TRADEOFF BETWEEN ENERGY CONSUMPTION AND LIFETIME IN DELAY-TOLERANT MOBILE NETWORK

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ABSTRACT

The lifetime of a wireless network is significantly affected by the energy consumed on data transmission. One approach which allows reduction of the transmission energy consumption is the new networking paradigm - the Delay Tolerant Networks (DTNs). The topology of DTNs consists of nodes with short transmission range, thus allowing the reduction of energy consumption. However, this short transmission range leads to very sparse network topologies, raising the challenge of an efficient routing protocol. Epidemic Routing Protocol (ERP), in which data packets are replicated on nodes that come in contact, is one of such DTN routing protocols. The basic ERP shows the shortest delay in packet delivery, but *this short delay comes at the expense of large energy consumption. In our past publications, we have proposed a number of new variants of ERP for DTN - the Restricted Epidemic Routing (RER) protocols - which allow to efficiently tradeoff between the energy consumption of a single packet and the packet delivery delay. In this paper, we extend our study to determine and to compare the overall lifetime of a network between the various RER protocols.*

1. INTRODUCTION

In an intermittently connected mobile ad-hoc network, packets are relayed from source to sink relying on mobile nodes and the future contingency of encountering other nodes, which results in long delay. Delay Tolerant Network (DTN) is an intermittently connected network that can tolerate packet delivery delay to some degree, while using a short transmission range to conserve transmission energy. Several protocols have been proposed for a DTN that consists of nodes with short transmission ranges. *Epidemic Routing* [1] uses packet flooding method which involves replication and propagation to increase the number of copies of the packet that is destined to the sink. When there are multiple copies in the system, the probability for the sink to receive one of the copies increases and hence the average delivery time reduces as well. However, Epidemic Routing results in excessive expense of resources such as the energy consumption of packet transmission and the network capacity.

There have been several publications proposing different ways to overcome the drawback of the Epidemic Routing protocol [2-9]. For example, *SWIM* [2, 3] uses an anti-packet which is created from the sink and propagated throughout the system using Epidemic Routing. When a node receives an anti-packet, it is notified that the sink has received the packet, and the node removes the copy of the data packet or blocks unnecessary transmission. The *Spray and Wait* routing scheme [4] finds a way to reduce the total number of copies in the system. Since it is impossible for the nodes to count the number of copies in the system, the packet itself should have the information of how many times it should be transmitted. In our past work [5] we proposed and evaluated several schemes using different methods of restricting the *Epidemic Routing* protocol. We derived the analytical models for these Restricted Epidemic Routing (RER) schemes using various Markov chain models. Among these schemes, we were able to find the most efficient tradeoff between energy consumption and delivery time delay.

These works, however, were focused only on conserving node energy for a single routing attempt. Node energy can be conserved by reducing the number of copies at the expense of longer delivery time delay [5-7]. When the battery capacity of each node is limited, after several attempts of Epidemic Routing some of the nodes batteries may get depleted faster than others. This reduces the number of active nodes and the average number of copies in the system. Hence the probability for the sink to receive a copy will decrease as well. This can be improved by simply using the residual battery energy information. This concept is similar to the energy aware routing in ad hoc networks, where nodes are forced to consume energy evenly [10-12].

The remainder of this paper is organized as follows. First we analyze the Epidemic Routing and its performance and try to define the lifetime of an Epidemic Routing network in Section 2. In Section 3, we will apply several Restricted

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Epidemic Routing schemes and see how much these schemes can extend the lifetime. In Section 4, we propose a scheme that uses residual battery information. Simulation and the evaluation results are shown in Section 5, and we conclude our work in Section 5.

2. LIFETIME OF EPIDEMIC ROUTING

Nodes in a DTN usually carry batteries with limited amount of energy. During multiple attempts of Epidemic Routing, before the last node battery gets depleted there will be a time period where the number of active nodes decreases gradually to zero. In this period, the packet delivery probability will also decrease gradually to zero. Hence, the lifetime of the network should be defined somewhere in this period.

2.1. Unrestricted Epidemic Routing (UER)

First, we analyzed the Unrestricted Epidemic Routing (UER) protocol in order to estimate the average number of copies in the system and the packet delivery probability as a function of time t. In our previous work [5], we proposed a stochastic model using a transition diagram of Markov chain model. In a finite area, the encounter between two particular nodes occurs at rate λ. Hence, we can assume that the time between each encounter is an exponential random variable T with parameter λ. Since we assume the encounter process is a Poisson arrival, more than one encounter cannot occur at the same time. Using this idea we can model a Markov chain for the UER.

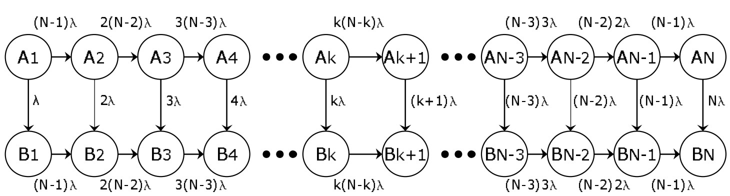

Figure 1: Transition diagram of Markov chain model for number of copies in UER

In Figure 1, state A_k represents that there are k number of copies in the system but none of them has yet reached the sink, and state B_k indicates that there are k number of copies in the system and at least one of them has reached the sink. Suppose there are k copies in the system, then the transition rate from the state A_k to the state B_k is kλ. Since there are (N-k) number of nodes that haven't received a copy, the rate of state increment from state k to (k+1) is k(N-k)λ for both states A_k and B_k. Using this Markov chain model, we can calculate the probability of the system being in each state.

$$P_k(t) = \int_0^t P_{k-1}(x)\cdot(k-1)\{N-(k-1)\}\lambda\cdot e^{-k(N-k)\lambda(t-x)}dx \quad (1)$$
$$(2 \le k \le N)$$
$$P_1(t) = e^{-(N-1)\lambda t}$$

$$P_{A,k}(t) = \int_0^t P_{A,k-1}(x)\cdot(k-1)\{N-(k-1)\}\lambda\cdot e^{-k(N-k+1)\lambda(t-x)}dx \quad (2)$$
$$(2 \le k \le N)$$
$$P_{A,1}(t) = e^{-N\lambda\cdot t}$$

$$P_{B,k}(t) = P_k(t) - P_{A,k}(t) \quad (3)$$

Using these probabilities, we can calculate the expected number of copies of the packet in the system and the cumulative distribution function of the sink node having received the packet at time t.

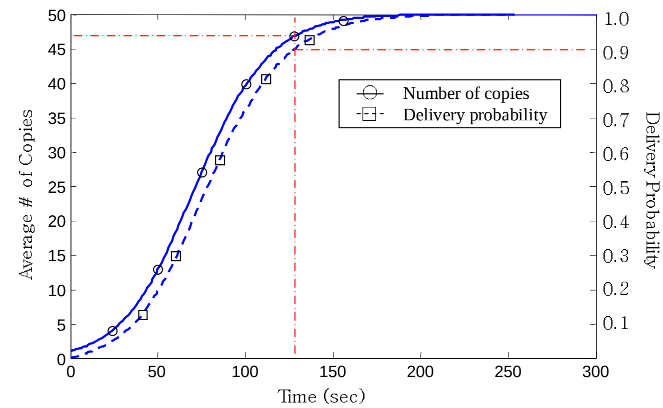

Figure 2: Average # of copies and delivery probability versus time

Figure 2 shows an example result of the average number of copies in the system, and the probability of the sink having received the packet versus time. The total number of nodes in the system is N = 50, and the total area is a 1000m x 1000m closed torus shape with encounter rate λ = 0.4043/sec. After 130 seconds from the packet creation, the average number of total copies in the system reaches 47 and the average packet delivery probability by this time is 90%.

2.2. Variance of energy consumption in UER

Now suppose the total battery energy (BE) capacity of each node is 40 BE, where a single packet transmission to another node costs 1 BE. Then, with 130 sec TTL, the average amount of energy used to propagate 47 copies in the system plus the energy transmitting to the sink is 47 BE. Suppose a packet is created from an arbitrary node every 150 sec. Then, the ideal lifetime of the network would be approximately 106 min (50·40[BE] ·150[sec] / 47[BE] ≈ 6383 sec).

However, this ideal lifetime holds only when every node battery gets depleted at the same time. It is obvious that the source node propagates more copies than other nodes since it carries the packet longer than any other node. After the source node creates a packet, the second copy is created when the source node encounters its first receiver and transmits its packet. Now, the third copy can be transmitted either by the source node (1^{st} node), or the node that carries the second copy, (2^{nd} node). Since either node can be the one to transmit with the same probability, the expected number of transmission by the 1^{st} node is 1/2, which is also same for the 2^{nd} node. By the same process, the n^{th} copy can be transmitted by any of the (n-1) nodes and thus the expected numbers of transmissions are equivalently 1/(n-1). Hence, when there are total of C number of copies in the system we can derive the expected value of the total number of transmission for the n^{th} node (TR_n) participated in the propagation.

$$TR_n = \sum_{x=n}^{C-1} \frac{1}{x} \qquad (1 \le n \le C\text{-}1) \qquad (4)$$

Eq. (4) shows that the energy consumed by each node is not equivalent. During multiple attempts of UER, some nodes will have their batteries depleted sooner than other nodes. When a node battery gets depleted, there will be (N-1) number of active nodes for the next UER, and every rate in the Markov chain will decrease, and the packet delivery probability at the sink will decrease. Thus, as the number of active nodes decreases, the delivery probability will decrease as well.

2.3. Defining lifetime of ER network

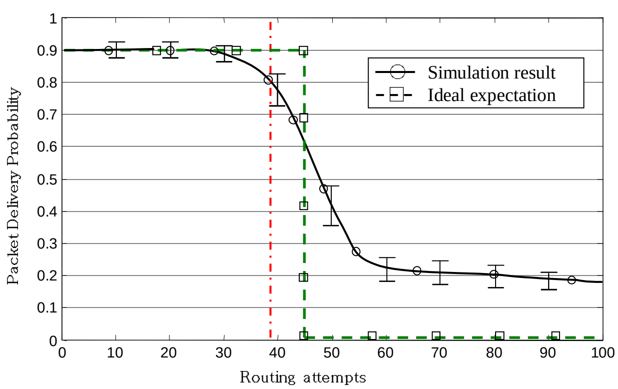

Figure 3: Delivery probability for multiple attempts of UER

Figure 3 shows the simulation result and the ideal expectation of the delivery probability during multiple attempts of UER. The network consists of 50 nodes in a 1000m x 1000m closed area (torus). The encounter rate is λ = 0.004043/sec, TTL is 130 sec, and a packet is created from an arbitrary node every 150 sec. The simulation results are averaged over 1000 samples of 100 trials (total of 100,000 trials), and the confidence level of each confidence interval is 95%. As we have seen in Figure 2, the delivery probability is 90% when all the nodes are active. As the nodes consume their battery energy, the number of active nodes decreases gradually and the delivery probability at the sink drops below 80% after 39 routing attempts. When the routing attempts reach the ideal lifetime of the network, which is 43 routing attempts ($50 \cdot 40$[BE] / 47[BE] = 43), the delivery probability at the sink is approximately 60%. We can see that even after the ideal lifetime there are some active nodes participating in Epidemic Routing, delivering packet to the sink. However, a network with low packet delivery probability is not reliable, especially in critical situations such as in a natural disaster or on the battlefield.

In order to define a lifetime of an ER network, we first need to set two delivery probabilities. The first one is the Target Delivery Probability (TDP), which is defined as the average delivery probability when all the nodes are active. The second one is the Minimum Delivery Probability (MDP), which is defined as the threshold of the packet delivery probability. Hence, the lifetime of the network will be the time or the number of packet routing attempts until the delivery probability at the sink drops below the minimum delivery probability, call it the MDP lifetime. In this paper, the TDP is set to be 90% and the MDP 80%. Figure 3, for example, shows that the MDP lifetime of UER is approximately 97.5 min ($39 \cdot 150 = 5850$ sec). The difference between the ideal lifetime and the MDP lifetime of this UER network is almost 9 min (533 sec).

In the next section, we will introduce three different schemes of *Restricted Epidemic Routing* (RER): the *Exclusion* scheme (EX-scheme), the *Limited Time* scheme (LT-scheme), and the *Limited Number of Copies* scheme (LC-scheme). We will see how these RER schemes increase the ideal lifetime and the MDP lifetime.

3. EXTENDING LIFETIME WITH RER SCHEMES

In our previous work, we derived the tradeoff functions for several RER schemes to evaluate their efficiency of reducing the number of copies at the expense of delivery time delay while maintaining the delivery probability. By reducing the number of copies, consequently the total energy consumption for a single routing attempt will be reduced and hence we can expect the lifetime of the network to extend.

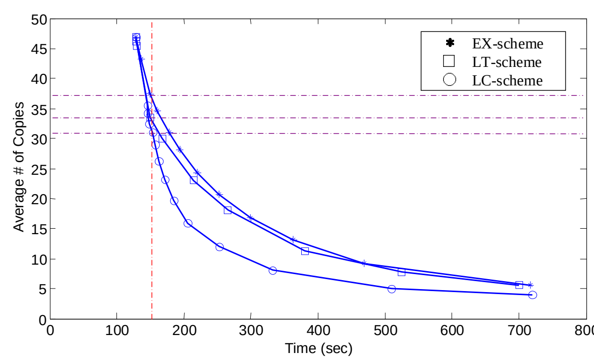

Figure 4: Tradeoff of the RER schemes (90% delivery probability)

Three graphs in Figure 4 indicate the tradeoff functions between the number of copies and the delivery time delay with 90% delivery probability for each RER scheme. From this tradeoff, we can estimate the required number of copies to obtain the TDP (90%) within the TTL. Suppose that a packet is created every 150 sec and we don't want to have multiple packets being routed in the system at the same time. Then, the TTL can be at maximum 150 sec. In Figure 4 at 150 sec, the points where the vertical line crosses with the tradeoff curves are the minimum number of copies required for each scheme. The required numbers of copies are 31 copies for LC-scheme, 33 copies for LT-scheme, and 37 copies for EX-scheme.

3.1. Exclusion scheme (EX-scheme)

EX-scheme excludes some of the nodes from epidemic routing. Before the source node encounters another node and propagates its packet, it decides randomly which nodes will be excluded from the epidemic routing process. This is merely the same UER except that the total number of nodes being used throughout the Epidemic Routing is reduced to a certain value of M that is smaller than N. Basically, the Markov chain model for EX-scheme is the same as Figure 1, except that the outgoing rate at each state and the total number of states decreases.

In order to find the total number of nodes being used (M) in EX-scheme which satisfies the TDP (90%), we first need to use the Markov chain model for the EX-scheme. Using the Markov chain model we can derive the number of copies in the system at 150 sec for different values of M. Consequently, the EX-scheme with 37 copies in the system at 150 sec is the one with the M value that limits the total number of nodes being used.

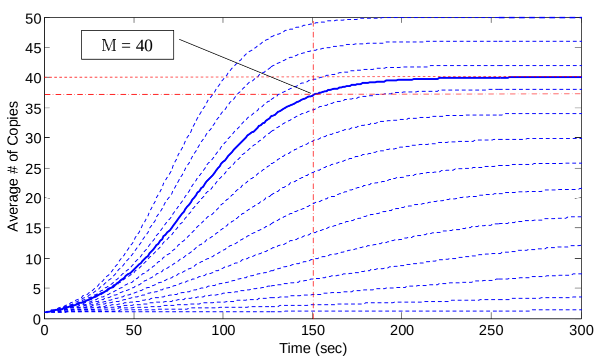

Figure 5: Average number of copies for EX-scheme with different values of M

Figure 5 shows that when the total number of nodes being used is limited to M = 40, then the average number of copies in the system becomes 37 at 150 sec. Hence, in order for the EX-scheme to satisfy the TDP (90%), the total number of nodes being used during epidemic routing should be limited to 40. Assuming that every node has battery capacity of 40 BE, since the average number of copies at 150 sec for this EX-scheme is 37, the ideal lifetime of this EX-scheme would be approximately 135 min (50·40[BE]·150[sec] / 37[BE] ≈ 8108 sec).

3.2. Limited Time scheme (LT-scheme)

Limited Time scheme (LT-scheme) has two different time limits. One is the TTL which is same as other schemes, and another is the time limit until the nodes can propagate the copy of the packet. After this Propagation Time Limit (PTL), all the nodes wait until they encounter the sink node, and then transmit the copy to the sink node. The Markov chain model for LT-scheme is exactly the same as Figure 1. Hence, the average number copies in the system will be also the same as UER until the time reaches the PTL. After the PTL, the number of copies does not increase.

This makes it simple to find the PTL for LT-scheme that satisfies the TDP (90%). Since the Markov chain model does not change, first we need to derive the average number of copies in the UER for each time. We have already seen that the LT-scheme requires 33 copies in order to satisfy TDP = 90%, and the corresponding PTL is the time point where the average number of copies in the system reaches 33.

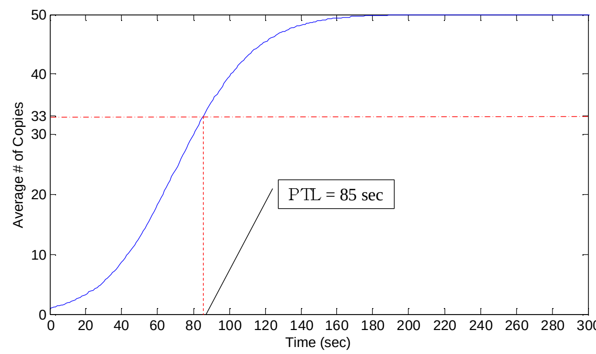

Figure 6: Average number of copies for LT-scheme

As we can see in Figure 6, when the PTL is set to 85 sec, the average number of copies in the system becomes 33. Assuming that every node has battery capacity of 40 BE, since the average number of copies at 150 sec for this LT-scheme is 33, the ideal lifetime of this LT-scheme would be approximately 151.5 min (50·40[BE]·150[sec] / 33[BE] ≈ 9091 sec).

3.3. Limited Number of Copies scheme (LC-scheme)

LC-scheme restricts the Epidemic Routing by limiting the total number of copies (m) that can be propagated in the system. In order to limit the total number of copies, each packet has the information of how many times it should be propagated. Unlike the other two RER schemes, the Markov chain model for LC-scheme is quite different from UER, since the number of copies and the number of nodes that can propagate are not equivalent. Hence, we need to use a 2-dimensional Markov chain model to derive the average number of copies in the system.

Figure 7 is an example of the 2-dimensional Markov chain model for LC-scheme where the number of copies in

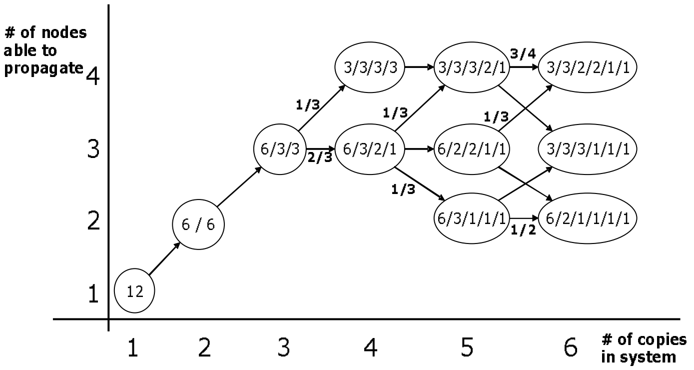

Figure 7: 2-D Transition diagram of Markov chain model for LC-scheme (max. 12 copies)

the system is limited to 12. The X- and the Y-axis indicate the number of copies in the system and the number of nodes that are able to propagate, respectively. A state is labeled with the number of nodes carrying packet copies and their loads.

In state [6/2/2/1/1], for example, there are 5 nodes carrying a copy of the packet. One of the nodes has 6 loads of copies, which means it has to propagate 5 more copies to other nodes. Two other nodes with just one load mean these two nodes do not propagate any more. The next state is determined by the number of nodes carrying more than one load in the present state and the assumption that each node has the same probability of encountering another node. Using the probability of being in each state, we can derive the average number of nodes that can propagate (n_k) when there is k number of copies in the system. Eventually what we get is a Markov chain model similar to Figure 1 with 2 by m states, and rate of state increment from state k to (k+1) becomes $n_k(N-k)\lambda$ for both states A_k and B_k.

In order to find the value m that limits the total number of copies for LC-scheme satisfying the TDP (90%), we use the same method used finding the value of M for EX-scheme. Using the 2-D Markov chain model we can derive the number of copies in the system at 150 sec for different values of m, and then we can find the m value corresponds to the LC-scheme that reaches 31 copies at 150 sec.

Figure 8 shows that when the total number of copies is limited to m = 36, the average number of copies in the system becomes 31 at 150 sec. In order for the LC-scheme to satisfy the TDP (90%), the total number of copies that can be propagated in the system should be limited to 36 copies. Assuming that every node has battery capacity of 40 BE, since the average number of copies at 150 sec for this LC-scheme is 31, the ideal lifetime of this LC-scheme would be approximately 161 min (50·40[BE]·150[sec] / 31[BE] ≈ 9677 sec).

3.4. MDP lifetime of RER scheme

So far we have seen how RER schemes can extend the

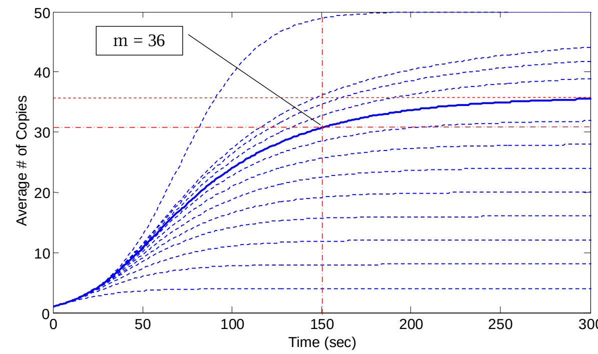

Figure 8: Average number of copies for LC-scheme with different values of m

ideal lifetime of the Epidemic Routing network. Figure 9 shows the simulation result of the MDP lifetime of the LC-scheme compared with the ideal lifetime. The simulation results are averaged over 1000 samples of 100 trials (total of 100,000 trials), and the confidence level of each confidence interval is 95%.

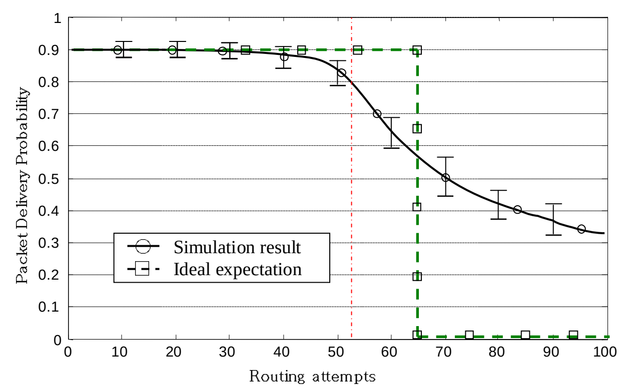

Figure 9: Delivery probability for multiple attempts of LC-scheme

According to Figure 9, the MDP lifetime of LC-scheme is approximately 130 min (52·150 = 7800 sec), 32.5 min extended from the MDP lifetime of UER. We have seen that the ideal lifetime of LC-scheme is approximately 161 min, which is 55 min extended form the ideal lifetime of UER. Clearly, the LC-scheme extended both the ideal lifetime and the MDP lifetime of UER, but instead the gap between the ideal lifetime and the MDP lifetime increased for 22.5 min (55 – 32.5).

4. RESIDUAL BATTERY INFORMATION

The performance of Epidemic Routing mostly depends on the number of active nodes in the system. Hence, decrease of active nodes results in poor performance, which means the delivery probability will drop. The ideal lifetime of a routing scheme is possible only when all of nodes batteries get depleted at the same time, which is practically impossible. However, it is possible to control the battery energy consumption of each node to some degree.

Suppose two nodes encounter and one node transmits its packet to the other node. By sharing their residual battery energy information the two nodes will know which one has more energy to propagate. Hence, it would be better for the node with more battery energy to propagate more copies than the other node. In the LC-scheme, when a node propagates a packet copy to another node, these two nodes can control the amount of copies that should be propagated by each node. Thus, it is easy to combine residual battery energy information to the LC-scheme than the other two RER schemes.

4.1. LC-scheme with residual battery information

Normally in LC-scheme, when a node transmits a copy to another node, it divides its load, the amount of copies need to be propagated, and passes half of the load on the receiving node. In that way, the two nodes will have the same amount of copies to propagate. However, if the nodes are aware of their residual battery energy information, they can divide the amount of copies according to the residual battery energy, instead. The simplest way to divide the load is to split the amount of copies in proportion to the residual battery energy. As a result, the node with more residual battery energy will have more amount of copy to propagate. We will call this scheme the LCB-scheme.

Since LCB-scheme is a variant of the LC-scheme, in order to find the value m that limits the total number of copies for LCB-scheme, we use the same method used for LC-scheme. Hence, the total number of copies that can be propagated in the system should be limited to 36 copies, where the average number of copies at TTL (150 sec) is 31. Same as LC-scheme, the ideal lifetime of this LCB-scheme is also approximately 161 min (50·40[BE]·150[sec] / 31[BE] ≈ 9677 sec).

5. SIMULATION RESULTS AND EVALUATION

The simulations were done in a 1000m x 1000m closed area, which is a torus, with N=50 mobile nodes plus one sink node that is stationary placed in the middle of the area. Each node has a transmission range of 25. The direction and the velocity for each node are uniformly distributed random variables where the direction is distributed from 0° to 360° and the velocity from 20/s to 50/s. Derived from these settings the rate λ is 0.004043. An arbitrary node creates a packet and starts to route the packet every 150 sec. The lifetime of the network is defined with TDP set to 90% and MDP set to 80%. In order to satisfy the TDP, TTL of the packet copies in UER is set to 130 sec and for the rest of the RER schemes TTL is 150 sec. The battery energy capacity for every node is 40 when the simulation starts. The restricting parameters for the RER schemes are what we derived from section 3.

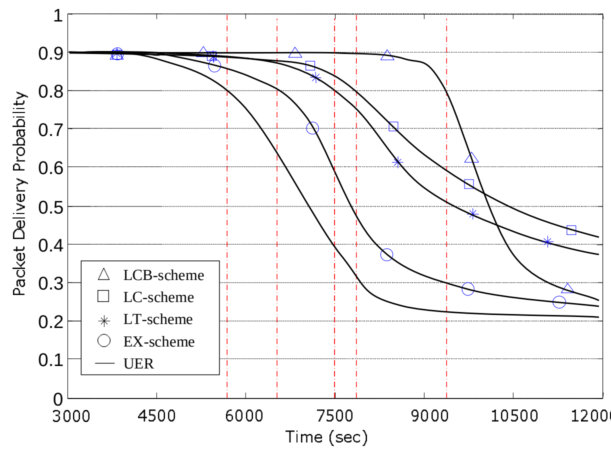

Figure 10: Lifetime of UER and RER schemes

5.1. MDP lifetime

Figure 10 shows the simulation results of packet delivery probability as the number of routing attempts increases for each scheme. After 4500sec, the packet delivery probability of UER starts to decrease and the rate drops below the MDP at approximately 5850 sec. We can see that the EX-scheme has the shortest MDP lifetime among the RER schemes and the LCB-scheme has the longest MDP lifetime.

It is obvious that LC-scheme has longer MDP lifetime than LT-scheme or EX-scheme since it propagates fewer number of copies for packet routing. An interesting thing is that even though LCB-scheme is very similar to LC-scheme, LCB-scheme has much longer MDP lifetime than LC-scheme. Another finding is that the delivery probability of LCB-scheme decreases sharply after it drops below the MDP, and the delivery probability becomes lower than the other schemes. We can see that for the LCB-scheme, most of the nodes batteries are depleted when it gets close to the MDP lifetime and after this time most of the nodes become inactive.

5.2. Evaluation of lifetime for each scheme

Table 1: Ideal lifetime and MDP lifetime for each scheme

Scheme	Ideal lifetime (α)	MDP lifetime (β)	α - β	E(n)	σ (n)	σ (n) /E(n)
UER	6383 s	5850 s	533 s	0.93	1.360	1.462
EX	8108 s	6450 s	1658 s	0.71	1.206	1.699
LT	9091 s	7500 s	1591 s	0.66	1.187	1.798
LC	9677 s	7800 s	1877 s	0.61	1.213	1.988
LCB	9677 s	9250 s	427 s	0.61	0.904	1.482

The MDP lifetimes are listed in Table 1 compared with the ideal lifetime for each scheme. E(n) indicates the average number of transmission per node, and σ(n) indicates the standard deviation of the number of transmission per node. The last column is the coefficient of variation values calculated by σ(n) / E(n).

It shows that LCB-scheme has the longest lifetime, and it is closer to the ideal lifetime than any other scheme. Although the rest of the RER schemes have longer lifetime than the lifetime of UER, the difference between the ideal lifetime and the MDP lifetime is larger. Results of E(n) shows that small number of transmission per node increases the lifetime due to less consumption of battery energy. It shows that, however, if the coefficient of variation for the average number of transmission per node is large, the MDP lifetime does get extended as long as the ideal lifetime.

5. CONCLUSION

In this paper, we expanded our previous work to investigate the lifetime of a DTN operating under various Restricted Epidemic Routing schemes. We modeled a DTN as a Markov Chain and evaluated its performance as a function of time. This transitional solution allows us to derive the limiting parameters for the RER schemes and to calculate their lifetimes. Then we introduced the Minimum Delivery Probability (MDP) parameter, which represents the lower bound on the acceptable delivery probability. We then computed the lifetimes of the various RER schemes, which we define as the time duration until when the delivery probability edges below the MDP. We also designed a scheme that maximizes the network lifetime.

An interesting result was that the Exclusion scheme, the Limited Time scheme, and Limited Number of Copies scheme did not extend the MDP lifetime as much as the ideal lifetime. Difference between the MDP lifetime and the ideal lifetime was even larger than that of the UER. However, the LC-scheme with residual battery information outperformed all the other schemes in terms of both ideal lifetime and MDP lifetime.

Based on these results, we speculate that the average number of transmissions alone is not the only factor in extending the network lifetime. Rather, decreasing the variance of the number of transmission may play a crucial in maximizing the network lifetime. Indeed, use of the information of residual battery energy is one method that can decrease this variance. In our future work, we intend to study the extension of the network lifetime by examining other schemes as well, which have not been discussed in this paper.

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