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Time Dependent Message Spraying for Routing in Intermittently Connected Networks

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***Abstract*—Intermittently connected mobile networks, also called Delay Tolerant Networks (DTNs), are wireless networks in which at any given time instance, the probability of having a complete path from a source to destination is low. Several routing algorithms have been proposed for such networks based on control flooding in which there is a fixed number of copies for each message.**

Although a DTN is delay tolerant by definition, often there is an upper bound imposed on message delivery delay. In this paper, we propose a novel spraying algorithm in which the number of message copies in the network depends on the urgency of meeting the expected delivery delay for that message. The main objective of this algorithm is to give a chance to early delivery with small number of copies in existence, consequently decreasing the average number of copies sprayed in the network. We derive the formula for the optimum borders of periods for spraying for two-period and three-period variants of our algorithm. We also present simulations of the method and compare their results with the analytical ones and observe the good match between them. Furthermore, we demonstrate that time dependent spraying algorithm provides a significant decrease in average copy count per message while preserving the percentage of the messages delivered before the upper bound of the acceptable delay expires.

I. INTRODUCTION

Intermittently connected mobile networks, also referred to as Delay Tolerant Networks (DTNs), are wireless networks in which at any given time instance, the probability that there is an end-to-end path from a source to destination is low. There are many examples of such networks in real life including wildlife tracking sensor networks [1], military networks [2] and vehicular ad hoc networks [4]. Since the standard routing algorithms assume that the network is connected most of the time, they fail in routing of packets in DTNs.

Routing algorithms for DTNs need to carefully consider the transient connectivity of the network. Hence, in recent years, new algorithms using buffering and contact time schedules have been proposed. Since most of the nodes in a DTN are mobile, the connectivity of the network is maintained by nodes only when they come into the transmission ranges of each other. If a node has a message copy but it is not connected to another node, it stores the message until an appropriate communication opportunity arises. The important considerations in such a design are (i) the number of copies that are distributed to the network for each message, and (ii) the selection of nodes to which the message is replicated.

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In this paper, we study how to distribute the copies of a message among the potential relay nodes in such a way that the predefined percentage of all messages meets the given deadline for delivery with the minimum number of copies used. Unlike the previous algorithms, we propose a time dependent copying scheme which basically considers the time remaining to the given delivery deadline.

The idea of our scheme is as follows. We first spray a number of copies smaller than the necessary to guarantee that the predefined percentage of all messages is delivered to the destination before the given delivery deadline. If the delivery does not happen for some time, then we spray some additional copies of the message to increase the probability of its delivery. Consequently, if an early delivery with small number of copies happens frequently enough, the average number of copies used by each message will be reduced compared to the algorithm with the constant number of messages.

The remaining of the paper is organized as follows. In Section II we review the previous work done on this topic and discuss some basic concepts of mobility assisted routing. We also differentiate our algorithm from others. In Section III we describe our algorithm in detail and provide analysis of its different variants. In Section IV, we present evaluation of the performance of the proposed scheme using simulations and demonstrate the achieved improvements. We also compare the results of our analysis with the simulation results. Finally, we offer conclusion and outline the future work in Section V.

II. RELATED WORK

Routing for delay tolerant networks are generally classified as either replication based or coding based [13]. In replication based algorithms, a number of message copies are generated and distributed to other nodes (often referred to as relays) in the network. Then, any of these nodes, independently of others, tries to deliver the message copy to the destination. In coding based algorithms, a message is converted into a large set of code blocks such that any sufficiently large subset of these blocks can be used to reconstruct the original message. As a result, a constant overhead is maintained and the network is made more robust against the packet drops when the congestion arises. However, these algorithms introduce an overhead of an extra work needed for coding, forwarding and reconstructing code blocks.

Epidemic Routing [3] is an approach used by the replication based routing algorithms. Basically, in each contact between any two nodes, the nodes exchange their data so that they both have the same copies. As a result, the fastest spread of copies is achieved yielding the optimum delivery time. However, the main problem with this approach is the overhead incurred by excessive use of bandwidth, buffer space and energy caused by the greedy copying and storing of messages. Hence, this approach is inappropriate for resource constrained networks. To address this weakness of epidemic routing, the algorithms with controlled replication or spraying have been proposed [5], [6], [7], [14]. In these algorithms, only a small number of copies are distributed to other nodes and each copy is delivered to the destination independently of others. Of course, such approach limits the aforementioned overhead and resources are efficiently used.

The replication based schemes with controlled replication differ from each other in assumptions that they make about the network. Some of them assume that the trajectories of the mobile devices are known, while some others assume that the contact times and durations of nodes are known. There are also some algorithms which assume zero knowledge about the network. The algorithms which fall in this last category seem to be the most relevant to applications because in most of the delay tolerant networks encountered in real life, neither the contact times nor the trajectories are known for certain. Consider the difficulty of acquiring such information in a wild life tracking application where the nodes are attached to animals that move unpredictably.

The algorithms which assume zero knowledge about the network include the one presented in [9], as well as MaxProb [12], SCAR [11] and Spray and Wait [8]. In each of these algorithms limited number of copies are used to deliver a message. Yet, the process of choosing the nodes for placing new replications is different in each of them. In [9] and MaxProb each node carries its delivery probability which is updated in each contact with other nodes. If a node with a message copy meets another node that does not have the copy, it replicates the message to the contact node only if that node's delivery probability is higher than its own. A similar idea is used in SCAR. Each node maintains a utility function which defines the carrier quality in terms of reaching the destination. Then, each node tries to deliver its data in bundles to a number of neighboring nodes which have the highest carrier quality.

In [8] Spyropoulos et al. propose two different algorithms called (i) Source Spray and Wait, and (ii) Binary Spray and Wait, respectively. While in the former, only the source is capable of spraying copies to other nodes, in the latter all nodes having the copy of the message are allowed to do so. In Binary Spray and Wait, when one node copies a message to another, it also gives the right of copying the half of its remaining copy count to that node. This results in distributed and faster spraying compared to the source spraying, but once the spraying is done, the expected delivery delay is the same. The authors provide the expected delay of message delivery in these two algorithms in [14].

Although there are many algorithms utilizing the controlled flooding approach, the idea of copying depending on the urgency of meeting the delivery deadline has not been used by any of them. To the best of our knowledge this idea is new and it helps to decrease the average number of copies generated in the network. We will describe the details of this idea in the next section.

While designing a routing algorithm for a mobile network, an important issue to be considered is the model of mobility of nodes in the network. Random direction, random walk and random waypoint mobility models are the most popular ones among those used by the previous routing algorithms in this field. Among these models, random direction model is considered more realistic than the others.

Node encounters in a mobility model are characterized by the expected meeting time (EM). It is assumed that the time elapsing between two consecutive encounters of any pair of mobile nodes is exponentially distributed with mean EM. This, and some other parameters are specific to each mobility model and can be derived when the network parameters are known [10].

III. Time Dependent Spraying

In this section, we start with listing the assumptions of our model and then we provide the details of our routing scheme and its analysis.

We assume that there are M nodes walking on a $\sqrt{N}$ x $\sqrt{N}$ 2D torus according to the random direction mobility model. Each node has a transmission range R and all nodes are identical. Following the assumptions of the standard Spray and Wait algorithm, we assume that the meeting times of nodes are independent and identically distributed (IID) exponential random variables. Furthermore, we also assume the buffer space in a node is infinite (not crucial since we use number of message copies that is comparable to the standard algorithm), and the communication between nodes is perfectly separable, that is, any communicating pair of nodes do not interfere with any other simultaneous communication. To be consistent with previous research, by L we denote the number of copies distributed to the network.

In some studies, authors find out the minimum number of copies needed to deliver the messages to a destination with a predefined probability before the given delivery deadline. As discussed previously, the optimal delay in a mobile network is obtained by epidemic routing in which there is a complete message exchange at every contact of any two nodes. Figure 1 shows the minimum number of copies (L_{min}) needed to achieve the expected delay by factor $'a'$ larger then the optimal delay [14].

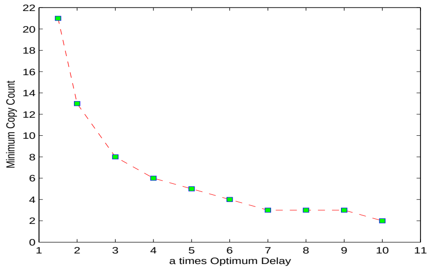

Fig. 1. Minimum L needed to meet the delay equal to $'a'$ times the optimum delay.

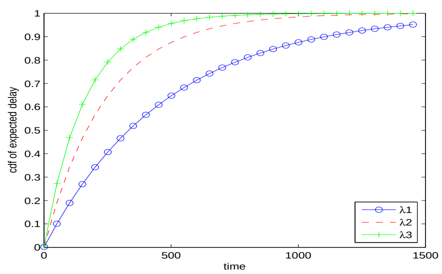

Fig. 2. The cumulative distribution function of probability of meeting the expected delay in Spray and Wait algorithm for different λ values, where $\lambda_1 > \lambda_2 > \lambda_3$

Given the mobility model, the expected delivery time of a message in the Spray and Wait algorithm is equal to [14]:

$$\sum_{i=1}^{L-1} \frac{EM}{M-i} + \frac{M-L}{M-1} EW$$

This formula assumes that in the first $L-1$ contacts, the source node does not meet with the sink node and thus a wait phase is needed (probability of this happening is $\frac{M-L}{M-1}$). Here, EW is the expected duration of wait phase which is actually exponentially distributed with mean $\frac{EM}{L}$. Note that, when $M >> L$ (which we enforce by limiting permissible values of L), duration of spraying phase is much shorter than the duration of waiting phase, so that we can assume that the expected time of delivery in Spray and Wait algorithm is exponentially distributed with mean $\frac{EM}{L}$.

Figure 2 shows the cumulative distribution function of the expected delay of Spray and Wait algorithm for different L values. Clearly, when L increases, mean value $(1/\lambda)$ decreases and the expected delay shrinks.

Our contribution to the spray and wait approach is to control spray of packets to other nodes based on the urgency of meeting the given delivery deadline. More precisely, the algorithm starts with spraying the message copies to fewer nodes than the minimum L needed and then waits for a certain period of time to see if the message is delivered. When delivery does not happen, the algorithm increases the number of copies sprayed and again waits for delivery. This process repeats until either the message is delivered or the delivery deadline

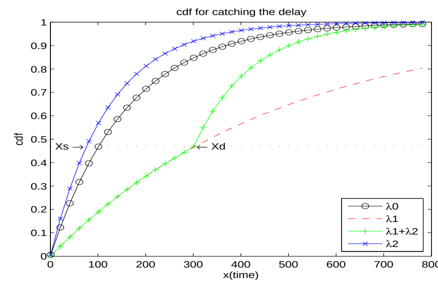

Fig. 3. The cumulative distribution function of delivery time of a message when spraying different numbers of copies in two different periods.

passes. Hence, as the time remaining to the delivery deadline decreases and delivery has not yet happened[1], the number of nodes carrying the message copy increases. To the best of our knowledge, this idea has not been used by any of the previously published algorithms for DTN routing.

Consider the Figure 3. It summarizes what our algorithm achieves. In this specific version of the algorithm, we allow two different spraying phases. The first one starts at the beginning, while the second one begins at time x_d. The main objective of the algorithm is to attempt delivery with small number of copies and use the large number of copies only when this attempt is unsuccessful. With proper setting, the average number of copies sprayed in the network till the message delivery or the delivery deadline will be lower than in case of spraying all messages at the beginning.

To analyze the performance of our algorithm analytically, we need to derive two formulas, one for the average copy count used by the algorithm, and the second one for the cumulative distribution of the probability of meeting the delivery deadline with mixed number of copies (and therefore mixed λ values). The goal is to achieve the same delivery rate of messages by the given message delivery deadline while using fewer copies on average than the standard Spray and Wait algorithm does.

In our scheme, term *period* refers to the time duration from the beginning of one spraying phase to the beginning of the next spraying phase. There may be multiple spray phases and the corresponding periods between them, each of different length. We start with the analysis of the two-period case to find out the optimal period length and the corresponding copy counts of each.

1) Two-Period Case: Since there are to be two periods before the message delivery deadline is reached, the division of time into two periods has to be decided together with the number of message copies that will be made in each. In other

[1] We assume that the destination acknowledges received messages using a broadcast to all nodes, thereby suppressing any spraying after the message delivery. Such acknowledgments are short and can be broadcast using more powerful radio that is often present at the destination node. Although this assumption might be quite strong, the initial results of our future work indicates that using epidemic like acknowledgment spreading may be sufficient. The additional cost of spraying caused by the epidemic delay of acknowledgments is quite small and our method still decreases the average copy count compared to the standard algorithm.

words, we need to choose such value of x_d in Figure 3 that the average copy count of used by the algorithm is minimized.

Let's assume that the standard Spray and Wait algorithm uses L copies (including the copy in the source node) of a message to achieve the probability $p_d \approx 1$ of delivery of the message by the deadline t_d. Let's further assume that the Two-Period Delayed Spraying algorithm sprays L_1 copies to the network at the beginning of execution and additional $L_2 - L_1$ copies at time x_d, the beginning of the second period. Then, the cumulative distribution function of the probability of delivering the message at or below time x is:

$$cdf(x) = \begin{cases} 1 - e^{-\alpha L_1 x} & \text{if } x \leq x_d \\ 1 - e^{-\alpha L_2 (x - x_s)} & \text{if } x > x_d \end{cases}$$

where, $\alpha = 1/EM$ is the inverse of the expected meeting time of any pair of nodes and x_s is the delay with which the spraying with L_2 copies would need to start to match the performance of our algorithm in the second period. To make it more clear, consider the two cdf's marked λ_2 and $\lambda_1 + \lambda_2$ in Figure 3. The second exponential function starts growing with mean $1/\lambda_1$ and at time x_d it changes its mean value to $1/\lambda_2$ and mimics the first function's behavior after time x_s. The value of the x_s can be found using the equality of both cdf functions at time x_d:

$$\begin{aligned} 1 - e^{-\alpha L_1 x_d} &= 1 - e^{-\alpha L_2 (x_d - x_s)} \\ x_s &= x_d \frac{L_2 - L_1}{L_2} \end{aligned}$$

The expected delivery ratio when L copies are used in the standard Spray and Wait algorithm is by definition $p_d = 1 - e^{-\alpha L t_d} \approx 1$. We have tested the success rates of meeting the deadline with different number of copies, where the delivery rate and L are chosen from the values in Figure 1. We want to match these delivery rates while decreasing the average number of copies below L, the number of copies used in the standard Spray and Wait algorithm. Hence, the following inequality must be satisfied:

$$1 - e^{-\alpha L_2 (t_d - x_s)} \geq 1 - e^{-\alpha L t_d}$$
$$L_2 (t_d - x_d + x_d L_1 / L_2) \geq L t_d$$

We can use this inequality to bound x_d as $x_d \leq t_d \frac{L_2 - L}{L_2 - L_1}$. Moreover, the larger x_d is the lower the average copy count is with the same L_1 and L_2 values. Since our algorithm aims at decreasing the average copy count while maintaining the delivery rate of the standard spraying algorithm, then the optimal x_d must be largest possible and therefore

$$x_d = t_d \frac{L_2 - L}{L_2 - L_1}$$

We want to minimize the average number of packets, $c_2(L_1, L_2)$ defined as:

$$c_2(L_1, L_2) = L_1 + (L_2 - L_1) e^{-\alpha L_1 t_d \frac{L_2 - L}{L_2 - L_1}}$$

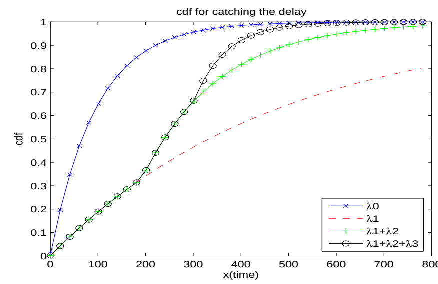

Fig. 4. The cumulative distribution function when spraying different numbers of copies in three different periods.

Taking derivative of c_2 in regard of L_2, and comparing it to zero, we obtain:

$$L_2 = L1 + \alpha L_1 t_d (L - L_1)$$

so $L_2 - L_1 = \alpha L_1 t_d (L - L_1)$ and therefore

$$c_2^*(L_1) = L_1[1 + \alpha t_d (L - L_1) e^{-\alpha L_1 t_d + 1}]$$

Taking the derivative of the above function, we can obtain a complicated formula for the optimal value of L_1^* as a function of L and t_d, and then taking the floor and ceiling of this value we can compute the corresponding optimal values of L_2^*. Then again floors and ceilings of the latter values can be used to arrive at the result. We can also prove that for $\alpha L_1 t_d > 1$ there is exactly one minimum of the cost function with positive value of L_1. A simple method to find this minimum is to enumerate all integer values for L_1 from 1 to $L - 1$ and compute floors and ceilings of each corresponding optimal L_2.

2) Three-Period Case: If there are three spray and wait periods, we need to find two different boundary points which separate these periods. Let x_{d1} and x_{d2} denote these boundary points, respectively. While the former stands at the boundary between the first and the second periods, the latter marks the boundary between the second and the third periods. The cumulative distribution function of the probability of delivering the message by the time x becomes:

$$cdf(x) = \begin{cases} 1 - e^{-\alpha L_1 x} & [0, x_{d1}] \\ 1 - e^{-\alpha L_2 (x - x_{s1})} & (x_{d1}, x_{d2}] \\ 1 - e^{-\alpha L_3 (x - x_{s2})} & (x_{d2}, x] \end{cases}$$

where x_{s_i} is the delay with which spraying with L_i copies would have to start to equal the cdf of our algorithm over the i^{th} spraying period. These values can be easily computed as:

$$\begin{aligned} 1 - e^{-\alpha L_1 x_{d1}} &= 1 - e^{-\alpha L_2 (x_{d1} - x_{s1})} \\ x_{s1} &= x_{d1} \frac{L_2 - L_1}{L_2} \end{aligned}$$

and analogously

$$\begin{aligned} 1 - e^{-\alpha L_2 (x_{d2} - x_{s1})} &= 1 - e^{-\alpha L_3 (x_{d2} - x_{s2})} \\ x_{s2} &= x_{d2} \frac{L_3 - L_2}{L_3} + x_{d1} \frac{L_2 - L_1}{L_3} \end{aligned}$$

Consider Figure 4 that illustrates our approach with three periods. As in the two-period case, we want to achieve no lower delivery rate p_d by the given deadline t_d while decreasing the average number of copies used compared to the standard spraying algorithm. That is, we need to satisfy the following inequality:

$$\begin{aligned} 1 - e^{-\alpha L t_d} &\leq 1 - e^{-\alpha L_3 (t_d - x_{s2})} \\ x_{d2}(L_3 - L_2) + x_{d1}(L_2 - L_1) &\leq t_d(L_3 - L) \end{aligned}$$

Using this inequality, we can eliminate x_{d2} because the larger x_{d2} is the smaller the average copy count is when all other parameters L_1, L_2, L_3 and x_{d1} are kept constant. So using the above inequality as an equality, we obtain:

$$x_{d2} = \frac{t_d(L_3 - L) - x_{d1}(L_2 - L_1)}{L_3 - L_2}$$

Furthermore, the average copy count used in this case is:

$$\begin{aligned} c_3(L_1, L_2, L_3, x_{d1}) &= L_1 + (L_2 - L_1)e^{-\alpha L_1 x_{d1}} \\ &\quad + (L_3 - L_2)e^{-\alpha L_2 (x_{d2} - x_{s1})} \end{aligned}$$

Continuing in the same way as in the two-period case (i.e., substituting x_{s1}, x_{d2}, taking partial derivative and comparing it to zero), we can obtain the formula for optimum x_{d1}.

$$x_{d1} = \frac{\alpha t_d L_2(L_3 - L) + \log(L_1/L_3)(L_3 - L_2)}{\alpha L_2(L_3 - L_1)}$$

Then, we can easily obtain formula $c_3^*(L_1, L_2, L_3)$ by substituting x_{d1} with its optimum value. Since $L_1 < L$, then we can easily enumerate all feasible values of L_1. For given t_d, L and L_1, we can simply bound L_2 from inequality $x_{d1} < t_d$ as $L_2 < L_1 + (L - L_1)e^{\alpha L_1 t_d}$, so for each value of L_1 we will have a small number of feasible values of L_2 to consider. Finally, from inequalities $x_{s1} > 0$ and $x_{d2} < t_d$ we have $L_3 < L_2 + (L - L_1)e^{\alpha L_2 t_d} - (L_2 - L_1)e^{\alpha(L_2 - L_1)t_d}$, so for each feasible pair L_1, L_2 we have small number of feasible L_3's to enumerate and find the optimal triple L_1, L_2, L_3.

IV. Simulation Results

In our simulations, we implemented the standard Source Spray and Wait algorithm using a Java based visual simulator. We deployed 100 mobile nodes, including the sink, onto a torus of the size 300 m by 300 m. All nodes (except the sink that has high range and uses it for acknowledgment broadcast) are assumed to be identical and their transmission range is set at R = 10 m. Nodes move according to random direction mobility model [10]. The speed of a node is randomly selected from the range [4, 13]m/s and once the speed of the node is determined, it goes in the same direction as long as an epoch lasts. Each epoch duration is again randomly selected from the range [8, 15]s. Accordingly, we set EM to 480, so $\alpha = 1/480$. All messages are generated at randomly selected nodes and are addressed to the sink node whose initial location is also assigned randomly. Then, we collected some useful statistics from the network. The results are averaged over 1000 runs.

We computed the optimal combinations of copy counts L_i for each period i analytically and tested them via our

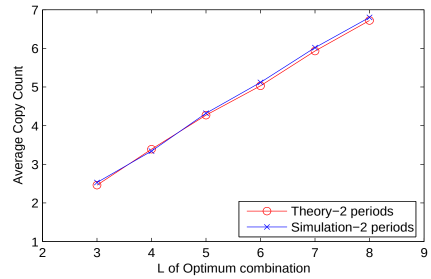

Fig. 5. A comparison of the average copy counts from theory and simulation when the optimum value in two-period case is used.

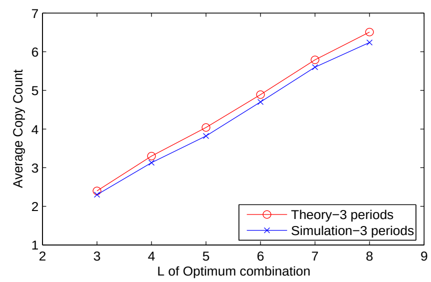

Fig. 6. A comparison of the average copy counts from theory and simulation when the optimum value in three-period case is used.

simulations. Table I shows these optimal L_i's for different L values.

We calculated the average number of copies used by both simulations and the theory when this optimum L_i combination is used. Figures 5 and 6 present these values for different L values, with two periods and three periods, respectively. In the two-period case, theoretical and simulation results are very close to each other. However in the three-period case, the difference gets bigger because in our analysis we ignored the effect of spraying phase. When number of periods increases, period lengths get smaller, so the effect of spraying phase on the cumulative distribution function increases.

To compare the performance of our algorithm with the standard spraying algorithm, we have measured some metrics of both of them via simulations. In these simulations, we used our algorithm with two periods. Figure 7 shows the the average value of delivery delay for messages. Figure 8 shows the average time of completing spraying. This value does not contain the average of cases when the message is delivered before spraying of all potential copies. In Figure 9, we show the success rate which is actually the percentage of all simulations that have delivery time less than or equal to

L	3	4	5	6	7	8
2 periods	(2,5)	(3,6)	(3,8)	(4,9)	(5,10)	(6,12)
3 periods	(2,3,6)	(2,4,7)	(3,5,9)	(4,6,10)	(5,7,11)	(5,8,14)

TABLE I
THE OPTIMAL L_i COMBINATIONS FOR THE GIVEN L.

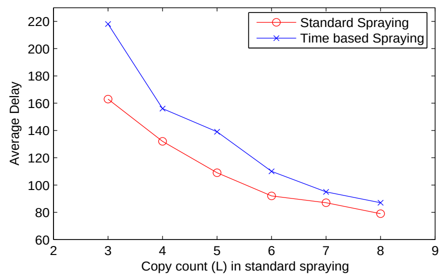

Fig. 7. A comparison of average delays in standard spraying and time based spraying.

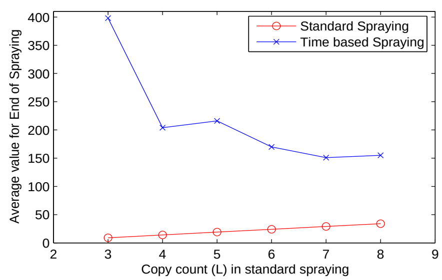

Fig. 8. A comparison of average end of spraying times in standard spraying and time based spraying.

the given deadline t_d.

Inspecting these three graphs, we observe that our time based spraying algorithm incurs higher average delay but it achieves the same delivery rate before the deadline as the standard spraying algorithm. Moreover, since our scheme postpones the spraying of all copies to later times, it finishes spraying later than the standard Spray and Wait algorithm. But this is not a drawback since it achieves the same delivery rate before the deadline.

Finally, Figure 10 shows the improvement achieved by our algorithm in the average number of copies per message for different L values. While the two-period case demonstrates about 16% benefit, the three-period case shows higher improvement of about 20%.

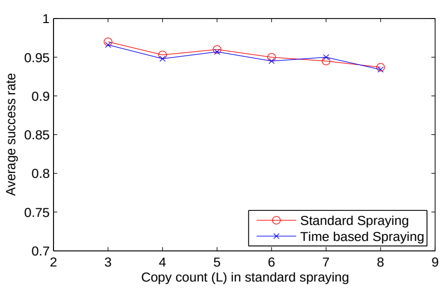

Fig. 9. The delivery rate comparison for standard spraying and time based spraying.

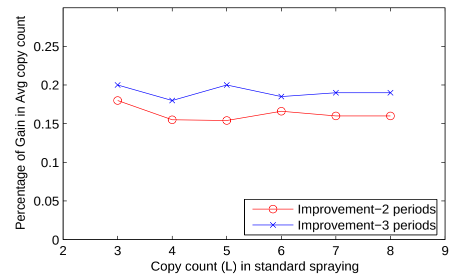

Fig. 10. The improvement in the average number of copies used delivered by the time based spraying .

V. Conclusion and Future Work

In this paper, we focus on the problem of routing for Delay Tolerant Networks in which the nodes are disconnected most of the time. We introduce a Time Dependent Spray and Wait algorithm and evaluate its performance with simulations. We observed that our algorithm uses fewer message copies on average than the standard Spray and Wait algorithm does.

We applied our algorithm with just two and three-period cases. In future work, we plan to apply it to binary spraying and consider cases with more periods. Furthermore, we will evaluate our algorithm with different mobility models and with a real test bed data such as a disconnected bus network.

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