

Message Scheduling and Forwarding in Congested DTNs

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ABSTRACT

Multi-copy utility based routing strategies have been considered the most applicable approaches to achieve message delivery in Delay Tolerant Networks (DTNs). They allow multiple message replicas to be launched to increase the ratio of message delivery or reduce its delay. This advantage, nonetheless, is at the expense of taking more buffer space at each node. The combination of custody and replication entails high buffer and bandwidth overhead. Therefore, efficient scheduling policies are needed to decide which messages to forward first when the available bandwidth is limited, and which messages to drop first when the buffer operates close to its capacity. This paper investigates an efficient message scheduling and dropping policies based on the theory of the encounter-based message forwarding, and the expected number of copies of the message that have been disseminated in the network, such that the forwarding and dropping decisions result in optimal message delivery delays. Extensive simulations results, based on a synthetic mobility model and real mobility traces, show that the proposed scheduling framework can achieve superb performance against its counterparts in terms of delivery delay.

Keywords

Routing, Scheduling, Buffer management, DTN.

1. INTRODUCTION

DTNs are characterized as sparsely connected, highly partitioned, and intermittently connected networks. In these challenging environments the end-to-end path between a given pair (source and destination) may never exist [1]. To cope with frequent, long-lived disconnections and deal with the variations in the links over time, a node in a DTN buffers a message and waits until it finds an available link to the next hop. The next hop node buffers and forwards the received message if the node is not the end destination. This process

continues until the message reaches its destination. It is usually referred as encounter-based, store-carry-forward, or mobility-assisted routing, because it exploits the node mobility as a significant factor for the forwarding decision of a message. This model of routing constitutes a significant departure from conventional ad hoc routing strategies where all the strategies operate based on the assumption that the network is always connected and there exists end-to-end path between any source and destination.

To improve the robustness, reduce the delivery delay, and increase the delivery ratio, extensive research efforts have been reported in design of efficient multi-copy routing algorithms [6, 3, 7, 17, 12]. Most DTN routing protocols have assumed negligible storage overhead [2], [4] without considering that each node could be with a limited buffer space. Note that buffering and forwarding unlimited number of messages may also cause intolerable resources and nodal energy consumption; and it is imperative to set up buffer limitations at the DTN nodes to better account for the fact that each node could be a hand-held and battery-powered device with stringent buffer size limitation. With such buffer limitations at the DTN nodes, message drop/loss could happen due to buffer overflow. This leads to a big challenge in the implementation of most previously reported schemes. An important issue in such a category of DTN routing is when and to which node the stored messages should be forwarded.

Obviously, the above schemes require additional efforts in order to incorporate with the given buffer space limitation at each node.

The paper introduces a novel message scheduling and dropping policy which can be incorporated with many encounter-based routing scheme that employ contact or inter-contact time as main factor on message forwarding decision making process, aiming to enable an effective decision process on which messages should be forwarded or dropped when the buffer is full. Such a decision is made by evaluating the impact of dropping each buffered message according to collected network information. In specific, we incorporated the mechanism of SAURP [17] in the evaluation of the proposed message scheduling policy.

The solution gives per-message utility values, which are calculated based on a simple theory, and the estimation of two parameters: the number of message copies, and the number of nodes who have "seen" this message (*the nodes that have either carried the message or rejected the acceptance of this message*). The per-message utility values at

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each node are then used for the decision on whether the buffered messages should be dropped in any contact. Simulation is conducted and the results confirm the efficiency and effectiveness of the proposed message scheduling scheme under SAURP.

The rest of this paper is organized as follows. Section 2 describes the related work in terms of utility-based DTN routing, and buffer management and scheduling in DTNs. Section 3 provides the background and system description which includes SAURP mechanism, and the network model. Section 4 introduces the proposed message scheduling framework. Section 5 provides experiment results which verify the proposed message scheduling policy. Section 6 concludes the paper.

2. RELATED WORK

A number of routing techniques have been introduced to handle routing issues in DTNs environment [11, 7, 6, 18, 17]. Yet, the impact of buffer management and scheduling policies on the performance of the system has not been largely considered by the DTN community. Only a few studies have examined the impact of buffer management and scheduling policies on the performance of DTN routing. Zhang et al. in [8] addressed this issue in the case of epidemic routing by evaluating simple drop policies such as drop-front and drop-tail, and analyzed the situation where the buffer at a node has a capacity limit. The paper concluded that the drop-front policy outperforms the drop-tail. Lindgren et al. in [9] evaluated a set of heuristic buffer management policies based on locally available nodal parameters and applied them to a number of DTN routing protocols. G.Fathima et al. in [21] proposed buffer management scheme based on dividing the main buffer to a number of queues. Each queue is maintained for a class of service. The messages are scheduled according to the class of service. When a particular queue is full, the message is placed in the subsequent queue. When the entire buffer is full, some of the messages should be dropped to give room for new messages. It is proposed to drop messages with least class of service. However, it is not clear how the messages are classified. Dimitriou et al. [23] proposed buffer management policy based on using two types of queues for two types of data traffic; a low-delay traffic (LDT) queue and a high-delay traffic (HDT) queue. Noticeably all the above mentioned policies based only on the local knowledge of some network information.

Dohyung et al. in [20], presented a drop policy which discards a message with the largest expected number of copies first, to minimize the impact of message drop. However, the scheduling were not addressed in their work. Erramilli et al. in [22] proposed policies in a conjunction with forwarding algorithms; one policy is based on forwarding the message that has the highest delegation number. The second one is based on forwarding the message that has the smallest delegation number. However, all these policies are heuristic, i.e. not explicitly designed for optimality in the DTN context. Moreover, these works do not address scheduling.

To the best of our knowledge, message scheduling problem under heterogeneous nodal mobility is firstly addressed by Balasubramanian et al. in [14]. The authors in [14] introduced the routing problem as resource allocation problem. The statistics of available bandwidth and the number of message replicas currently in the network are considered in the derivation of the routing metric to decide which message to

Algorithm 1 The forwarding strategy of SAURP

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On contact between node  $A$  and  $B$ 
Exchange summary vectors
for every message  $M$  at buffer of custodian node  $A$  do
  if destination node  $D$  in transmission range of  $B$  then
     $A$  forwards message copy to  $B$ 
  end if
  if  $\Delta T_{(A,D)}^{(i)} > \Delta T_{(B,D)}^{(i)}$  do
    if message tokens  $> 1$  then
      apply weighted copy rule
    end if
    else if  $\Delta T_{(A,D)}^{(i)} > \Delta T_{(B,D)}^{(i)} + \Delta T_{th}$  then
       $A$  forwards message to  $B$ 
    end if
  end if
end for

```

replicate first among all the buffered messages in the custodian node. The derivation of the routing metric, nonetheless, is not related to buffer status. In the same research line, the authors in [10] proposed a forwarding and dropping policies for a limited buffer capacity. The decision under these policies is made based on the value of per-message marginal utility. The parameters of the utility function are estimated under the assumption of the homogeneous nodal mobility. These policies nonetheless lose their performance under heterogeneous nodal mobility. It is clear that the above mentioned studies leave a large room to improve, where a solution for DTN buffer management and message scheduling that can well estimate and manipulate the network status is absent.

3. BACKGROUND AND SYSTEM DESCRIPTION

This section presents the background of protocol under consideration as well as the network model for utility-based routing.

3.1 SAURP

Self adaptive utility-based routing protocol (SAURP) for DTN [17], is designed to solve the online distributed DTN routing problem, where a group of nodes can cooperate with each other and make a forwarding decision for the stored messages based on a utility function at each contact with another node. The protocol is characterized by not only considering the contact time statistics under a novel contact model, but also looks into the feedback on user behavior and network conditions, such as congestion and buffer occupancy sampled during each previous contact with any other node. The complete mechanism of the forwarding strategy in SAURP is summarized as shown in Algorithm 1.

where ΔT is the utility function value represents the inter-contact time duration between a node and the destination of message i . From more details about SAURP the reader is referred to [17].

Although SAURP is aiming to reroute messages around congested regions in order to reduce the message delivery delay and increase the delivery ratio, we have found it is still subject to respective problems and implementation difficulties. In case of high traffic load and buffer limitations at the DTN nodes, messages may get queued for longer time causing drop/loss of messages due to buffer overflow. This

Table 1: Notation

Variables	Description
$Sr_j(t)$	The source of message j
$Dst_j(t)$	The destination of message j
T_j	Elapsed time since the creation of the message
R_j	Remaining lifetime of the message ($R_j = Tx_j - T_j$)
$n_j(t)$	Number of copies of message j
$m_j(t)$	Number of nodes who have "seen" message j

leads to a big challenge in the implementation, in which packet drops could result in a significant degradation of performance and scalability. Thus, efficient message scheduling and dropping policy is needed in order to enhance the performance of SAURP. The main challenge of coming up with efficient message scheduling and dropping policy is how to make accurate prediction about the network state when the nodal mobility is heterogeneous. We introduce new message prioritization scheme supported by SAURP mechanism using real measurements such as inter-encounter time, buffer capacity, and message life time (TTL).

3.2 Network Model

For any given node, A , it is assumed that $J_A(t)$ messages are stored in its buffer at time t . Each message j , $j \in [1, J_A(t)]$ is denoted by a tuple of variables denoted in Table 1.

The encounter (or mixing) rate between A and B , denoted as β_{AB} , is the inverse of the expected inter-encounter time for the two nodes: $\beta_{AB} = \frac{1}{\Delta T_{AB}}$. We assume that ΔT_{AB} , $A, B \in [1, N]$ follows an exponential distribution (or referred to as with an exponential tail [13]). It has been shown that a number of popular mobility models have such exponential tails (e.g., Random Walk, Random Waypoint, Random Direction, Community-based Mobility [5, 15]). Recent studies based on traces collected from real-life mobility examples [16] argued that the inter-encounter period and the encounter durations in these traces demonstrate exponential tails after a specific cutoff point. The historical information becomes more accurate and the adaptation of the mobility characteristics becomes precise with a greater elapse of time.

4. MESSAGE SCHEDULING FRAMEWORK

4.1 Network State Estimation

During each contact, the network information summarized as a "summary vector", is exchanged between the two nodes through an in-band control channel, which includes the following data: (1) statistics of inter-encounter time of every node pair maintained by the nodes, (2) statistics regarding the buffered messages, including their IDs, remaining time to live (R_j), destinations, the stored $n_j(T_j)$, and $m_j(T_j)$ values for each message that were estimated in the previous contact. We call the strategy of updating $n_j(T_j)$, and $m_j(T_j)$ values as Encounter History-Based Prediction (EHP).

Since it is not practical to estimate global knowledge about the network due to heterogeneity nature of the nodal mobility, when ever two nodes encounter each other they update

each other with respect to the messages they have in common, and the values of $m_j(T_j)$, and $n_j(T_j)$, $\{\beta_{1,d_j}, \beta_{2,d_j} \dots \beta_{n,d_j}\}$, and $\{\beta_{1,d_j}, \beta_{2,d_j} \dots \beta_{m,d_j}\}$ are updated accordingly, where β_{n,d_j} and β_{m,d_j} represent the encounter rate between the n^{th} custodian of the n^{th} copy of message j with the destination of message j , and the encounter rate of m^{th} node who has seen the message with the destination of message j , respectively. These parameters are further taken as inputs to calculate the proposed per-message utility function.

4.2 Utility Calculation

Based on the problem settings and estimated parameters, the following question should be answered at a node during each nodal contact: Given $n_j(T_j)$, $m_j(T_j)$, and limited buffer space for supporting SAURP routing, what is an appropriate decision on whether the node should drop any message in its buffer or reject any incoming message from the other node during the contact, such that the average delivery ratio or delivery delay can be optimized?

4.2.1 Minimization of Average Delivery Delay

Let us assume that nodes A and B are in contact, and message j in A 's buffer is to be forwarded to node B according to SAURP forwarding policy, while the buffer is full at node B and there is a message i with elapsed time T_i in a network that has K messages at the moment at which the decision should be made by node B with respect to dropping a message from all messages in its buffer.

To minimize the delivery delay of all messages, the decision of dropping message i should result in least increase of delivery delay of message i , while forwarding message j from node A to B should result in most decrease in the delivery delay of message j (i.e., node B should discard a message such that the expected delivery delay of all messages can be reduced the most). Since the delivery delay of the messages is mainly affected by the nodal inter-encounter time, we assume that all message have infinite or large enough Tx and derive the utility function such that it is affected by number $n_j(T_j)$, $m_j(T_j)$, $\{\beta_{1,d_j}, \beta_{2,d_j} \dots \beta_{n,d_j}\}$, and $\{\beta_{1,d_j}, \beta_{2,d_j} \dots \beta_{m,d_j}\}$.

To achieve the minimum average delivery delay, node B should drop the message that satisfies the following:

$$Umin_i = argmin_i \left| \left[\exp\left(-\sum_{k \in m_i(T_i)} \beta_{k,d_i} T_i\right) \left(\frac{1}{\sum_{l \in n_i(T_i)} \beta_{l,d_i}} - \frac{1}{\sum_{l \in n_i(T_i) \setminus B} \beta_{l,d_i}} \right) \right] \right| \quad (1)$$

and the decision of forwarding message j from node A to node B should satisfy one of two cases; based on whether message j is in spraying phase, or in forwarding phase. If message j is still in spraying phase, the decision of forwarding message j should satisfy following:

$$Umax_j = argmax_j \left| \left[\exp\left(-\sum_{k \in m_j(j_k)} \beta_{k,d_j} T_j\right) \left(\frac{1}{\sum_{l \in n_j(T_j)} \beta_{l,d_j}} - \frac{1}{\sum_{l \in n_j(T_j) \cup B} \beta_{l,d_j}} \right) \right] \right| \quad (2)$$

which represents the margin decrease in the delivery delay of message j if node A forward a copy to node B .

If message j is in forwarding phase, the decision of forwarding should satisfy following:

$$Umax_j = \underset{j}{\operatorname{argmax}} \left[\exp\left(-\sum_{k \in m_j(T_j)} \beta_{k,d_j} T_j\right) \left(\frac{1}{\sum_{l \in n_j(T_k)} \beta_{s,d_j}} - \frac{1}{\sum_{l \in (n_j(R_j) \setminus A) \cup B} \beta_{l,d_j}} \right) \right] \quad (3)$$

The relation represents the margin decrease in the delivery delay if node A hands over message j to node B .

Proof of (1): Let random variable T_d represents the delivery delay of message j . Then, the expected delay in delivering a message that still has copies existing in the network can be expressed

$$D_j = P\{\text{message } j \text{ not delivered yet}\} * E[T_d | T_d > T_j]$$

$$D_i = \exp\left(-\sum_{k \in m_j(T_j)} \beta_{k,d_j} T_j\right) * E[T_d | T_d > T_j] \quad (4)$$

where

$$Pr\{\text{message } j \text{ not delivered} | \text{not delivered yet}\} =$$

$$\prod_{l=1}^{n_j(T_j)} \exp\left(-(\beta_{l,d_j} R_j)\right) = \exp\left(-\left(\sum_{l=1}^{n_j(T_j)} \beta_{l,d_j} R_j\right)\right) \quad (5)$$

$$E[T_d | T_d > T_j] = \left[T_j + \frac{1}{\sum_{l \in n_j(T_j)} \beta_{l,d_j}} \right] \quad (6)$$

When a node buffer is full, the node should make a drop decision that leads to the least increase on D_j . To find the local optimal decision, D_j is differentiated with respect to $n_j(T_j)$, and ∂D_j is then discretized and replaced by ΔD_j :

$$\Delta D_j = \frac{\partial D_j}{\partial n_j(T_j)} * \Delta n_j(T_j), \text{ which equivalent to}$$

$$\Delta D_j = \exp\left(-\sum_{k \in m_j(T_j)} \beta_{k,d_j} T_j\right) *$$

$$\left[\frac{1}{\sum_{l \in n_j(T_j)} \beta_{l,d_j}} - \frac{1}{\sum_{l \in n_j(T_j) \setminus B} \beta_{l,d_j}} \right] \Delta n_j(T_j)$$

To reduce the delivery delay of all messages existing in the network, the best decision is to discard the message that maximizes the total delivery delay, $D = \sum_{j=1}^{K(t)} D_j$, among all $K(t)$ messages existing in the network. Therefore, the optimal buffer-dropping policy at node B that leads to minimization of the delivery delay is thus to discard the message that has the min value of $|\Delta D_j|$ (or $-\Delta D_j$), which is equivalently to choose a message with a value for $Umin_i$ that satisfies (1), which represents the marginal increase in the delivery delay of message i if its copy at node B is dropped. While the optimal buffer-forwarding policy at node A that leads to minimization of the delivery delay is thus to forward a copy of message j (or message j itself) to node B that leads to the max decrease of ΔD_j , which is equivalently to choose a message with a value for $Umax_j$.

Proof of (2) and (3): The proof follows same steps of deriving (1) with considering the marginal decrease of delivery delay of message j at node A if it get copied or forwarded to node B .

Algorithm 2 SAURP-based forwarding and dropping policy

On contact between node A and B

Exchange summary vectors

01: If (buffer at node B is full)

02: for every message j at the buffer of custodian

02: node A do

03: if (B is not source node of i) then

04: if (remaining tokens of message

04: $j \geq$ remaining tokens of i) &&

04: $(\Delta T_{B,d_i} \succ \min\{\Delta T_{1,d_i}, \Delta T_{2,d_i} \dots$

04: $\dots, \Delta T_{n-1,d_i}\})$ then

05: if destination node d_j in

05: transmission range of B then

06: B drops message i

07: A forwards a copy of message j to B

08: end if

09: else if $(Umax_j - Umin_i > 0)$ then

10: B drops message i

11: A forwards message j to B

12: end else if

13: end if

14: end if

15: end for

16: end if

18: else (apply SAURP)

18: end

4.3 SAURP-based Forwarding and Dropping Policy (SAURP_FDP)

With the per-message utility, the node firstly sorts the buffer messages accordingly from the highest to the lowest. The messages with lower utility values have higher priorities to be dropped when the node's buffer is full, while the messages with higher utility values have higher priorities to be forwarded to the encountered node. Algorithm 2 illustrates the forwarding and dropping actions which largely based on the fact that; if the utility $Umax_j$ of message j (the message with the highest utility value) buffered in A is higher than $Umin_i$ of message i (the message with the lowest utility value) at node B , then message i is dropped and replaced by message j or copy of it, if the buffer of B is full during the contact between the two nodes. To enhance the performance of the algorithm, the lowest priority of dropping is given to a message that has higher number of remaining message tokens and/or the inter-contact time between its current custodian and the message destination is the best one found so far.

5. SIMULATION STUDY

To examine the efficiency of the proposed SAURP-based Forwarding and Dropping Policy (SFDP) under EHP strategy, experiments were conducted, and the results presented in this section. We call SFDP under EHP as SFDP_E.

5.1 Experimental Setup

To better understand the performance of the proposed strategies and their gain over SAURP, we also implemented another estimation strategy for the values of $m_i(T_i)$, and $n_i(T_i)$, namely Global Knowledge-based Management (GKM). The GKM assumes knowing the exact values of $m_i(T_i)$, and

Table 2: Simulation parameters

Mobility pattern	CBMM	Infocome06
Simulation duration (seconds)	30000	270000
Simulation area	700 × 700	—
No. of Nodes	110	98
Average speed (m/s)	-	-
TTL (sec)	9000	90000

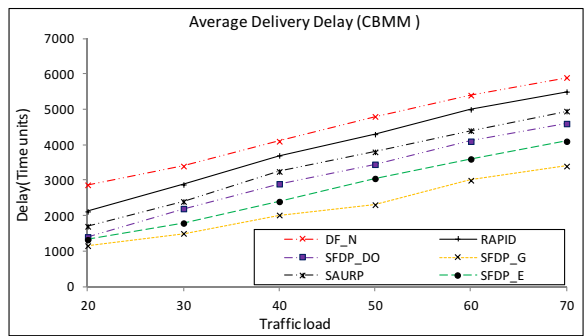
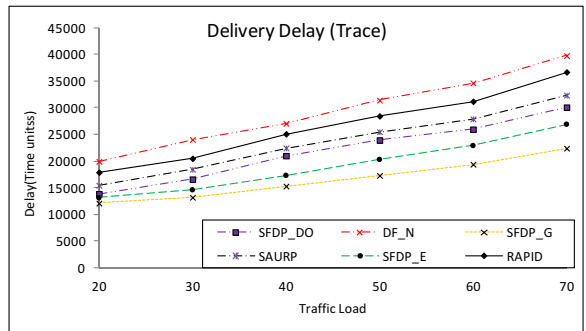
$n_i(T_i)$, and is supposed to achieve the best performance. Since such an assumption is not practical [11], the result of GKM is taken as a benchmark for the proposed GHP scheme. We call SFDP under GKM strategy as SFDP_G.

In addition to the above prediction strategy, we compared the proposed buffer management policies with three well-known scheduling schemes listed as follows:

- Drop oldest (DO) drops the message with shortest remaining TTL when the buffer is full. This policy obtains the best performance of all the policies used by Lindgren et al. in [9]. We call DO under SFDP as SFDP_DO.
- Delegation forwarding scheme employs dropping policy based on drop message with highest number of forwards (DF_N) by Erramilli et al. in [22].
- RAPID scheme employs dropping policy based on drop message that is most likely to miss the deadline [14].

We assume a message issued at a node (termed sourced messages) has the highest priority at the node. If all buffered messages are sourced ones and the newly arrived message is also a source message at the node, then the oldest one is dropped. This idea was examined in [8] and has been proved with improved delivery ratio.

To evaluate the proposed policies, a DTN simulator similar to that in [19] is implemented. The simulations are based on two mobility scenarios; a synthetic one based on community based mobility model (CBMM) [4], and a real-world encounter traces collected as part of the Infocom 2006 experiment, described in [24]. The traces consists of 98 nodes. The simulation parameters are as shown in table 2. Each node has a transmission range, $D = 30$ meters, to obtain sparsely populated network. Euclidean distance is used to measure the proximity between two nodes (or their positions). A slotted collision avoidance MAC protocol with Clear-to-Send (CTS) and Request-to-Send (RTS) features was implemented in order to arbitrate between nodes that contend for a shared channel. The message inter-arrival time is uniformly distributed in such a way that the traffic can be varied from low (20 messages generated per node) to high (80 messages generated per node). The buffer size is set to a low capacity (10 messages), to push the network towards a congestion state when the traffic is getting higher. Message delivery ratio and the delivery delay are taken as two performance measures. Each data is the average of the results from 30 runs.

**Figure 1: The effect of traffic load (CBMM scenario).****Figure 2: The effect of traffic load (real trace scenario).**

5.2 Simulation Results

This section examines the proposed policy for maximizing the average delivery delay under the considered scenarios. The plots of the delivery delay obtained under CBMM and infocom2006 traces is shown in Figure.1 and Figure.2.

As expected, the SFDP_G gives the best performance under all traffic loads for both scenarios under consideration, while the SFDP_E is the second best and is competitive with the SFDP_G in the case of low traffic. As the traffic increases, the demand on the wireless channel and buffers increases, causing a long queuing delays and substantial message loss that negatively affect the performance of all the examined policies. Figure.1 shows the results under CBMM scenario. We have observed that the SFDP_E outperforms the SAURP, RAPID, DF_N, and SFDP_DO. SFDP_E is better than SAURP by 21%, RAPID by 35%, DF_N by 44% , SFDP_DO by 16%, and a longer delay of only 23% of that achieved by SFDP_G. Under the real trace scenario as shown in Figure.2, SFDP_E achieved delivery delay better than SAURP by 27%, RAPID by 43%, DF_N, by 56%, SFDP_DO by 20%, and a longer delay of 14% of that achieved by SFDP_G.

6. CONCLUSION

This paper has investigated a novel buffer management policy for a utility-based forwarding routing in heterogeneous delay tolerant networks (DTNs), aiming to optimize the message delivery delay. The proposed framework incorporates a suit of novel mechanisms for network state estimation and utility derivation, such that a node can ob-

tain the priority for dropping each message in case of buffer full. Using simulations based on two mobility models; a synthetic (Community based Mobility Model) and a real trace (Infocom2006), the simulation results show that the proposed buffer management policy can significantly improve the routing performance in terms of the performance metrics of interest under limited network information.

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