Message Scheduling and Forwarding in Congested DTNs

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***Abstract*—Multi-copy utility-based routing has been considered as one of the most applicable approaches to effective message delivery in Delay Tolerant Networks (DTNs). By allowing multiple message replicas launched, the ratio of message delivery or delay can be significantly reduced compared with other counterparts. Such an advantage, nonetheless, is at the expense of taking more buffer space at each node and higher complexity in message forwarding decisions. This paper investigates an efficient message scheduling and dropping policy via analytical modeling approach, aiming to achieve optimal performance in terms of message delivery delay. Extensive simulation 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.**

***Index Terms*—Routing, Scheduling, Buffer management, DTN.**

I. 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 variations in link condition over time, a node in a DTN buffers a message and waits until it finds an available link to the next hop, which in turn 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 each message. This model of routing constitutes a significant difference from conventional ad hoc routing strategies which assume there exists an end-to-end path between any source and destination at any time.

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 [2], [4], [5], [6]. Although with excellent performance compared with single-copy routing schemes, multi-copy routing algorithms introduce additional power consumption and hardware requirement by being subject to higher computation complexity, and requiring more transmissions and buffer space. It is envisioned that the future DTNs are composed of miniature and hand-held devices (e.g., smart phones and PDAs), and could be subject to extensive congestion due to dense nodal distribution and large traffic volumes. Thus far, a few studies have considered buffer space limitation and contention of wireless links in the algorithm design [4], [10], [17], [20]. However, none of the previously reported studies provided a complete study on an efficient message scheduling and buffer management algorithm under heterogeneous DTNs.

Motivated by its importance, the paper investigates DTN routing by introducing a novel message scheduling and buffer management approach. Our goal is to come up with a solid framework which can be incorporated with many encounter-based routing schemes employing contact or inter-contact time as main factor on message forwarding decision making process. In particular, the proposed approach enables an effective buffer management policy which determines 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. Based on the proposed buffer management policy, we analyze the message delay on a generic message forwarding scheme reported in [17], called Self Adaptive Utilty-based Routing Protocol (SAURP). The contributions of the paper are as following:

- Developing new utility-based message scheduling mechanism that incorporates with SAURP message forwarding. This new mechanism provides per-message utility values, which are calculated based on a simple theory that based on inter-contact time, 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 each node are then used for the decision on whether the buffered messages should be dropped in any contact.
- Gaining understanding on the efficiency and effectiveness of the proposed approach by comparing it with counterparts using extensive simulations.

The rest of this paper is organized as follows. Section II describes the related work in terms of utility-based DTN routing, and buffer management and scheduling. Section III provides the background of the study which includes the SAURP mechanism and the system model. Section IV introduces the proposed message scheduling approach. Section V provides experimental results which verify the proposed approach. Section VI concludes the paper.

II. RELATED WORK

Numerous studies have been reported to address the DTN routing issues [3], [4], [5], [6], [11], [12], [17], [18]. Yet, the impact of buffer management and scheduling policies on the performance of DTNs has only been investigated in a few studies. Zhang et al. [8] addressed this issue in the case of epidemic routing by evaluating a number of simple drop policies such as drop-front and drop-tail, and analyzed the situation where the nodal buffer has a capacity limit. The paper concluded that the drop-front policy outperforms the drop-tail. Lindgren et al. [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. [21] proposed a buffer management scheme based on dividing the main buffer into a number of queues, each being maintained for a class of service and scheduled accordingly. When a particular queue is full, the message is placed in the subsequent queue. When the entire buffer is full, some of the messages with least class of service should be dropped to yield room for new messages. However, it is not clear how the messages are classified. Dimitriou et al. [23] proposed a buffer management policy based on using two types of queues. A low-delay traffic (LDT) queue and a high-delay traffic (HDT) queue. Noticeably all the aforementioned policies are only based on very limited knowledge that is locally available to each node.

Dohyung et al. [20] presented a drop policy which discards a message with the largest expected number of copies first, to minimize the impact of message drop, while leaving the issue of scheduling untouched. Erramilli et al. [22] introduced a set of policies in conjunction with their forwarding algorithm. One policy is based on forwarding the message that has the highest delegation number and the other favours the smaller delegation numbers, which serve as heuristics without any optimization effort in the DTN context. Moreover, the aforementioned studies did not address issues of scheduling.

Message scheduling under heterogeneous nodal mobility was firstly addressed by Balasubramanian et al. [14], in which a resource allocation problem was formulated. The statistics of available bandwidth and the number of message replicas in the network are considered in the derivation of the routing metric to decide which message to 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, Krifa et al. [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 homogeneous nodal mobility, thus the scheme could be subject to considerable performance impairment under heterogeneous nodal mobility which is considered a more practical scenario. It is clear that the aforementioned 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.

Algorithm 1 The forwarding strategy of SAURP

```
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 $\triangle T^{(i)}_{(A,D)} > \triangle T^{(i)}_{(B,D)}$ do
        if message tokens >1 then
            apply weighted copy rule
        end if
        else if $\triangle T^{(i)}_{(A,D)} > \triangle T^{(i)}_{(B,D)} + \triangle T_{th}$ then
            $A$ forwards message to $B$
        end if
    end if
end for
```

III. BACKGROUND AND SYSTEM MODEL

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

A. Self Adaptive Utility-based Routing Protocol (SAURP)

SAURP [17] is designed to solve the DTN routing problem in terms of how to select a next hop for each carried massage. Specifically, it initiates cooperation among a group of nodes in making message forwarding decision for the stored messages based on a utility function at each contact with another node. Algorithm 1 shows detailed SAURP mechanism, where the utility function value ($\triangle T$) simply represents the inter-contact time duration between a node and the destination of message i, while the routing decision for the message is made according to whether message i is in the spraying phase (i.e., the number of message i copy tokens > 1), or in the forwarding phase (i.e., the remaining number of message i copy tokens = 1). If the message is in spraying phase, a rule called weighted copy rule is applied for message forwarding decision. For more details about SAURP, the reader referred to [17].

Although SAURP can effectively select the next hop to forward a message, it lacks the ability to intelligently tell which message should be dropped when the buffer is full. This particularly becomes a problem in case of high traffic load and stringent buffer limitation, where a node has to drop some buffered messages that are less unlikely to be delivered to the destination while accommodating those with more likelihood to be successfully delivered, in order to achieve better performance. Thus, an efficient message scheduling and dropping policy should be in place as a countermeasure of the aforementioned situation. The main challenge lies on how to

Table I
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
Tx	Message time-to-live

accurately predict the network state in a distributed manner according to the collected historical data under heterogeneous nodal mobility. The paper answers the question by investigating a novel message scheduling and dropping policy that incorporates with SAURP.

B. Network Model

For any given node A, let a number of $J_A(t)$ messages be 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: $\beta_{AB} = \frac{1}{\triangle T_{AB}}$. We assume that $\triangle T_{AB}$, 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 [7], [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 elapsed of time.

IV. PROPOSED MESSAGE SCHEDULING SCHEME

A. 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_i), destinations, the stored $n_i(T_i)$, and $m_i(T_i)$ values for each message that were estimated in the previous contact. We call the strategy of updating $n_i(T_i)$, and $m_i(T_i)$ values as Encounter History-Based Prediction (EHP).

Since it is not practical to estimate global knowledge about the network due to the heterogeneous nature of the nodal mobility, when ever two nodes encounter each other they update each other with respect to the messages they do not have in common, and the values of $m_j(T_j)$, and $n_j(T_j)$, $\{\beta_{1,d_j}, \beta_{2,d_j} ... \beta_{n,d_j}\}$, and $\{\beta_{1,d_j}, \beta_{2,d_j} ... \beta_{m,d_j}\}$ are updated accordingly, where β_{n,d_j} and β_{m,d_j} represents 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.

B. Utility Calculation

Based on the problem settings and estimated parameters, the following question should be answered at each node during every nodal contact: Given $n_j(T_j)$, $m_j(T_j)$, 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 delay can be optimized?

To ansewr this quetion, 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 $n_j(T_j)$, $m_j(T_j)$, $\{\beta_{1,d_j}, \beta_{2,d_j} ... \beta_{n,d_j}\}$, and $\{\beta_{1,d_j}, \beta_{2,d_j} ... \beta_{m,d_j}\}$.

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

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

Derivation 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

$$D_j = P\{message\, j\, not\, deliverd\, yet\} * E[T_d \mid T_d > T_j]$$

$$D_i = exp(-\sum_{k \in m_j(T_j)} \beta_{k,d_j} T_j) * E[T_d \mid T_d > T_j] \tag{2}$$

where

$$Pr\{message\, j\, not\, delivered\, yet\} =$$

$$\prod_{l=1}^{n_j(T_j)} exp - (\beta_{l,d_j} R_j) = exp(-(\sum_{l=1}^{n_j(T_j)} \beta_{l,d_j} T_j)) \tag{3}$$

,

$$E[T_d \mid T_d > T_j] = \left[T_j + \frac{1}{\sum_{l \in n_j(T_j)} \beta_{l,d_j}} \right] \tag{4}$$

When a node buffer is full, the node should make a drop decision that leads to the least increase in 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 $\triangle D_j$:

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

$$\triangle D_j = exp(-\sum_{k \in m_j(T_j)} \beta_{k,d_j} T_j) *$$
$$\left[\frac{1}{\sum_{l \in n_j(T_j)} \beta_{l,d_j}} - \frac{1}{\sum_{l \in n_j(T_j) \setminus B} \beta_{l,d_j}} \right] \triangle n_j(T_j)$$

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 $\mid \triangle D_j \mid$ (or$-\triangle D_j$), 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 $\triangle D_j$, which is equivalently to choose a message with a value for $Umax_j$.

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 the following:

$$Umax_j = argmax_j \left| \left[exp(-\sum_{k \in m_j(T_j)} \beta_{k,d_j} T_j) \left(\frac{1}{\sum_{l \in n_j(T_j)} \beta_{l,d_j}} - \frac{1}{\sum_{l \in n_j(T_j) \cup B} \beta_{l,d_j}} \right) \right] \right| \quad (5)$$

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 the following:

$$Umax_j = argmax_j \left[exp(-\sum_{k \in m_j(T_j)} \beta_{k,d_j} T_j) \left(\frac{1}{\sum_{l \in n_j(T_j)} \beta_{l,d_j}} - \frac{1}{\sum_{l \in (n_j(T_j) \setminus A) \cup B} \beta_{l,d_j}} \right) \right] \quad (6)$$

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

Derivation of (5) and (6): The derivation 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
If (buffer at node B is full)
    for every message $j$ at the buffer of custodian
    node $A$ do
        if ( $B$ is not source node of $i$) then
            if (remaining tokens of message
             $j \geq$ remaining tokens of $i$) &&
            ($\triangle T_{B,d_i} \succ min\{\triangle T_{1,d_i}, \triangle T_{2,d_i}..$
            $.., \triangle T_{n-1,d_i}\}) then$
                if destination node $d_j$ in
                transmission range of $B$ then
                    $B$ drops message $i$
                    $A$ forwards a copy of message $j$ to $B$
               end if
                else if ($Umax_j - Umin_i > 0$ ) then
                    $B$ drops message $i$
                    $A$ forwards message $j$ to $B$
               end else if
            end if
        end if
    end for
end if
else ( apply SAURP)
end
```

C. 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 are 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 or the inter-contact time between its current custodian and the message destination is the best one found so far.

V. SIMULATION STUDY

Simulation is conducted to examine the efficiency of the proposed scheme, namely SAURP_based Forwarding and Dropping Policy (SFDP). SFDP under EHP is denoted as SFDP_E.

A. Experimental Setup

To better understand the performance of the proposed strategies and their gain over SAURP without buffer management, 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). GKM assumes knowing the exact values of $m_i(T_i)$, and $n_i(T_i)$, 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 scheme. We call SFDP under GKM strategy as SFDP_G.

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

- Drop oldest (DO) drops the message with shortest remaining T_x 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 a dropping policy based on drop message with highest number of forwards (DF_N) by Erramilli et al. in [22].
- RAPID scheme employs a 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 and newly arrived message are from itself, the oldest is dropped.

A DTN simulator similar to that in [19] is implemented. The simulations are based on two mobility scenarios: a synthetic one on community based mobility model (CBMM) [24], and a real-world encounter traces with 98 nodes collected as part of the Infocom 2006 experiment, described in [25]. The simulation parameters are as shown in Table II. Each node has a transmission range of $D = 30$ meters to achieve a sparsely populated network, the size of all messages is same, and each message transmission takes one time unit. Euclidean distance is used to measure the proximity between two nodes and their positions. A slotted collision avoidance MAC protocol with Clear-to-Send (CTS) and Request-to-Send (RTS) features is implemented in order to arbitrate the contention on a shared channel between nodes. The message inter-arrival time at a node is uniformly distributed in such a way that the traffic can be varied from low (10 messages generated per node) to high (70 messages generated per node). The buffer size is set to 10 messages, which is quite low compared with the considered traffic arrival rates such that the network could easily go into a congestion state. Message delivery ratio and the delivery delay are taken as two performance measures. Each data is the average of the results from 30 runs.

B. Simulation Results

This section examines the proposed policy for minimizing 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 long queuing delays and substantial message loss that negatively affect the performance of all the examined policies.

Table II
SIMULATION PARAMETERS

Mobility pattern	CBMM	Infocom06
Simulation duration (seconds)	30000	270000
Simulation area	700 × 700	–
No. of Nodes	110	98
Average speed (m/s)	-	-
T_x(seconds)	9000	90000

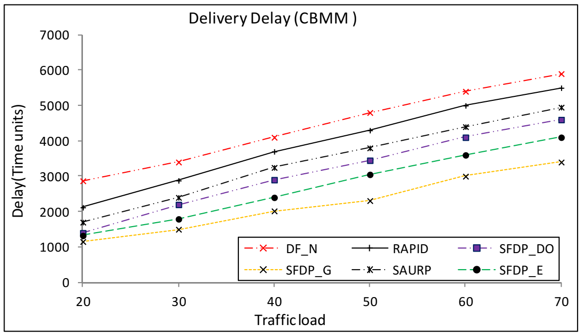

Figure 1. The effect of traffic load (CBMM scenario).

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.

VI. CONCLUSION AND FUTURE WORK

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

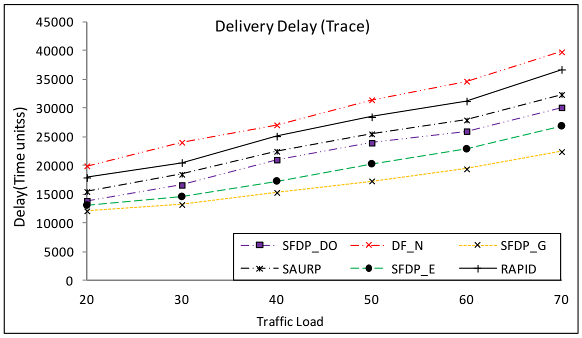

Figure 2. The effect of traffic load (real trace scenario).

suit of novel mechanisms for network state estimation and utility derivation, such that a node can obtain 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.

Note that in this work, our objective was optimizing the message delivery delay. It would be interesting to introduce a utility function to optimize the delivery ratio of all messages. Also, in this study we considered relatively small network size, and all messages have the same size and same T_x value. It is important to study the performance of our proposed scheme under various network set up, and develop buffer management policies accordingly. For example, in case of larger network size under high congestion, we expect that the cost of the update of the parameters could consume larger amount of available bandwidth, which may affect the network throughput. Thus, this issue should be taken in consideration.

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