DTN Routing with Back-Pressure based Replica Distribution

Zhenzhen Jiao, Rui Tian, Baoxian Zhang, and Cheng Li

Abstract: **Replication routing can greatly improve the data delivery performance by enabling multiple replicas of the same packet to be transmitted towards its destination simultaneously. It has been studied extensively recently and is now a widely accepted routing paradigm in delay tolerant networks (DTNs). However, in this field, the issue of how to maximize the utilization efficiency of limited replication quota in a resource-saving manner and therefore making replication routing to be more efficient in networks with limited resources has not received enough attention. In this paper, we propose a DTN routing protocol with back-pressure based replica distribution. Our protocol models the replica distribution problem from a resource allocation perspective and it utilizes the idea of back-pressure algorithm, which can be used for providing efficient network resource allocation for replication quota assignment among encountered nodes. Simulation results demonstrate that the proposed protocol significantly outperforms existing replication routing protocols in terms of packet delay and delivery ratio.**

Index Terms: **Back-pressure, delay tolerant networks (DTN) routing, replication.**

I. INTRODUCTION

Delay tolerant networks (DTN) enable communications between wireless nodes with intermittent contacts due to node mobility, power management, and etc., which has been regarded as a networking paradigm for many special scenarios, e.g., deep space communications and animal monitoring [1]. Unlike traditional communications networks, connected path between communication endpoints does not always exist in DTNs, which makes the DTN routing problem challenging. Recently, a new type of routing strategy, namely replication routing, has been increasingly accepted as an effective solution to support DTN routing and it has attracted much attention [2]–[15].

Replication routing allows multiple replicas of the same packet to be transmitted towards its destination simultaneously, which has been proved to be effective for improving the data delivery performance in DTNs. In such a paradigm, a key issue is to design an efficient routing scheme which can achieve a good tradeoff between replication gain and network resource consumption. Existing replication routing protocols can be divided into two categories based on the amount of replicas created, i.e., flooding-based protocols and quota-based protocols. Flooding-based protocols greedily create replicas when certain conditions (e.g., when encountering a node with qualified utility or replicating a particular packet can obtain desirable performance gain) are met. However, such a way of replication can lead to unlimited number of replicas in many cases. As a result, it can exhaust the network resources and is not always practical. To address this issue, some work in this aspect (e.g., RAPID [6] and MaxProp [7]) has already considered the issue of limited network resources in their protocol design. However, their implementations may still lead to excessive replication in some cases and therefore affect the network performance [10]. In contrast, quota-based protocols intentionally limit the total number of replicas allowed to be created in a network (e.g., Spray-and-wait [8], Spray-and-focus [9], capacity-constrained replication (CCR) [10], Multi-phase spraying [11], and encounter-based routing (EBR) [12]). However, these existing protocols often suffer from the issue of inaccurate estimation of nodes' ability for delivering a packet, which may lead to low probability of packet end-to-end delivery (for overestimation case) or a waste of the limited network resources (for underestimation case).

To address the above issue, in this paper, we propose a DTN routing protocol using back-pressure based replica distribution (BAR for short). BAR models the replica distribution problem from a resource allocation perspective and it utilizes the idea of the back-pressure algorithm, an efficient scheduling solution for efficient network resource allocation [16], [17], to schedule the distribution of replicas and also quotas. BAR takes into account several key factors when making the scheduling decisions, including replication limit, each node's ability for delivering a packet (estimated based on node contact probability), and limited network resources. BAR uses the idea of backpressure based scheduling for disseminating a packet's replica quota among neighbor nodes based on the quota currently kept at each node and also their respective abilities (delivery probabilities) for delivering the actual data packet to its target destination. Moreover, in BAR, the use of nodes' packet delivery abilities into the transmission scheduling decision making can also guide data packets to be forwarded to nodes with high delivery abilities, which can to a large extent suppress unnecessary replica exchanging in the network. To the best of our knowledge, our work in this paper is the first time that the idea of backpressure based scheduling is used for efficient replica quota distribution in DTNs. We evaluate the performance of BAR on the widely

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used network simulator ONE [18] by comparing it with several well-known replication routing protocols for DTNs. Simulation results show that BAR significantly outperforms existing work in terms of packet end-to-end delay and successful delivery ratio. The rest of the paper is organized as follows. Section II presents the network model under study and the design details of our protocol BAR. Section III conducts extensive simulations for performance comparison. Section IV briefly reviews related work. Section V concludes this paper.

II. BAR: A DTN ROUTING PROTOCOL WITH BACK-PRESSURE BASED REPLICA DISTRIBUTION

In this section, we propose the detailed design description of BAR. We first present the system model and then describe how each component in BAR works in details.

A. System Model

In this paper, we study a DTN constituent of nodes with intermittent contacts between them as they move randomly, which can be modeled by graph $G = (V, E)$, where V represents the set of nodes and E represents the set of links in G. Each link $E(G)$ represents a contact between two nodes, which is a time-varying function. The available bandwidth during a contact (i.e., when two nodes meet each other) and the buffer space of nodes are both assumed to be limited.

In this paper, we model the replica distribution as a resource allocation problem which is somewhat similar to the work in [6]. The difference is that our replica distribution model in this paper works in a back-pressure style in order to achieve efficient network resource allocation [16], [17], [19], [20].

Back-pressure scheduling algorithm was first proposed in [16], wherein it was proven that queue-length based resource allocation in back-pressure scheduling is throughput optimal, i.e., it can stabilize a network when arrival rates lie within the network capacity region. Furthermore, it can achieve efficient resource allocation in stochastic networks when combined with rate control [17].

The classical back-pressure algorithm in [16] works as follows. At the beginning of time slot t, for each link $(n, m) \in E(G)$, its link-weight is assigned as the maximum backlog differential of all the flows passing through the link (i.e., the maximum flow-weight, ties broken arbitrarily):

$$W_{nm}(t) = \max_{f:(n,m)}[U_n^f(t) - U_m^f(t)] \qquad (1)$$

where $U_n^f(t)$ represents the queue backlog of flow f on node n at time t. Thus, packets belonging to flow f will be transmitted over link (n, m) if (n, m) is to be activated under a schedule $\pi(t)$ which is derived from the following optimization problem:

$$\pi(t) = \arg\max_{\pi \in \Gamma} \sum_{(n,m)} W_{nm}(t) r_{nm}(t) \qquad (2)$$

where Γ represents the set of all feasible schedules according to given link interference model and $r_{nm}(t)$ represents the link rate of (n, m).

In this paper, we shall utilize back-pressure scheduling to support efficient replica distribution of each data packet in an intermittent connected DTN, in order to achieve high packet delivery performance. For this purpose, we make the following assumptions. In BAR, we view the delivery of each individual data packet from its source to its target destination as a virtual flow, a viewpoint significantly different from existing work, in which all the data packets moving from one node to another node are treated as a flow. Specifically, let p represent a data packet and also consider p as a virtual flow, with a slight abuse of notation. Once p is generated at its source node, it is assigned a quota, i.e., the total amount of replicas that it can generate when traveling across the network, denoted by $Q_{src(p)}^p$, where $src(p)$ is the source node of packet p. For each node $n \in V(G)$, if it has p's replica in its queue with a quota Q_n^p, then we say that the queue length of the virtual flow p at node n is Q_n^p, i.e., $\tilde{U}_n^p(t) = Q_n^p$, where $\tilde{U}_n^p(t)$ represents the queue length of virtual flow p at node n.

B. Protocol Overview

In this subsection, we give an overview of our protocol BAR. BAR realizes the replica distribution using back-pressure based scheduling of quota exchanging. As introduced in the preceding subsection, in BAR, each packet in the network is viewed as a virtual flow. For each node n, which stores a packet p with a quota Q_n^p, the queue length of the virtual flow p is Q_n^p, i.e., $\tilde{U}_n^p(t) = Q_n^p$. Accordingly, an intuitive method for realizing back-pressure based scheduling will be as follows: Substitute the virtual queue p's length $\tilde{U}$ into (1) and accordingly calculate the virtual-flow-weight associated with link (n, m) as follows.

$$\tilde{W}_{nm}(t) = \max_{p:(n,m)}[\tilde{U}_n^p(t) - \tilde{U}_m^p(t)]. \qquad (3)$$

Apparently, based on (3), the packet with the highest replication emergency will be encouraged to transmit its replica first. Here, a higher replication emergency of p is indicated when p has higher undistributed quota at n (as the sending side) or lower quota (or zero) at m (as the receiving side). Both cases can be interpreted as that p has not been well sprayed to the network comparing with other packets with lower virtual queue length differentials.

However, the above way of link weight calculation has not taken into account nodes' abilities for delivering a particular packet. Similar to the replication mechanisms in [10] and [11], (3) may lead to greedy replication of packets when a pair of nodes encounter, no matter whether the packet receiver is a worse carrier than the sender or not, e.g., the receiver actually has little chance to have a path to the packet's destination.

To address the above issue, BAR takes into account each node's packet delivery ability and a data packet's replication emergency degree as calculated in (3) altogether when making scheduling decisions.

Accordingly, we introduce a cost model, which estimates the nodes' ability for delivering a certain packet via node mobility knowledge. The cost model used here is well-accepted in the literature but is for the first time being used in the context of back-pressure scheduling. Specifically, the cost model determines the cost for using a node n to deliver a packet p (denoted by C_n^p) as

follows. It first assigns a cost to each path departing from node n to p's destination, which is calculated by using the contact probability between neighbor nodes constituent of the path. Next, it assigns the path with the least cost among all possible paths as n's cost. In this way, a node n with lower C_n^p is considered to have higher ability for delivering packet p.

After defining each node's ability for forwarding a particular packet, next, we integrate it together with the packet replication emergency degree in (3) into back-pressure scheduling for guiding a node to make efficient replication decision. To be specific, we design a shadow queue whose queue length equals the product of node delivery ability and packet replication emergency degree, i.e., $\tilde{U}_n^p(t)C_n^p$. Furthermore, we conduct the back-pressure based scheduling based on the lengths of these shadow queues. Under this scheduling mechanism, for each time a transmission opportunity appears, a node can make a forwarding decision via one simple calculation: 1) Whether to replicate a packet to current encountering node; 2) if yes, then which packet and also how much quota need to be transmitted; 3) if there exist multiple candidates that can be used as forwarders but the contact duration or bandwidth only allows limited packet(s) to be transmitted, then which combination of packet(s) and forwarder(s) will be the most efficient.

After a node n has made a scheduling decision for forwarding a packet p's replica to a neighbor node m, the next job for node n is to distribute p's replication quota to m according to the scheduling decision. As we mentioned previously, the replication quota of a packet at a node is the permitted replicating amount of the packet at the node. If the packet p is generated at n, i.e., n is p's source node $src(p)$, then the replica quota $Q_{src(p)}^p$ is assigned as a pre-determined value; otherwise, the quota Q_n^p is determined by the quota that n's last-hop node is going to send to n and also the quota that node n locally keeps (if any) before the transmission. BAR's replication quota distribution mechanism follows the back-pressure scheduling's principle: A node with higher delivery ability and further has not carried too much quota (for the same packet) can be seen as a promising forwarder and is encouraged to be assigned more quota.

In the next three subsections, we will respectively introduce how each component in BAR works, including cost model for estimating a node's packet delivery ability (see Section II.C), shadow queue based scheduling mechanism (see Section II.D), and quota distribution mechanism (see Section II.E).

C. Cost Model

In this subsection, we introduce the cost model which determines the delivery cost from a node n to packet p's destination, denoted by C_n^p. C_n^p also represents node n's delivery ability for forwarding packet p. Actually, estimating a node's delivery ability is also a key issue in DTNs and has been widely studied in the literature. Several methods have been proposed for this purpose in previous work. In this paper, we utilize nodes' contact probabilities to quantify nodes' delivery ability. This strategy is adaptive to many mobility scenarios due to its simplicity, which is helpful to enable BAR to be useful in various application scenarios.

Specifically, in BAR, each node $n \in V(G)$ records its contact probability with every other node in the network. Let $B_{n,m}$

represent the contact probability recorded by n for it to meet $m \in V(G) - \{n\}$. For each node n in the network, the initial value of $B_{n,m}(m \in V(G) - \{n\})$ is set to $1/(|V| - 1)$, where $|V|$ represents the number of nodes in the network, and the updating of $B_{n,m}$ is as follows. Once n meets a node m, $B_{n,m}$ is first increased by one, then the contact probability for all nodes $\in V(G) - \{n\}$ kept at n is re-normalized. To illustrate how this works, we here give an example. Consider a network containing 6 nodes. For a node $i \in V(G)$ in the network, its contact probability to every other node $j \in V(G) - \{i\}$, i.e., $B_{i,j}$, is initially set to 0.2. When i encounters a node $\in V(G) - \{i\}$, denoted by a, $B_{i,a}$ is first increased to 1.2. Then, all the probabilities, including $B_{i,a}$ and $B_{i,j}$ for $\forall j \in V(G) - \{a\}$, will be re-normalized to keep their sum to be one. As a result, $B_{i,a} = 0.6$ and $B_{i,j} = 0.1$ for $\forall j \in V(G) - \{a\}$. This is the so-called incremental averaging strategy, which was also used in other work (e.g., [7]). In this way, nodes who meet each other infrequently will have lower meeting probability over time. Once two nodes meet each other, they exchange all their recorded contact probabilities. At the same time, they also exchange the information of quotas of packets they carry, which is necessary for making scheduling decisions.

Next, a node n calculates the cost C_n^p for it to reach the destination of packet p, denoted by $dst(p)$. Specifically, C_n^p is calculated as follows.

$$C_n^p = \min_{paths\{n, dst(p)\}} \sum_{x=n}^{dst(p)-1} (1 - B_{x,x+1}) \qquad (4)$$

where $paths\{n, dst(p)\}$ represents the set of all possible paths from node n to $dst(p)$. Apparently, based on (4), a node with high cost to reach a packet's destination will be seen as a forwarder with low probability, and vice versa. Besides, the cost of $dst(p)$ always equals zero, i.e., $C_{dst(p)}^p = 0$.

D. Shadow Queue based Scheduling Mechanism

In this subsection, we introduce a shadow queue based link weight calculation and scheduling decision making mechanism to enable the joint consideration of per-node delivery ability and packet's replication emergency degree.

Specifically, let V_n^p denote the shadow queue for a packet p at node n, its length is calculated as follows.

$$V_n^p(t) = \tilde{U}_n^p(t)C_n^p \qquad (5)$$

where C_n^p represents the cost from node n to $dst(p)$, and $\tilde{U}_n^p(t)$ is the replication quota of p at n, as we introduced earlier. Accordingly, we define the weight of link (n, m) based on shadow queue lengths as follows.

$$\tilde{W}_{nm}(t) = \max_{p:(n,m)} [V_n^p(t) - V_m^p(t)]. \qquad (6)$$

Here, recall that $C_{dst(p)}^p = 0$, which makes $V_{dst(p)}^p(\infty) = 0$ and thus strongly attracts those packets destined to $dst(p)$ to be scheduled in (6), which encourages the packet destined to its destination to be scheduled for transmission. Moreover, when calculating $V_m^p(t)$ for a node m which is not the destination of packet p, its replication quota of p is considered to be at least

one, even if this node actually has no replica of p locally. The reasons for doing so are as follows. First, this setting enables us to clearly distinguish an intermediate node from the packet destination from a scheduler's viewpoint. Second, think about that if we allow an intermediate node m's virtual queue length $\tilde{U}_m^p(t)$ equals zero, then it is highly possible that a transmission to such a node m will be scheduled no matter what the value of C_m^p is based on (5) and (6), which may cause a lot of unnecessary replica exchanging.

After defining the weight of link (n, m) based on the shadow queue length, the scheduling process is given by (7), which follows a back-pressure based scheduling manner: Packets will be allowed to be replicated over link (n, m) if (n, m) will be activated under a schedule $\pi(t)$ which is derived from the following optimization problem.

$$\pi(t) = \arg\max_{\pi \in \Gamma} \sum_{(n,m)} \tilde{W}_{nm}(t). \tag{7}$$

It should be noted that deriving the global optimal schedule set by (7) cannot be deployed in a purely distributed manner because of obtaining the global network state information is in general not practical in dynamic DTNs. Here, we present a heuristic implementation of BAR as follows: Each node n ($n \in V(G)$) always makes a greedy localized forwarding decision by selecting the packet in its local queue and the next hop, whose joint weight contributes to the maximum in (7) within its one-hop neighborhood.

The scheduling mechanism in BAR encourages packets with higher replication quota to disseminate its replica(s) and quota to nodes who have low quota or do not have the packets in their queues. In this process, the delivery abilities of both sender and receiver play a key role in the decision making. The purpose for doing so is to achieve a balance between appropriate fault tolerance in packet delivery and assigning replication quotas to good forwarders.

E. Quota Distribution Mechanism

Next, we introduce the replication quota management and distribution mechanism in BAR.

The replication quota of a packet at a node represents the permitted replicating amount for this packet by the node. If the packet p is generated at n, i.e., n is p's source node $src(p)$, then the replica quota $Q_{src(p)}^p$ is assigned as a pre-determined value; otherwise, the quota Q_n^p is determined by n's last-hop node according to the scheduling decision and also the quota of p that node n locally keeps (if any) before the transmission.

Specifically, when at time t, a packet p stored at node n is scheduled to be replicated or distributing some of its quota over link (n, m) to m, then at the time when the transmission is finished (denoted as $t + 1$), the dynamics of quotas of p at sender n and receiver m will evolve, respectively, as follows.

$$\tilde{U}_n^p(t+1) = \begin{cases} \infty, & \text{if } m = dst(p); \\ \max\{\frac{V_n^p(t) - V_m^p(t)}{V_n^p(t)} \times \tilde{U}_n^p(t), 1\}, & \text{otherwise.} \end{cases} \tag{8}$$

$$\tilde{U}_m^p(t+1) = \begin{cases} 0, & \text{if } m = dst(p); \\ \tilde{U}_m^p(t) + \max\{\tilde{U}_n^p(t) - \tilde{U}_n^p(t+1), 1\}, & \text{otherwise.} \end{cases} \tag{9}$$

Table 1. Simulation parameters.

Parameters	Description
Simulation area	4,500 m × 3,400 m
Number of nodes	200
Communication range	50 m
Node buffer	50 Mb
Packet size	1 Mb
Replication quota	10 for both of BAR and Spray-and-wait

Some further explanations are as follows. First, for the destination of a packet p, its replication quota of p always equals zero, i.e., $\tilde{U}_{dst(p)}^p(\infty) = 0$. Second, when a packet reaches its destination, a common method for noticing other nodes about its successful delivery is to broadcast an acknowledgement (ACK) network-wide. In BAR, when a node n transmits a packet p to its target destination, n immediately sets $\tilde{U}_n^p(t) = \infty$. Further, when n or $dst(p)$ exchanges its quotas and contact probabilities with other nodes, the met nodes will also update their quotas for p to infinite and spray it like done by n and $dst(p)$. Note that such information is only needed to be stored in the network for a time period sufficient for spraying it to all nodes which still hold undistributed quota of p. A packet with an infinite quota will always be ignored in (5) when making scheduling decisions. This method for acknowledgment dissemination can avoid use of extra control messages for ACKs and thus reduce the bandwidth consumption. Third, a node needs to really transmit a data packet's replica to an encounter only when the encounter does not have that packet in its buffer; otherwise, only quotas are exchanged according to the scheduling and also the corresponding quota distribution decision, which can be finished via exchange of control messages and is much less resource consuming than the exchanging of actual data packets.

F. Buffer Management

In BAR, packets stored at each node are sorted according to their residual quotas. The packet with the least residual quota is believed to have already been spayed the best (at least from the current node's perspective) for providing certain delivery assurance, or this node is assigned with a low quota because of its poor forwarding efficiency, and thus will be first removed from the buffer when the buffer is going to be full. Besides, packets with infinite quota will be deleted when the storing timer expires.

III. PERFORMANCE EVALUATION

In this section, we evaluate the performance of BAR using the widely used simulator ONE [18] and compare it with the following three replication routing protocols: Epidemic [4], Spray-and-wait [8], and RAPID [6].

In our simulations, a road network with more than 50 intersections is considered, which is extracted from the map of Helsinki as shown in Fig. 1. In the simulations, network nodes consist of four different groups, in which one group is cars whose speeds are randomly chosen within [2.7, 13.9] m/s and the other
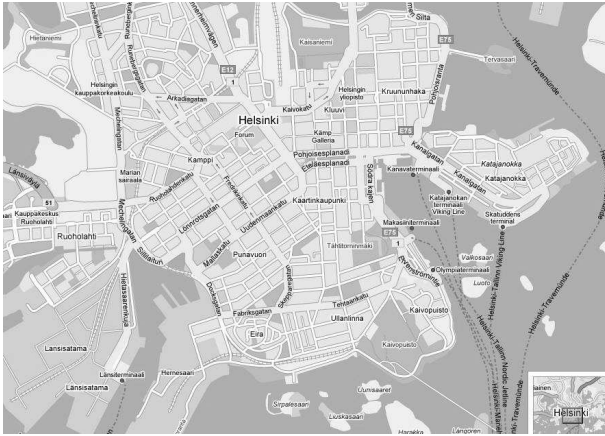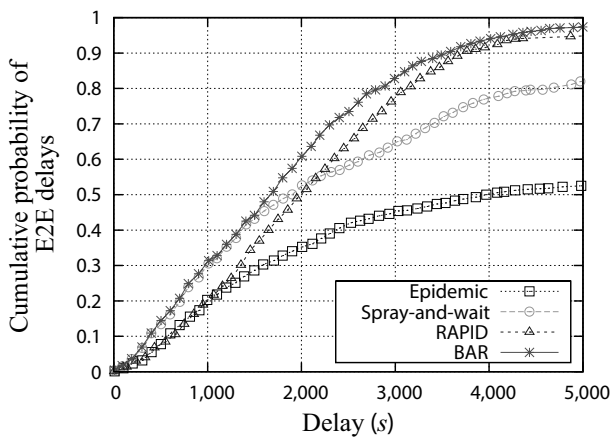
Fig. 1. A snapshot of the simulation area.

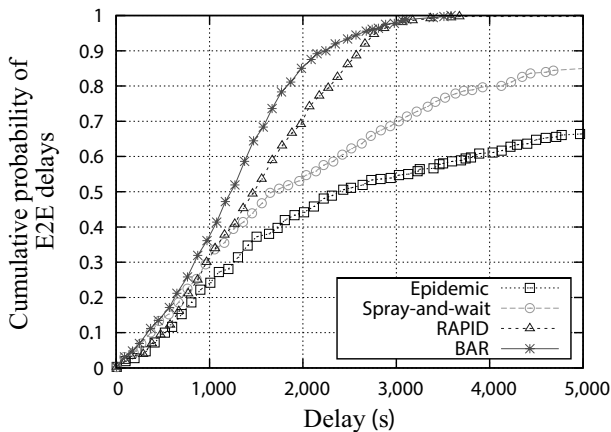Fig. 2. Cumulative probability of E2E delays when packet generating interval is 5 s.

Fig. 3. Cumulative probability of E2E delays when packet generating interval is 10 s.

three groups are pedestrians, whose speeds are randomly chosen within [0.5, 1.5] m/s. Each group has 50 nodes and with different interest points under a random waypoints movement model. Data packets were generated by randomly chosen nodes subject to a given generation interval and the packet destinations were also randomly chosen. Each simulation lasts for 2 h with a 12 h
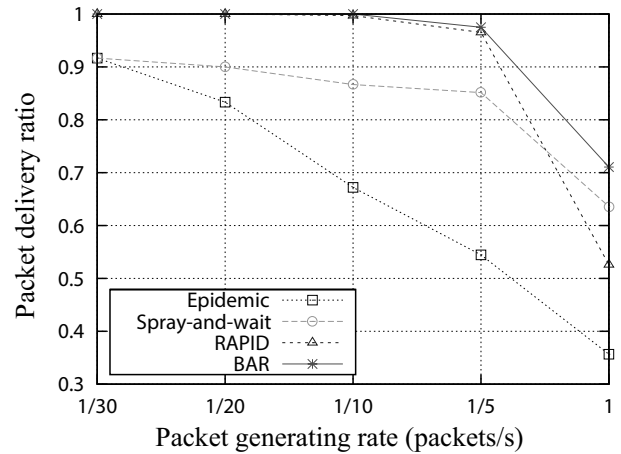

Fig. 4. Packet delivery ratio versus different packet generating rates.
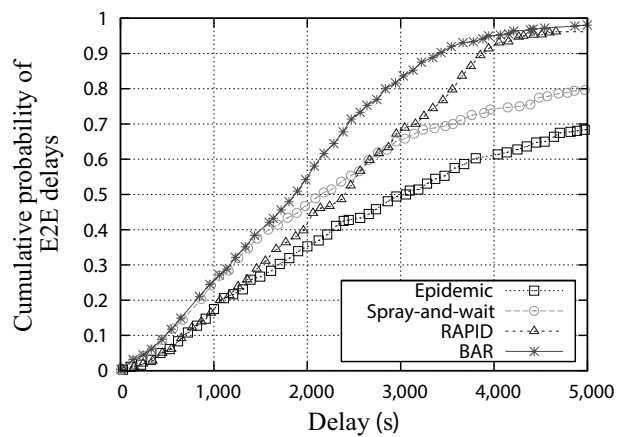

Fig. 5. Cumulative probability of E2E delays when channel rate is 1 Mbps.

warm-up time. More parameters can be found in Table 1.

Figs. 2 and 3 show the cumulative probability of the end-to-end (E2E) delays by different protocols when the packet generation intervals are 5 and 10 s, respectively. The channel rate is 2 Mbps. From the figures, it is seen that BAR significantly outperforms the other three protocols in terms of E2E delay and packet delivery ratio. For any given delivery delay, BAR always performs the best. The reason is as follows. In our simulations, we considered limited node buffer space and channel bandwidth. In such an environment, Epidemic has the highest possibility of buffer overflow and thus packet discarding. As a result, it has the lowest delivery ratio. Similarly, RAPID may also generate more replicas and waste resources. The Spray-and-wait limits the replication quota, however, it never considers the receivers' ability for delivering its replicas and thus often uses up its quota instead of distributing the replicas to good relays. As a result, as can be seen in the figures, it delivers more packets to nearer destinations (i.e., with lower delivery delay) than to remote ones (i.e., with longer delivery delays).

We further increase the packet generation rate to 1 packet per second. In Fig. 4, it is seen that the packet delivery ratio by the other three protocols decreases much sharply than that by BAR.

This result demonstrates that, by limiting the total replication quota and using the back-pressure based scheduling, BAR can achieve higher replica usage efficiency than other protocols under limited network resources.

Fig. 5 shows the cumulative probability of E2E delays when reducing the channel rate to 1 Mbps. In this case, the number of packets can be transmitted in each transmission opportunity is reduced, which is helpful to estimate the performance gain brought by limited transmission bandwidth. As shown in Fig. 5, BAR also outperforms the other three protocols in terms of E2E delay and delivery ratio, which illustrates the higher forwarding efficiency of BAR than others.

IV. RELATED WORK

In this section, we present a brief overview of existing replication routing protocols in DTNs. Existing replication routing protocols can be divided into two categories based on the number of replicas created, i.e., flooding-based and quota-based.

Flooding-based protocols greedily replicate packets according to some node- or packet-specific utility. In this category, epidemic routing [2] enables nodes to replicate a packet once encountering a node. Thus, the number of replicas generated under epidemic routing is directly dependent on the number of nodes in the network and apparently to be resource-consuming. In [6], RAPID models DTN routing as a resource allocation problem and aims at optimizing specific routing metrics, such as the worst-case delivery delay, or fraction of packets that can be delivered within a deadline. When a transmitting opportunity appears, RAPID replicates packets in the decreasing order in terms of their utilities. Here, the packet utility is defined using, for example, packet expected delay, which is deduced using encounter probability. Likewise, MaxProp [7] uses delivery probability to define packet utility. Similar replication schemes can also be found in [3]–[5], which use different methods for determining node- or packet-specific utility. One key problem with these flooding-based mechanisms is that they do not restrict the number of replicas that can be generated in a network, which may lead to excessive replication in some extreme cases and therefore affect the network performance.

Quota-based protocols uses replication quota to limit the maximum number of replicas for each packet. Among the existing protocols in this category, Spray-and-wait in [8] uses a fixed bound to limit the maximum allowable number of replicas to be created in a network. In Spray-and-wait, routing process is divided into two phases, i.e., spray and wait phases. In spray phase, the source distributes a fixed number of packet replicas to the first few relays encountered. In wait phase, these relays carry the replicas being assigned and wait until encountering the targeted destination. A follow-up protocol called Spray-and-focus [9] uses a similar spray phase. The difference is, a new focus phase is proposed in [9] which enables the replicas be further forwarded to help increase network performance. Spray-and-wait and Spray-and-focus succeed in limiting the overhead of flooding-based protocols. However, their delivery ratios suffer. Consider that fixed limit used in [8] and [9] may either underestimate or overestimate the network resource in some cases, in [10], Wu *et al.* proposed CCR, which explores the residual

network capacity for adaptively adjusting replication limit of packets. However, CCR did not consider the delivery ability of nodes when making forwarding decisions. In [11], Bulut *et al.* proposed a Multi-phase spraying mechanism which divides the spray phase of replicas into multiple periods. In [11], a latter round of spraying only starts when its former rounds cannot achieve the pre-defined performance. However, similar to CCR in [10], when spraying and forwarding replicas to nodes, the mechanism in [11] also did not consider the nodes' ability for improving the delivery performance and sometimes may lead to a waste of the limited replication quota. EBR proposed in [12] takes a node's packet delivery probability into account when making quota distribution decisions. However, EBR's quota distribution manner still allows a node with very low packet delivery probability to be allocated with a certain amount of quota, which is not efficient especially when the total quota is very limited.

In summary, much significant progress has been made in recent years and enables replication routing to be increasingly efficient and practical. However, how to maximize the efficiency of each replication for achieving a good tradeoff between network performance and network resource consumption still deserves in-depth study.

In this paper, we for the first time leverage back-pressure scheduling to reconstruct the replica distribution in replication routing for DTNs. There has been some previous work that also used back-pressure based routing and scheduling in the context of DTN routing. In [21], Ryu *et al.* proposed a two-level back-pressure routing protocol for DTNs consisting of clusters of nodes intermittently connected via mobile carriers and they used different routing strategies for intra- and inter-cluster routing. In [22], a back-pressure based single-copy routing protocol for DTNs was proposed. In [23], the authors proposed an adaptive redundancy technique to address back-pressure routing's poor delay performance under short-lived flows in DTNs. In [23], replicas are only generated when traffic load in the network is very low. Further, these replicas will be only transmitted when there is no original packet that can be transmitted in forwarding queues. Such kind of replication method is used for addressing the so-called last-packet problem existing in back-pressure based networks. Different from the above mentioned work, our protocol BAR proposed in this paper uses the idea of back-pressure scheduling to schedule the distribution of (limited) replica quota in a DTN, while the transmission of actual data packet does not rely on the queue backlog differential between neighbor nodes like done in traditional back-pressure algorithms [21]–[23].

V. CONCLUSION

In this paper, we proposed BAR, a DTN routing protocol with back-pressure based replica distribution. BAR models the replica distribution problem from a resource allocation perspective and it utilizes back-pressure scheduling for scheduling the replication quota allocation in the network. Simulation results demonstrate that BAR can achieve high replication efficiency and outperform existing protocols in terms of packet end-to-end delay and delivery ratio.

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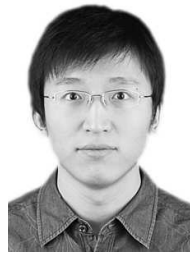
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