Erasure-coding Based Data Delivery in Delay Tolerant Networks

Khalil Massri, Roberto Beraldi, and Andrea Vitaletti

Dipartimento Di Ingegneria Informatica Automatica e Gestionale
Università degli Studi di Roma "La Sapienza"
Roma, Italy
{massri,beraldi,vitale}@dis.uniroma1.it

Abstract. We consider the data delivery problem in delay tolerant networks, where a data content is located in a fixed source need to be delivered to a specific destination. We assume nodes have limited storage and computational capabilities. In this paper, we initially, explore the data delivery problem, for both unbiased and biased contact models. Based on our observations, we propose a data delivery scheme that can reduce both storage overhead and delivery delay. Our scheme combines erasure coding technique and the framework of simulated annealing optimization, in order to maximize the content delivery probability to the destination.

Keywords: Routing, Delay Tolerant Networks (DTNs), Erasure Coding

1 Introduction

Delay-Tolerant Networks, DTNs [1], are intermittently connected mobile wireless networks that may suffer from frequent partitions, and thus a path connecting source and destination cannot be maintained over time. Routing in DTNs is one of the main challenges; the use of efficient routing schemes is a key element to performance of DTN networks. Therefore, the usability and applicability of DTN deployments are conditioned by efficient and optimized routing algorithms. Nodes exploit mobility in order to carry the message to the intended destination.

Due to the wide diversity in contexts in which DTN routing is applicable, many different protocols have been proposed in the literature. In our previous work [2], we classified most of the recently proposed protocols in the literature. In particular, we consider forwarding, replication and queue management as the main techniques for DTN protocols and we show how each protocol can be classified according to the techniques it adopts. Forwarding techniques control whether or not a node can forward a message to the other node when there is a contact. While replication techniques control the duplication of a message among nodes.

In this work, we explore the problem of data content delivery in DTNs, where relay nodes are limited-resources devices. Namely, when the delivery of the data content to a given destination requires a number of packets. Our objective is to reduce the delivery delay for the whole content. At the same time, we want also to reduce storage overhead in the network. Two main factors mainly affect the delivery delay. The first one is the time needed by the source to disseminate the data content into the network. The second one is the technique used among the relay nodes to fasten the delivery of the data packets to the destination.

Erasure coding [3] is a powerful technique used in routing protocols for DTNs. It enables the source to inject redundant packets in the network, with fixed replication overhead. Our first concern is, to what extend would this replication overhead reduce the collecting time needed by the destination for the data packets required to restore the original content. Moreover, an interesting question arise here: how should these coded packets be forwarded or replicated among relay nodes in order to gain this reduction.

In a homogeneous environment, all node movements have the same stochastic characteristic, and thus, a good strategy to reduce the delivery delay is to replicate the same packet in the network. We call such scenario unbiased contact model. On the other hand, in a heterogeneous environment, some nodes may be "better" relay nodes for a given destination than others, because they meet the destination more often. In this case, called biased contact model, a good strategy to reduce the delay is to forward packets from one node to another with a higher probability of meeting the destination.

In this paper we study data delivery in both biased and unbiased cases, using real and synthetic mobility traces. For the biased case we adopted a Simulated Annealing (SA) algorithm that searches for the "best carriers" nodes available in the network. The algorithm is based on the framework reported in [4]. In our proposed scheme, the source exploits erasure coding technique as a mean of splitting the data content into packets suitable to be carried by the nodes, and to inject data packets into the network, with minimum replication overhead. We show that the amount of replication required to reduce the delay could be small and of the same order of magnitude of the original content.

To evaluate our scheme, extensive simulations were carried out. In our simulations we used both synthetic mobility, and real movement traces. Evaluation results confirm our observations about data delivery problem in DTNs, also they show that our data delivery scheme for biased contact model, reduces the delivery delay using fixed storage overhead.

2 Related Work and Background

Many different protocols for DTNs routing have been proposed in the literature. In our previous work [2], we evaluated a wide variety of them. We proposed a clear identification of the main techniques characterizing DTNs routing protocols in order to better understand and classify the solutions proposed in the literature.

Coding-based routing protocols are recently proposed to improve the delivery performance in DTNs. Depending on where the coding functionality is performed, they are divided into two families: erasure coding [3] and network coding based protocols [5]. In the erasure code family, coding operations are all done at the source, and coded packets are disseminated into the network. Well known examples of erasure coding include Raptor, Tornado and Reed-Solomon codes.

In [6] the authors explored the benefit of erasure coding based routing, showing that with coding the best worst-case performance can be achieved for a fixed overhead. Other important works include [7], that studied the problem of optimal routing in a DTN in the presence of path failures with different failure probabilities; [8] that proposed an adaptive protocol that estimates the Average Contact Frequency, used to regulate the spreading phase of a protocol that uses erasure coding; [9] that proposed an Inter-Coding protocol, where coded blocks are interleaved in order to cope with uncertainty about link failure probabilities prediction, and [10] that studied how the cost of erasure coding based routing protocols can be reduced, by leverage different spraying algorithms, right parameter selection and splitting spraying phase on the cost of message delivery.

Erasure-Coding Based Data Delivery: In erasure coding (EC) the source node splits the original content into G data packets, or fragments $E_1, E_2, ..., E_G$ of equal size, and it emits $K = rG$ packets. It first emits the original G packets followed by other $K-G$ linear combinations over them. r is the replication factor (r is such that K is an integer). An encoded packet x is a liner combination over $GF(2)$. $x = \kappa_1 E_1 \oplus \kappa_2 E_2 \oplus ... \kappa_G E_G$ where κ_i are random binary values, called the encoding vector. Assuming optimal erasure coding is used, the content can fully decoded in the destination when receiving any G out of K packets.

Optimization in Opportunistic Networks: In [4] the authors presented a distributed stochastic algorithm, based on the Markov Chain Monte Carlo method (MCMC) to search for the optimal solution in maximizing a utility function. Their method is based on the well-known simulated annealing algorithm. Their framework can be applied to many problems in opportunistic networking such as, routing, buffer management and content/service placement. Providing efficient local algorithms that can converge to a globally optimal solution. It aims at maximizing a distributed utility function (in their case study, sum of carriers node degree) based on using simulated annealing techniques.

3 Data Collection Model

In this section we present a mathematical model to estimate the impact of erasure coding replication overhead on the expected collection delay needed by the destination. Then, we estimate the impact on this delay when there are two classes of carriers, one of which is more frequently contacted by the destination.

We assume a source generates $K = rG$ packets using an ideal erasure coding protocol. The K packets are uniformly disseminated in the network (in the next section we show how). Each node has a buffer space sufficient to allocate only one data packet. The destination can retrieve the content as soon as it collects any G out of the K packets.

Our first concern is the effect of K on the delivery delay under the unbiased case. The destination node undergoes a sequence of contacts with nodes that come in-range. These are opportunities for the destination to pull a data packet. Let Ω_i be the number of *new packets* the destination collects during the i-th contact ($i \geq 1$), and let $\mathbb{E}[\Omega_i]$ be the expected number of *new packets* the destination gets at contact i. Therefore, $\mathbb{E}[\Omega_1] = 1$, because the destination always gets a new packet in the first contact. Then we have:

$$\mathbb{E}[\Omega_i] = \frac{K - \sum_{j=1}^{i-1} \mathbb{E}[\Omega_j]}{K} \tag{1}$$

From which we also have:

$$\mathbb{E}[\Omega_{i+1}] = \frac{K - \sum_{j=1}^{i} \mathbb{E}[\Omega_j]}{K} \tag{2}$$

Now, by subtracting equation (1) from (2) we get:

$$\mathbb{E}[\Omega_{i+1}] = \mathbb{E}[\Omega_i](1 - \frac{1}{K})$$

From which we get:

$$\mathbb{E}[\Omega_i] = (1 - \frac{1}{K})^{i-1} \tag{3}$$

Then, the number of contacts (delay) d_G required in collecting G packets is:

$$d_G = \min_i \{i| \sum_{j=1}^{i} \mathbb{E}[\Omega_i] \geq G\} \tag{4}$$

In Fig.1 we see the delay as a function of K, for different values of G. We see how the delay sharply decreases with K, until it becomes pretty close to the minimum at a replication factor $r = 2$ *i.e.,* $K = 2G$.

Lets now consider a simplified biased scenario, where two different type of nodes exist characterized by different meeting probabilities. The first type belong to class C_1 and the other, to class C_2. At each contact, the destination has a probability β_1 to make a contact to C_1, and $\beta_2 = 1 - \beta_1$ to make a contact to C_2. Let's assume that class C_1, carries α_1 *different packets*, and class C_2 carries α_2 *different packets.* where $\alpha_1 + \alpha_2 = K$.

Let $\mathbb{E}[{\Omega^{c_1}}_i]$ and $\mathbb{E}[{\Omega^{c_2}}_i]$ be the average number of *new packets* the destination gets from C_1 and C_2 respectively at contact i. Then, the probability of getting a useful packet at contact i from C_1 is: $p_i = \frac{\alpha_1 - \sum_{j=1}^{i-1} \mathbb{E}[{\Omega^{c_1}}_j]}{\alpha_1}$, from which:

$$\mathbb{E}[{\Omega^{c_1}}_i] = \beta_1 (\frac{\alpha_1 - \sum_{j=1}^{i-1} \mathbb{E}[{\Omega^{c_1}}_j]}{\alpha_1}) \tag{5}$$

As we did in equation (3):

$$\mathbb{E}[{\Omega^{c_1}}_i] = \beta_1 (1 - \frac{\beta_1}{\alpha_1})^{i-1} \tag{6}$$

As well, for class C_2:

$$\mathbb{E}[\Omega^{c_2}{}_i] = \beta_2 (1 - \frac{\beta_2}{\alpha_2})^{i-1} \tag{7}$$

Then, the average number of packets the destination gets at each contact i is:

$$\mathbb{E}[\Omega_i] = \mathbb{E}[\Omega^{c_1}{}_i] + \mathbb{E}[\Omega^{c_2}{}_i] \tag{8}$$

From which we can get the delay d_G as in equation (4).

We confirm the validation of this model using numerical simulation reported in Fig.1 and Fig.3. Fig.3 shows the delay as a function of α_1 for $G = 20$ and $K = 40$. As expected, the delay reduces with α_1. However, it worth to note that the delay becomes small even when we are able to allocate a slightly more than G packets to class C_1. These results will drive us to design our proposed protocol.

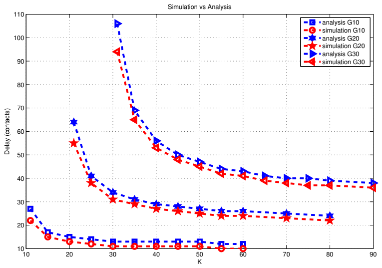


Fig. 1. Delay(contacts) vs K. (blue) theoretical model. (red) simulating the model

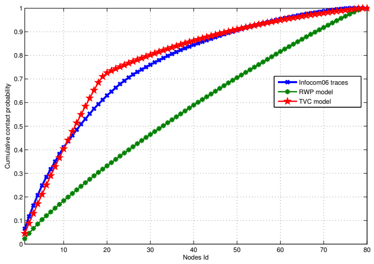
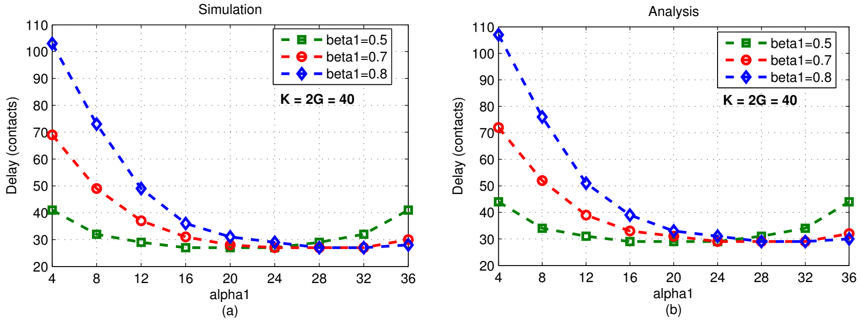


Fig. 2. cumulative contact probability. b/w the destination and other nodes.



(a)

(b)

Fig. 3. Effect of β and α on the Delay, given $K = 2G = 40$. (a)is simulated, (b)is the theoretical model

4 Forwarding and Replication

In this section we discuss the techniques most suitable for data delivery in unbiased and biased contacts cases. We start by analyzing three types of movements traces to see their contact characteristics.

The first movements are synthetic traces generated by simulating 80 nodes moving according to the random way-point model (RWP) [11]. These traces supposed to produce non-biased contacts among the nodes. Simulation area is a square of dimension 1000 by 500 meters. Nodes transmission range is 20 meters with movement speed uniformly selected from the range of [1.0, 2.0] meters per second (walking speed), and maximum pause time of 100 seconds. Time duration is 4-days.

The second movements are also synthetic traces, using similar simulation settings as above. But nodes are moving according to the time-variant community mobility model (TVC) [12], which defines communities that are visited often by the nodes to capture skewed location visiting preferences. In particular, we define 4-communities each of 20 nodes. Nodes undergoes two epoch stages, of duration 100 and 30 seconds respectively. For each stage a different aggregation value is used to aggregate the nodes around the community center (we used 0.5, 0.0 respectively). The more this value approximates to 1, the nodes will be more aggregated and closer to the group center. With aggregation 0, the nodes are randomly distributed in the simulation area. Both RWP and TVC contacts are averaged over 50 runs.

The last movements are from Infocom06 [13] real traces extracted from CRAWDAD [14]. These traces were logged using devices carried by 78 users, during 4-days experiment. More details about this traces are in section 6.

In Fig. 2 we plot the cumulative contact probability between a selected destination and each other node. The x-axis represents the contacted node Ids, sorted by their contact probabilities, while the y-axis is the cumulative contact probability between the destination and these nodes.

Infocom06 traces and TVC model clearly show how the cumulative contact probability rapidly increased up to specific group of nodes, then it increased slowly. This indicates that there is a *small* group of nodes in the network which the destination is more biased to contact than the rest of other nodes. On the other hand, the cumulative contact probability generated by RWP increases linearly with respect to the contacted nodes, which indicates that the destination has no biasing in contacting any node.

4.1 Unbiased Contact Model

In the unbiased contact case, such as in RWP, all nodes have the same probability to reach the destination. Hence, the optimal approach to maximize the probability for the destination to get any coded packet at each contact, is to uniformly replicating the K packets among all relays. This can be achieved by Binary Spraying protocol (BSW) with parameter $L = \frac{N}{K}$, where N is the total number of nodes. Indeed, in [15], its proven that, binary spraying optimally minimizes the dissemination time. As discussed in the previous section, also shown in Fig. 1, using $K = 2G$ is sufficient to reduce the collecting time by the destination, also its a good compromise to reduce the time consumed by the source to inject the data packets.

4.2 Biased Contact Model

In real environments, things are different. Some nodes may be "better" relays, such, for example, could be nodes that tend to see the destination more often, or have similarity in their movements pattern, as discussed in Infocom06 and TVC. We approximate this behavior to our model of two classes of nodes. For example in Fig. 2 we see, in both infocom06 and TVC the destination, approximately, contacts a node from the first 20 ones with probability $\simeq 0.7$.

If we adopt the replication based approach (used in biased contact case), where each packet is replicated $\frac{N}{K}$ times, then class C_1 will carry $\alpha_1 = \frac{N_1}{N} \times K$ different packets, where N_1 is the number of nodes in C_1. Now, to have at least G packets in C_1, assuming $r = 2$, then N_1 must be $\geq N/2$, however, this is not realistic for the destination to be biased or to have similar movements to half of network nodes.

An alternative approach is to use a forwarding scheme that search for the optimal K carriers that maximize the delivery probability to the destination in the whole network.

5 Proposed Data Delivery Scheme

In this section we design a scheme for data delivery under biased contact model. We aim at reducing the delivery delay and storage overhead. We assume that each node has a storage buffer size of one packet. This assumption is motivated by our goal of providing a lower bound for the use of erasure coding in a network of resource-constrained devices.

Initially, the source erasure-codes the data content and generates $K = 2G$ coded packets, then forwards them to the first K nodes. The source needs to exploit every contact to inject the data packets for two main reasons: 1) since each node can carry only one packet, the source need several contacts to disseminate the whole content, 2) the "best carriers" nodes not necessarily have high contacts probability with the source. Since they may have different movement patterns.

5.1 Estimation of Node's Contact Probability

Each node estimates its contact probability to the destination. We adopt a simple and effective approach, used in many previous DTNs routing algorithms [16], namely: exponentially weighted moving average (EWMA). More specifically, each node i maintains its contact probability μ_i to the destination, which is updated every time slot t, according to the following formula:

$$\mu_{i,t} = \begin{cases} (1-\delta)\mu_{i,t-1} + \delta & \text{meeting occurs} \\ (1-\delta)\mu_{i,t-1} & \text{no meeting} \end{cases}$$

Where δ is a constant parameter between 0 and 1. Clearly, this is a dynamic process, and thus μ_i doesnt necessarily equal to the actual contact probability P_i . However, In [16] it's shown that if nodes i and j have a probability of P_{ij} to meet in every time slot, then, the mean of EWMA converges to P_{ij}. Applying it to our case, yields:

$$\mathbb{E}[\mu_{i,1}] = (1-\delta)\mu_{i,0} + \delta P_i$$

$$\mathbb{E}[\mu_{i,2}] = (1-\delta)^2\mu_{i,0} + \delta P_i(1 + (1-\delta))$$

$$\mathbb{E}[\mu_{i,t}] = (1-\delta)^t\mu_{i,0} + \delta P_i \sum_{j=1}^{t} (1-\delta)^{j-1}$$

From which we get:

$$\lim_{t\to\infty} \mathbb{E}[\mu_{i,t}] = \delta P_i \frac{1}{\delta} = P_i$$

5.2 Forwarding Technique

By our forwarding technique we aim at finding the subset C_K of K nodes that maximize the utility function $U(C_K) = \sum_{\forall j \in C_K} \mu_j$. In [4], a well done framework is proposed where simulated annealing (SA) algorithm is employed for optimization problems for opportunistic networks. They showed that SA algorithm can be employed in DTNs for globally selecting a subset of nodes that maximizes a utility function.

SA employs randomization in searching for the optimal solution, which not only accepts states that increase the utility function but also some changes that decrease it, to avoid becoming trapped at local maxima. The latter are accepted with a probability $p = \exp(\frac{-\Delta U}{T})$, where ΔU is the decrease in U, and T is a control parameter (temperature). This randomization is controlled by the parameter T. The way in which the temperature is adapted is called a "cooling schedule": starts with a relatively high T, so that more randomization is used in searching for the high utility states, and gradually cool down the system, in order to converge to the maximum utility. In our implementation we used an empirical exponential cooling schedule.

As proved in [4], and since our utility function is evaluated locally, this enables a fully distributed implementation of the optimization algorithm. This implies that the marginal contribution of each node is independent of the of other nodes. Accordingly, when a relay node r carrying a packet *pkt* contacts an empty node e, the technique explained in Algorithm 1.

Algorithm 1 SA Forwarding Technique

```
$U_r = \mu_r$
$U_e = \mu_e$
if $U_e \geq U_r$ then
    forward $pkt$ to node $e$
else
    $\Delta U = U_e - U_r$
    $p = \exp(\frac{-\Delta U}{T})$
    if $p \geq rand(0, 1)$ then
        forward $pkt$ to node $e$
    end if
end if
```

6 Evaluation

To evaluate data content delivery schemes, we create two simulating scenarios. For the first scenario, which reflects the biased case, we use Infocom06[13] real traces, which were logged by iMote devices (with wireless range around 30 meters) carried by 78 volunteers, joined a 4-days experiment conducted at Infocom 2006. The source and the destination were selected from two of the 20 static long range (around 100 meters) iMote devices, that were placed at various locations of the conference venue. We parsed these traces to be injected into the ONE simulator [11]. For the second scenario, which reflects the unbiased case, we use synthetic mobility generated by RWP model with the simulation settings as discussed in section 4. Two fixed nodes are selected to be the source and the destination. Data content is generated in the source after a reasonable warm-up time.

6.1 Discussion

Initially, we compare our delivery scheme (SA), against Binary Spray and Wait (BSW) with replication $L = N/K$ (number of packet copies). Recall that BSW with $L = N/K$ will uniformly disseminate the K packets among all the nodes. Fig. 4, depicts the delivery delay for these two protocols in both scenarios. In plot (a), (Infocom06 scenario), not only SA has less delay than BSW in all cases of G, but also after $K = 2G$ the delay is almost constant. This indicates that SA succeed in finding the high utility relay nodes, thus, injecting more packets has no impact on the delivery delay. On the other hand, BSW has the least delay when $K = 2G$, while after this point the delay increases. This is because, larger K will require the source to contact more nodes to inject them into the network. Also since $L = N/K$ the spraying time for all the K packets among nodes will be increased.

However, things are different with RWP scenario, in plot (b), BSW performs better than SA. This is because there is no biasing, thus, SA can't find the "best carriers". As a consequence, the delay just reduced by increasing K.

It is important to note that storage overhead, which is the total number of packets in the network, is an important factor. In particular when there are more than one content to be delivered. SA generates, in total, just the K packets. While BSW, to gain its optimal performance, floods the K packets among all nodes. Fig. 5 depicts in (a) the delay, when there is one or two data contents to be delivered. Its clear that the delay of SA almost doesn't affected when there are two data contents. In plot (b) the number of total transmissions needed by SA is almost similar to BSW, even its less with small G.

The other objective, is to evaluate our scheme against a protocol uses not only replication but also forwarding for data delivery. We select Binary Spray and Focus (BSF) [17] which has two phases, it binary sprays L copies for each packet in the spray phase, then starts the focus phase, in which, packets are forwarded to nodes having lower age of last contact time with the destination.

To illustrate the impact of erasure coding, we run BSF with different L values in two cases: 1) when the source generates just the G packets, as in Fig.6, 2) when the source generates $K = 2G$ packets(we call it EC-BSF), as in Fig.7. In both figures we see how SA outperforms BSF or EC-BSF in terms of delivery delay and total transmissions. In addition, SA doesn't employ any replication among nodes while in BSF or EC-BSF each packet is replicated L times. If we compare BSF with EC-BSF as in Fig.6 (a) and Fig.7 (a) respectively. We notice that the delay is reduced using erasure coding; for example the delay in EC-BSF with $L = 2$ is less than the delay in BSF with $L = 4$.

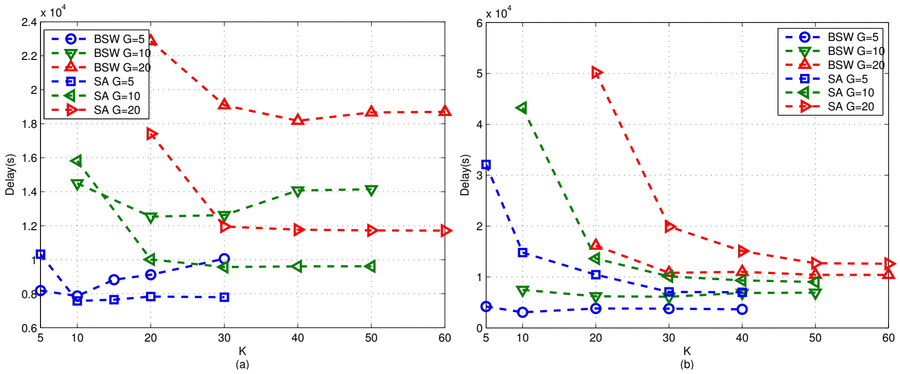
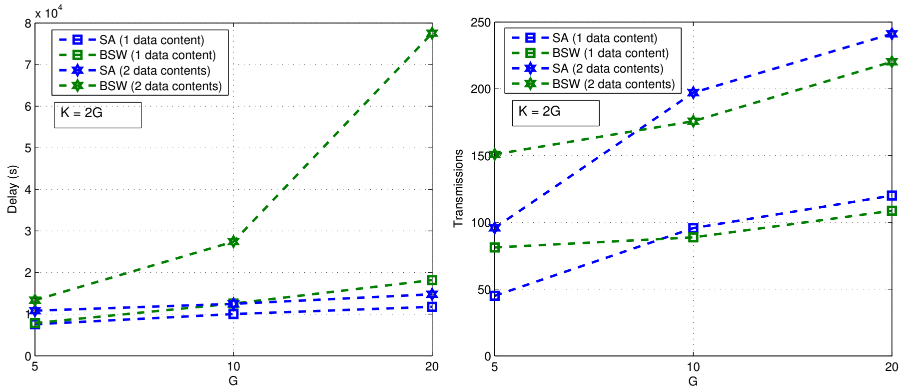


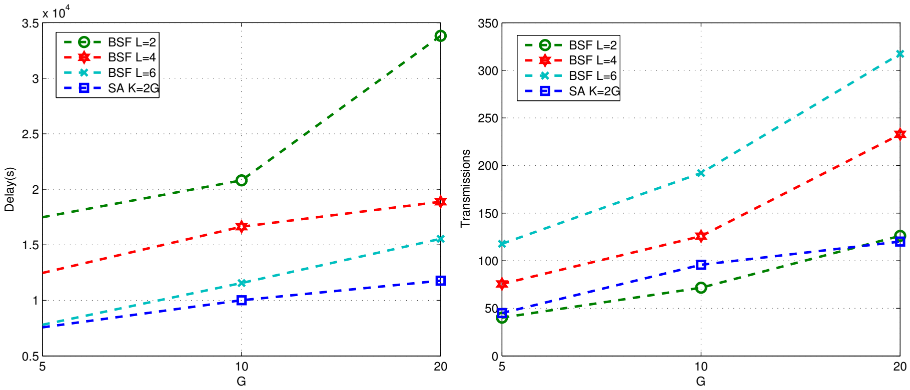
Fig. 4. Delivery delay vs K for different G. (a) using Infocom06 traces, (b) using RWP model



(a)

(b)

Fig. 5. SA and BSW protocols under Infocom06 contacts where the source generates one data content, or two data contents. (a) Delivery delay, (b) Number of transmissions



(a)

(b)

Fig. 6. SA with $K = 2G$, and BSF with $K = G$ packets each replicated L times. Under Infocom06 contacts. (a) Delivery delay and (b) Number of Transmissions

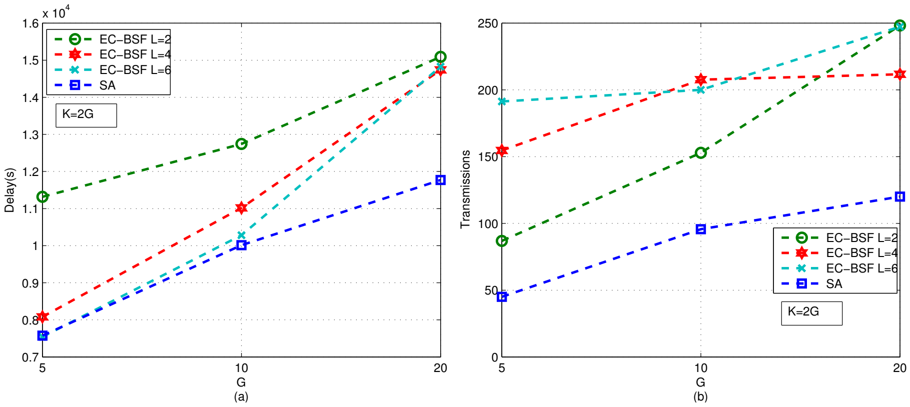


Fig. 7. SA with $K = 2G$, and EC-BSF with $K = 2G$ packets each replicated L times. Under Infocom06 contacts. (a) Delivery delay and (b) Number of Transmissions.

7 Conclusion

In this paper we have studied data delivery in DTNs for both biased and unbiased contact models. The source exploits erasure coding as a mean of splitting the data content that doesn't fit in a single packet, into a number of encoded packets suitable to be carried by the nodes. We showed that the erasure coding replication factor required to reduce the decoding delay could be small and of the same order of magnitude of the original content.

This small replication overhead reduces the time consumed by the source to inject the data packets into the network. Then, the underlying movement patterns of the nodes must be taken into consideration when designing the routing technique. For the unbiased contact model reducing the delivery time is proportional to replicating every packet. While in the biased case selecting the high utility group of nodes as data carriers is the key factor. For this issue, we have designed a scheme for data delivery, which is based on Simulated Annealing (SA) algorithm to searches for the best carrier nodes available in the network.

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