the buffer management. We first propose a cooperative message transfer scheme to deal with the bandwidth constraint. We also propose a buffer management strategy to deal with the constraint of buffer space. Finally, we propose an improved strategy to utilize the extra contact duration between each pair of encountering nodes to further improve the performance.

4.1. Cooperative message transfer scheme

4.1.1. Broadcast and phantom message

In opportunistic networks, the broadcast characteristic of wireless channel can benefit the message forwarding. When a node transmits a message to its receiver, both the indicated receiver and all other neighbors can receive this message. Thus the broadcast can transmit the message to more receivers without extra bandwidth or energy consumption.\(^1\) Take the scenario in Fig. 2(a) as an example, when node A transmits a message \(m_k\) to node \(E\) using the broadcast, both nodes B and C can also receive \(m_k\). As \(m_k\) is duplicated to more nodes, its delivery probability will increase. However, the broadcast increases the number of replicas of the broadcasted message, which may bring a huge extra overhead into the network. To solve this problem, we employ the phantom message, which is the message that will not be exchanged between two encountering nodes, except that the phantom message can be transferred to its destination (or the destination group) when the node which is carrying this phantom message meets the destination directly (or the destination group).

Each message \(m_k\) has a property attribute prop which is defined as follows:

\[
m_k\text{prop} = \begin{cases} 
0, & \text{if } m_k \text{ is a phantom message;} \\
1, & \text{elsewise.} 
\end{cases}
\]

\(^1\) In our work all the nodes in the network are assumed to keep in the active state to make full usage of the limited bandwidth. Though the duty-cycle based scheme [27] can reduce the energy consumption, it may sacrifice the bandwidth usage. Thus, the duty-cycle based scheme is not discussed in this paper and we claim that the adoption of phantom message will not introduce extra bandwidth and energy consumption.
Initially, the property of each generated message is set as 1 and normally it will not be changed during the disseminating or forwarding procedure. When two encountering nodes exchange a message, all other nodes overhear the broadcasted message and set the prop to 0, i.e., they will treat the overhead message as a phantom message. Note that the phantom message will not cause extra overhead because it will not be distributed to the network directly.

The node which is carrying the phantom message can directly deliver it to the destination when they encounter so as to increase the message delivery probability. For example, in Fig. 2(a), node A has a message $m_k$ with the destination node J. When node A meets node E, it disseminates some replicas of $m_k$ to node E using the broadcast. Node E can receive $m_k$ normally while nodes B and C can overhear the broadcasted $m_k$ and mark it as a phantom message since they are within the broadcast area of node A. Note that a node with a full buffer will not receive any phantom message, as it may require to delete some non-phantom message to vacate buffer space which will affect the delivery of this message. When node C meets node J (as shown in Fig. 2(b)), as node C has a phantom message of $m_k$ which is destined to node J, it can deliver $m_k$ to node J directly. Thus, the direct delivery of the phantom message requires two nodes to make it successfully delivered.

Though the phantom message does not bring extra bandwidth or energy consumption into the network, it may still occupy the node's storage which will affect the storage of other messages when the buffer space is used out. To avoid this negative effect, a node can delete its phantom messages to free some buffer space when it needs to receive messages from its encounter while its buffer is fully used. The details will be introduced in the buffer management strategy subsection.

4.1.2. Delivery probability estimation

In this paper, we adopt the quota-based routing scheme, in which each message initially has a predefined number, which is denoted as $\rho$, of replicas in the network. A message is considered as being successfully delivered when any replica of the message arrives at the destination within the message’s time-to-live (TTL).

In the opportunistic network routing, the prediction of the future contact information between each pair of nodes can be used to make the routing decision. As mentioned in the system model, in an opportunistic network with $n$ nodes, each node can record the past meeting intervals between itself and the other $n-1$ nodes. The set of recorded past meeting intervals between each pair of nodes $v_i$ and $v_j$ is denoted as $R_{ij} = \{\Delta t_{ij}^1, \Delta t_{ij}^2, \ldots, \Delta t_{ij}^{\rho-1}\}$, where $\Delta t_{ij}^s$ represents the past $s$th meeting interval between $v_i$ and $v_j$ and $\Delta t_{ij}^s$ is the total number of recorded meeting intervals between $v_i$ and $v_j$. Here, $\Delta t_{ij}^s = t_{ij}^s(s) - t_{ij}^s(s)$, where $t_{ij}^s(s)$ and $t_{ij}^s(s)$ are the $s$th leaving time and the $s$th meeting time between $v_i$ and $v_j$ respectively. When $v_i$ and $v_j$ encounter, they will update the recorded past meeting interval between the pair. After that, node $v_i$ can predict the meeting interval $\Delta t_{ij}^s$ between itself and $v_j$ as follows:

$$\Delta t_{ij}^s = \frac{1}{\rho-1} \sum_{s=1}^{\rho-1} \Delta t_{ij}^s.$$

Due to the exponential distribution of the inter meeting intervals [5,18], the probability $P_{ij}(T)$ that node $v_i$ will encounter $v_j$ within time interval $T$ can be estimated as:

$$P_{ij}(T) = 1 - \exp\left(-\frac{T}{\Delta t_{ij}^s}\right).$$  \hspace{1cm} (1)

Note that in our paper, the calculation of the meeting probability $P_{ij}(T)$ itself does not rely on the assumption that the inter meeting intervals follow the exponential distribution. If the inter meeting intervals do not actually follow the exponential distribution, then using other estimation method which better matches the distribution pattern of the inter meeting intervals will result in even better performance.

As the nodes within the same group meet each other frequently, their connections are relatively stable. Thus, as long as the message is delivered to the destination group, it can be approximately considered as being successfully delivered to the destination. For a message $m_k$ held by node $v_i$ with $\text{TTL}_k$, suppose the destination group of $m_k$ is $G_d$, then the probability $P_{ij}(m_k)$ that $m_k$ can be successfully delivered is:

$$P_{ij}(m_k) = \max \left\{ P_{ij}(\text{TTL}_k) \quad \forall v_j \in G_d \right\}$$

\hspace{1cm} $= \max \left\{ 1 - \exp\left(-\frac{\text{TTL}_k}{\Delta t_{ij}^s}\right) \quad \forall v_j \in G_d \right\}.$ \hspace{1cm} (2)

4.1.3. Priority order of message transfer

As the intra-contact duration between each pair of encountering nodes is limited, and may not last long enough for the exchange of all the messages, two encountering nodes need to cooperate with each other to schedule the message transfer order between them, which can efficiently make use of the limited contact duration. Note that the intra-contact duration here means the duration that two nodes keep in contact, while the inter-contact duration indicates the elapsed time between two successive contacts of a pair of nodes. When two nodes encounter, they will exchange the messages with the following priority order:

1. All the messages (including the phantom messages) destined to the current encounter are transferred.
2. All the messages (including the phantom messages) destined to the current encounter’s group members are transferred.
3. For other normal messages with multiple replicas, the two encountering nodes will split them according to the ratio of the messages’ estimated delivery probabilities. Note that no operation will be conducted for the messages simultaneously held by both the two encountering nodes.
4. For the normal messages with single replica, the encountering nodes will make the forwarding decision according to the messages’ estimated delivery probabilities.

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2 We make this assumption to approximately estimate the delivery probability of the message in the network, while in the simulations, the message will be considered to be successfully delivered only if it reaches the destination node within its TTL.

3 Note that the message splitting indicates the distribution of replicas of a message between two encountering nodes after which both the two nodes will have the replica of the message, while the message forwarding indicates the transfer of a message between two encountering nodes after which the sender will not keep the replica of the message.
When two nodes meet, the message destined to the current encounter can immediately be delivered successfully, so it has the highest priority to be transferred. As the connections among the nodes within the group are relatively stable, the messages destined to the current encounter’s group members will have the second highest priorities if the two encounters are from different groups since the transfer of these messages can greatly increase the delivery probability of these messages. On the other side, if the two encountering nodes are within the same group, the messages destined to other nodes within this group will have the second highest priorities to be transferred inside the group.

After that, the messages with multiple replicas will be split between two encountering nodes according to the ratio of the messages’ estimated delivery probabilities. Assume that nodes \( v_i \) and \( v_j \) hold a set of messages \( \mathcal{M} = \{ m_1, m_2, \ldots, m_k \} \) with multiple replicas, where \( M_k (M_k > 1) \) represents the number of replicas of message \( m_k \). For each message, only node \( v_i \) or \( v_j \) has it. The messages which are held by both \( v_i \) and \( v_j \) will not be split between them, thus they are excluded of \( \mathcal{M} \) and no operation will be conducted on them here. The split of multiple replicas of the message to different nodes can increase the message’s delivery probability. Thus, when \( v_i \) and \( v_j \) encounter, they can sort the set of messages \( \{ m_1, m_2, \ldots, m_k \} \) with a descending order of the current number of replicas of each message, and the message with a larger number of replicas has a higher priority to be transferred. However, for the messages with the same number of replicas, their transfer priorities will be determined based on the improved delivery probabilities of the transfer. Suppose a subset of messages \( \mathcal{M}' \subset \mathcal{M} \) have the same number of replicas. For each message \( m_k \in \mathcal{M}' \), the improved delivery probability \( \Delta P(m_k) \) of the split is

\[
\Delta P(m_k) = P_P(m_k) - P^F_P(m_k),
\]

where \( P_P(m_k) \) denotes the delivery probability of \( m_k \) by \( v_i \) or \( v_j \) after the split and \( P^F_P(m_k) \) denotes the delivery probability of \( m_k \) by \( v_i \) or \( v_j \) before the split. Here, \( P_P(m_k) = 1 - (1 - P_P(m_k))(1 - P_P(m_k)) \) and \( P^F_P(m_k) = a(m_k)P_P(m_k) + a(m_k)P_P(m_k) \), where \( a(m_k) \) is defined as

\[
a(m_k) = \begin{cases} 
1, & \text{if } m_k \text{ is held by } v_i \text{ before the split}; \\
0, & \text{otherwise}.
\end{cases}
\]

Note that each message \( m_k \) is held by only one node \( (v_i \text{ or } v_j) \), that is, \( a(m_k) + a(m_k) = 1 \).

Thus, we can get:

\[
\Delta P(m_k) = a(m_k)P_P(m_k) + a(m_k)P_P(m_k) - P_P(m_k)P_P(m_k).
\]

For the messages in \( \mathcal{M}' \), their transfer priorities can be determined based on the improved delivery probabilities of the dissemination and the message \( m_{k_{\text{max}}} (m_{k_{\text{max}}} \in \mathcal{M}') \) with the maximum improved delivery probability will be transferred firstly.

To distribute the replicas of each message to different nodes efficiently, the messages with multiple replicas, which are held only by one of the two encountering nodes, can be split between two encountering nodes according to the ratio of their estimated delivery probabilities. For instance, suppose nodes \( v_i \) and \( v_j \) are from different groups, when they meet, if node \( v_i \) holds a message \( m_k \) with \( M_k (M_k > 1) \) replicas and node \( v_j \) has no replica of \( m_k \), then both nodes \( v_i \) and \( v_j \) will calculate their estimated delivery probabilities \( P_P(m_k) \) and \( P_P(m_k) \) for \( m_k \) using Eq. (2). After exchanging the estimated delivery probabilities with each other, \( v_i \) will pass

\[
\frac{M_k}{P_P(m_k) + P_P(m_k)} \cdot \frac{P_P(m_k)}{P_P(m_k) + P_P(m_k)}
\]

replicas of message \( m_k \) to \( v_j \).

The messages with single replica have the lowest priorities. The method to determine the transfer priorities of the messages with single replica is similar to that with the multiple replicas, which is based on the improved delivery probabilities of the forwarding. Suppose that nodes \( v_i \) and \( v_j \) hold a set of messages \( \mathcal{M}' \) with single replica in which each message is held by only one of the two nodes. For each message \( m_k \in \mathcal{M}' \), the improved delivery probability \( \Delta P(m_k) \) of the forwarding is:

\[
\Delta P(m_k) = P_P(m_k) - P^F_P(m_k),
\]

where \( P_P(m_k) \) denotes the delivery probability of \( m_k \) by \( v_i \) or \( v_j \) after the forwarding and \( P^F_P(m_k) \) denotes the delivery probability of \( m_k \) by \( v_i \) or \( v_j \) before the forwarding. As \( P_P(m_k) = a(m_k)P_P(m_k) + a(m_k)P_P(m_k) \) and \( P^F_P(m_k) = a(m_k)P_P(m_k) + a(m_k)P_P(m_k) \), we can get

\[
\Delta P(m_k) = (a(m_k) - a(m_k))(P_P(m_k) - P_P(m_k)).
\]

Thus, for the messages in \( \mathcal{M}' \), their transfer priorities can be determined based on the improved delivery probabilities of the forwarding and the message \( m_{k_{\text{max}}} (m_{k_{\text{max}}} \in \mathcal{M}') \) with the maximum improved delivery probability will be transferred firstly.

After calculating the forwarding priorities of the messages with single replica, the node will decide whether to forward them to the encounter or not. As the message forwarding will consume the limited bandwidth, we employ a threshold \( \delta_P \) in the forwarding decision to balance the tradeoff between the overhead and delivery ratio. When nodes \( v_i \) and \( v_j \) encounter, for a single-replica message \( m_k \) carried by node \( v_i \), both two nodes will calculate their estimated delivery probabilities \( P_P(m_k) \) and \( P_P(m_k) \) for \( m_k \) using Eq. (2). If:

\[
\Delta P(m_k) < P_P(m_k) - P^F_P(m_k) > \delta_P,
\]

node \( v_i \) will forward \( m_k \) to \( v_j \); otherwise, there will be no operation for \( m_k \) between them.

4.1.4 Cooperative message transfer algorithm

We design a transfer priority function to calculate the message transfer priorities of all the messages between two encountering nodes. When nodes \( v_i \) and \( v_j \) encounter, the transfer priority function of message \( m_k \) for \( v_i \), denoted as \( f_{\text{TP}}(m_k) \), is defined as follows:

\[
f_{\text{TP}}(m_k) = \begin{cases} 
\lambda + 2, & \text{if } m_k \text{ is sent to } v_i; \\
\lambda + 1, & \text{if } m_k \text{ is sent to } v_j \text{ group member}; \\
M_k + \Delta P(m_k), & \text{elsewhere}.
\end{cases}
\]

Here \( \lambda \) is the initial number of replicas of \( m_k \) and \( M_k \) is the current residual number of replicas of \( m_k \). If \( \lambda > 1 \), \( \Delta P(m_k) \) is calculated using Eq. (4); otherwise, if \( \lambda = 1 \), \( \Delta P(m_k) \) is calculated using Eq. (7). It is obvious \( 0 \leq \Delta P(m_k) \leq 1 \). If \( m_k \) is destined to the encounter, we set its transfer priority as \( \lambda + 2 \), which indicates that it has the highest priority to be transferred. If \( m_k \) is destined to the encounter’s group member, we set its transfer priority as \( \lambda + 1 \), which indicates that it has the second highest priority to be transferred. Otherwise, we set the transfer priority of \( m_k \) as \( M_k + \Delta P(m_k) \). Since \( M_k < \lambda \) and \( \Delta P(m_k) < 0, M_k + \Delta P(m_k) < \lambda + 1 < \lambda + 2 \), which indicates that \( m_k \) will have a lower transfer priority than the previous two cases. At the same time, the multiple replicas case \( (M_k > 1) \) will have a higher transfer priority than the single replica case \( (M_k = 1) \).

When nodes \( v_i \) and \( v_j \) encounter, the procedure of the cooperative message transfer between them is described as follows:

1. Nodes \( v_i \) and \( v_j \) update their contact histories and calculate the up-to-date average meeting interval.
2: Nodes $v_i$ and $v_j$ calculate the transfer priorities of their held messages and exchange the priorities with each other.
3: Nodes $v_i$ and $v_j$ exchange their held messages in a descending order of the transfer priorities.

Example. Fig. 3 illustrates the cooperative message transfer procedure between two encountering nodes $S$ and $A$ for the sample opportunistic network given in Fig. 1(b). Assume that the initial number of replicas of each message is 10, i.e., $\lambda = 10$. Before the two nodes meet, node $S$ holds messages $m_1$, $m_2$, $m_3$, and $m_4$. The destination of $m_1$ is node $D$ and node $S$ has 3 replicas of $m_1$. The destinations of $m_2$ and $m_3$ are nodes $B$ and $A$ respectively. And node $S$ only has one replica of $m_4$ with the destination node $C$. The other node $A$ holds messages $m_5$ and $m_6$ with the destinations nodes $S$ and $E$ respectively. When nodes $S$ and $A$ encounter, they can calculate the transfer priorities as follows: $f_{TP}(m_1) = M_1 + \Delta P(m_1) = 3 + \Delta P(m_1)$, $f_{TP}(m_2) = \lambda + 1 = 11$, $f_{TP}(m_3) = \lambda + 2 = 12$, $f_{TP}(m_4) = M_4 + \Delta P(m_4) = 1 + \Delta P(m_4)$, $f_{TP}(m_5) = \lambda + 2 = 12$ and $f_{TP}(m_6) = \lambda + 1 = 11$. Note that $0 \leq \Delta P(m_1) \leq \Delta P(m_4) \leq 1$. Thus, nodes $S$ and $A$ will firstly exchange $m_3$ and $m_5$ and then exchange $m_2$ and $m_6$. After that, they will exchange $m_1$. Assume the estimated probability that node $S$ can successfully deliver $m_1$ is $P_s(m_1) = 0.3$ and the estimated probability that node $A$ can successfully deliver $m_1$ is $P_a(m_1) = 0.6$. Thus $\Delta P(m_1) = P_s(m_1) - P_a(m_1)P_s(m_1) = 0.3 - 0.6 = 0.3 = 0.12$ and $f_{TP}(m_1) = 3.12$, then node $S$ will pass $m_1$ to node $A$. Finally, assume $P_s(m_4) = 0.4$ and $P_a(m_4) = 0.6$, thus $\Delta P(m_4) = P_s(m_4) - P_a(m_4) = 0.2$ and $f_{TP}(m_4) = 1.2$. So $m_4$ is with the lowest transfer priority and node $S$ will determine whether to forward $m_4$ to node $A$ by comparing $\Delta P(m_4)$ with the threshold $\delta_f$.

4.2. Buffer management strategy

In opportunistic networks, the combination of the store-carry-and-forward mechanism and multiple replicas of each message may easily make each node’s buffer fully used due to the limited buffer space. Therefore, it is necessary to design an efficient buffer management strategy such that the messages that cannot be transferred in current contact are stored in nodes’ buffer and may get another transfer opportunity in next contact. The buffer management strategy aims to reduce the negative effects of the message dropping on the delivery probability, that is, to avoid dropping the important messages.

In the cooperative message transfer scheme, the phantom message is used to increase the delivery probability of a message without extra bandwidth or energy consumption. However, the storage of the phantom messages will affect the storage of other messages under the constraint of limited buffer space. To avoid the negative effects brought by the phantom message, when the buffer is full, each node will firstly check whether it holds a phantom message. If it does, then it will drop the phantom message directly to free some buffer space to receive other messages from its encounter. As the phantom message is a free byproduct of the broadcast, dropping the phantom message will not affect the delivery probability remarkably. However, if the node holds no phantom message, it can adopt the following cooperative caching scheme.

As the nodes within the same group may have relatively stable connections, they can cooperatively cache the messages. Since the transfer of the message will bring extra bandwidth and energy consumption overhead, we further make use of the phantom message, which can be conducted without really transferring the message, to design a cooperative message caching mechanism. When the buffer of a node is fully used, it will check with its neighbors whether they hold any phantom message of its normal messages. For example, as shown in Fig. 2(a), when node $A$ uses out its buffer and needs to receive messages from node $E$ and node $A$ has not any phantom message, it can enquire its neighbors, i.e., nodes $B$, $C$ and $E$ whether they hold any phantom message of its own normal messages. Suppose node $A$ has message $m_k$, and node $B$ has a phantom message of $m_k$. Then node $A$ can send a control message to inform node $B$ to convert the phantom message of $m_k$ into a normal message (i.e., change the prop attribute of the message from 0 to 1) with the same number of replicas of the normal message $m_k$ in node $A$. After that, node $A$ can delete $m_k$ to free its buffer space to receive messages from node $E$. Thus, the cooperative message caching can be achieved between nodes $A$ and $B$ without really transferring any message. Note that the control message only requires to contain very limited information, including the message type, receiver ID, message ID, and number of replicas, the size of control message would be very short (with the order of ten bytes). However, the size of normal data messages delivered in the network would be relatively large (with the order of one hundred KB, as shown in Table 1), we can claim that the overhead brought by the control message can be ignored.

If the node still needs more buffer space, it can enhance the cooperative message caching by forwarding some messages to its neighboring nodes who have spare buffer space. To select the most preferable message (with multiple replicas or single replica) to be forwarded, the node can calculate the improved delivery probability of the message forwarding using Eq. (7) and forward the message with the highest improved delivery probability to its neighboring node to free the buffer space.

However, if none of its neighboring nodes has spare buffer space, then the node has to directly drop some messages from its buffer. To minimize the negative effect of the message dropping on the delivery probability, the node can use an occupying priority function to determine the priority of each message for occupying the buffer. The occupying priority function of message $m_k$ in node $v_i$, denoted as $f_{OP}$, is defined as follows:

$$f_{OP}(m_k) = M_k + P_s(m_k),$$

### Table 1

<table>
<thead>
<tr>
<th>Simulation settings.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes in the network ($n$)</td>
<td>60–150</td>
</tr>
<tr>
<td>Number of nodes in each group</td>
<td>4–8</td>
</tr>
<tr>
<td>Initial number of replicas of each message ($\lambda$)</td>
<td>10</td>
</tr>
<tr>
<td>Threshold used in the forwarding ($\delta_f$)</td>
<td>0.5</td>
</tr>
<tr>
<td>Time to live of each message (TTL)</td>
<td>20 min</td>
</tr>
<tr>
<td>Size of each message ($S_m$)</td>
<td>100 KB</td>
</tr>
<tr>
<td>Buffer size of each node ($S_b$)</td>
<td>1 MB</td>
</tr>
<tr>
<td>Transmission rate ($T_c$)</td>
<td>250 Kbps</td>
</tr>
<tr>
<td>Transmission range ($R$)</td>
<td>100 m</td>
</tr>
<tr>
<td>Message generation rate</td>
<td>2 per min</td>
</tr>
</tbody>
</table>
where $M_i$ is the current residual number of replicas of $m_i$ in $v_i$ and $P_i(m_i)$ is the estimated probability that node $v_i$ can successfully deliver $m_i$, which is calculated by using Eq. (2). Obviously, $M_i \leq i$ and $0 \leq P_i(m_i) \leq 1$. According to Eq. (9), the message with a larger number of replicas will have a higher occupying priority. For the messages with the same number of replicas, the one with a higher estimated delivery probability will have a higher occupying priority. After the occupying priorities of all the messages are determined, the node will firstly drop the one with the lowest occupying priority. Note that the occupying priority function of each message already considers the possibility that the message will be time out in the buffer before being transferred since the TTL of each message is included in the calculation of priority.

4.3. Improved strategy with extra bandwidth

The phantom messages are the extra information obtained due to the broadcast characteristic and the direct delivery of the phantom messages to the destinations can increase the delivery probabilities. However, if two encountering nodes are still connected after finishing the messages exchange, we can further utilize this contact duration by converting the held phantom messages into normal messages and splitting them between the two nodes.

We define the procedure of converting the phantom message into normal message as the activation of the phantom message. Before the activation of phantom message, one of its corresponding normal messages in the network has to be converted into phantom message. Furthermore, the number of replicas of the converted message (the previous phantom message before the conversion) will be set to the number of replicas of the converted phantom message (the previous normal message before the conversion). However, the activation of the phantom message can be conducted only if one of the node’s neighbors has the corresponding normal message. The node can conduct the activation of phantom message after sending a control message to inform the neighboring node to convert the corresponding normal message into a phantom one. Therefore, the number of replicas of the normal message will be the same after the activation.

For example, as shown in Fig. 2(a), node A has a message $m_i$ with $M_i$ replicas whose destination is not in group $G_1$, $G_2$ or $G_3$. When node A meets node E, it will split some replicas of $m_i$ to node E, which is based on the ratio of their estimated delivery probabilities. As node A uses the broadcast to disseminate $m_i$ to node E, both nodes B and C can overhear $m_i$ as a phantom message. After that, when node C meets node J as shown in Fig. 2(b), it will first exchange the messages with node J. If nodes C and J are still connected after exchanging all the messages, node C can further convert the phantom message $m_i$ in its buffer into a normal one, before which it sends a control message to inform node A to convert the normal message $m_i$ into a phantom one. Also, the number of replicas of the converted normal message $m_i$ in node C should be set to that of replicas of the original message $m_i$ in node A. After the activation of the phantom message $m_i$, node C can efficiently utilize the extra contact duration by disseminating $m_i$ with node J based on the ratio of their estimated delivery probabilities for $m_i$.

5. Performance evaluation

In this section, we will evaluate our proposed group aware cooperative routing (GAR) protocol with the three performance metrics: message delivery ratio, latency and goodput in the Opportunistic Network Environment simulator (ONE) [28]. We will illustrate the effectiveness of our proposed GAR protocol by comparing it with other existing opportunistic network routing protocols. We will also analyze the effects of the network parameters on the routing performance of the proposed routing protocol.

5.1. Simulation settings

In the simulations, we employ the Reference Point Group Mobility (RPGM) [29] as the mobility model. Each group has a logical “center”, the motion of which defines the entire group’s motion behavior. And the movement of each group center follows the random waypoint mobility model. The moving process of each node is the combination of its group movement with a random motion vector, which allows the independent random motion behavior of each node within the group. The movement of each group in the network is independent, and the random motion vector for a node inside the group is also independent with that of other nodes in the same group. In the implementation of simulations, the logical center of each group moves with the speed varying from 2.7 to 13.9 m/s within an area of 4500 m × 3400 m. The other simulation settings are listed in Table 1.

5.2. Performance metrics

To evaluate the effectiveness of our proposed GAR protocol, we will compare it with other seven popular protocols: CR [22],¹ Spray-and-Wait [18], Spray-and-Focus [19], EBR [21], Epidemic [8], Prophet [4] and MaxProp [9]. In the above seven protocols, the CR, Spray-and-Wait, Spray-and-Focus and EBR are quota-based protocols, while the Epidemic, Prophet and MaxProp are epidemic based protocols.

Three performance metrics will be employed into the performance evaluation, including the delivery ratio, latency and goodput. The definitions of these three metrics are as follows:

- **Delivery ratio:** The ratio of the number of successfully delivered messages to the number of all the generated messages;
- **Latency:** The average end-to-end delivery delay between each pair of source and destination in the network;
- **Goodput:** The ratio of the number of successfully delivered messages to the number of relayed messages in the network.

5.3. Simulation results

Fig. 4 shows the performance comparison between the GAR and other seven protocols. We set \( l = 10 \) for the GAR, CR, Spray-and-Wait, Spray-and-Focus and EBR protocols. Fig. 4(a) shows the delivery ratio of the eight protocols. The figure shows that the GAR protocol achieves the highest delivery ratio, even higher than those of the epidemic based protocols. In the resource-constraint opportunistic networks, only a small set of messages can be successfully transferred during a single contact, while the epidemic based protocols do not well design the message transfer order. Moreover, the epidemic based protocols do not deliberately consider the buffer management; they do not adopt the cooperative caching scheme and cannot guarantee that the node will always drop the least important messages. Consequently, the delivery ratios of the epidemic based protocols are lower than that of GAR. The delivery ratio of the EBR protocol is the lowest. Fig. 4(b) shows the latency of the protocols. The GAR protocol achieves the second shortest latency. As a whole, the latency of epidemic based protocols is longer than that of the quota based protocols, because the

¹ The CR protocol is a community based routing protocol, which also takes the advantage of the group feature. We compare our proposed GAR protocol with the CR protocol to evaluate its effectiveness.
message redundancy of the epidemic based protocols would be serious as the messages are flooded in the network while the buffer management is not well considered. Fig. 4(c) shows the goodput of the protocols. Obviously, the epidemic based protocols require the largest number of transfer so their goodput is lower than those of other protocols. The goodput of the EBR protocol is the highest since the nodes in the EBR are seldom to transfer the messages (thus the delivery ratio of EBR is the lowest). The GAR protocol achieves the second highest goodput. Overall, the proposed GAR protocol performs effectively compared with other seven protocols.

Fig. 5 shows the composite performance comparison between the GAR protocol and other seven protocols. A composite metric is proposed in [21] to evaluate the overall performance of a specific protocol. The composite metric is defined as \( \text{Ratio} \times (1/\text{Latency}) \times \text{Goodput} \), which encourages the one with a high message delivery ratio and high goodput and penalizes it with a long end-to-end delivery delay. The figure shows that the proposed GAR protocol outperforms other protocols, which illustrates the effectiveness of the proposed GAR protocol.

Fig. 6 shows the effects of \( \lambda \) on the performance of our proposed GAR protocol. The value of \( \lambda \) varies from 6 to 12 with an increment of 2. The delivery ratio of the GAR protocol rises when the value of \( \lambda \) increases because each message is considered to be successfully
delivered if only one of its replicas arrives at the destination within the TTL and the increase of $k$ can increase the delivery probability of each message. The increase of $k$ will reduce the latency. However, the increase of $k$ can heighten the overhead as it will cause a larger amount of transfers in the network thus the GAR protocol will achieve a lower goodput. Therefore, it is a tradeoff to determine an appropriate value of $k$.

6. Conclusions and future work

In this paper, we have introduced the system model for the opportunistic network with group feature and proposed a cooperative routing protocol including the cooperative message transfer scheme and the buffer management strategy. In the cooperative message transfer scheme, the constraint of bandwidth is considered and the message transfer priorities are designed to maximize the improved delivery probability. In the buffer management strategy, by considering the constraint of buffer space, we propose the cooperative message caching scheme and the dropping order of the messages is designed to minimize the reduced delivery probability. Then we propose an improved strategy to utilize the extra contact duration between each pair of encountering nodes to further improve the performance. Finally, we conduct the simulations based on the RPGM mobility model in the ONE simulator to illustrate the effectiveness of the proposed routing protocol.

A future work that interests us is that we would further investigate the impact of various mobility models on the proposed scheme. The other direction of our future work is to evaluate our proposed GAR protocol based on the real trace.

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References