EFFICIENT TRADEOFF OF RESTRICTED EPIDEMIC ROUTING IN MOBILE AD-HOC NETWORKS

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ABSTRACT

Energy consumption for data transmission in mobile ad hoc networks can be reduced by decreasing the transmission range of each node. However, a transmission range that is too short reduces the node density to the extent that it becomes impossible to maintain a fully connected network. Consequently, each node has to rely on its mobility to first bring itself into the transmission range of another node before propagating the data packets, thereby leading to a longer delay in data delivery. On the other hand, if a network such as the Delay Tolerant Network (DTN) can tolerate this delay to some degree, using a short transmission range will be of great advantage to conserving transmission energy.

Epidemic Routing is a protocol proposed for a DTN that consists of nodes with short transmission ranges. In this paper, we ascertain how Epidemic Routing works and address its drawbacks. Then we propose several schemes using different ways of restricting Epidemic Routing and evaluate the performance of each scheme. In order to evaluate the schemes we use a method of deriving the performance of each scheme and comparing the schemes from the standpoint of the tradeoff between energy consumption and time delay, while maintaining a fixed delivery rate. The efficacy of this method is shown through both evaluation and simulation results.

1. INTRODUCTION

In mobile ad hoc networks, energy consumption for data transmission can be reduced by decreasing the transmission range of each node using multi-hop routing protocols. However, a transmission range being too short reduces the node density to the extent that the connections between the nodes become intermittent. In such an intermittent connectivity mobile ad-hoc network, full connection from source to sink cannot be expected. Consequently, packets should be relayed from the source to the sink using interoperability between nodes and their mobility by accommodating long delays. However, if a network such as the *Delay Tolerant Network* (DTN) can tolerate this delay to some degree, using a short transmission range will be of great advantage to conserving transmission energy.

Several protocols have been proposed for a DTN that consists of nodes with short transmission ranges. Epidemic Routing [2] is a peer-to-peer concept protocol used in a DTN which involves replication and propagation of a data packet. Epidemic Routing results in the shortest time delay for packet delivery but with an expense of resources such as transmission energy and network capacity. The process of Epidemic Routing has been studied using a Markov chain model [3] and probabilistic routing [15]. Adapted from infectious disease spread modeling [1], Ordinary Differential Equation (ODE) was used with Markovian models [5] to study the source-to-sink delivery delay. The performances for these studies were evaluated in [15] using ODE models. In the studies of the Shared Wireless Infostation Model (SWIM) [6] and the Spray and Wait routing scheme [9], they proposed several ways to overcome the drawbacks of the Epidemic Routing protocol.

One of the drawbacks is that without any restriction the nodes in the network system will keep on propagating a data packet until all the nodes in the network have a copy of the same packet. Although this unrestricted approach results in the shortest delay in packet delivery, it is possible only when the nodes have infinite energy and capacity. Therefore, in a network with limited resources, some restrictions should be imposed on the routing protocol.

SWIM [5, 6] uses TTL and the Anti-packet concept to reduce the redundant copies in the system. For each data packet a TTL variable is set to inform the nodes when to erase their copy of the data packet. Anti-packets are propagated by the sink node throughout the system to notify the other nodes that it has received the packet and to make sure each node erases the copy of the data packet. The Spray and Wait routing scheme [9] finds the minimum number of copies of the packet required for the sink node to receive one of the copies by a certain time. This way the source node knows how many copies it has to spray in the system, thus reducing the number of nodes being used for Epidemic Routing.

In this paper we use the TTL concept to erase the redundant copies in the system. We also propose several schemes using different methods of restricting the Epidemic Routing protocol. Using the transition Markov chain model for each scheme, we show how to calculate the number of copies in the system and the probability of the sink node having received the copy at a given time. With these results we evaluate the efficiency of the schemes by comparing the

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results from the standpoint of the tradeoff between energy consumption and time delay while maintaining a fixed delivery rate.

The remainder of this paper is organized as follows. First we analyze the Unrestricted Epidemic Routing process in Section 2.1 and state our approach to solving the drawback of Epidemic Routing in Section 2.2. In Section 3 several Restricted Epidemic Routing schemes are proposed and analyzed. All the simulation and the evaluation results are shown in Section 4, and we conclude our work in Section 5.

2. APPROACH TO PROBLEM

When the energy and capacity of the nodes are infinite, the Epidemic Routing protocol is the fastest way to deliver the packet from the source to the sink since the packet is propagated through the nodes encountered. However, this can result in a waste of capacity and transmission energy by replicating many redundant packets in the network system. Hence in our work we set a TTL in the packet to erase the copies in the system thus sparing more capacity. We also use several methods to restrict the propagating action in order to reduce the number of copies in the system.

2.1. Unrestricted Epidemic Routing (U-scheme)

First, we need to see how Unrestricted Epidemic Routing works and we call the scheme using this protocol the Unrestricted scheme (U-scheme). When a node encounters another node in the U-scheme (when they come into transmission range) the two nodes communicate and share the information of their carrying packets. If a node sees a packet that it doesn't have, it asks the other node for the packet, which is then transmitted to the receiver, thus replicating a copy of the packet. As the nodes encounter other nodes by their mobility, packets will be spread throughout the network system just like an infectious disease.

A model for infectious disease [1] has been studied in the past and was applied to mobile ad hoc networks as a stochastic model [2]. When there are a total of N mobile nodes in a finite area, the encounter between two particular nodes occurs at a certain rate λ. The time between each encounter is an exponential random variable T with parameter λ. Since we assume the encountering process is a Poisson arrival, two encounters cannot occur at the same time. Using this idea we can model a Markov chain for the U-scheme.

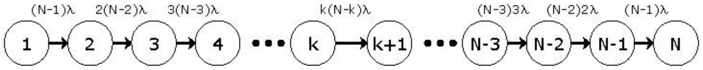


Figure 1: Transition diagram of Markov chain model for number of copies in U-scheme

When we are in state k, where there are k copies of the packet in the system, the rate of state increment, from k to k+1, becomes k(N-k)·λ since there are k nodes that have the packet and (N-k) nodes that don't. We can see that starting from state 1, where the source node is the only node carrying the packet, the rate of state increment for each state increases until it gets to state k = N/2 (or k = (N±1)/2 when N is an odd number) and then decreases, as the number of copies of the packet in the system increases to N. Hence, the maximum value for the rate of state increment for this state is $(N/2)^2 \cdot \lambda$ (or $(N^2-1)\cdot\lambda/4$ when N is an odd number). Taking the sink node into consideration we get an expanded Markov chain model.

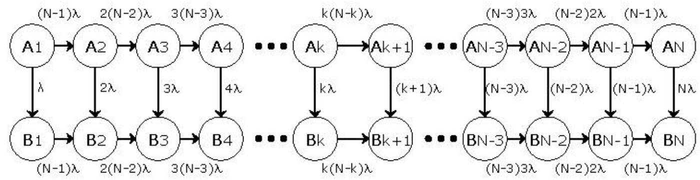


Figure 2: Transition diagram of Markov chain model for number of copies in U-scheme with sink

Since there are still N nodes in the system and the sink node is counted as an extra node, the **λ** value stays the same. State A_k indicates 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 is k number of copies in the system and at least one of them has reached the sink, which means that the sink has received a copy of the packet. The rate of state changing from A_k to B_k is kλ, and the rates of state increments stay the same in both states A and B. The probability of the system being in state k at time t in Figure 1 (Pr[state = k | time = t]) is the same as the probability of the system being in state A_k or state B_k at time t in Figure 2 (Pr[state = $A_k \cup B_k$ | time = t]).

$$\Pr[\text{state} = k \mid \text{time} = t] = P_k(t)$$
$$\Pr[\text{state} = A_k \cup B_k \mid \text{time} = t] = P_{A,k}(t) + P_{B,k}(t)$$
$$P_k(t) = P_{A,k}(t) + P_{B,k}(t)$$

The probability of the system being in state k, $P_k(t)$, is calculated by multiplying the probability of being in state k-1 at time x, where x is between 0 and t, by the probability of the state increasing to k during a very short time dx, times the probability of staying in state k for the rest of the time t-x, and then integrating this product over x from 0 to t.

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

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

$$P_1(t) = e^{-(N-1)\lambda t}$$
$$P_{A,1}(t) = e^{-N\lambda t}$$
$$P_{B,k}(t) = P_k(t) - P_{A,k}(t)$$

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. These formulas are used for the restricted schemes as well.

$$\text{E[\# of copies| time = t]} = \sum_{k=1}^{N} kP_k(t)$$

$$\text{CDF(t)} = \sum_{k=1}^{N} P_{B,k}(t)$$

As we can see in Figure 1, the number of copies in the system will increase as time flows and eventually the system will stay in state N. As shown in Figure 2, due to the increase of the rate of state change from A to B, the more copies in the system the more probable the sink node will receive the packet. According to Figure 2, as time flows the system will be in one of the B_k states with k close to N, where there are many redundant copies in the system with the sink node having received one of the copy of the packet. However, we want the system to be in one of the B_k states with k small as possible, where there aren't many redundant copies in the system with the sink node having received the packet. Notice in Figure 2 that we cannot do anything about the rates of state change from A to B, but we can adjust the rates of state increments. Since the U-scheme is the fastest way to propagate the packet throughout the system, it is impossible to increase the rates of state increments, and hence we can only decrease the rates.

2.2. Restricted Epidemic Routing

Several restricted epidemic routing schemes will be introduced in this paper and we will see how we can decrease the rates of state increments with different methods. If we decrease the rates of state increments, it is certain that there will be a smaller number of copies in the system at a particular time than there is using the U-scheme, but the CDF value of the sink node having received the packet at that time will be also smaller, which means the sink node has to wait for a longer time delay. Based on one of the methods, the rates of state increments can be also reduced to different values depending on the degree of the restriction.

In the next section we will propose 4 schemes of Restricted Epidemic Routing: Limited Hop scheme, Exclusion scheme, Limited Number of Copies scheme, and Spray and Wait scheme. For the Limited Hop scheme, the degree of restriction is adjusted by limiting the maximum hop count to integer numbers, while for the Exclusion scheme, it is adjusted by limiting the number of nodes being used to integer numbers, and for the rest of the schemes it is adjusted by limiting the total number of copies in the system to integer numbers.

3. METHODS OF RESTRICTION

3.1. Limited Hop scheme (LH-scheme)

The first example of a restricted epidemic routing scheme is the Limited Hop scheme (LH-scheme), which was introduced by R. Groenevelt, P. Nain, and G. Koole in their paper [3]. They limited the maximum hop count to 2 through which the packet can be relayed, where the source node is the only node that can propagate copies of the packet, and all the other peer nodes can only receive those copies. The sink node receives the packet when it encounters a node with a copy of the packet.

When the maximum hop count is limited to 2, the rates of state increments in Figure 2 decrease as the state increases, because the number of nodes that can receive a packet decreases while the number of nodes that can transmit is only one. The Markov chain model gets complicated when the limit of the maximum hop count increases.

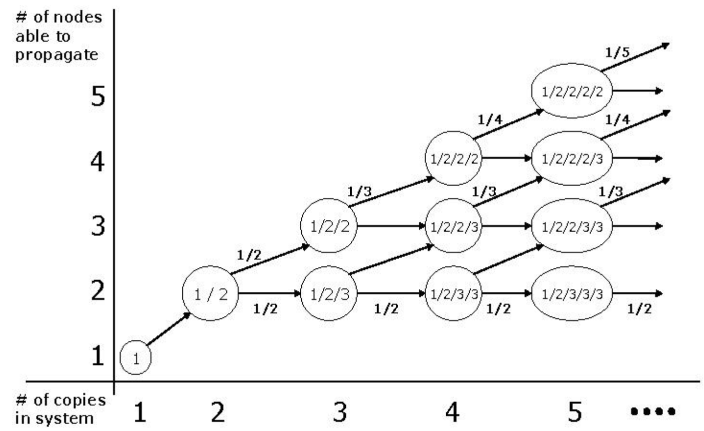


Figure 3: 2-D Markov chain model for number of copies in LH-scheme (max. 3 hops)

Let's say we limit the maximum hop to three. When a packet is first created the source node is the only node in the system that can propagate its packet. When it transmits a copy of the packet to the first node it encounters, there are then two nodes that can propagate. But when the total number of copies increases to three, the number of nodes that can propagate may increase to three or stay at two, depending on which of the two nodes transmitted to the third node. In Figure 3, each number in a state indicates the nodes carrying a copy of the packet and their hop count. In state [1/2/2/3/3], for example, there are 5 nodes carrying a copy of the packet: one is the source node, two are the second hop transmitter, and the other two are the third hop transmitter. The next state is determined by the number of nodes that have not yet reached the maximum hop, and the assumption that each node has the same probability of encountering another node. Since we know the probability of being in each state, we can calculate the average number of nodes(n_k) that can propagate for a given number of copies(k) in the system.

Table 1: Average # of nodes that can propagate in state k for different limits of hop count (LH-scheme)

k	1	2	3	4	5	6	7	8	..
2 hops	1	1	1	1	1	1	1	1	..
3 hops	1	2	2.5	2.92	3.28	3.6	3.89	4.16	..
4 hops	1	2	3	3.83	4.57	5.24	5.88	6.47	..

The average numbers of nodes are listed in Table 1. Applying these values n_k. to the Markov chain model, the probability of the system being in each state is calculated as follows.

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

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

$$P_1(t) = e^{-n_1(N-1)\lambda t}$$

$$P_{A,1}(t) = e^{-\{n_1(N-1)+1\}\lambda t}$$

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

The expected number of copies of the packet in the system and the CDF value of the sink having received the packet at time t, are derived by the same equations used for the U-scheme except for the changed probabilities above.

3.2. Exclusion scheme (EX-scheme)

The second restricted epidemic routing scheme is the Exclusion scheme (EX-scheme) in which some of the nodes are excluded from epidemic routing. Before the source node encounters another node and propagates its packet, it decides randomly which nodes will be excluded from the packet propagation in the system. This is merely the same U-scheme except the total number of nodes being used throughout the delivery from source to sink is reduced to M from N.

Since the total number of nodes being used is reduced from N to M, the number of copies in the system for the rightmost state is limited to M, and the rates of state increments are all decreased. Since the only change is the total number of nodes being used, this is the only change in the calculation of the probability of the system being in each state, the expected number of copies in the system, and the CDF, for a given time t.

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

The next restricted epidemic routing scheme is the Limited Number of Copies scheme (LC-scheme). Assuming that all nodes are notified of how many copies there are in the system during Epidemic Routing, the LC-scheme stops the nodes from propagating copies of the packet when the total number of copies reaches the limit m. The distinctive feature of the LC-scheme compared to other restricted schemes is that none of the rates of state increments are reduced except for the rates after state m, where rates are reduced to zero.

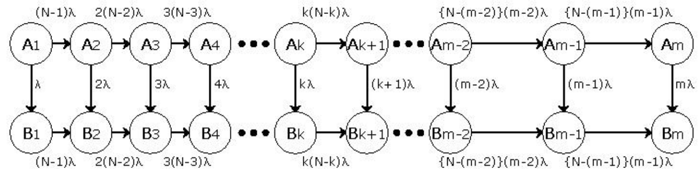


Figure 4: Markov chain model for number of copies in LC-scheme with sink

In the LC-scheme, Figure 4, the probability of the system being in each state is the same as in the U-scheme, except for state m since there cannot be more than m copies, and the probability of being in states larger than m is 0.

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

$$P_m(t) = \int_0^t P_{m-1}(x) \cdot (m-1)\{N-(m-1)\}\lambda \cdot dx \quad \text{(when } 2 \le k \le m-1)$$

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

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

$$P_1(t) = e^{-(N-1)\lambda t}$$

$$P_{A,1}(t) = e^{-N\lambda t}$$

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

3.4. Spray and Wait scheme (SW-scheme)

The last restricted epidemic routing scheme is the Spray and Wait scheme (SW-scheme) which was introduced by T. Spyropoulos, K. Psounis, and C. S. Raghavendra in their paper [9]. In the previous scheme (LC-scheme) we assumed that the nodes can be notified of the total number of copies of the packet in the system. This assumption may not be possible since notifying all the nodes will cost a large amount of energy and effort. Without notifying the nodes how many copies there are in the network system, one way to limit the total number of copies of the packet is to inform each node how many copies it can propagate when it receives a copy of the packet. We can think of this as each node having a load of copies that needs to be propagated, and every time a node with a load of copies encounters a node without any load, it dumps to the receiving node a certain amount of its load, until the load is reduced to one copy. In the Binary Spray and Wait scheme [9], which is optimal, the amount of copies being dumped is half the number of load of copies.

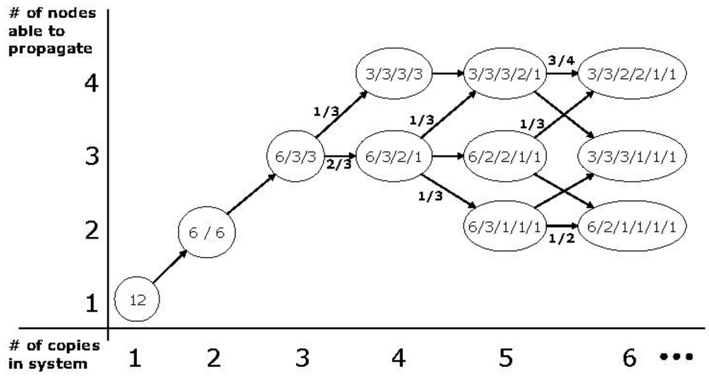


Figure 5: 2-D Markov chain model for number of copies in SW-scheme (max. 12 copies)

Assume we want to propagate a packet up to 12 copies in the system with N mobile nodes and one sink node. After the source node encounters another node it splits its 12 copies and gives the half of it to the encountered node which makes each node have a load of 6 copies. Whenever they encounter another node they split their load and give half to the receiving node until they are left with only one copy. As we can see in Figure 5, where each number in a state indicates the nodes carrying a copy of the packet and their load, the number of nodes that can propagate does not exceed 4 even though the total number of nodes carrying a copy increases to 12. In state [6/2/2/1/1], for example, there are 5 nodes carrying a copy of the packet: one node with a load of 6 copies, two nodes with 2, and two other nodes with just one which means no load. The next state is determined by the number of nodes carrying a load in the present state and the assumption that each node has the same probability of encountering another node. Since we know the probability of being in each state, we can calculate the average number of nodes that can propagate for a given number of copies in the system.

The values for the average number of nodes ($n_{k\cdot}$) that can propagate when there is k number of copies in the system are listed in Table 2. Applying these values $n_{k\cdot}$ to the Markov chain model, the expected number of copies in the system, and the CDF, for a given time t, are calculated using the same formulas of the LH-scheme except that k is limited to m.

Table 2: Average # of nodes that can propagate in state k for different limits of number of copies (SW-scheme)

k	1	2	3	4	5	6	7	8	..
m=2	1	0	0	0	0	0	0	0	..
m=3	1	1	0	0	0	0	0	0	..
m=4	1	2	1	0	0	0	0	0	..
m=5	1	2	1.5	1	0	0	0	0	..
m=6	1	2	2	1.5	1	0	0	0	..
m=7	1	2	2.5	1.67	1.83	1	0	0	..
m=8	1	2	3	2.67	2.33	2	1	0	..

4. SIMULATION RESULTS AND EVALUATION

In this section we evaluate and verify the performance of each restricted Epidemic Routing scheme by plotting the graph of E[# of copies| time = t] with the same restriction but with different degrees, using the formulas from the previous section and then connecting the points with a fixed CDF value. This way we can evaluate the optimal solution of reducing the redundant packets in the system with as short a delay time as possible, while maintaining a fixed delivery rate. All of these analytical results are compared with the simulation results

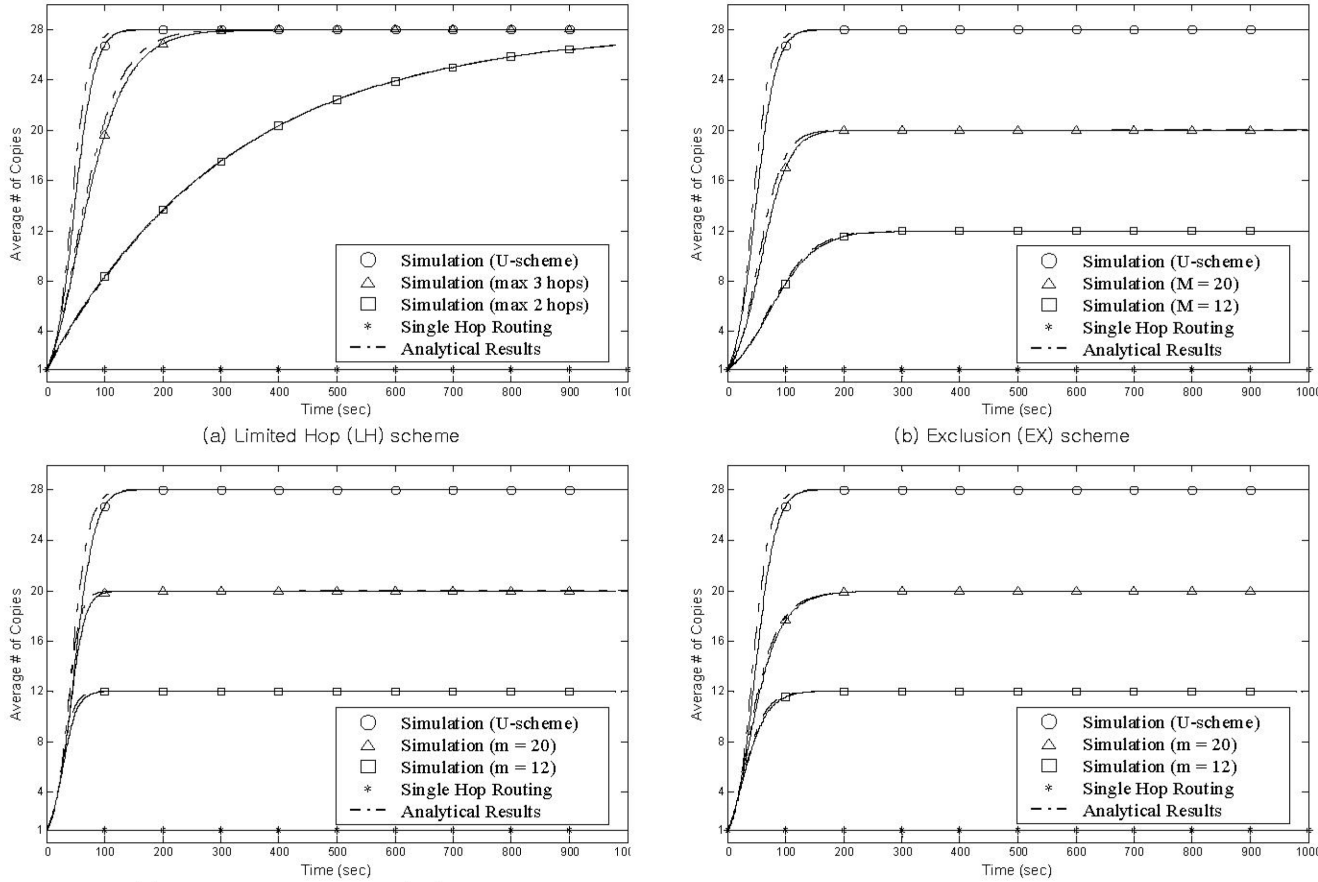
The simulations were done in a 1000x1000 closed area, which is a torus, with N=28 mobile nodes plus one mobile sink node where each node has a transmission range of 50. The direction and the velocity for each node are uniformly distributed random variables where the direction is distributed from 0° to 360° and the velocity from 0/s to 50/s. Derived from these settings the rate λ we get is 0.003152.

4.1. Average number of copies at a given time

Figure 6 shows the average number of copies in the system at a given time for different methods and degrees of restricting Epidemic Routing. Depending on the degree of a restriction, the routing protocol will act like the U-scheme if there is less restriction, and act like single hop routing if there is more restriction. We can observe this in each graph: as the restriction gets stronger the plotted lines indicating the average number of copies in the system gets closer to a straight line with the number of copies fixed to 1. The dotted lines, indicating the analytical results, tell us that the calculations using our formulas from the past section are quite accurate, except that the average number of copies increases a little faster for the analytical graphs. The gap between the simulation and analytical result we see in each graph is due to the fact that some of the nodes can be close enough to overlap their transmission range, which makes the probability of other nodes encountering these two nodes smaller than when the two nodes do not overlap.

4.2. Tradeoff between the average number of copies in the system and the time delay of packet delivery

Now we need to evaluate which is the most efficient method to restrict Epidemic Routing. Based on Figure 6, only with more data, we connect the points that have the same CDF value for the sink node having received a copy of the packet. We call this connected line the Tradeoff Line (T-Line) of a certain CDF value since it shows the tradeoff between the average number of copies and the time delay. According to this T-Line, as the restriction gets stronger the average number of copies gets smaller, resulting in a longer delay time for the sink node to receive a copy of the packet.



(a) Limited Hop (LH) scheme

(b) Exclusion (EX) scheme

(c) Limited Number of Copies (LC) scheme

(d) Spray and Wait (SW) scheme

Figure 6: Simulation and analysis results of avg. # of copies for different methods and degrees of restriction

4.3. Evaluation of the Tradeoff Line

Since we have the T-Line for each method, we can compare these T-Lines and evaluate which method is more efficient. In Figure 7, notice that all the tradeoff curves start and end at the same point. Both the simulation and analytical results show that the T-Line of the LC-scheme has a much rapid decrement than other schemes, which means the LC-scheme outperforms all the other schemes. According to the simulation results, when we want the time delay to be no longer than 150s and the CDF value fixed at 95%, for example, the LC-scheme can reduce the average number of copies in the system to approximately 8, while the SW-scheme can reduce the number to slightly more than 8 and other schemes more than 12. However, the LC-scheme may not be a practical scheme since it is not easy for the nodes to know how many copies are in the system. The T-Line of the SW-scheme is very close to that of the LC-scheme, especially when the average number of copies in the system is limited to less than 8. Hence we can consider the LC-scheme as a lower bound and it is clear that the SW-scheme is the closest to the lower bound, compared to other schemes.

5. CONCLUSION

In this work, we analyzed Epidemic Routing using transition Markov chain models, and confirmed that by adjusting the rates of state increments in the Markov chain model we can reduce the redundant number of copies in the system, which is the drawback of Unrestricted Epidemic Routing. Reducing the number of copies costs more delay time in packet delivery from source to sink. We examined several restricted Epidemic Routing schemes to find the scheme which costs less delay time. For each restricted Epidemic Routing scheme, we used a transition Markov chain model that matches the scheme to calculate the average number of copies in the system and the CDF value of the sink node having received a copy of the packet at a given time. Using the results of the calculation we were able to confirm the most efficient scheme and these analytical results were justified by our simulation results. Both simulation and analytical results indicated that limiting the total number of copies in the system costs less energy consumption, since each copy costs transmission energy, and less delay time in packet delivery, compared to other schemes.

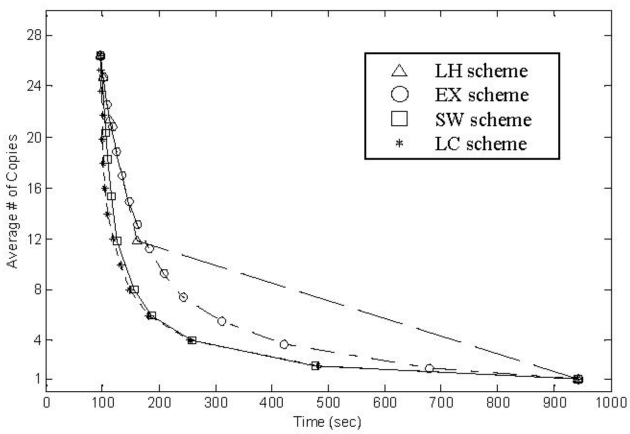


Figure 7: Comparison of tradeoff curves of CDF value 95% between different methods of restriction

Since the nodes are not aware of the total number copies in the system, the LC-scheme may not be practical and one way to limit the total number of copies is to use the SW-scheme. According to the analytical and simulation results, the T-Line of the SW-scheme was closest to the T-Line of the LC-scheme, and thus the SW-scheme is the most efficient practical scheme so far. However, there are other ways to limit the total number of copies in the system, and in our future work we plan to confirm the best way to do this. In addition, we intend to expand our work to analyzing Epidemic Routing with multiple packets being delivered to the sink node.

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