Lexicographical order Max-Min Fair Source Quota Allocation in Mobile Delay-Tolerant Networks

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Abstract—**There is a big potential to enable more efficient data dissemination in mobile Delay-Tolerant Networks (DTNs) with the concurrent use of multi-copy forwarding and social metrics. However, this also leads to the possibility of severely overloading the relay nodes with high social metrics, and consequent performance degradation. We propose a fair source quota allocation algorithm to effectively alleviate the load while ensuring their dissemination fairness, i.e, Lexicographical order Max-Min Fairness(LMMF). In this paper, A fair source quota allocation algorithm along with an implementation scheme was presented to take advantage of the features of social networks and social forwarding for higher delivery performance. Extensive simulations based on trace data demonstrate that our mechanism greatly reduces the delivery-ratio degradation caused by uneven load while ensuring fairness among the network users.**

I. INTRODUCTION

With the rapid growth of applications involving multimedia sharing or information exchange such as mobile advertisements, there are increasing interests in exploring content-centric message forwarding with mobile nodes as relays. Delay-Tolerant Networks (DTN) are proposed to satisfy this communication requirement without the need of pre-established network infrastructure [1], where mobile nodes take a *store-carry-forward* strategy to carry and forward messages opportunistically upon encountering each other.

To achieve more reliable data delivery, the earlier mechanisms adopt a *data-replicate and random-forward* transmission pattern, where several copies of data are sent through randomly selected relays with the cost of high data redundancy thus resource consumption [3] [4]. Inspired by the knowledge of social science, some later work exploits *contact-compare-forward* scheme for a data holder to select an encountering node with higher social metric as the relay [6] [7] to continue forwarding the data.

Intuitively,as orthogonal techniques, multi-copy forwarding may be applied along with the relay selection based on social metrics to further improve the transmission reliability. However, the nodes with higher social metrics will be more likely selected as relays and receive the messages to forward. If the number of message is too large for the node to handle, it will lead to congestion which significantly degrades the network performance. Particularly, buffer overuse can contribute to as much as 40% performance degradation [2].

Although some common approaches have been proposed in the literature to reduce the load of a general network buffer,the buffer management in social DTNs faces some special challenges although some common approaches have been proposed : 1) ***Uncontrollable buffer consumption***, where a source node cannot control the amount of buffer space it consumes from a relay due to the nature of opportunistic forwarding and the possibility for a relay to carry a message copy for a longer period of time before meeting another node to send to. 2) ***Incomplete information of the network conditions***, where a node has difficulty of acquiring the complete and consistent network information due to intermittent network connections and uncertain human mobility. 3) ***Opportunistic message forwarding***, which makes it difficult to predict the message dissemination range and the network buffer usage. These three challenges make it hard to control the buffer resource usage of an individual node and the overall network.

Existing efforts for load control mainly fall into three categories: 1) ***Replication adjustment to vary the message replication rate based on the load***. In Retiring Replicants [2], CAFREP [9], two encountering nodes adjust the replication quotas based on the message dropping ratio, buffer occupancy and contact relationships. 2) ***Messages offloading and dropping***, where an overloaded relay offloads its messages to the nodes nearby [10] [11] [12] or simply drops some messages to relieve congestion [21] [22]. 3) ***Forwarding refusal***, which classifies nodes based on their load levels to prevent overloading relays. [13] divides the nodes into three states, i.e., normal state (NS), congestion adjacent state (CAS), and congestion state (CS) based on the storage utilization, and avoids forwarding messages to nodes in CAS or CS. All these methods do not address the primary source of buffer overloading as a result of the large number of message copies, or consider the fairness in buffer resource allocation.

The paper [14] assume the existence of some ferry nodes dedicated to forward packets for regular nodes in DTNs and fairly allocate ferry resources, while it is difficult to find dedicated ferry nodes in social DTNs often formed with random peer nodes.

As nodes with high social metrics are susceptible to high load, we propose a local buffer management scheme to effectively prevent buffer overburden while ensuring fairness in social DTNs. Different from conventional buffer management schemes, an overloaded node will fairly allocate the copy quotas to sources that contribute to the load to prevent messages from selected sources to reach the node.

Our contributions in this work are summarized as follows:

- We analyse the system model and propose a novel buffer load control mechanism for bottleneck nodes to adapt quotas of relevant sources.
- Max-min fairness (MMF) is widely used in the network resource allocation, and we extend the traditional max-min fairness to discrete Lexicographical order Max-Min Fairness (LMMF), and to the best of our knowledge, this is the first work that applies LMMF in social DTNs.
- We design an independent module to adjust the quota allocation according to current network conditions, which is extended to use with other multi-copy-based social forwarding algorithms.

The rest of this paper is organized as follows. Section II discusses the system model and features of social forwarding and provides an overview of our design of fair load control in social DTNs. In Section III, we propose a fair quota algorithm and implement this algorithm. We evaluate the performance of our load control and adaptive quota allocation mechanisms through extensive simulations in Section IV, and conclude the work in Section V.

II. SYSTEM MODEL AND MOTIVATION

In this section, we introduce our system model, the basic metrics used in the design, and the concept of fairness.

A. Network model and Features

We consider a social DTN which consists of N nodes and forwards multiple copies of message based on the social metrics of contacting nodes. We denote the set of sources by $S = \{s_1, s_2, \ldots, s_n\}$. If a source s_i has a copy quota k_i, it is allowed to replicate its message into k_i copies in the network. For a relay node j, E_j represents the number of message copies it can process per time unit. A threshold $\theta (0 < \theta < 1)$ is set based on the buffer occupancy percentage, beyond which a node j is considered to be overloaded.

Different from the intuitive understanding that the message forwarding path of social DTNs is very dynamic, social DTNs are mostly considered to use in scenarios such as conferences and campus, where people perform similar activities thus have a higher chance of meeting each other. With intrinsic social relationship, nodes in this type of social DTNs are generally willing to forward data for others. Based on the studies of mobility patterns of more than one hundred thousand of human individuals for more than six months, the work in [5] shows that human individuals tend to have restricted daily activities and stay at very few geographic locations such as home or workplace. Therefore, nodes tend to have regular neighbors, and the network topology is relatively stable.

Compared to message transmissions at fine time granularity of seconds, minutes or hours, social relations between human individuals vary at a much slower pace, in the units of day, week, or even year. For example, the *centrality* of a teacher is always higher than students since he/she often contacts all students in several classes while a student only contacts some others sitting around. This feature is exploited to design Bubble Rap in [6]. Authors in [6] exploit this stability to design Bubble Rap and the results turn out to be reasonable.

Given the two regularities discovered above, i.e., *stable contact topology* and *stable social relation*, a node's next-hop relays will also be relatively stable.

B. Buffer Metric and Buffer Allocation Fairness

The total buffer consumption from a source s_i on all relays is proportional to the number of message copies, k_i, it sends into the network. A larger k_i usually provides s_i a higher message delivery opportunity at the cost of higher buffer usage. We define k_i as s_i's utility metric to represent the number of message copies it is allowed to generate and their impact on the buffer occupancy of relays in the network.

Several methods such as [15] and [4] disseminate message copies with a fixed copy quota. With the message distribution range restricted, BSW [4] is shown to achieve the fastest message dissemination ratio with less resource consumption. By equal splitting the message quota between the current node and a forwarder, messages generated by s_i propagate at most $\lfloor log_2 k_i \rfloor$ hops in BSW, beyond which messages will be carried by the last relay until it reaches the destination.

Messages from different sources may go through the same relay, and the relay with a higher social metric may become the bottleneck. The problem becomes more severe when the messages tend to go through the similar set of relays as a result of the relatively stable social relationship. To prevent overloading a node of higher social metric, a source may be given a different path at the risk of lower delivery ratio by passing traffic through nodes with lower social metrics, or the traffic may be forwarded around an overloaded node locally at the risk of cascaded congestions and network path oscillation.

To alleviate the relay load, we keep the original social forwarding path but control the message spreading ranges of selected sources so their messages won't reach the congested relay. Motivated by the transmission principle of BSW, the control of the message range can be realized by adapting the copy quota of the source. Taking advantage of the strong message distribution capability of popular social nodes, the reduction of message quotas thus copies has little impact on the network performance as shown in our performance studies.

In Fig. 1(a), three sources s_1, s_2, and s_3 (blue) are around an overloaded relay c (red), each generating messages at rate 1. The blue curves represent the message dissemination directions. Node c has the highest social metric and can handle the message at the rate $E_c = 2$. The initial values of k_1, k_2, k_3 are all 8, so the messages from all three sources can reach the relay c. To alleviate the load of c, there are two choices to reduce the quota of a source: 1) In Fig. 1(b), k_3 is set to 2 to prevent the messages of s_3 from reaching c. The three quotas are 8, 8, 2 ranked in the increasing order for the convenience of comparison of allocation performance. 2) In Fig. 1(c), k_1 is

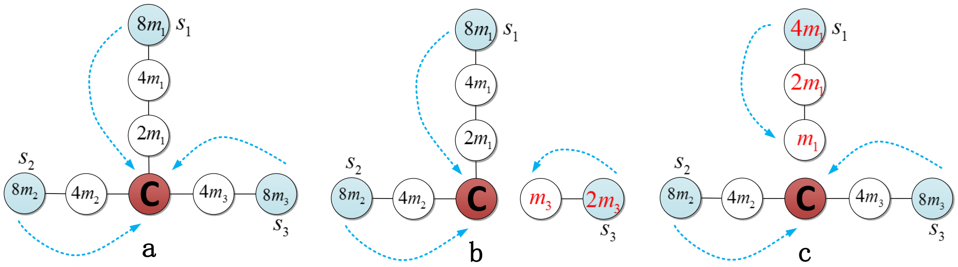


Fig. 1: Two choices to relieve congestion of node

set to 4 to prevent messages generated by s_1 from reaching c, and thus the quotas are 4, 8, 8. Obviously, the result of case 2 is fairer and has the overall lower quota reduction. Therefore, it is critical to have a good load control algorithm to ensure a higher system utility and transmission fairness.

In some complicated cases, the source(s) may affect the load of more than one relay. It is necessary to find an optimal quota reduction scheme under multi-dimensional constraints resulted from multiple overloaded nodes.

III. FAIR SOURCE QUOTA ALLOCATION ALGORITHM AND IMPLEMENTATION

We propose a load control algorithm to facilitate concurrent use of multi-copy transmission and social forwarding to improve the overall delivery ratio of DTNs while not overloading the popular social nodes. To facilitate the practical implementation and the performance evaluation of our load control algorithm, we introduce a basic multi-copy-based social forwarding scheme, and discuss the mechanisms and considerations for implementing the algorithm in a dynamic social DTN network.

A. Basic Terminologies and Algorithm

Generally, there is a tradeoff between improving the total system delivery ratio and ensuring the fair transmissions from individual users. We first extend the basic max-min fairness to discrete space and introduce the concept of Lexicographical order Max-Min Fairness (LMMF), which has not been studied before in social DTNs. To alleviate the load of the congested relays and avoid the consequent significant reduction of the network delivery ratio,we design a algorithm to achieve dissemination fairness.

1) Basic Terminologies: The key issue for efficient and fair buffer allocation at an overloaded relay is to determine the appropriate copy quota for a source to restrict its message distribution range.

We consider a configuration $K = \{k_1, k_2, \dots, k_n\}$ with copy quotas for all sources in the network, and a set of congested relay nodes $C = \{c_1, c_2, \dots, c_l\}$. Let S_{c_j} represent the set of sources that affect the relay node c_j, and E_j be the maximum number of messages a relay j can handle in a unit time, we have the following definitions.

Definition 1: ***Feasible Configuration.*** Assume a source s_i send messages at the rate r_i. If $\sum_{s_i \in S_{c_j}} r_i \leq E_j$, the load at congested relay c_j is relievable. A configuration K is feasible if it can relieve the congestions of all nodes in C.

Depending on the application scenarios, fairness has various definitions, such as max-min fairness, proportional fairness and utility fairness. Widely used in the network resource allocation, Max-min fairness (MMF) is ensured by maximizing the utility of the node allocated with the minimum resource [16], and can be theoretically achieved for continuous parameters [17]. However, the values of copy quota are discrete and positive integers. Therefore, we consider extending the definition of max-min fairness to the discrete space [18].

The goal of this work is to make the minimum quota assigned to the sources as high as possible. We solve the buffer allocation problem based on *Lexicographical order Max-Min Fairness (LMMF)* in the discrete space, and use the terms MMF and LMMF inter-changeably in this paper.

Definition 2: ***Lexicographical order Max-Min Fairness (LMMF).*** In a social DTN, each source has equal right to send its message to the network. This can be ensured by allocating the sources with proper copy quotas to control the buffer resources they can use. Lexicographical order max-min fairness configuration is achieved by sorting elements in $K = \{k_1, k_2, \dots, k_n\}$ into the lexicographical order $K' = \{k_1', k_2', \dots, k_n'\}$ and maximizing the minimum quota.

For two feasible configurations K_1 and K_2 whose elements are sorted in the nondecreasing order, we call K_1 is lexicographically greater than K_2 if they meet the following condition: the quota at the position i of the sorted list $K_1'[i] \in K_1'$ is larger than the quota $K_2'[i] \in K_2'$ at the i_{th} position of K_2', and for any $0 < j < i$, $K_1'[j] \in K_1'$ is equal to $K_2'[j] \in K_2'$. Of all the feasible configurations, the largest configuration in lexicographical order satisfies the LMMF.

2) Fair Source Quota Allocation Algorithm: In order to derive a feasible configuration, We design our algorithm with linear complexity. Furthermore, we minimize the impact on the network delivery by giving sources closer to the congested node a higher priority to keep large quotas in our algorithm.

For each $si \in S$, the state is $active$ so the quota can be increased. The basic process of the algorithm operated at a congestion node is presented in Algorithm 1. $S(c)$ denotes the set of source nodes that lead to relay node c congested. Function *Sort*($S(c)$, hop) sorts source nodes in $S(c)$ by hops in the ascending order and Q_i represents the quota that causes s_i's messages to stop right before the overloaded node. Function *feasible* checks if the configuration is feasible.

Algorithm 1 FairQuota

```
INPUT : $S(c)$, $MAX$
OUTPUT: Quota Configuration $K$
upon reception of package from other node do
if shouldCongestionControl()==true then
    while $S_i \in S(c)$ do
        $S_i.status \leftarrow active$
    end while
    Sort($S(c)$, hop)
    for $i = 1$ to $|S(c)|$ do
        $k_i \leftarrow 2^{MAX}$
        if feasible($K$)==false then
            $S_i.status \leftarrow active$
            break
        else
            $S_i.status \leftarrow stop$
        end if
    end for
    for $i = 1$ to $|S(c)|$ do
        if $S_i.status == active$ then
            $k_i \leftarrow Q_i, S_i.status \leftarrow stop$
        end if
    end for
    return $K$
end if
```

B. Algorithm Implementation

As none of existing social DTN forwarding schemes concurrently exploit both strategies, to evaluate our work, we propose social BSW to realize our algorithm, in order to effectively control the relay load while ensuring fair allocation of copy quotas among data sources. With data generation and dissemination following the model in Section II, we exploit *centrality* and *community* [6] for relay selection.

A data carrier sets an encountering node as its next-hop relay in two cases: (1) The data carrier is not in the *community* of the destination and meets a neighbor with a higher global *centrality*; (2) The data carrier is in the *community* of the destination and meets a neighbor with higher local *centrality*.

The data dissemination process will follow BSW [4], where a node gives half of its data copies (i.e., half of the quota along with one physical copy) to the relay. If the current node holds only one data copy, it no longer shares its copy with others but waits until it meets the destination to deliver the data.

1) load Control with Fair Source Quota Allocation: To implement the fair source quota allocation algorithm, each relay in the network monitors its buffer condition. When the buffer occupancy of a relay c reaches θ, c tries to relieve its load by taking the following actions:

(i) Determining the set of sources, denoted as S_c, whose message pass through c based on the data copies received within a time period w (i.e., an empirical value).
(ii) Calculating the quota allocation for sources in S_c based on Algorithm 1, and sending the control message along the reverse path recorded in the header of the message to reset k_i of each source s_i in S_c.

If a node c can only handle data from n_s sources but has m_s ($1 \leq n_s < m_s$) sources with equal hop distance, for fair resource allocation, node c allows n_s sources which have the least number of copies in its buffer to transmit.

2) Source Copy Quota Adaptation: If the quota k_i of a source s_i is set to a small value permanently, its delivery ratio would be low. Instead, we adapt the quota allocation based on the network condition to make full use of the network resources for a higher performance. The change of quota k_i can be implemented similar to Additive Increase Multiplicative Decrease (AIMD) in TCP [20]. A source s_i can periodically increase its k_i to probe if there is any chance to disseminate more message copies into the network. If s_i receives a load control message, it resets k_i accordingly; otherwise, it increases the quota in the next period until the maximum value is reached. The probing period P is determined based on network conditions. If P is too small, the source quota would grow too fast and lead the network to be overloaded again. On the other hand, too large a P will waste some transmission opportunities.

IV. PERFORMANCE STUDIES

This section evaluates the performance of social BSW and fair quota allocation based on two real datasets which reflect the contact characteristics of human activities, Infocom06 and Cambridge [19], collected from the university environment and conference environment respectively. These datasets capture contacts between nodes using Bluetooth devices, and the parameters are summarized in [6].

The simulations are carried out in two parts. First, we study the impact of different quota values on network performance and social BSW forwarding. Then, fair quota allocation combined with social BSW is evaluated in details from three perspectives, namely benefits of load control, fairness and the network utility.

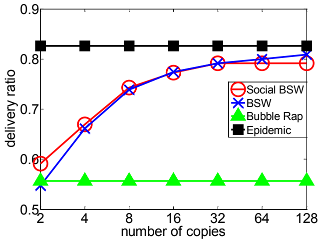
In the simulations, messages are generated every 30s with sources and destinations randomly selected. The size of the message is set to 80KB and its TTL is 24 hours. Based on the empirical simulation, we set the time period ω to 0.5 hours and the congestion threshold θ to 60%. As it is critical to ensure high delivery ratio and low delivery cost for social DTNs while the relatively long delay is tolerable, we apply the following metrics [6] in our studies:

1) **Delivery ratio**: The ratio of messages that have been delivered out of the total number of raw messages sent.
2) **Delivery cost**: The total number of forwards incurred to transmit data between a pair of source and destination.

A. Performance of Social BSW

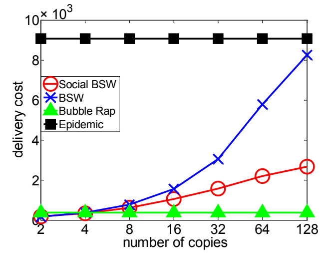
BSW is a typical quota-based multi-copy DTNs message distribution scheme. We extend it to apply social metric to select the next-hop relays while keeping its schemes for quota management and copy replication unchanged. We first evaluate its performance without using our load control scheme.

We compare the performance of social BSW with that of the original BSW under a wide range of quota values. Single-copy version of Bubble Rap is used as the benchmark of forwarding which only exploits the social properties of nodes



(a) Infocom06 (b) Cambridge

Fig. 2: Delivery ratio under different quotas



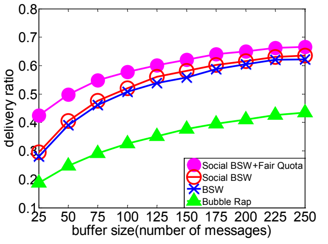
(a) Infocom06 (b) Cambridge

Fig. 3: Delivery cost under different quotas

without data replication. Epidemic floods copies to the entire network, so we take it as the benchmark for high message delivery. To evaluate the impact on performance purely due to the forwarding schemes, we assume there are no buffer constraints in any node in this simulation.

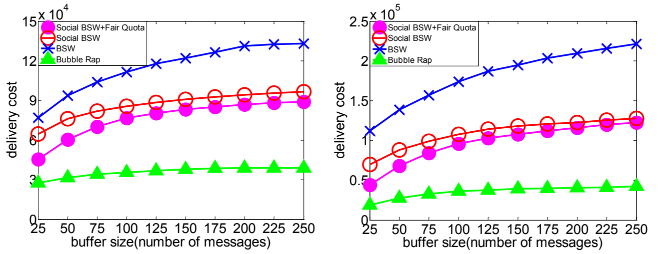
In Fig. 2, when the quota is below an optimum value (16 for Infocom06 and 32 for Cambridge), the delivery ratios of both social BSW and BSW increase quickly with the augment of quota. The delivery ratio of social BSW is higher than that of BSW when the quota is below 16 in both cases, and then is slightly lower than that BSW. After several initial hops, it gets harder for social BSW to meet a relay with higher social metric and take full advantage of the allowable quota to replicate messages. The delivery ratio of Bubble Rap is very low in all the conditions, which indicates the importance of using multiple message copies in social DTNs.

In Fig. 3, the delivery cost of Epidemic is apparently much higher than other DTN forwarding schemes due to its use of flooding. The cost of BSW is much higher than that of social BSW when the quota is large and quickly approaches that of Epidemic, while its gain in delivery is very small. When the quota is set to a proper value such as 16, the delivery ratio of social BSW is equal to or slightly higher than that of BSW while the cost of social BSW is 20%∼50% less depending on the dataset. In addition, the delivery ratio of social BSW is 35%∼80% higher than that of single-copy Bubble Rap.



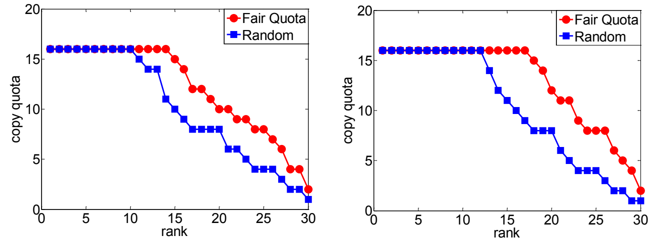
(a) Infocom06 (b) Cambridge

Fig. 4: Delivery ratio under different buffer sizes



(a) Infocom06 (b) Cambridge

Fig. 5: Delivery cost under different buffer sizes



(a) Infocom06 (b) Cambridge

Fig. 6: Distribution of sources' quotas under fair quota allocation and random mechanism

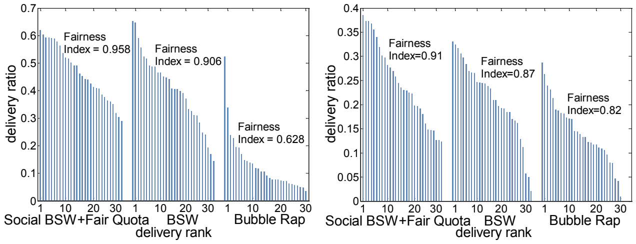
These results clearly demonstrate the benefit of combining multi-copy forwarding with relay selection based on social metrics for message dissemination in social DTN.

B. *Performance of fair quota allocation*

1) Benefits of Load Control: We vary the buffer space of nodes to simulate different load levels. In Fig. 4, the delivery ratios of all four schemes fall as the buffer space gets more constrained. The performance of BSW and social BSW are close. However, the delivery ratio of social BSW improves when added in fair quota allocation, and is 30% to 60% higher than those of BSW and social BSW when the buffer space is most constrained. This demonstrates that our fair source quota allocation algorithm is very effective in increasing the delivery ratio.

The benefit of applying fair quota allocation with social DTNs is shown in Fig. 5. Social BSW reduces the cost about 20% to 40% compared to that of BSW as its use of social metric comparison inherently limits the message replications. Social BSW combined with fair quota allocation reduces the cost up to 40% as it reduces the message quota thus the message replication, especially when the buffer is small.

In summary, social BSW combined with fair quota allocation effectively alleviates the load to improve the message delivery ratio while reducing the forwarding overhead.



(a) Infocom06 (b) Cambridge

Fig. 7: Distribution of delivery ratio

2) Fairness: Since there is no literature work on directly controlling the source quota, to evaluate the performance of our LMMF scheme, we take a random quota allocation mechanism as the reference. An overloaded node randomly selects as many sources as possible to assign with the maximum quota and assigns other sources with reduced quotas so their message will just stop being forwarded to the node.

We take some snapshots of the networks and record the sources' quotas in Fig. 6. The maximum quotas allowed by the network is 16 in this study. The quotas of all 30 sources are sorted in the descending order to compare the lexicographical order. Compared with the random mechanism, the fair quota allocation has more sources assigned with the maximum quota and a larger minimum quota, and is thus fairer.

In Fig. 7, the delivery ratios of all source are sorted in the descending order. The delivery ratios of sources in Bubble Rap differ largely, with the highest one 29 times that of the lowest one in the Cambridge dataset. The results indicate that fair quota allocation brings fairness to the network when alleviating the load, and the poorest sources can get higher delivery ratio.

V. CONCLUSION

We propose a novel load control mechanism which fairly allocates buffer resource among network users for efficient data transmissions in social DTNs. We analyze the characteristics of data distribution in social DTNs and devise a method to alleviate load by fairly allocating data copy quotas to each source. Then, we design an algorithm to achieve LMMF. Finally, we introduce an interactive and adaptive mechanism to facilitate practical implementation of the algorithm. Extensive simulations show that our design greatly reduces the delivery-ratio degradation caused by high load and ensures more fair transmissions among network users.

VI. ACKNOWLEDGEMENT

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