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Congestion control in social-based sensor networks: A social network perspective

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Abstract Social-based sensor networks are prone to congestion due to the limited storage space on each node and the unpredictable end-to-end delay. In this paper, we aim to develop an efficient congestion control approach from the social network perspective. For this purpose, we first identify the role of social ties in the process of congestion and specify a list of major congestion factors. Based on these factors, we then model the congestion control as a multiple attribute decision making problem (MADM), in which the weight of congestion factors is measured by an entropy method. We present a MADM-based congestion control approach that determines a set of forwarding messages and its transmission order on each encounter event. Moreover, we design a buffer management scheme that deletes messages whose removal would incur the least impact upon the network performance when the buffer overflows. Extensive real-trace driven simulation is conducted and the experimental results finally validate the efficiency of our proposed congestion control approach.

Keywords Social-based Sensor Networks · Congestion Control · Social Network · Multiple Attribute Decision Making

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1 Introduction

In the past few years, with the pervasiveness of portable mobile devices such as smart phones and tablet computers, a new mobile sensor network is formatted by these popular pocket-sized terminals embedded with a set of versatile sensors, which could supply an abundance of data about individuals, human social and environments. This new sensor network provides a new horizon for ubiquitous sensing at a low cost, which is extremely beneficial to the development of sensor networks. The most notable feature of this sensor network is that the movement of nodes is influenced by the social ties between them; familiar nodes often encounter, while strange nodes rarely meet. This sensor network is often referred to as social-based sensor network (SSN).

In SSN, nodes always move and end-to-end paths are rarely available. To overcome these challenges, numerous routing protocols for sensor networks [1–4] adopt a “store-carry-and-forward” scheme, which requires intermediate nodes to take part in the routing process of others, e.g., storing messages in a local buffer for others. However, nodes are of limited storage capacity in reality. When intermediate nodes cache messages for others, their storage space can be quickly overwhelmed. As a result, it leads to congestion and ultimately to a reduced delivery ratio. Furthermore, intermittent connectivity and unpredictable end-to-end delay

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will extend the dwelling time of messages at each node and finally aggravate the congestion. Thus, it is important and necessary to develop a congestion control approach for SSN.

Over the past decade, much attention has been paid to the congestion control issue in traditional sensor networks, and a number of solutions have been put forward. On the one hand, some schemes [5, 6] are based on traffic control, which utilizes the feedback congestion information to reduce the rate at which the source nodes inject packets into the network. Obviously, they significantly rely on the feedback speed of congestion information, which is challenging for SSN. Moreover, the obtained congestion mitigation comes at the expense of the reduced throughput. On the other hand, others explore other mechanisms for congestion control. CAR [7] assigns different priorities to different classes of data, and forward primarily high-priority traffic. TADR [8] is a traffic-distribute-based congestion control mechanism, which offloads messages from the congested zone of a network. All of the above-mentioned schemes overlook the social feature between nodes, which greatly affect the movement of nodes. However, message transmission is completed by the encounter opportunities of nodes in SSN. Therefore, exploiting social ties to control congestion is an ideal and efficient approach for SSN.

The goal of our work is to gain an understanding of congestion behavior in social-based sensor networks, where nodes exhibit long-term regularity mobility law and social ties, and then to develop an efficient congestion control approach from the social network perspective. The proposed could achieve an improved network efficiency, e.g., an increased delivery ratio, a reduced delivery overhead, or a shortened average delivery delay. Due to the unpredicted end-to-end delay in SSN, we abandon the feedback-based congestion control strategy, and consider the traffic-distribute-based scheme. More specifically, we discuss the role of social ties in the process of congestion in SSN, and identify several congestion factors, and employ such factors to change the direction of message-flow to avoid the congestion zone of a network. The main contributions of our work are summarized as follows.

- We analyse the congestion phenomenon in SSN and identify the role of social ties during the process of congestion. We also specify the major congestion factors.
- By measuring the congestion factors, we model the congestion control problem as a multiple attributes decision making problem (MADM), and develop a MADM-based congestion control approach. To our best knowledge, this is the first work that utilizes the decision theory to cope with the congestion problem in SSN.
- To validate our proposal, we compare a number of representative routing algorithms against their congestion-aware version, incorporating our MADM-based congestion control approach, by using real-trace driven simulations. The evaluation results show that the MADM-based congestion control approach can effectively cope with the congestion problem and improve the network efficiency.

The remainder of this paper is organized as follows. Section 2 reviews the related work. Section 3 gives the network model and the congestion model. Section 4 mentions the overview of our solution. Section 5 details the design of the MADM-based congestion control approach. Section 6 evaluates its performance by comparing some representative routing algorithms with and without our MADM-based congestion control approach. Finally, Section 7 concludes our work.

2 Related work

2.1 Congestion control in traditional sensor networks

Congestion in sensor networks can be classified into *link congestion* and *storage congestion*. Link congestion occurs when two or more nodes within the transmission range of each other compete with the same channel, while storage congestion happens only when messages contend for the use of limited buffer. In the remainder of this paper, we will use the term "congestion" to refer to the "storage or buffer congestion" that frequently occurs in sensor networks.

Over the past decade, there has been a sustained interest in the problem of congestion control in sensor networks [5–16]. CODA [5] proposes the first detailed investigation on congestion control in sensor networks. It detects congestion by sampling the wireless channel and monitoring the buffer occupancy. Once congestion emerges, the congestion information will be fed back to the source node to throttle the traffic volume so as to alleviate congestion. Similarity, ECODA [6] is also a traffic-control-based congestion control mechanism. It utilizes dual buffer thresholds and weighted buffer difference for congestion detection, and then employs bottleneck nodes to reduce the source sending rate. Obviously, these schemes based on traffic control significantly rely on the feedback speed of congestion information. However, social-based sensor networks often suffer the unpredictable end-to-end delay, which greatly weakens the effectiveness of traffic-control-based schemes. Moreover, the obtained congestion mitigation comes at the expense of a reduced throughput.

Except for these schemes based on traffic control, there have been some attempts to explore other mechanisms for congestion control in sensor networks. Congestion-aware routing (CAR) [7] investigates a differentiated routing approach to discover the congested zone of a network that exists between high-priority data sources and the data sink, and to dedicate this portion of a network to be forwarded primarily high-priority traffic. TADR [8] is a traffic-distribute-based congestion control approach. It is to change the direction of data-flow and scatter the excessive messages along multiple paths consisting of idle and underloaded nodes. Although these schemes could effectively alleviate congestion for sensor networks, they overlook the social feature of SSN. Therefore, they are not the best congestion control scheme for social-based sensor networks.

2.2 Multiple attributes decision making

Multiple attributes decision making (MADM) [17] is an approach employed to make decisions in the presence of multiple, usually conflicting criteria. In general, there is not a unique optimal solution for such problems, and thus it is necessary to utilize decision maker's preferences to differentiate between solutions. MADM specifies how attribute information is to be processed in order to arrive at a choice. More specifically, it requires both inter- and intra-attribute comparisons, and involves appropriate explicit tradeoff to help the decision maker to make decisions.

MADM can usually be represented in the criterion space. If different criteria are combined by a weighted linear function, it can also be expressed in the weight space. Since each attribute has a different meaning, it cannot be assumed that they all have equal weights, and as a result, finding an appropriate weight for each attribute becomes a key problem. Various methods for measuring weights can be categorized into two groups: subjective and objective. Compared with subjective methods, the weights measured by objective ones are more reliable since they are not affected by the preference of decision makers. The most typical objective approach is entropy proposed by Shannon [18]. In this paper, we employ the MADM to evaluate multiple congestion factors and understand the role of different congestion factors.

3 Model

In this section, the network model and the congestion model are presented. For readability, some important notations used in the rest of the paper are summarized in Table 1.

3.1 Network model

We consider a class of social-based sensor networks, in which one node can directly communicate with another if they move into the reciprocal radio communication range of each other. A node can simultaneously serve as a source/destination of a message and a relay for others' messages. A message traverses a network by being relayed from one node to another until it reaches its destination. In such network, node movement is affected by social ties, and the long-term regularity mobility is usually exhibited. For example, some pairs of nodes (e.g., acquaintances) consistently meet more frequently than other pairs (e.g., strangers) over time. Hence historical contact information implies future encounter opportunities. This has been extensively verified [3]. In addition, we assume that all nodes are selfless and are willing to forward messages for others. Moreover, nodes are credible, and no node will attack others.

Table 1 List of notations

Variable	Description
n_i	node i
m_j	message j
cf_k	congestion factor k
w_k	the weight of congestion factor cf_k
$v_{j,k}$	the value of message m_j for cf_k
S_{m_j}	the size of message m_j
FB_{n_i}	the free buffer size of node n_i
D_{n_i,m_j}	the node delay for message m_j in node n_i
U_{m_j}	the utility value of message m_j
$\mathbb{M}_{n_i}$	a set of messages stored in n_i
$\mathbb{D}_{n_i}$	a set of node delay of messages in n_i
Set_{n_i,n_j}	the forwarding set of n_i to n_j

All mobile nodes are resource constrained, e.g., with limited storage space. When a plenty of messages is generated and traversed in a network, nodes are prone to congestion since they have to store messages for others. Although messages in SSN are delay tolerant, they are usually with a specified lifetime, which is often evaluated as the time-to-live (TTL). A message will be discarded when its TTL expires.

3.2 Congestion model

In SSN, message transmission is completed by using encounter opportunities of nodes. When messages are not forwarded to unsuitable nodes, e.g., congested nodes, newly arrived messages may be discarded and the transmission opportunity may also be wasted. Thus, it is important to avoid transmitting messages to the congested zone of a network during the process of message delivery.

Contact frequency and contact duration are often used to measure the movement behaviour of nodes. Contact frequency denotes the number of node encounter in a period of time, while contact duration represents the interaction time in an encounter. As mentioned in the above section, node movement is affected by social ties. The higher the contact frequency is, the stronger the strength of social ties is. Also, the longer the contact duration is, the more intimate social relations are. Therefore, we consider the contact frequency and the contact duration, and give a new definition, called **message's node delay**, to measure social ties between nodes. This definition is described as follows:

$$D_{n_i,m_j} = \frac{\sum_{k=1}^{l} f_{n_i,n_d}(k)}{l}, \tag{1}$$

where l is the total contact number between n_i and n_d in the elapsed time, and $f_{n_i,n_d}(k)$ denotes the k-th inter-contact time between nodes n_i and n_d. Message's node delay refers to the dwelling time of a message at a node, which determines the utilization efficiency of storage space. Buffer is a reusable resource. The shorter the message's node delay is, the more the number of messages could be cached in a period of time, and the higher the buffer utilization efficiency is. Thus, it is crucial to take message's node delay into account when designing a congestion control approach.

In SSN, congestion is often induced by numerous factors, not limit to social-aware congestion factors. Except for message's node delay, we also identify several social-oblivious congestion factors, listed in the following.

Free buffer size It denotes the size of the buffer space available. A buffer with larger capacity implies that it can store more messages, and thus the probability of the occurrence of congestion is reduced. An extreme example is that no congestion will happen in a node with infinite storage space.

Message size The larger a message size, the smaller the number of messages stored are. Consequently, the probability of congestion is increased. Thus, it is reasonable to consider message size when designing an efficient congestion control approach. In our work, we prefer to forward those messages with small size.

Message TTL In SSN, messages must be stored by intermediate nodes for a period of time in the process of routing. The shorter the stored message's TTL is, the higher the probability that the message is discarded. This will result in a waste of storage resource and transmission opportunity. Thus, it is reasonable to consider message's TTL when designing an efficient congestion control approach. In our work, we would also prefer to forward messages with a long TTL.

4 Overview of our proposal

4.1 Problem statement

To overcome communication challenges in SSN, most existing routing algorithms work in the "store-carry-and-forward" way, in which intermediate nodes have to store others' messages in its limited buffer for a period of time. However, storage resource is constrained for nodes. Consequently, a mass of messages traversing a network will aggravate node load and further give rise to congestion. Moreover, the intermittent connectivity and the unbounded/unpredictable end-to-end delay will extend the dwelling time of messages at each node and finally aggravate the congestion situation.

In this paper, we aim to design an efficient congestion control approach, which could cope with the congestion problem without causing any side effect on a network. In particular, we study the following two sub-problems to achieve our target.

Problem 1 Forwarding set determination problem It is to determine a set of candidate forwarding messages and their forwarding order. In congestion control, the ideal forwarding set should include these messages, which are most likely to alleviate congestion to the recipient, with higher forwarding priority. Nevertheless, the congestion process in SSN is very complicated, and it is always caused by several factors comprehensively. On the other hand, identifying the congestion effect of messages to a recipient always needs the global network information, which is difficult to be obtained in SSN. Therefore, it is challenging to determine the forwarding set with the partial information.

Problem 2 Buffer Management Problem. It refers to determining which messages should be discarded when the buffer overflows. An efficient buffer management is to delete the messages with the least effect on the overall network performance. However, it is difficult to find these messages because of lacking of the global network information.

4.2 Methodology

The congestion process is very complicated, and is always induced by several factors but not a simple one. An effective way to control congestion is to figure out the role of different congestion factors in the process of congestion, and to measure the congestion effect of messages when they are forwarded to a specify node.

Numerous previous works in other fields have proven that the multiple attribute decision making method [17] is an ideal and mature way in decision-making environments. It is concerned with structuring and solving decision and planning problems involving multiple attributes. Thus, it is reasonable to adopt the multiple attribute decision making method to measure the congestion effect of messages by considering various congestion factors, including social-based factors and social-oblivious ones.

In addition, since each attribute has a different meaning, it cannot be assumed that they all have equal weights, and as a result, finding the appropriate weight for each attribute becomes a key problem. We utilize the entropy approach proposed by Shannon [18] to quantify the weight of different congestion factors.

4.3 Solution overview

Here we mainly give an overview of our MADM-based congestion control approach and explain how it works. The overall architecture of MADM-based is shown in Fig.1, in which routing modular and congestion control module work together to make message forwarding decisions. During a contact chance, each module exchanges status data with its peer: the routing module exchanges routing information such as delivery probability, while the congestion control module exchanges node buffer statistics, e.g., free buffer space, the node delay of messages. In addition, each node acts independently to avoid to forward messages to those congested nodes.

After the routing module chooses the encountered node as a relay, the congestion control approach is triggered. Different from the routing that aims to choose the most appropriate node as a relay, our proposed congestion control approach is to determine the forwarding set and its transmitting order by forwarding messages that are likely to alleviate congestion to the recipient node.

Moreover, congestion control in SSN is closely related to buffer management. When the buffer overflows, the buffer management will delete those messages with the largest effect on the overall performance of a network from the local buffer.

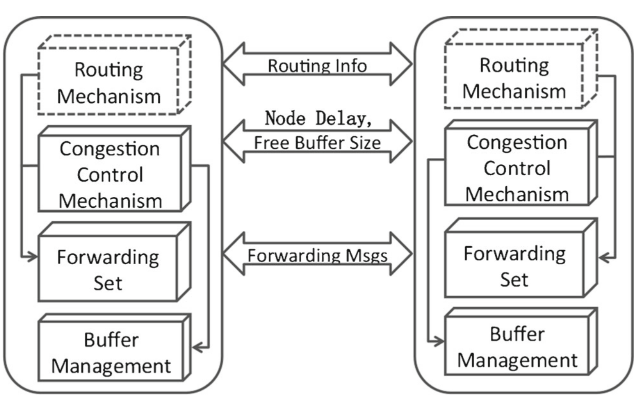


Fig. 1 The overall structure of our MADM-based congestion control approach

5 MADM-based congestion control

In this section, we model the congestion control problem as a multiple attributes decision making problem to determine the forwarding set and its transmission order. After that, we propose a MADM-based congestion control approach and a buffer management.

5.1 Weight determination

Among congestion factors considered, some are associated with a particular message, e.g., message size, message TTL and message's node delay, while others are the same for all messages, e.g., free buffer size. Therefore, we only consider the former three factors, referred to as cf_1, cf_2, and cf_3, respectively, in the following. We utilize an entropy [18] method to decide the weight of each attribute. Detailed steps are outlined as follows. Moreover, the congestion factor free buffer size will be utilized to determine the maximum number of messages in the forwarding set.

Step (1). Build an attribute matrix described as follows:

$$\begin{array}{c} \\ cf_1 \\ cf_2 \\ cf_3 \end{array} \begin{array}{c} \begin{array}{ccc} m_1 & m_2 & m_3 \end{array} \\ \begin{pmatrix} v_{1,1} & v_{2,1} & v_{3,1} & \cdot\cdot \\ v_{1,2} & v_{2,2} & v_{3,2} & \cdot\cdot \\ v_{1,3} & v_{2,3} & v_{3,3} & \cdot\cdot \end{pmatrix} \end{array}$$

where rows and columns represent the congestion factor and the message id, respectively. Each entry $v_{i,j}$ in the matrix is the value of message m_i with respect to factor cf_j.

Step (2). Normalize the matrix by

$$p_{i,j} = \frac{v_{i,j}}{\sum_{j=1}^{n} v_{i,j}}, \qquad i \in [1,3],\ j \in [1,n].$$

where n is the number of messages. The raw data are normalized to eliminate anomalies in different measurements. This process transforms different scales and units among various criteria into common measurable units to allow comparisons of different criteria.

Step (3). Compute entropy e_i as

$$e_i = -e_0 \sum_{j=1}^{n} p_{i,j} \ln p_{i,j}, \qquad i \in [1,3].$$

where e_0 is the entropy constant and is equal to $(\ln n)^{-1}$.

Step (4). Measure the degree of diversification of entropy as

$$d_i = 1 - e_i, \qquad i \in [1,3].$$

Step (5). Compute the weight w_i of congestion factor cf_i as

$$w_i = \frac{d_i}{\sum_{k=1}^{3} e_k}, \qquad i \in [1,3].$$

5.2 Forwarding set determination

In order to measure the congestion effect incurred by a message to a specific node, we introduce a new metric called message utility, to characterize such probability. The larger the utility value is, the smaller the congestion probability is. By considering various congestion factors in a comprehensive way, the utility of message m_i, denoted as U_{m_i}, is defined as the sum of all congestion factors considered, i.e.,

$$U_{m_i} = \sum_{k=1}^{3} w_k \times v_{i,k}, \tag{2}$$

where U_{m_i} is the utility value of message m_i.

Instead of deciding how many messages should be included into a forwarding set, here we utilize a greedy approach to determine the forwarding set. The basic idea of such approach is to circularly put the message with the largest utility value into the forwarding set until the free buffer capacity of the recipient node is depleted.

Furthermore, due to the uncertainty of contact duration, messages in the forwarding set may not be all sent out in a connection. Therefore, it is important to determine the forwarding order. We forward messages in a descending order of their values until the contact disappears or no message is left in the forward set. In this way, the total utility value of messages transferred is always maximized, and thus the probability of congestion caused by transferring messages to the receiver is expected to be minimized.

5.3 MADM-based congestion control design

Based on the above work, we develop a MADM-based congestion control approach, which models the congestion control problem as a multiple attributes decision making problem. This mechanism works together with a routing module to complete data transmission. After a node determines to forward messages to the encountered node, it is triggered. Detailed procedures of the MADM-based congestion control approach are summarized in Algorithm 1.

Two nodes first exchange their buffer state and node delay information. The forwarding set Set_{n_i,n_j} is then initialized by including messages in $\mathbb{M}_{n_i}$ that must satisfy the following two conditions: 1) its node delay in n_j is shorter than that in n_i, and 2) its node delay is shorter than its TTL. After that, n_i will measure the weight of congestion factors and compute the utility value of all messages in Set_{n_i,n_j}, as revealed by lines 3-6 of Algorithm 1. Subsequently, n_i will update Set_{n_i,n_j} to ensure that the sum size of messages in Set_{n_i,n_j} is not greater than the free buffer size of node n_i, denoted as FB_{n_j}, as shown in lines 7-14 of Algorithm 1. This could ensure that the total utility value of the messages transferred is always maximized. After Set_{n_i,n_j} is finally determined, n_i starts to transmit messages until the connection is interrupted or no message in Set_{n_i,n_j} is left.

Algorithm 1 MADM-based Congestion Control at n_i

Require: FB_{n_j}, $\mathbb{M}_{n_i}$, $\mathbb{D}_{n_i}$, $\mathbb{D}_{n_j}$
Ensure: Set_{n_i,n_j}
1: exch. state info.
2: initialize Set_{n_i,n_j}
3: evaluate congestion factors
4: **for** $m_i \in Set_{n_i,n_j}$ **do**
5:     compute U_{m_i}
6: **end for**
7: sort Set_{n_i,n_j}
8: **for** message m_k in Set_{n_i,n_j} **do**
9:     **if** $S_{m_k} < FB_{n_j}$ **then**
10:         FB_{n_j} = FB_{n_j} - S_{m_k}
11:     **else**
12:         $Set_{n_i,n_j} = Set_{n_i,n_j} \setminus \{m_k\}$
13:     **end if**
14: **end for**

5.4 Buffer management

Owing to the limitation of buffer capacity, it is impractical to keep all received messages in its local buffer. Therefore, we shall consider a buffer management scheme to determine which messages should be deleted when the buffer fills up. The target is to drop those messages that have less impact on the overall performance of a network, e.g., end-to-end delay. More specifically, we adopt an utility-based buffer management, in which the message with the lowest utility value is dropped firstly to ensure that the total utility value of messages buffered is always maximized. Note that, unlike the MADM-based congestion control approach, only the node delay of the current node is considered to measure the weight of congestion factors in our buffer management.

6 Performance evaluation

6.1 Simulation setup

To evaluate the performance of the MADM-based congestion control approach, we implement it in a widely-used network simulator ONE [19]. Three practical mobility data sets, e.g., Infocom2006 [20] and Sassy [21] and Pmtr [22], are incorporated into ONE. Detailed information of these data sets is summarized in Table 2. We believe that these data sets cover a rich diversity of network environments, from small conference (Infcom2006) to spacious campus (Sassy), with a duration of several days (Infocom2006) to

Table 2 The characteristics of mobility data sets

Dataset	Infocom2006	Sassy	Pmtr
Device	iMote	T-mote	iMote
Network type	Bluetooth	Bluetooth	-
Duration	3	79	19
Granularity	120	6.6	-
No. of nodes	98	27	44

more than two months (Sassy). Without loss of generality, we consider the same buffer size at each node. Messages are generated periodically at the source, and their destination is selected uniformly at random from the entire network. The message size is also uniformly distributed from a range. Detailed simulation parameters in our simulation are listed in Table 3.

To simulate different congestion levels of a network, we consider two different approaches to achieve it. One is to change the buffer size of nodes. The buffer size directly determines the number of messages a node can cache. When the buffer size becomes large, the node can include more messages. It means fewer messages will be discarded and the congestion level of a network is reduced. The other is to change the message generation interval or message sending rate at sources, denoting the amount of messages in a network. The network capacity is constant. When the message generation interval becomes smaller, more messages are generated, and thus the congestion level of a network is improved.

We consider three representative routing protocols, listed as follows.

– Epidemic [23] floods many copies to its neighbours within transmission range so that copies are quickly distributed through a network.
– Spray&Wait [24] spreads multiple copies to the first encountered nodes, and then relies on them to finish the final message transmission.

Table 3 Simulations parameters

Parameter	Value
TTL (Time-to-live)	300 minutes
Warmup time	30 % of the whole time
Range of Message size	20 ∼ 80 kB
Node buffer size (default)	6 M
Message creation interval (default)	30 seconds
Copies in Spray&Wait	6
Spray way in Spray&Wait	binary mode
Initial aging time unit in Prophet	30 seconds

– Prophet [25] first estimates a probabilistic metric called delivery probability, and forwards messages to nodes which have an increased delivery probability.

To validate our MADM-based congestion control approach, we also implement their congestion-aware versions, called Epidemic-c, Spray&Wait-c and Prophet-c, respectively. By comparing the original version of these algorithms against the congestion-aware version, we can check the effectiveness of our MADM-based mechanism.

In addition, we use the following performance metrics.

– **Delivery Ratio**: the ratio between the number of messages that are successfully delivered to their destination nodes within their lifetime to the total number of messages generated.
– **Delivery Overhead**: the total number of forwarding until all generated messages to be successfully received.
– **Delivery Delay**: the average time required to deliver a message to its destination node since its generation time.

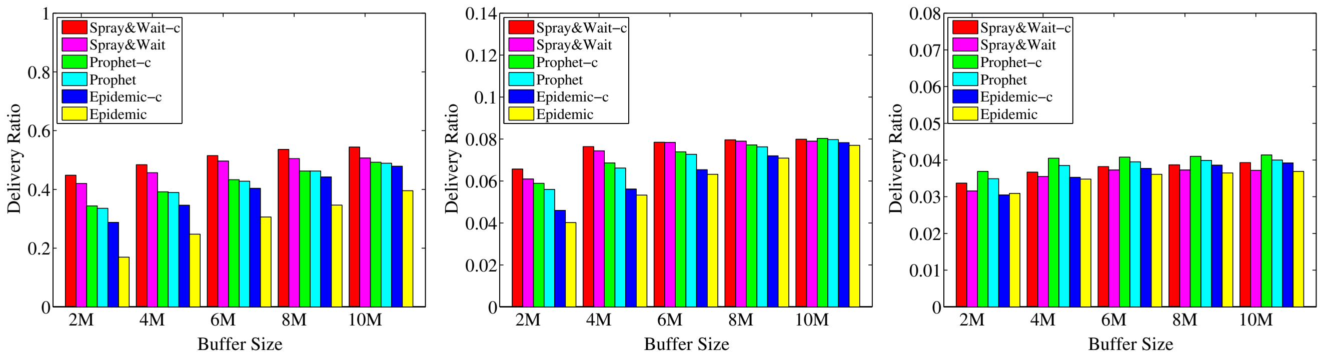
6.2 On the effect of node buffer size

In order to mimic different congestion levels of a network, we change the buffer size of nodes, and then evaluate the performance of our MADM-based congestion control approach in various congestion environments.

6.2.1 Delivery ratio comparison

Figure 2 shows the delivery ratio of all algorithms on various data sets, as a function of buffer size. The larger the buffer capacity is, the higher the delivery ratio is. The reason behind is that the buffer size of a node determines the maximum number of messages buffered. A larger buffer space means more messages will be stored in intermediate nodes, and thus these messages have more chances to be delivered to their destination nodes.

We can also see clearly from Fig. 2 that all congestion-aware algorithms are of superior performance to original ones under different scales of buffer size. Taking data set Infocom2006 as an example, we observe that Epidemic-c outperforms Epidemic by 69 % and 39 % when the buffer size is $2M$ and $4M$, respectively, as shown in Fig. 2(a). We attribute the advantage of the congestion-aware algorithm over the original one to three factors. Firstly, congestion-aware algorithms only forward messages to those nodes that could provide sufficient space to buffer incoming messages. This could avoid message loss caused by no available storage space at the receiver. However, all original algorithms fail to achieve it. Secondly, when a contact opportunity occurs, congestion-aware algorithms only forward those messages that are most unlikely to incur



(a) Infocom2006 (b) Pmtr (c) Sassy

Fig. 2 Performance evaluation results of the delivery ratio

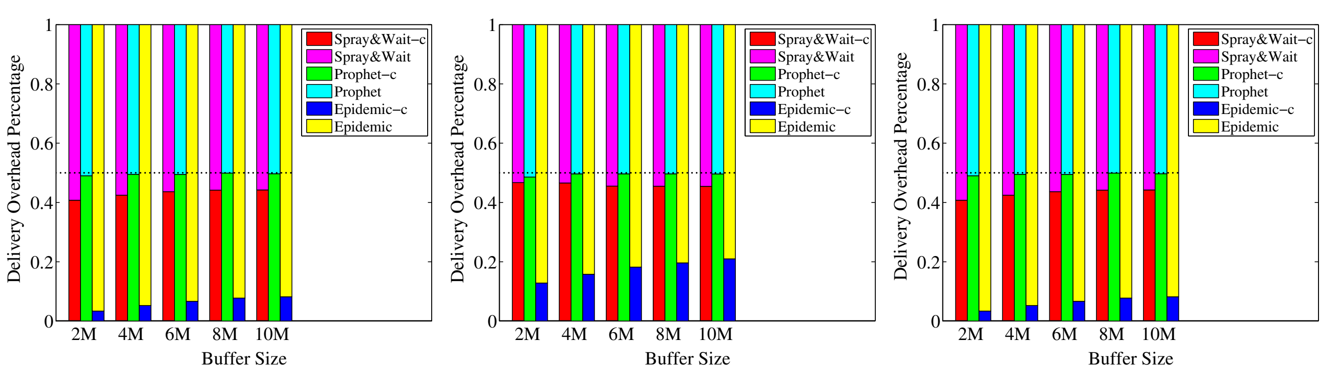
congestion to the recipient node, while the original ones do not consider it. Thirdly, congestion-aware algorithms use a reasonable buffer management to discard the appropriate messages when a node is about to get congested. Nevertheless, original algorithms all overlook the importance of buffer management and utilize a simple buffer management, e.g., random drop.

In addition, another interesting phenomenon noticed from Fig. 2 is that the superiority of congestion-aware algorithms becomes smaller with the increment of buffer size. This indirectly proves that the effectiveness of our proposed congestion control mechanism, because the buffer size of nodes implies the congestion level of a network. When the buffer size of nodes in networks increases, the congestion level of a network reduces.

6.2.2 Delivery overhead comparison

Figure 3 reveals the evaluation results on the delivery overhead of all routing algorithms on different values of buffer size. Due to the large span of the delivery overhead of different algorithms, it is difficult to show their absolute values on one figure clearly. Instead, we disclose the results in *delivery overhead percentage*, i.e., a ratio of overhead generated by the original algorithm or its congestion-aware version over their sum, to better illustrate the delivery overhead of all algorithms. In other words, if the delivery overhead percentage of a congestion-aware algorithm is less than 50 %, this congestion-aware algorithm has an improved performance in terms of the delivery overhead, comparing with the original algorithm.

As shown in Fig. 3, it is obvious that all congestion-aware algorithms perform better than their original ones in terms of delivery overhead as the delivery overhead percentage of all congestion-aware algorithms below the black dotted line. The most typical example is Epidemic-c in Infocom2006. The delivery overhead of Epidemic-c is 3.4 % and 5.5 % of Epidemic when the buffer size is $2M$ and $4M$, respectively. Recall that we achieve such high performance with the lowest overhead ratio as shown in Fig. 2. These advantage results come from two reasons: 1) MADM-based congestion control approach; and 2) message utility-based buffer management.



(a) Infocom2006 (b) Pmtr (c) Sassy

Fig. 3 Performance evaluation results of the delivery overhead

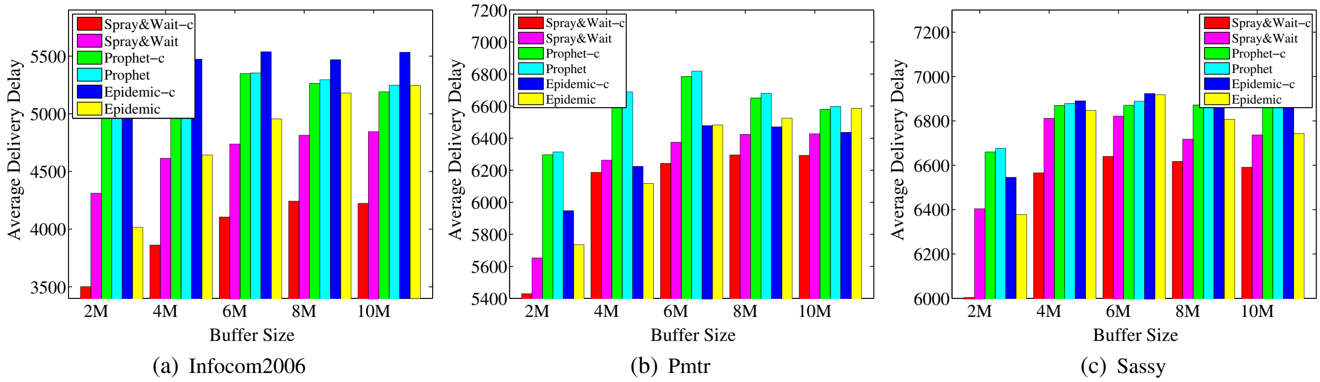


Fig. 4 Performance evaluation results of the average delivery delay

Furthermore, we can observe from Fig. 3 that the performance gap between the congest-aware version and the original one of Epidemic is much larger than that of Spray&Wait and Prophet. This is caused by Epidemic's flooding nature. Epidemic spreads numerous copies upon every contact opportunity, which significantly aggravates node load, and in turn leads to message loss. However, other two algorithms only generate limited replicas into a network. The congestion level of a network is much lower, and the improvement space of the delivery overhead is also narrowed.

6.2.3 Delivery delay comparison

Figure 4 gives the evaluation results on the delivery delay of all protocols on different data sets. It is clearly seen that all congestion-aware algorithms have a shorter delivery delay than original ones. This phenomenon comes from three factors. The first one is that congestion-aware algorithms forward messages to the node with a relatively short node delay. The second one is that congestion-aware algorithms only deliver messages to the node that has sufficient storage space for newly arrived messages. This could avoid message loss caused by overflow, and thus induce the source node to retransmit the original data. The third one is the buffer management utilized in congestion-aware algorithms that only discards those messages with the least effect on the network performance.

6.3 On the effect of message generation interval

We also mimic various congestion levels of a network by changing the message generation interval when the buffer size is constant. The smaller the message generation interval is, the more messages generated are, and thus the higher the congestion level of a network is. We evaluate the performance of the MADM-based congestion control mechanism in different congestion environments, and the simulation results of different message generation intervals are obtained from data sets Infocom2006, revealed in Fig. 5. Compared with the original algorithm, the congestion-aware one has the improved network performance in terms of the delivery ratio, the delivery overhead and the delivery delay. This is attributed to the advances of our proposed congestion control approach, which can effectively cope with the congestion problem without giving any side effect to a network.

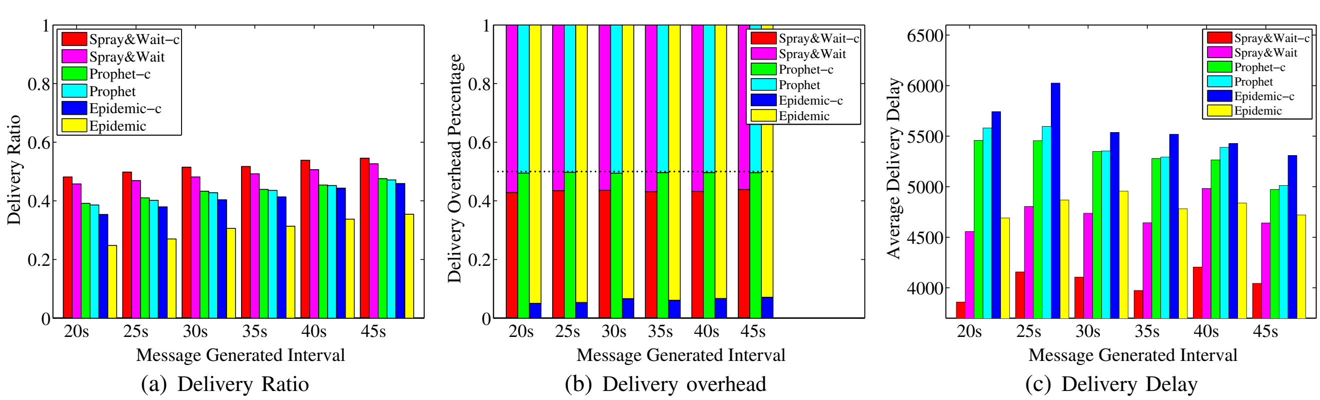


Fig. 5 Performance evaluation results of the effect of message generation interval

In addition, compared with the original algorithm, the benefit of a congestion-aware algorithm is not evident when the message generation interval becomes larger. The reason behind is that a larger interval implies that fewer messages will be created and injected into a network, and the congestion level of a network is also reduced. Thus, the benefit of the congestion-aware algorithm is limited.

Similar results on the effect of the message generation interval are also obtained from data sets Pmtr and Sassy. We do not display and discuss them for saving space.

7 Conclusion

In this paper, we aim to develop a congestion control approach from the social network perspective. We first analyse the congestion phenomenon in SSN and identify the role of social ties during the process of congestion in order to find the major congestion factors. Then, we model the congestion control problem as a multiple attribute decision making problem so as to identify messages with the least potential congestion effect upon the recipient. The weight of congestion factors is measured by an entropy method, and the congestion effect of each message stored upon a specific node is evaluated by the metric called message utility. After that, we present a MADM-based congestion control approach, which decides the forwarding set. Moreover, we also present a utility-based buffer management which considers the context of nodes and messages. Extensive real-trace driven simulation results finally validate the efficiency of our proposed congestion control approach.

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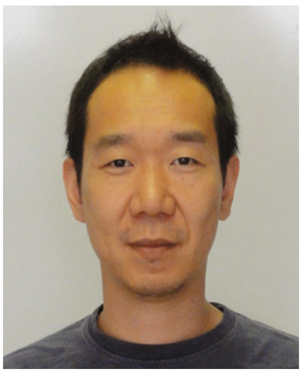

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