

Epidemic-based Approaches for Reliable Multicast in Mobile Ad Hoc Networks^o

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ABSTRACT

We present a classification of epidemic-based approaches utilized in the context of mobile ad hoc networks (MANET) with a focus on reliable multicast protocols. We provide a brief description of the other approaches to reliable multicasting in MANETs as well. Then, we describe our protocol, namely EraMobile, offering Epidemic-based Reliable and Adaptive Multicast for Mobile ad hoc networks. EraMobile's target is group applications requiring high-level of reliability and the protocol aims to provide fully reliable multicast data delivery with minimal network overhead even in the adverse network conditions. EraMobile utilizes an epidemic-based method in multicast operation to cope with dynamic and unpredictable topology changes arising from the mobility. Our epidemic mechanism does not require the maintenance of any tree- or mesh-like structure for multicasting. It also needs neither having global or partial view of the network nor having information of neighboring nodes and group members. Besides, it substantially minimizes the overhead incurred by eliminating redundant data transmissions. Another distinguishing feature of EraMobile is its capability of adapting to varying node densities in order to provide reliable data delivery in both sparse networks, where the network connectivity is prone to interruptions, and dense networks, where congestion is likely to occur. EraMobile is shown to achieve fully reliable multicast data delivery studied through extensive simulations by outperforming the other protocols compared, especially in terms of both packet delivery ratio and overhead efficiency.

Keywords

Adaptive, Epidemic, Mobile ad hoc networks, Reliable multicast

1. INTRODUCTION

Mobile ad hoc networks have gained considerable interest and popularity in recent years as they have enormous military and commercial potential. The infrastructure-less, self-organizing and mobility features are the main reasons behind the popularity of MANETs. However, these also impose important challenges, e.g. highly dynamic and unpredictable topological changes, low bandwidth, high error rates and limited power sources, to the protocols and applications for ad hoc networks. Therefore, new

approaches and distinctive changes are required in the network protocol designs including multicasting.

We propose a reliable and adaptive multicast solution for mobile ad hoc networks. We have utilized an epidemic method for our solution since its stateless character is well matched with the non-deterministic nature, which arises from highly dynamic and unpredictable topology changes, of MANETs. The epidemic method of EraMobile is inspired from the Anti-Entropy technique described in [1]. This technique was proposed for dissemination of updates to replicated databases through gossip messages. Each node in the network periodically selects a random node and sends a gossip message which contains the digest of database content to this node. Then, they recover differences in their databases by exchanging data messages. Similar probabilistic methods were used for multicasting in wired [2] and mobile ad hoc networks [3, 4]. These probabilistic methods require the nodes have partial or global information of the multicast group to select a random node from others for gossiping. Since the cost of obtaining such information in the dynamic environment of ad hoc networks is considerably high, we have modified the usual use of gossip messages to exploit the broadcast nature of wireless medium. The nodes locally broadcast the gossip messages to the neighboring nodes instead of selecting a random node from a pre-defined list and sending the gossip message to this node as unicast. Thus, our model does not require any underlying routing protocol. It also needs neither having global or partial view of the network nor having information of neighboring nodes and group members for multicast delivery.

Our solution aims strong reliability by use of periodic gossip messages which enable the nodes to recover missing data packets. This feature provides the robustness to the protocol against transient adverse network conditions and delivery failures. Besides the reliability, the use of gossip messages improves the bandwidth and energy savings reducing the network overhead. Considering many routing protocols, e.g. ODMRP, MAODV, in ad hoc networks use beacon messages, to be aware of changes in network topology, we believe that use of periodic small-sized gossip broadcasts does not place an undue burden on the network.

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We have additionally reinforced our model with an adaptivity mechanism. This mechanism can adjust the protocol parameters dynamically according to varying node densities.

In the next section, we present a classification of epidemic-based approaches utilized in the context of MANETs with a focus on reliable multicast protocols. We provide a brief description of the other approaches to reliable multicasting in MANETs as well. In Section 3, we describe our solution EraMobile in detail. Section 4 concludes the paper and gives future directions.

2. RELATED WORK

Previous studies proposed several multicast protocols for MANET environments [5, 6, 7, 8, 9, 10, 11, and 12] and investigated their performance through extensive analysis [13, 14, 15, 16, 17 and 18]. Several surveys discuss classifications for these multicast protocols [19, 20]. However, for application areas with a desire of strong reliability features, these *best-effort* multicast protocols provide insufficient packet delivery guarantee. In order to support reliability features in multicast communications over MANETs, there exist several *reliable multicast* techniques [21, 22, 23, 24, 3 and 4]. These protocols are classified as deterministic versus probabilistic according to their reliability guarantees [25] and ARQ (Automatic Retransmission reQuest)-based versus gossip-based as their recovery mechanisms [26]. Different from these classifications, Rizzo and Vicisano [27] proposes a FEC (Forward Error Correction) and ARQ-based hybrid reliable multicast protocol named Reliable Multicast Data Distribution Protocol (RMDP). Their technique uses erasure coding methods to tolerate some level of data loss at the receiver side in exchange for some redundancy.

RMA [21], a reliable multicast algorithm for mobile ad hoc networks, provides reliability employing acknowledgment (ACK) messages from receivers to sources. This protocol is a representative of deterministic class of reliable multicast protocols that guarantees full packet delivery between group members. RMA works in two phases: 1. unreliable multicast, and 2. retransmission of lost packets according to ACKs received from nodes. The protocol assumes that senders have full group membership information that is maintained by flooding of JOIN and LEAVE messages throughout the network without any reliability guarantees. However, the unreliable join and leave mechanism can degrade the reliability degree of the protocol [25].

RALM (Reliable Adaptive Lightweight Multicast) [22, 23] is a transport protocol built on ODMRP (On-Demand Multicast Routing Protocol) [5] to enhance its packet delivery ratio in small group operation scenarios. RALM aims to achieve reliability employing a congestion control mechanism using adjustable window sizes. It uses negative acknowledgment (NACK) feedback messages to adjust the congestion experienced by multicast receivers. Similar to RMA, RALM assumes that senders have full group membership information. Simulation results [22, 23] show that, this deterministic protocol operates well in static networks where the packet losses generally stem from congestion. In the highly mobile networks, the congestion control mechanism may not solve the reliability problem [25, 26]. Enhanced version of RALM with a *local recovery* mechanism is named as Reliable, Adaptive, Congestion-Controlled Ad hoc Multicast Transport

Protocol (ReAct) [24]. In ReAct, receivers first attempt to recover packet losses from the nearby nodes such as an up-stream group member in the multicast structure. This local recovery mechanism improves the performance of protocol by preventing unnecessary back-offs and rate reductions.

Other widely accepted probabilistic reliable multicast mechanisms rely on epidemic, or gossip-based dissemination methods. Epidemic communication concept was first proposed to spread updates in replicated databases [1], and the epidemic concept was utilized for several purposes such as group membership tracking [29] and multicasting in wired networks [2, 30, 31 and 32]. In general, epidemic-based approaches have been used for several purposes in MANETs. Example services include a self-organizing, selective information dissemination for MANETs called Autonomous Gossiping [33], route discovery such as epidemic routing [34] and gossip-based ad hoc routing [35], and gossip-based reliable broadcasting called RGB [36] which is adaptive to dynamic conditions of mobile ad hoc networks. Besides, there exist analytical modeling studies for epidemic information dissemination in MANETs [37, 38]. As our main focus in this paper, epidemic methods are also utilized to provide reliable multicasting in mobile ad hoc networks. Anonymous Gossip (AG) [3] and Route Driven Gossip (RDG) [4] protocols are well-known studies in this area. Fig.1 summarizes the major features of the mentioned overall multicast protocols and epidemic-based approaches in MANETs. Next, we discuss these epidemic reliable multicast protocols with their pros-cons. After that, we compare EraMobile with these approaches in the same category.

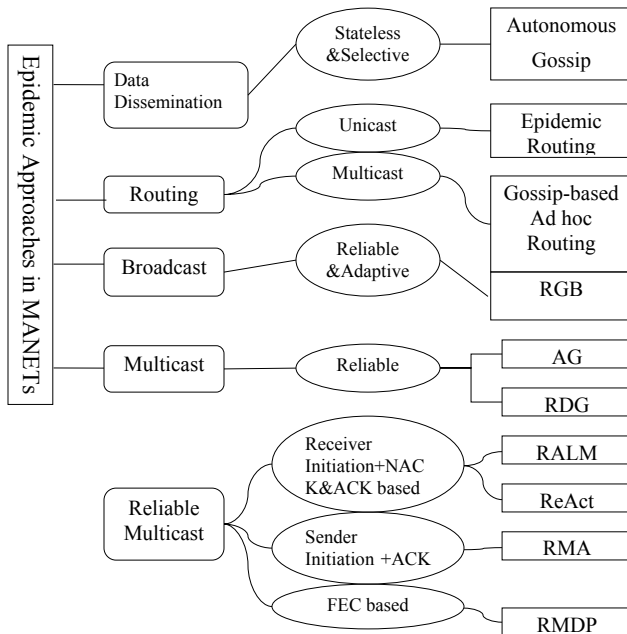


Figure 1. Epidemic and reliable multicast approaches in MANETs

Anonymous Gossip (AG) [3] is one of the earlier protocols utilizing an epidemic-based approach for providing reliable multicast data dissemination in mobile ad hoc networks. It offers a method that can be implemented on top of any tree and mesh based best-effort multicast protocols. The protocol advances in two phases. In the first phase, the underlying unreliable multicast protocol, currently Multicast Ad hoc On-Demand Distance Vector (MAODV) [6], is used to disseminate the multicast data to the group. In the concurrent second phase, anonymous gossip mechanism recovers the missing messages to guarantee the almost all reachable members receive the multicast packets. The recovery phase is performed by use of gossip mechanism. Each node randomly selects one of its neighbors, nearest nodes with higher probability and distant nodes with lower probability, and sends a gossip message to it. If the receiver node is not a member of multicast group then it forwards the message one of its neighbors, which is a member of the multicast group addressed by the gossip message. When a member node receives a gossip message, it randomly decides to either accept the gossip message or forward it. A node accepting a gossip message compares the content of gossip message, which includes the ids of message(s) missed by the sender, and the sequence number of the next expected message with its history of messages received. A node accepting a gossip message compares the content of gossip message, which includes the ids of message(s) missed by the sender, and the sequence number of the next expected message with its history of messages received. If it realizes a message sought by the gossip initiator in its history then it unicasts this data message back to the gossip initiator as the gossip reply. The simulation results show that it greatly improves the packet delivery of pure MAODV. However, its performance is highly dependent on MAODV and this makes it impossible to analytically predict its probabilistic delivery ratio [25].

Route Driven Gossip (RDG) [4] protocol uses a pure gossip schema for reliable multicasting in ad hoc networks. Unlike AG, RDG does not rely on a multicast routing protocol but on an on-demand unicast routing protocol like Dynamic Source Routing (DSR) or Ad Hoc On-Demand Distance Vector (AODV) [39]. It disseminates data in the periodic gossip messages together with membership information and negative acknowledgements. The gossip receivers are randomly selected from the partial list of group members. RDG does not employ an additional mechanism to form the list of group members. Instead, it utilizes the underlying routing protocol to collect group membership information together with routing information. The gossip messages contain new data, the ids of missing messages, the view on the membership and whether the node wishes to leave the group. The gossip receiver first updates its view by removing and adding the nodes then delivers the data and responds to gossip sender by sending missing messages if the node has the data packet requested. RDG aims to achieve a probabilistic reliability which is expected to be predictable based on simple information like packet loss ratio. The paper presents an additional protocol named TA-RDG, topology aware RDG. This variant uses partial topological information to utilize a similar heuristics to AG in order to pick a closer member with higher probability for gossiping. Therefore, different weights are assigned to the members in an active view according to the length of the routing path to them. The major novelty of RDG is its analytical performance estimation schema. The simulation results follow the

trend of these analytical predictions very well. However, there is little information about the overhead associated with the protocol [25]. The new data packets are transmitted within gossip messages additional to gossip content for pre-defined times by different members. This situation may result in redundant data transmissions and increase the overhead. It may also degrade the performance of the protocol in dense ad hoc networks which are highly open to congestion.

Our solution is quite different than these approaches. EraMobile is not based on any underlying routing protocol. It disseminates and recovers the data by use of a full gossip based schema. It requires neither routing nor multicast group information. However, AG requires the information about neighboring nodes while RDG needs the partial view of the group member nodes. Our solution exploits the broadcast nature of wireless medium to disseminate the gossip messages, instead of having information about the possible gossip receivers a priori. The performance of these protocols is also limited by underlying routing protocols. Additionally, these approaches claim they provide probabilistic reliability whereas our solution aims to provide fully reliable packet delivery.

3. ERAMOBILE

EraMobile aims to provide reliable multicasting in mobile ad hoc networks even under adverse network conditions. It distributes the burden of data dissemination among the nodes instead of leaving it completely on the source by utilizing a peer-to-peer epidemic mechanism. The source node just broadcasts the new data packets once generated. Then, all nodes participate in the data dissemination through periodic gossip rounds. This schema prevents the single point-of-failures and bottlenecks. The nodes of EraMobile have the ability to adapt to variable node densities by setting the protocol parameters to appropriate values. In sparse networks, the nodes can just focus on delivering the data in a reliable manner without having a congestion concern. In dense networks, the nodes should take into account the broadcast nature of wireless medium which is highly prone to congestion. EraMobile reduces the traffic only generated by the nodes subject to congestion in dense zones suiting the heterogeneous environment of mobile ad hoc networks. This technique spreads the overhead in space and time in order to avoid congestion. Since EraMobile performs the data delivery by equal participation of the nodes, such a reduction in the traffic rate increases delays. However, EraMobile has not already been developed for delay-sensitive applications like real-time streaming data.

EraMobile is shown to achieve fully reliable multicast data delivery studied through extensive simulations on ns-2 network simulator by outperforming the other protocols compared, especially in terms of both packet delivery ratio and overhead efficiency. The performance of the EraMobile was evaluated in comparison with plain Flooding and MAODV routing protocol. The Flooding was chosen because it is like a common currency in performance evaluation of multicast and broadcast protocols proposed for ad hoc networks. It is involved in most of the performance comparisons and generally shows best packet delivery ratios. Therefore, comparing EraMobile with Flooding gives a general idea about its packet delivery performance. MAODV was chosen since it causes the lowest overhead among the leading multicast protocols. A comparison with MAODV could be helpful

to investigate the overhead efficiency of EraMobile. In order to investigate the packet delivery, reliability and overhead performance of the protocol, we used the following metrics: throughput, reliable-throughput and receive-overhead. In the simulations, we examined the effect of mobility, group size and number of multicast groups and senders on the performance of the protocols. For the interested reader, extensive performance analysis results are reported in [40, 41].

The operation of EraMobile is handled by three main units. The data dissemination and recovery of missing data are performed by Data Dissemination unit. The Adaptivity unit is responsible for setting the operating modes of a number of sub-components dynamically based on node density, number of neighbors around a node, observed. The Buffer Management unit administrates the buffers of the protocol.

3.1 Data Dissemination Unit

Data dissemination is performed by use of gossip messages without employing any underlying multicast or unicast routing protocol. A gossip message carries the digest of the sender's data buffer contents. Every node in the network broadcasts gossip messages to their neighboring nodes at a rate determined by the gossip interval parameter. Upon receipt of a gossip message, a gossip receiver compares the list of data packet ids in the gossip contents with the list of its own missing data packets. If it notices its missing packet(s) in the gossip contents, the node may request the related packet(s) sending a request message to the gossip sender. Then, the gossip sender may transmit the data packet(s) to the requester.

The main schema mentioned above can be divided into three phases: Gossip digest construction, gossip propagation and data distribution.

Gossip Digest Construction:

The protocol proceeds in gossip rounds initiated by the gossip timer. The period of the gossip rounds is a parameter of the protocol. In each gossip round, a node scans its data buffer and collects the ids of the data packets whose gossip counts, packet-specific variables incremented in each gossip round, are less than the stability threshold value. The stability threshold parameter is used to determine how many times id of a packet should be put into gossip messages, in other words, how many rounds a packet should be kept in the data buffer. Collected ids of data packets are bundled into a gossip message together with the source and multicast group ids of the packets.

Gossip Propagation:

Gossip messages are propagated to all nodes in the wireless range of the gossip sender. This method does not require having knowledge of which nodes are in the wireless range before transmission since it exploits the broadcast nature of the wireless medium. A node, which has gossip message to send, just puts the message on air and its neighbors, nodes in the wireless range of this node, receive the gossip message. The small size of gossip messages and random delays on gossip sending times reduce the probability of collisions and packet losses that may arise from broadcasts to neighbors.

Data Distribution:

A new data packet is broadcast by the source node to its neighbors just once when the packet is originated. The goal of this duplicate-free broadcast is to increase the reliability of the protocol and propagation speed of the data by enabling more nodes to have the new data packet in the gossiping stage. Then, data distribution is completely performed by use of gossip mechanism through peer-to-peer communications. Upon receipt of a gossip message, nodes compare the packet ids placed in the gossip contents with the ids of their missing data packets. If nodes notice one or more packet ids which exist in the gossip contents but in their data buffer then they may request the missing packet(s) from the gossip sender. This requesting process is performed by use of request messages which carry the missing packet id(s). The number of data packets that a node can request in one gossip round is limited by a parameter. Thus, a node, which has missed many packets and realized this situation upon receipt of a gossip message, is not allowed to congest the network by high amount of request messages.

A node that has received a request message may transmit the related data to the requester. The transmission decision is based on the number of data packets transmitted in one gossip round. The maximum number of data packets which can be transmitted in a gossip round is determined by a parameter. A node does not answer the request messages if it has reached the transmission limit for one gossip round. Instead, the transmission can be performed by different nodes over several gossip rounds, spreading the overhead in space and time.

3.2 Buffer Management Unit

The buffer management has an important role on the performance of the protocol. The nodes should have sufficient number of data packets within their buffers in order to contribute to recovery of missing packets of the other nodes. However, mobile nodes may have memory constraints so the size of buffers should not exceed the limits. Additionally, considering the fact that gossip messages carry the digest of data buffers, a larger data buffer leads to bigger-size gossip messages, thereby increasing the overhead and the congestion probability in dense networks.

Buffer management unit carries out critical tasks for the reliability and the efficiency of the protocol. It maintains both buffers of the protocol and performs data delivery in FIFO order as explained below.

Buffer Maintenance:

The data buffer of the protocol is maintained by use of a garbage collection mechanism which is operated periodically at a pre-defined rate. This mechanism makes a decision about the status of every packet based on its gossip count, which is a packet-specific variable incremented in each gossip round. If the gossip count attached to a packet is greater than or equal to the stability threshold then it is removed from the data buffer. A missing packet which could not be recovered during stability threshold times gossip rounds is declared as lost and the protocol does not attempt to recover it any more.

Besides the data buffer, EraMobile maintains a second buffer for missing packets. Upon receipt of a gossip message, if there is a gap between the sequence number of the last received data packet and the greatest id in gossip contents, the protocol puts the id(s) of

the missing packet(s) into the missing data buffer. This buffer is used for making fast comparisons between the missing packets and the list of ids in the contents of gossip messages received. The garbage collection mechanism also controls the missing data buffer. It removes a packet from this buffer when the missing packets are received or declared as lost.

FIFO Order Delivery:

The packets in the data buffer are queued in FIFO order. Upon receipt of a data packet, the buffer management unit performs a delivery operation on the data buffer. The packets are delivered to upper layer if they are in FIFO order and there is not a gap between them. Otherwise, they are hold in the buffer until the missing packets causing the gap are received or declared as lost.

3.3 Adaptivity Unit

The mobility of the nodes in a mobile ad hoc network causes the occurrence of variable and unpredictable network conditions. The adaptivity unit enables the protocol to adapt to the changes by adjusting the parameters of the protocol dynamically. The node density, number of neighbors around a node, observed is taken into account by the adaptivity unit in decision making. It was chosen as the adaptation criterion based on the preliminary result analysis of substantial number of simulation studies. We observed that node density has significant influence on the performance of our protocol. The reason is that, since the data delivery is performed by the participation of all members through gossip rounds, high density increases the traffic load that nodes expose while low density results in poor network connectivity and hence inadequate data delivery.

As it is stated previously, EraMobile does not employ a separate mechanism to have the information of neighbors around a node. Instead, it utilizes the periodic gossip broadcasts and request messages received. The senders of both messages are considered as neighboring nodes. EraMobile counts those senders during pre-defined gossip rounds to make sure every neighboring node has broadcast at least one gossip message. Then, it calculates the average number of neighbors. However, the adaptivity unit does not set the protocol parameters each time the node density is calculated. Instead, it periodically operates waiting for an adaptivity period, in which node density can be calculated several times, to prevent oscillations. Then, it uses the average of pre-calculated node density values to determine the density level.

We defined three separate density levels, low, normal and high, according to the results obtained through ns simulations and taking into account the related work [42, 43 and 44]. The density levels are based on the number of neighbors observed around a node. The low density level comprises the nodes having less than 6 neighbors. The normal density level is defined for the nodes having neighbors between 6 and 20. The nodes having more than 20 neighbors are accepted in the high density level.

In low density level, the spread of data all over the network is likely to be a challenging task because of the poor network connectivity. As in a real epidemic, the nodes should utilize each contact opportunity to disseminate the data. In mobile ad hoc networks, the time that two nodes will spend within the wireless range of each other is variable. It may be too small to be aware of each other or to complete the data exchange. Thus, a node needs to broadcast the gossip messages more frequently to catch another

mobile node as soon as their wireless ranges cover each other. The gossip interval parameter of the protocol is decreased for more frequent gossip broadcasts. Additionally, the request limit and the transmission limit for a gossip round are broadened for allowing the nodes to perform data transmission as much as need in the congestion-free environment of sparse networks. The low node density may also cause a number of nodes to be isolated from the rest of the network for some time. Those nodes should be brought up to date when they get rid of isolation. Therefore, the messages should be kept for a longer time in the data buffers of the nodes which are able to receive data messages. The isolated nodes should also wait for a longer time to declare the missing messages lost. The adaptivity unit increases the stability threshold value to deal with such situations. A higher stability threshold value retards the removal of the messages from the data buffer and declaration of missing messages lost.

In normal density level, nodes maintain the protocol parameters in moderate values since they have suitable network conditions for communication.

In high density level, even mild traffic rates generated by the nodes may make the network congested. Such a congested network causes high number of packet losses arising from collisions and ultimately wastes limited bandwidth. The adaptivity unit decreases the traffic rate of the nodes experiencing congestion, thereby spreads the overhead in space and time. The reduction in traffic rate is carried out in two dimensions: extending the gossip intervals and limiting the number of request and data messages transmitted in a gossip round. Extending the gossip intervals decreases the number of gossip broadcasts. Besides, it reduces the traffic of request and data messages indirectly. The request and transmission limits per round are also decreased in order to alleviate the congestion. Additional to request limit, the adaptivity unit defines a probability value, request sending probability, which is reduced by increasing node density, for request sending. This probability is used by the nodes to make a decision on whether to send a request message. Request sending probability aims to prevent a request explosion when a gossip message, which includes the ids of newly generated data packets, broadcast in a dense zone.

The final congestion avoidance technique is putting random jitters based on the node density onto message transmission times. The adaptivity unit puts random jitter onto transmission time of each request and gossip message according to the formula below.

$$\text{jitter (sec)} = k * (\# \text{ neighbors around the node}) / 100$$

(k is a constant randomly chosen from a uniform distribution on the range 0 to 1)

EraMobile also has an adaptation mechanism for energy conservation. Each node adds a small amount of time, gossip interval addition, to its gossip interval value in every gossip round until it reaches a pre-defined upper limit, gossip interval upper limit. Upon receipt of a data message, the extended value of gossip interval is reset to its original value. This method aims to reduce energy consumption by eliminating redundant gossip broadcasts when the data traffic is stopped. The addition value and the upper-limit for the gossip intervals are determined based on the node density level. In dense networks the gossip interval is

extended more quickly and the upper-limit is chosen larger to assist the congestion control mechanism.

4. CONCLUSION AND FUTURE WORK

A classification of epidemic-based approaches utilized in the context of MANETs with a focus on reliable multicast protocols, and a brief description of the other approaches to reliable multicasting in MANETs are presented. Then, design of EraMobile, our epidemic-based reliable multicast protocol for MANETs, and its adaptivity mechanism for varying node densities are provided. Performance and efficiency of EraMobile have been studied through comprehensive simulations. It can be utilized by applications, which are not delay sensitive, aiming reliable multicast delivery with minimal overhead in highly dynamic environment of mobile ad hoc networks. As further work, we intend to study the delay characteristic of EraMobile in varying conditions such as mobility and node density. We also consider enhancing our protocol with a global congestion control mechanism to slow the data rate of the senders when the network is highly loaded.

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