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Invited Paper

Application of Linear Network Coding in Delay Tolerant Networks

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ABSTRACT

In this paper, we study the application of Linear Network Coding to routing in sparse networks, where the average number of neighbors of a node is less than one. Routing in such networks is facilitated by mobility of the nodes, which create sporadic connections in the network. Due to the long end-to-end packet delivery delays, such networks can support only Delay Tolerant applications. Techniques such as Epidemic Routing are then used to reduce the packet delivery delay. However, when the nodes are equipped with limited storage, the effectiveness of Epidemic Routing partially vanishes and the reliability of packet delivery is reduced. We show that through the use of Linear Network Coding, the probability of packet delivery can be improved for certain region of the network operation. We derive a mathematical model for the condition of this improvement and we confirm our results through simulations.

1. INTRODUCTION

Sparse networks are network topologies where the average number of neighbors is small, typically less than one. Consequently, a large fraction of the time, a network node has no connectivity to other nodes. The *store-carry-forward* [1] paradigm, which relies on mobility to create intermittent network connectivity, is often employed for routing is sparse networks. However, this type of routing can introduce longer, often substantially longer, end-to-end packet delivery delays, compared with the traditional mobile ad hoc networks. Thus, the *store-carry-forward* paradigm can be used only in networks which can tolerate such large and unpredictable delays. This type of networks is referred to as *Delay Tolerant Networks (DTN)*.

An example of a *store-carry-forward* routing protocol is the *Epidemic Routing Protocol (ERP)* [2] in which a node that carries a copy of a packet, replicates the packet on every other node that it comes in contact with. The basic idea is referred to as packet flooding and resembles the process of a disease spread in epidemiology [3-7]. The replication of a packet in ERP increases the number of nodes carrying the packet, in turn, increases the probability of delivering a copy of the packet to its destination node by some time deadline. Of course, the copying operation requires additional energy, thus exhibiting the "*energy vs. delay*" tradeoff. Furthermore, limited amount of memory at the network nodes may require discarding of the stored packets prematurely, lowering the probability of delivering a copy of the packet to its destination.

To increase the probability of a packet delivery, several stochastic routing protocols have been proposed in which each relaying node tries to forward its packets to such nodes that would increases the delivery probability. For example, a relaying node can choose its recipient based on mobility pattern, encounter history of other nodes, or other information. Algorithms proposed in [8-12] use one-hop information, while [13-15] accumulate end-to-end information. In [16-20], usage of special nodes with high mobility and high storage capacity has also been proposed, making it easier to select the recipient nodes, since only the special nodes are selectable.

Several variants of the ERP have been proposed [1, 21-26] to overcome the nodes memory restriction and to improve the delivery probability. More specifically, coding-based protocols [27-29] compress multiple packets in the limited memory. With erasure-coding [28], smaller sized "abbreviated packets" carry only partial information of the original data packet. Network-coding [29] was also used to combine multiple different packets into smaller number of packets. With coding, the sink has to receive more than one packet to recover an original data packet. In this paper, we focus on how to increase the probability of packet delivery in ERP when nodes have limited memory. In particular, we study the use of linear network coding [30] for this purpose.

This paper is organized as follows. In Section 2, we analyze the packet delivery probability when nodes have limited memory. In Section 3, we apply network coding to ERP, and we analyze the scheme's performance in Section 4. Simulation results are shown in Section 5. Section 6 concludes the paper.

2. PACKET ROUTING IN DTN

2.1. Epidemic Routing Protocol (ERP)

In the *Epidemic Routing Protocol (ERP)* [2], a packet is replicated on every node that comes in contact with another node that carries a copy of the packet. This replication increases the packet delivery probability, since the probability of the

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destination encountering a node carrying a copy of the packet increases as well.

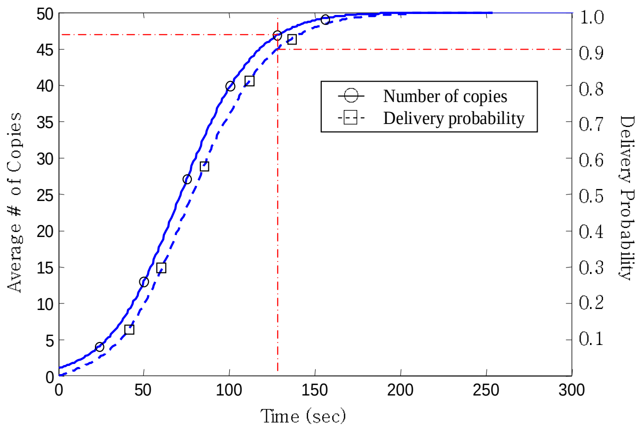


Figure 1: Number of copies and delivery probability versus time

Figure 1 shows the average number of packet copies and the packet delivery probability as a function of time, when the total number of mobile nodes in the system is $N = 50$ and the network area is 1000m by 1000m closed torus shape. The encounter rate of two nodes is λ = 0.001/sec. For example, 130 seconds after the packet creation, the average number of copies in the system reaches 47 and the average packet delivery probability is 90% by that time.

Of course, given enough time, the delivery probability will eventually become 1, if the packet copies are still present in the system at that time. However, if packet's copies are erased from the system, for example due to lack of available memory at the network nodes, the delivery probability will cease increasing with time.

2.2. Sequential Packet Routing

To study the effect of limited node memory, we assume the extreme case where each node can store one packet only. In our scenario, there is a single source node that routes packets to a single destination (sink) node. The time interval between generations of packets, T_d, is 40 seconds. Since each node can carry only one packet, the nodes have to decide whether or not to remove a stored packet, when encountered with a node carrying a different packet. We claim that priority should be given to the more recently generated packet; i.e., the node carrying the more recent packet should transmit its packet to the other encountered node, which should replace its packet with the received one.

Figure 2 depicts the number of copies of the first packet (referred to as P_1) with sequential packet generation. As distinct from Figure 1, the number of copies of P_1 does not increase up to N=50, but rather at most barely exceeds 20 at 100 sec. After 100 sec, the number of P_1 copies starts to decrease and after 250 sec it equals almost zero. Notice the drop at 40 sec, which is the time of the second packet (P_2) generation. With P_2 injected into the network, the number of P_1 copies instantly decreases by one. When there are enough latter packets (P_3, P_4 …) injected into the network, the total number of packets that are not P_1 increases up to N=50, reducing the number of P_1 copies to zero.

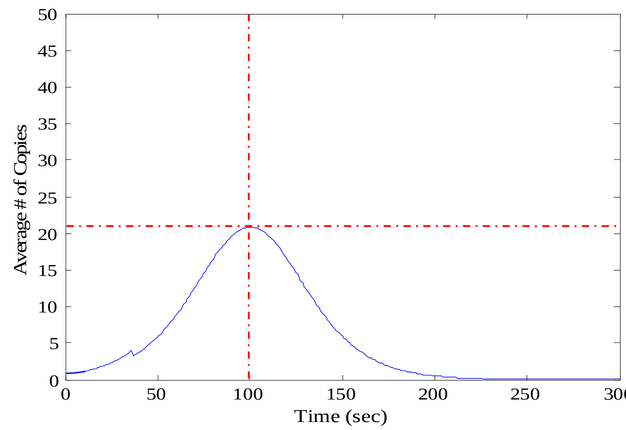


Figure 2: Number of copies of a single sequentially routed packet

2.3. Sequential Delivery Probability (SDP)

Since the time duration between packets' generations is fixed at T_d=40 sec and since the storage priority is given to the more recent packets, the number of copies of all packets will be the same as in Figure 2. Hence, the packet delivery probability as a function of time of all the packets will also be the same, as shown in Figure 3 for 10 sequential packets. Again, compared to Figure 1, the maximum delivery probability of all packets, equal to 0.8 in our case, is decreased. We refer to this maximum delivery probability as the *Sequential Delivery Probability (SDP)*.

Although ERP exhibits the highest packet delivery probability for single packet, this is not necessarily so when sequential routing is considered. Indeed, in this paper, we will propose a new algorithm using Network Coding, and we will demonstrate how it is capable of improving the SDP.

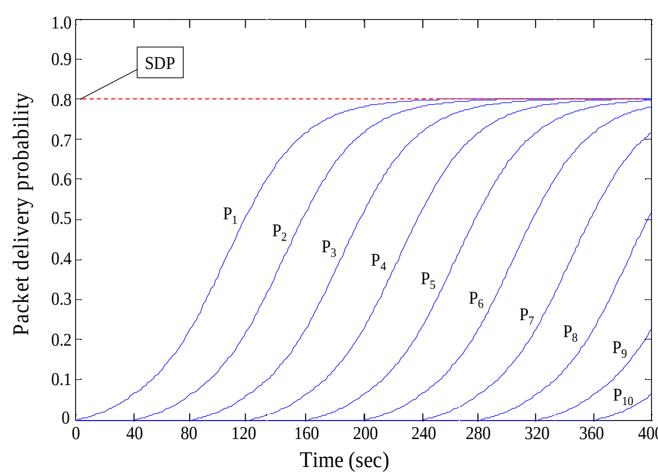


Figure 3: ERP delivery probability for sequentially routed packets

3. APPLICATION OF NETWORK CODING TO ERP

We recall that our model allows each node to store a single packet only. We also assume that all the network nodes, including the source and the sink nodes, are capable of processing *Linear Network Coding (LNC)*. Using LNC, a node may combine at most two consecutive packets.

3.1. Network-Coding Epidemic Routing Protocol

Our *Network-Coding Epidemic Routing Protocol (NC-ERP)* operates as follows. The initial packet, P_1, is routed in the network based on the regular ERP. For subsequent packets, when a new packet, P_k, is generated, the source creates a combination packet, C_k, referred to here as the k^{th} combination and the value of k is called the epoch. C_k is a linear combination of the packets P_k and P_{k-1}:

$$C_k = \alpha_0 P_k + \alpha_1 P_{k-1}, \qquad (1)$$

where α_0 and α_1 are coding coefficients randomly chosen from a Galois field. The combination vector $[k, \alpha_0, \alpha_1]$ is saved in the packet header, and the packet with its header is stored in the source node's memory. We define G_k as the group of nodes that carry a combination which combines the packets P_k and P_{k-1}.

The source creates and transmits a different combination every time that it encounters another node which is not in G_k. When two nodes come into contact with each other, they first exchange their combination vector. If the two combination vectors at the two nodes are identical, no further transmission occurs. However, when the value of the epoch is different at the two nodes, say k and k-1, the node carrying the k^{th} epoch combination, C_k, transmits it to the node carrying the $(k\text{-}1)^{th}$ epoch combination. If a node carrying a combination C_k encounters a node that does not carry any combination, the combination C_k is copied onto the empty node.

Suppose now that two nodes that belong to the same G_k, but carrying different combinations, C_k^0 and C_k^1, come into contact with each other, where $C_k^0 = \alpha_{00} P_k + \alpha_{01} P_{k-1}$ and $C_k^1 = \alpha_{10} P_k + \alpha_{11} P_{k-1}$, each one of the two nodes creates a new combination in the form:

$$C_k^i = \beta_{0i} C_k^0 + \beta_{1i} C_k^1, \qquad (2)$$

where $i = 0$ and $i = 1$ represent the two nodes. Since C_k^i is a linear combination of C_k^0 and C_k^1, the new combinations C_k^i ($i = 0,1$) are also linear combinations of the packets P_k and P_{k-1}. The two new combination vectors, $[k, \gamma_{0i}, \gamma_{1i}]$, ($i = 0,1$) are calculated as $\gamma_{0i} = \beta_{0i}\alpha_{00} + \beta_{1i}\alpha_{10}$ and $\gamma_{1i} = \beta_{0i}\alpha_{01} + \beta_{1i}\alpha_{11}$, and are saved in the headers of the two nodes. Since the coding coefficients are chosen randomly from a large Galois field, the combinations C_k^i are likely to be different from each other with high probability.

Each node can recombine only once in each epoch, so once a node in G_k recombines, its combination will not change until it encounters a node in G_j where $j > k$.

3.2. Sequential Recovery Probability (SRP)

Based on the above model, at any time, the size of the group G_k is the same as the number of packets P_k in ERP. Hence the probability of the sink encountering one of the nodes in G_k under NC-ERP is the same as the probability of the sink receiving P_k under ERP, which equals to SDP.

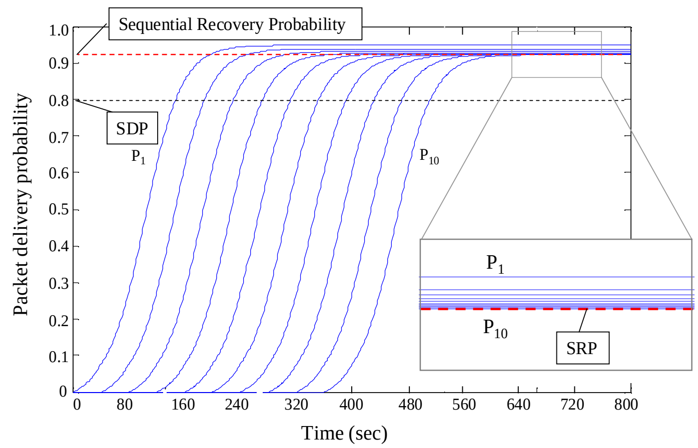


Figure 4: Recovery Probability for sequential routing in NC-ERP

Except for the initial packet P_1, the sink node can recover the packet P_k in NC-ERP either from C_k or C_{k+1}. Recovering P_k from C_k requires the sink to recover P_{k-1} first, or recover both at the same time by receiving at least two independent combinations C_k. In a similar way, P_k can be recovered from C_{k+1} if P_{k+1} has been recovered first, or both P_k and P_{k+1} can be recovered at the same time by receiving at least two independent combinations C_{k+1}.

Fig. 4 depicts the probability of recovering 10 sequential packets while routing 50 packets under NC-ERP. The SDP for routing the same number of packets under ERP is 0.8. We note that the recovery probability for the initial packet P_1 is the highest. We can see that the recovery probabilities for the latter packets decrease and converge to a certain value, which we referred to as the *Sequential Recovery Probability (SRP)*.

4. MATHEMATICAL MODEL

Although for the results in Figure 4, SRP (≈ 0.92) is larger than SDP ($= 0.8$), this may not be true in every case. We study here the condition for which SRP > SDP.

4.1. Multiple packets and packet delivery probability

Suppose that there are n copies of the packet P_k and that the probability of the sink encountering a copy is q. For example, in Figure 2, if n=21, q is the probability that the sink encounter a copy during 100 sec. The probability, D, of the sink receiving at least one copy is:

$$D = 1 - (1-q)^n. \qquad (3)$$

Now, if instead n copies of the packet P_k, there are n combinations C_k, the sink has to receive at least two combinations to recover P_k. The probability of this event is $1-(1-q)^n - nq(1-q)^{n-1}$, which is smaller than the probability D. However, P_k can be also be recovered from a single combination C_k or C_k, if either P_{k-1} or P_{k+1} were recovered first, respectively.

4.2. Initial Packet Recovery Probability

We now calculate the probability of recovering the first packet P_1. Since P_1 is routed without creating any combination, the probability of the sink receiving P_1 is D; i.e., $\Pr(P_1 \leftarrow P_1) = D$. After the source routes C_2, the sink can also recover P_1 from two independent combinations C_2. Thus, if at any time, the sink receives two independent combinations C_k, the sink can recover all the packets between P_1 and P_k from a single combination for each epoch *2* to epoch *(k-1)*; i.e., C_2, C_2, … C_{k-1}.

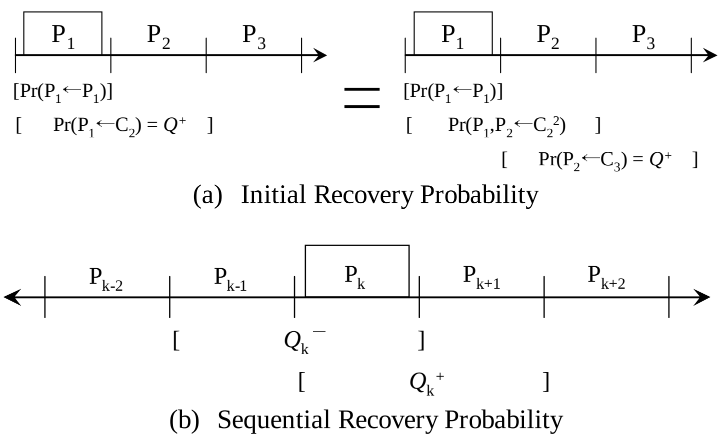


Figure 5: Packet Recovery Probabilities

Let Q^+ be the probability of recovering P_1 from C_2; i.e., $\Pr(P_1 \leftarrow C_2) = Q^+$. As mentioned , the sink can recover P_1 by receiving two independent combinations C_2 with probability $\Pr(P_1,P_2 \leftarrow \{C_2^0, C_2^1\})$, or by receiving only one combination C_2 while recovering P_2 from C_3. As we can see from Figure 6(a), the probability of recovering P_2 from C_3 equals Q^+; i.e., $\Pr(P_2 \leftarrow C_3) = Q^+$. Hence, Q^+ can be calculated as follows:

$$Q^+ = 1-(1-q)^n - nq(1-q)^{n-1} + nq(1-q)^{n-1}Q^+$$
$$Q^+ = 1-\frac{(1-q)^n}{1-nq(1-q)^{n-1}} \quad . \qquad \textbf{(4)}$$

Next we define Q_1 as the total probability of the sink receiving (or recovering) P_1. Since Q^+ is independent of the sink receiving P_1 directly, we derive Q_1 using Eqs. 3 and 4:

$$Q_1 = D + (1-D)\cdot Q^+ = 1-\frac{(1-q)^{2n}}{1-nq(1-q)^{n-1}} \, . \qquad \textbf{(5)}$$

Since q is in [0,1], Eq. 4 shows that Q^+ is in [0,1], and Eq. 5 indicates that probability Q_1 is in $[Q^+,1]$. Eq. 5 reveals that $Q_1 \geq D$. In other words, since SDP = D, the probability of receiving P_1 is always larger with NC-ERP.

Similarly, the probability of the sink recovering P_2 is:,

$$Q_2^- = 1-(1-q)^n - nq(1-q)^{n-1} + nq(1-q)^{n-1}\cdot D \,,$$
$$Q_2 = Q_2^- + (1-Q_2^-)\cdot Q^+$$
$$\textbf{(6)}$$

where Q_2^- is the probability of recovering P_2 from C_2, since P_2 can be recovered from two independent combinations C_2, or by receiving one combination C_2 together with P_1.

Since $0 \leq q \leq 1$ and $0 \leq D \leq 1$, using Eq. 6, we obtain that:

$$Q_2^- = D - nq(1-q)^{n-1}(1-D) = D - nq(1-q)^{2n-1} \leq D \,;$$

i.e., $Q_2^- \leq D$. Also, from Eq. 5 and Eq. 6, we deduce that $Q_2 \leq Q_1$.

For $k \geq 3$, Q_k can be derived in a similar way. As illustrated by Figure 5(b), Q_k is the union of Q_k^- and Q_k^+, where Q_k^- is the probability of recovering P_k from C_k, Q_{k-1}^- is the probability of recovering P_{k-1} from C_{k-1}, and Q_k^+ is the probability of recovering P_k from C_{k+1}, where $Q_k^+ = Q^+$:

$$Q_k^- = 1-(1-q)^n - nq(1-q)^{n-1} + nq(1-q)^{n-1}\cdot Q_{k-1}^- \,.$$
$$Q_k = Q_k^- + (1-Q_k^-)\cdot Q_k^+$$
$$\textbf{(7)}$$

Using Eq. 7, we derive:

$$Q_k^- - Q_{k-1}^- = nq(1-q)^{n-1}\cdot(Q_{k-1}^- - Q_{k-2}^-)$$
$$Q_k^- = Q_{k-1}^- + \left(nq(1-q)^{n-1}\right)^{k-2}\cdot(Q_2^- - D) \,.$$

Since, $Q_2^- \leq D$, we conclude that Q_k^- is a non-increasing function of k. Hence by Eq. 7, we postulate that Q_k is also a non-increasing function of k, bounded by $[Q^+,1]$. Thus we have demonstrated that the probability Q_k converges to a certain value, as depicted in Figure 4.

4.3. Sequential Recovery Probability (SRP)

The probability of recovering P_k from C_{k+1} is Q^+ and the probability of recovering P_k from C_k is Q_k^-. After routing many packets (k >>1), Q_k^- becomes equal to Q_{k+1}^-. As per Figure 5(b), after the system converges, $Q_k^- = Q_{k+1}^- = Q^-$, and $Q^+ = Q^-$, where Q^+ and Q^- are two independent identical probabilities in steady state. Using Q^+ from Eq. 4 and the convergence $Q^+ = Q^-$, we derive the probability of recovering a packet in steady state (SRP), R, as follows:

$$R = Q^+ + (1-Q^+)\cdot Q^- = Q^+(2-Q^+)$$
$$= 1-\left(\frac{(1-q)^n}{1-nq(1-q)^{n-1}}\right)^2 \qquad \textbf{(8)}$$

Using Eq. 3, we express this equation as a function of D:

$$R = 1 - \left(\frac{1-D}{1-n\left(1-(1-D)^{1/n}\right)(1-D)^{n-1/n}} \right)^2$$

(Eq. 8 can also be derived from Eq. 7 as $k \to \infty$.)

4.4. Improvement of SRP

Since SDP = D and SRP = R, the difference between SDP and SRP, $I = R - D$, expresses the improvement in packet recovery probability under NC-ERP. To evaluate the improvement of NC-ERP, we establish the conditions when $I > 0$. From Eq. 3, $D = 0$ when $q = 0$, $D = 1$ when $q = 1$. Hence, using Eq. 8, we confirm that the improvement $I = 0$ when $D = 0$ or $D = 1$.

Next we derive the derivative of I with respect to D. The derivative of R respect to q is:

$$\frac{dR}{dq} = \frac{2n(1-q)^{2n-1} \cdot \left(1-(1-q)^{n-1}\right)}{\left(1-nq(1-q)^{n-1}\right)^3}, \qquad \textbf{(9)}$$

and the derivative of D respect to q is:

$$\frac{dD}{dq} = n(1-q)^{n-1}. \qquad \textbf{(10)}$$

Hence, the derivative of I respect to D is:

$$\frac{d(R-D)}{dD} = \frac{2(1-q)^{n} \cdot \left(1-(1-q)^{n-1}\right)}{\left(1-nq(1-q)^{n-1}\right)^3} - 1. \qquad \textbf{(11)}$$

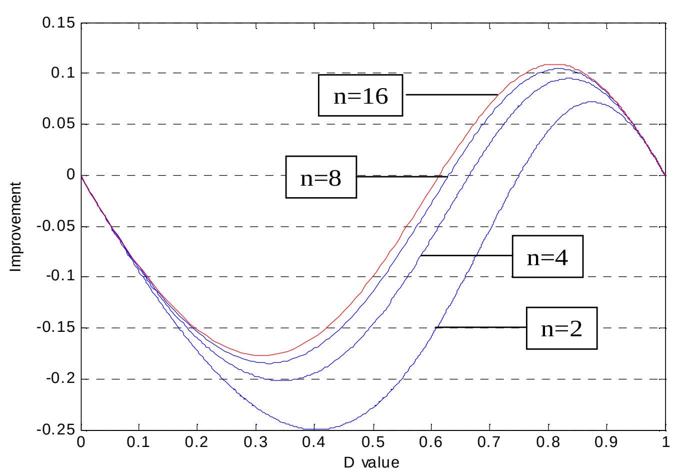


Figure 6: Improvement of SRP

From Eq. 11, we realize that the derivative of I at D=0 and at D=1 (or, equivalently, for q=0 and q=1) equals -1. Since I = 0 at these two points and I is a continuous function of q, this confirms that for D close to 1, I is strictly positive. Similarly, for D close to 0, I is strictly negative. Thus, theer are values of D for which NC-ERP improves the SRP, as compared with the SDP of ERP.

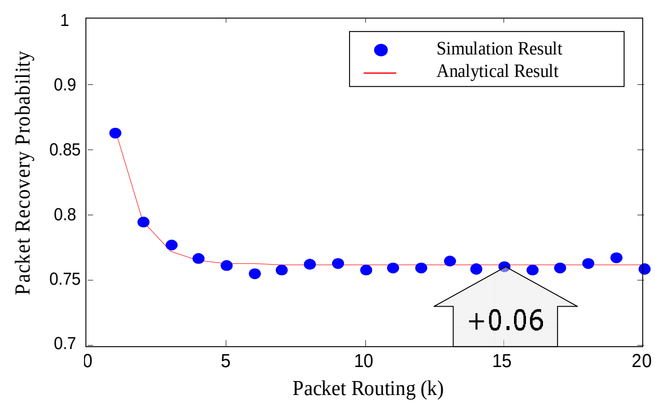
Figure 6 presents the SRP improvement, I, as a function of D for different number of copies n. We note the two regions of D; *negative range* where I is negative and *positive range* where I is positive. We further observe that as the number of copies increases, the range of D where I is positive increases as well.

5. SIMULATION RESULTS

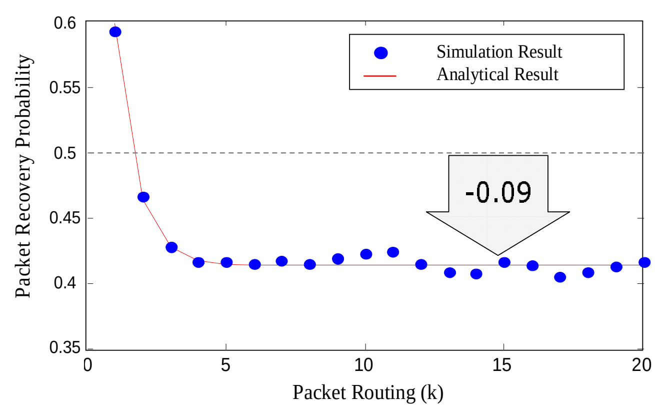
We performed our simulations in a 1000 m by 1000 m closed torus-like area, with the network consisting of N=50 mobile nodes plus one sink node. The transmission range of a node is 25 m. The movement direction of each node is uniformly distributed in [0, 2π] and the speed is uniformly distributed in [20, 50] m/s. Each node changes its velocity every 5 sec. In this random mobility model, the encounter rate λ between any two nodes is 0.001 contacts/sec. All the simulation results are averaged over 1000 runs.

Fig. 7 shows the simulation result of recovery probabilities for the first 15 source packets under NC-ERP for different time intervals T_d, compared with the analytical result derived by Eqs. 5, 6, and 8. Figure 7(a) depicts 6% improvement of NC-ERP when the SDP value is 70%. However, when the SDP value is 50%, Fig. 7(b) shows that NC-ERP improvement is negative 0.9%.

Based on the analytical result, Q_k is a decreasing function of k. Both analytical and simulation results show that the packet recovery probability converges to SRP.



(a) T_d = 25 sec, n = 20, q = 0.06, SDP = 0.7



(b) T_d = 18 sec, n =16, q = 0.04, SDP = 0.5

Figure 7: Initial Recovery Probability

6. CONCLUSIONS

In this paper, we proposed a new protocol, termed NC-ERP, which applies Linear Network Coding to ERP. For scenarios of limited nodal memory and high packet creation rate, the NC-ERP advantage stems from the fact that any combination carries partial information of multiple packets. Although to recover a packet the sink is required to receive multiple combinations, this is naturally supported in ERP through the replication operation.

We derived a mathematical model for the NC-ERP, where the nodes can store one packet only, and a combination is created from only two consecutive packets. Using the mathematical model, we proved that there exists a certain range for which NC-ERP improves the SDP. We verified the accuracy of our mathematical model by simulations.

Our results are more general - the advantage of applying linear network coding to sequential packet routing is not limited to the ERP only. Indeed, as long as the source routes multiple packets and the sink can receive these packets with high probability, linear network coding can improve the packet delivery probability.

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