# Cost Efficient Erasure Coding based Routing in Delay Tolerant Networks

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***Abstract*—Routing in delay tolerant networks (DTNs) in which most of the nodes are mobile and intermittently connected is a challenging problem because of unpredictable node movements and lack of knowledge of future node connections. To ensure reliability against failures and increase the success rate of delivery, erasure coding technique is used to route messages in DTNs. In this paper, we study how the cost of erasure coding based routing protocols can be reduced. Specifically, we analyze the effects of different spraying algorithms, right parameter selection and splitting spraying phase on the cost of message delivery. We also perform simulations to evaluate the proposed approaches and demonstrate that the cost of erasure coding based routing can be reduced considerably with the proposed strategies while maintaining the delivery rate and delay objectives.**

## I. Introduction

Delay tolerant networks (DTN) are wireless networks in which the connectivity between nodes is provided intermittently because of mobility of the nodes and low node density in the network area. Moreover, it is usually not possible to find an end-to-end path from a source to a destination at any given time instance. Therefore, routing of messages in DTNs is more challenging than in traditional networks where the connectivity of nodes is mostly stable and most of the time paths from source to destination do not change throughout the message delivery. Some of the examples of DTN networks in real life are wildlife tracking [1], military networks [2] and vehicular ad hoc networks [3].

Erasure coding technique is an interesting and a powerful approach which is used in routing of messages in DTNs. The technique offers a scheme which first divides a message into $k$ data blocks and then converts these $k$ blocks into a large set of $\Phi$ blocks (encoded messages) such that the original message can be constructed from any subset of $\Phi$ blocks of sufficient cardinality. Here, $\Phi$ is usually set as a multiple of $k$ and $R = \Phi/k$ is called replication factor of erasure coding. Under *optimal erasure coding*, $k$ blocks are sufficient to construct the original message. However, because of the fact that optimal coding is expensive in terms of CPU and memory usage, near optimal erasure coding is used requiring $k+\epsilon$ blocks to recover the original message.

There are several erasure coding algorithms including Reed-Solomon coding and Tornado coding [13]. These algorithms differ in terms of encoding/decoding efficiency, replication factor $R$ and minimum number of code blocks needed to recover the original message. Due to the simplicity and linear time complexity (the benefit of this will be explained later), we use Tornado codes in this paper. Besides, in [13], the average value of $\epsilon$ is reported as $k/20$ for Tornado codes. Therefore, as in previous studies, for simplicity we ignore $\epsilon$ in this paper.

The most important advantage of erasure coding based routing of messages over replication based routing algorithms[1] is that erasure coding algorithms strengthen the robustness of the network against failures. That is, the more messages are spread to the network, the higher is the probability of message delivery to the destination, regardless of the rate of message failures.

Although the usage of erasure coding technique increases reliability in routing of messages in DTNs, it may bring extra cost to the routing algorithm. Unlike the previous work which mostly look at the advantages of erasure coding based routing in providing high delivery rate, small delivery delay and reliability, in this paper we focus on the cost[2] of erasure coding based routing algorithms and discuss different schemes to reduce the cost.

The rest of the paper is organized as follows. In Section II we summarize previous work in the literature. In Section III, we give the details of cost reduction schemes proposed in this paper. Then, in Section IV, we give simulation results. Finally, we conclude and outline the future work in Section V.

## II. Related Work

In literature[3], several routing algorithms are proposed based on erasure coding technique. One of the first studies utilizing the erasure coding approach is [7]. In that study, Wang et al. present the advantages (robustness to failures etc.) of erasure

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[1] In replication based routing algorithms [4], [5], [6], a number of copies of the same message are generated at source node and distributed to other nodes in the network. Then, any of these nodes, independently of others, tries to deliver the message copy to the destination.

[2] We define the cost as the number of bytes transferred between the nodes.

[3] Since in this paper we focus on erasure coding based algorithms, we do not present here the details of the previous replication based algorithms.

TABLE I
NOTATIONS

| Symbol | Definition |
|---|---|
| $M$ | Average size of a message (bytes) |
| $k$ | Number of equal size blocks that a message is split into |
| $k_{max}$ | Upper bound for $k$ |
| $R$ | Replication factor used in erasure coding of a message |
| $\Phi$ | $k \times R$, total number of blocks generated in erasure coding based routing |
| $R_{opt}$ | Optimum value of $R$ in single period case |
| $t_d$ | Message delivery deadline (or TTL of messages) |
| $P(x)$ | Probability of delivery at time x |
| $d_r$ | Desired delivery rate |
| $\tau$ | Total cost of delivery of a message |
| $T_s$ | End of distributing all messages to relay nodes |

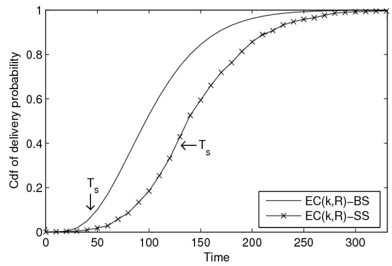


Fig. 1. Comparison of delivery probabilities in erasure coding based routing with binary and source spraying.

coding based routing over the replication based routing. In [8], the split of erasure coded blocks over multiple delivery paths (contact nodes) to optimize the probability of successful message delivery is studied. A similar approach focusing on the distribution of encoded blocks among the nodes is presented in [9]. Based on the realistic assumption that the nodes do not behave identically, an estimation based erasure coding based routing algorithm is proposed. As an extension of this work, in [10], authors also utilize the information of a node's available resources (buffer space, remaining energy level etc.) in the evaluation of the node's capability to successfully deliver the message. In [11], a hybrid routing algorithm combining the strengths of replication based and erasure coding based approaches is proposed. In addition to encoding each message into large amount of small blocks, the algorithm also replicates these blocks to increase the delivery rate.

The main objective of all the above algorithms is to route messages efficiently such that a high delivery rate and small delivery delay is obtained. Unlike previous work, in this paper we focus on the cost of the erasure coding based routing and discuss different schemes to reduce the cost. The only previous work which also considers the overhead of erasure coding based routing algorithm is [12]. However, even in that study the cost is not analyzed as deeply as we do in this paper. Only the optimal parameter selections are considered in that study with the goal of achieving a desired delivery rate eventually. However, the effect of neither distribution nor TTL of messages on the delivery cost is studied.

To improve readability, the list of symbols used in the rest of the paper and their meanings is given in Table I.

## III. PROPOSED APPROACHES

### A. Reducing Cost by Selecting Right Spraying Algorithm

In erasure coding based routing, spraying of all messages takes more time than it takes in replication based routing algorithms because more encoded messages (which are $k$ times smaller) are transferred to many relay nodes. Therefore, the way the messages are distributed to other nodes in the network is a significant factor affecting the performance of the algorithm. The faster they are sprayed to other nodes, the higher is the delivery rate. On the other hand, the spraying stage contributes significantly to the cost of the algorithm. Previous work always assumed that the fast distribution of messages using binary spraying is used [5]. However, using binary spraying may be less cost efficient than source spraying in which only source node can spray the messages to other nodes.

Figure 1 shows the cumulative distribution functions (cdf's) of delivery probabilities in two erasure coding based routing algorithm, each using the same $k$ and $R$ parameters but using different spraying algorithm. (The figure is obtained from a sample run on a network with the same features as used in all simulations used in this paper). The plots clearly show that using binary spraying in erasure coding routing can shorten $T_s$ (the time of completion of distribution of all messages to relay nodes) and increase the delivery probability initially faster than in the case of source spraying. However, using binary spraying increases the cost of erasure coding routing dramatically. According to binary spraying rules, each node having more than one encoded message transfers half of its messages to the first node it meets[4]. But this causes the transmission of many messages between nodes over and over. Hence, the cost of distributing $\Phi$ messages ($\tau(\Phi)$) in erasure coding based routing via binary spraying is:

$$\begin{aligned}\tau(\Phi) &= 2\tau(\Phi/2) + (M/k)(\Phi/2), \text{ where } \tau(1) = 0 \\ \tau(\Phi) &= \frac{M\Phi\log\Phi}{2k} = O(MR\log(kR))\end{aligned}$$

If a node has $\Phi$ messages, it transfers half of them to the first node it meets with cost $(M/k)(\Phi/2)$. Then each of these nodes continues distribution of their own messages independently, incurring the cost $\tau(\Phi/2)$.

On the other hand, source spraying has a cost of $O(\phi) = O(MR)$, however it achieves a slower distribution of messages than binary spraying. This is clear from the plot in Figure 2 which compares the cost of binary and source spraying with different $R$ values (to obtain this plot, we set $M = 100Kb$ and $k = 4$).

[4]In replication based algorithms, the copies of the original message are generated, therefore a node with a right to make Ł copies do not need to give $\lfloor \frac{Ł}{2} \rfloor$ of them to the first node it meets. Instead it can give only one copy to this encountered node together with the right to make $\lfloor \frac{L}{2} \rfloor - 1$ more copies in the same manner. But in erasure coding based routing, the source node generates $\Phi$ encoded messages with different contents, so the same update in the message transfer process between nodes can not be applied.

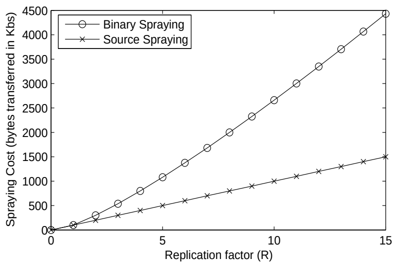


Fig. 2. Comparison of spraying cost in erasure coding based routing with binary and source spraying.

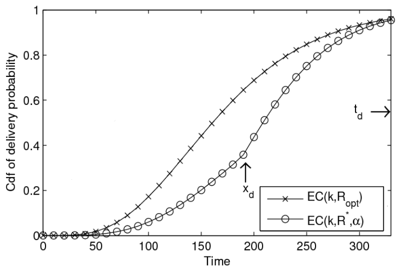


Fig. 3. Cumulative distribution function of delivery probability in two period erasure coding routing.

From the above discussions and the plots in Figures 1 and 2, it is clear that there is a tradeoff between the high delivery probability and the cost of the algorithm. When binary spraying is used to obtain high delivery probability quickly, cost is increased dramatically.

In an erasure coding routing, the cost of source spraying with parameters $k$ and $R$ matches the cost of binary spraying with parameters $k$ and $R'$ when $R'$ is set to the value obtained from $R' \log(kR') \approx 2R$. Clearly, $R'$ must be smaller than $R$ (i.e. in Figure 2, the cost of source spraying with $R$=15 is matched by the cost of binary binary spraying with $R' = 7$). Yet, the binary spraying with $kR'$ encoded messages cannot achieve the same delivery rate as the source spraying with $kR$ messages does. Thus, we conclude that the source spraying is more beneficial than the binary spraying in erasure coding based routing.

### *B. Reducing Cost by Right Parameter Selection*

In previous section, we showed the benefit of source spraying over binary spraying. To reap the full benefit of source spraying, the right parameters needs to be used.

Assume that in a DTN the messages have a user defined TTL value and the objective of routing is to achieve a desired delivery rate ($d_r$) by the time at which the TTL of messages expire. We will refer to TTL of messages as delivery deadline, $t_d$, in the rest of the paper. To minimize the cost of erasure coding based routing, the right parameters ($k$ and $R$) have to be selected.

Let $p(x)$ denote the cdf of a single node's probability of meeting the destination after $x$ time units has passed since it is given an encoded message (If the total number of encoded messages to distribute is not too large and $t_d >> T_s$, for the sake of simplicity, we can assume that all relay nodes in the network get encoded messages at about the same time). Then, the probability that there are already $k$ messages gathered at the destination node at time $x$ becomes:

$$P(x, \Phi) \quad = \quad \sum_{i=k}^{\Phi} \binom{\Phi}{i} p(x)^i (1 - p(x))^{\Phi - i}$$

It should be noted that the erasure coding based routing reduces to the replication based routing when $k = 1$.

Assuming that $t_d$ and the desired delivery rate ($d_r$) at $t_d$ are given, we can determine the optimum parameters minimizing the cost while achieving $d_r$ at $t_d$ using the following relation:

$$(k, R) = \arg\min\{\tau | P(t_d, \Phi) \geq d_r\}$$

From the previous section, we know that changing $k$ does not change the cost. It only affects the slope of the curve, and therefore the delivery rate. Although the value of $k$ can change from 1 to infinity in theory, when $k$ is large, many small blocks are created (in some cases exceeding the total number of nodes in the network) incurring high processing cost and low bandwidth utilization. Therefore we assume some upper bound ($k_{max}$) for $k$. Once, we know $p(x)$, $k_{max}$, $d_r$ and $t_d$, we can find the parameters that minimize the cost of the algorithm using the above inequality by enumeration of all possible $k$ and $R$ values.

### *C. Reducing Cost by Spraying in Multiple Periods*

The cost of erasure coding algorithms can further be reduced by spraying messages to other nodes in multiple periods (while maintaining $d_r$ at the $t_d$). For instance, in two period variant of the proposed scheme, instead of distributing all messages at the beginning (this strategy corresponds to single period), we can spray only some of them at time 0 and wait for the delivery of sufficient number of messages at the destination. If the delivery has not happened yet at a certain time ($x_d$), we distribute more messages to the network so that we increase the probability of delivery. The question is, *'can we reduce the average cost while maintaining $d_r$ at $t_d$?'*

Plot of $EC(k, R^*, \alpha)$ in Figure 3 illustrates the goal we want to achieve in two periods. Assume that in single period case, the optimum parameters are $k$ and $R_{opt}$. In erasure coding routing with two periods, source node generates $\Phi_2 = kR^*$ (remember that complexity of encoding is linear so this will cause a linear increase in the complexity) encoded messages at the beginning and allows the distribution of only $\Phi_1 = \alpha k R^*$ of them ($0 < \alpha < 1$) in the first period. Then, at the beginning of the second period (after time $x_d$), the remaining messages are distributed so that the probability of gathering of $k$ messages at the destination is increased.

In the first period of two period erasure coding routing, the cdf is P($x$,$\Phi_1$). But in the second period, we need to combine the independent delivery probabilities of first period messages and second period messages which are distributed to the network with a delay of $x_d$ time units. The delivery probability in the second period at time $x$ is:

$$P(x,\Phi_1,\Phi_2)=\sum_{i=k}^{\Phi_2}\left(\sum_{j=l_1}^{l_2}P'(x,j,\Phi_1)P'(x\text{-}x_d,i\text{-}j,\Phi_2\text{-}\Phi_1)\right)$$

$$\text{where } P'(x,j,\Phi_1)=\binom{\Phi_1}{j}p(x)^j(1-p(x))^{\Phi_1-j}$$

$$l_1=\max\{0,i-\Phi_2+\Phi_1\} \text{ and } l_2=\min\{i,\Phi_1\}$$

The goal is, for a given $\Phi$, to find a ($\Phi_1$,$\Phi_2$) pair that lowers the average cost while maintaining $d_r$ by $t_d$. First of all, to be able to catch the delivery rate of single period, the following inequalities must be satisfied:

$$\begin{aligned} R^* &> R_{opt} \\ P(t_d,\Phi_1,\Phi_2) &\geq P(t_d,\Phi) \end{aligned}$$

Moreover, to lower the average cost compared to the cost in a single period, the following inequalities must be satisfied as well:

$$\begin{aligned} P(x_d,\Phi_1)\Phi_1+(1-P(x_d,\Phi_1))\Phi_2 &\leq \Phi \\ \frac{\Phi_2-\Phi}{\Phi_2-\Phi_1} &\leq P(x_d,\Phi) \end{aligned}$$

Using source spraying in two-period erasure coding based routing also provides an extra benefit in terms of the cost. As soon as the second period starts at time $x_d$, source node starts distributing remaining messages at a slower rate than binary spraying. With each message distributed to a relay node, the chance of having $k$ encoded messages at the destination increases. In the mean time, if the message is delivered ($k$ encoded messages have arrived destination) and the source node receives acknowledgment of this delivery, then the source node stops distributing remaining messages, so the average cost is reduced further.

## IV. Simulation Model and Results

We have implemented a Java based simulator to evaluate the performance of proposed cost reduction schemes. We randomly deployed 100 mobile identical nodes (including the sink) on a 300 m $\times$ 300 m torus. The nodes move according to random walk model [14][5]. Each node selects a random direction ([0, $2\pi$]) and a random speed from the range of [4m/s, 13m/s], then goes in that direction during a randomly selected epoch of duration from the range of [8s, 15s]. When the epoch ends, the same process runs again and new direction, speed and epoch duration are selected. The transmission range of the nodes is set to 10 m (Note that under this setting the generated network is very sparse which is the most common case in real DTN scenarios).

Since our goal is to reduce the cost, we modeled the simulation environment in such a way that we eliminate the effects of the other parameters. We assume that the buffer space in each node is large enough to avoid any buffer overflows. We also assume a high bandwidth that allows the transmission of all messages during each node meeting. All messages are assumed to have an average size of $M = 100$ Kbytes. Each message is generated at a randomly selected source node and then addressed to the sink node whose initial location is also chosen randomly. After all the messages are distributed, the destination waits until it receives sufficient number of messages. It is also important to remark that if one of the nodes carrying a message (or messages) meets the destination during the spraying period, it transfers all of its messages to the destination. Therefore some messages can be directly transferred to the destination without being given to relay nodes, thus yielding a saving in total message transfer cost. For the simulations here, we set $d_r = 99\%$, which is a reasonable delivery rate for real scenarios. In the future work, we will also look at the effect of different $d_r$ values on the performance of the algorithm. The presented simulation results are averaged over 1000 different runs.

We first present results regarding the right spraying algorithm selection. Figure 4 shows the average costs per message achieved with different deadlines when source spraying and binary spraying are used. In both algorithms, assuming that the same $k$ value is used, we first found $R$ values achieving the same delivery rate by the deadline (Note that erasure coding algorithm with binary spraying (EC-BS) uses a smaller $R$ value than it is used in the erasure coding algorithm with source spraying (EC-SS) to achieve the same delivery rate by the deadline) and computed the cost when these $R$ values are used. As the results show, EC-BS generates higher cost than EC-SS even though it uses smaller $R$ value. This result again proves the advantage of source spraying over binary spraying.

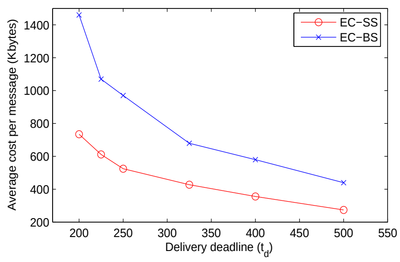


Fig. 4. Average costs achieved in single period erasure coding routing when source spraying and binary spraying are used in message distribution.

Before looking at the performance of multi-period spraying approach, we first discuss two different types of acknowledgments for delivered messages. Here, we assume the multi-period source spraying is used.

*TYPE I:* When destination receives a message, it first creates an acknowledgment for that message and sends it to other nodes within its range, which is assumed to be same for all the nodes in this case. Then, using epidemic routing, this acknowledgment is spread to all other nodes whenever there is a contact between a node carrying the acknowledgment and a node without it. Note that since the acknowledgment

[5]We also performed simulations using random direction and random waypoint models. Since the results are similar, for brevity and due to the lack of space, we did not include them here.

messages are much smaller than data messages, the cost of this epidemic-like acknowledgment process is small compared to the cost of routing data messages. Therefore, we ignore the cost incurred by acknowledgment distribution. However, we do take into account the effect of acknowledgment distribution on data message distribution. When the destination node gathers enough messages to accomplish delivery (by combining $k$ encoded messages), the source node will continue to distribute copies (further increasing the total message transfer cost) until it receives acknowledgment of the delivery.

*TYPE II:* In this type of acknowledgment, we assume that the destination uses one time broadcast over more powerful radio than the other nodes (this assumption is often satisfied in practice). Thus, the broadcast reaches the source node of the message at the exact time of delivery of the message. Like in the previous case, the acknowledgment message is short, so its broadcast is inexpensive.

It is clear that Type II acknowledgment results in better performance of delayed spraying than Type I acknowledgment. However, it may require higher energy consumption. In simulations, we compare the performances of both methods by showing how they impact the results of our algorithm.

Table II shows the minimum costs incurred by *EC-1p* (suffix "xp" denotes x-period version of EC routing) and *EC-2p* algorithms with the aforementioned two different types of acknowledgments. In both algorithms, we found the optimal parameters which provide minimum average costs using the formulations from previous section. In *EC-2p* algorithm, we used $k_{max} = 5$.

First of all, even though we did not show it here for the sake of brevity, in both algorithms the desired delivery rate is achieved by the given deadlines. But their costs are different. In all $t_d$ values shown, as it is expected the cost of an algorithm when Type I acknowledgment is used is higher than the cost of the same algorithm when Type II acknowledgment is used. This is simply because of the extra time needed in Type I acknowledgment to inform the source node about the delivery with epidemic like acknowledgment. Even though the message reaches the destination, source node can still continue distributing the remaining encoded messages it has, thus the cost of algorithm increases. Moreover, for almost all $t_d$ values, the cost of *EC-2p* algorithm is smaller than the cost of *EC-1p* when either Type I or Type II acknowledgment is used. This clearly shows the superiority of *EC-2p* over *EC-1p* algorithm. We also observe that as the deadline gets tight (decreases), the improvement achieved (percentage of reduced cost with respect to *EC-1p* algorithm) by *EC-2p* algorithm decreases. This is because as the deadline decreases, more encoded blocks are generated so that the time to distribute all encoded blocks and also the time needed to inform source node in Type I acknowledgment increases. As a result in some cases ($t_d$=200s), the cost of *EC-2p* algorithm becomes higher than the cost of *EC-1p* algorithm. However, in most of the cases, *EC-2p* has a better performance than *EC-1p* algorithm. Moreover, remark that for the same $t_d$ values, the cost difference between Type I and Type II mechanisms in *EC-2p* is larger than the difference in *EC-1p* algorithm. This is because of the higher number of blocks (which requires more time to inform source node in Type I mechanism) distributed in *EC-2p* algorithm compared to *EC-1p* algorithm.

| $t_d$ | Cost of EC-1p-SS (Kbytes) | | | Cost of EC-2p-SS(Kbytes) | | |
|---|---|---|---|---|---|---|
| sec | Opt(R,k) | Type I | Type II | Opt($R^*$,$\alpha$, $x_d$) | Type I | Type II |
| 600 | (3,2) | 343 | 342 | (5, 0.4, 410) | 323 | 319 |
| 500 | (3,3) | 357 | 356 | (5, 0.4, 345) | 299 | 295 |
| 400 | (4,3) | 445 | 443 | (6, 0.5, 270) | 412 | 398 |
| 300 | (5,3) | 536 | 532 | (7, 0.5, 200) | 515 | 495 |
| 250 | (5,5) | 525 | 517 | (8, 0.5, 185) | 538 | 510 |

TABLE II
MINIMUM AVERAGE COSTS OF SINGLE AND TWO PERIOD ERASURE CODING ALGORITHMS.

## V. CONCLUSIONS AND FUTURE WORK

In this paper, we studied the erasure coding based routing problem in DTNs. Unlike the previous work, we investigated the problem in terms of the cost of the algorithm. We proposed several cost reduction schemes and performed simulations to show their ability to reduce the cost of the algorithm. As a future work, we will extend our simulations and study the effects of other parameters on the cost of the algorithm. We also plan to apply the proposed schemes on real DTN traces.

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