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An Energy-Efficient n-Epidemic Routing Protocol for Delay Tolerant Networks

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***Abstract*—In Delay Tolerant Networks (DTN), as disconnections between nodes are frequent, establishing routing path from the source node to the destination node may not be possible. However, if a node transmits packets to all its encounters, its batteries will be used up quickly. Many researches have been done on routing and forwarding algorithms in DTN, but few of them have explicitly address the energy issue. In this paper, we propose n-epidemic routing protocol, an energy-efficient routing protocol for DTN. The n-epidemic routing protocol is based on the reasoning that in order to reach a large audiences with low number of transmissions, it is better to transmit only when the number of neighbors reaching a certain threshold. We compare the delivery performance of n-epidemic routing protocol with basic epidemic routing protocol using both analytical approach and empirical approach with real experimental dataset. The experiment shows that n-epidemic routing protocol can increase the delivery performance of basic epidemic-routing by 434% averagely.**

I. Introduction

In Delay Tolerant Networks (DTN), source-based techniques are expected to be inappropriate since the calculated path will most likely be invalid before it is used [1] [2]. If the nodes move unpredictably with high speed, disconnections between the nodes would be frequent and the end-to-end path between any node-pair may not be always possible.

Like infectious diseases spreading in human being when people meet each other, mobile nodes can forward packets in the same way. Nodes send messages to encounter nodes and these encounter nodes relay this packet to other encounter nodes. This packet delivery is analogous to the spread of infectious diseases [3] [4] [5]. This kind of routing is referred to as *epidemic routing*. Epidemic routing can result in many replicas of the packet in the network. If a copy of the packet reaches the destination node, the transmission is successful.

Many routing protocols have been developed for DTN [6] [9] [10] . However, these routing protocols do not consider the energy consumption issue. In these epidemic-type routing protocols, relays may send a packet to different encounter nodes at different time. But, since the mobile devices are in general powered by batteries and are not able to charge batteries expediently, energy is a major constraint in the mobile scenarios [14] [15]. If the device sends each packet many times, it will use up its battery energy quickly and can not relay other packets for other nodes. Thus, the overall network capacity is not high.

In the nature, salmons travel more than thousands of kilometers to return to the freshwater where they were born to spawn because salmons have only one opportunity to spawn and they have to choose the ideal place to do it. Inspired by salmons traveling back to where they were born, if we consider the energy consumption of each transmission, we have to take advantage of the broadcasting nature of the wireless channel and limit the number of times that a relay forwards a packet. A relay does not forward a packet whenever it meets another node. It has to wait for more neighbors so its packet transmitted can be received by more neighbors. This can reduce the energy consumed for forwarding a packet and save more energy to forward more packets. We study how to guarantee that more node can receive the packet.

This paper is organized as follows: We review the related work in Section 2. Section 3 is the introduction of basic epidemic routing. In section 4, we introduce the proposed n-epidemic routing protocol and establish the delivery ratio model. Then, we evaluate the delivery performance of n-epidemic routing and basic epidemic routing in section 5. In the following section 6, there is an experiment on human contact datasets and section 7 will be the conclusion of the whole paper.

II. Related Work

There are lots of work on DTN routing algorithms. One of the simplest approaches is to let the source or a moving relay node carry the message all the way to the destination [7]. Although this scheme performs only one transmission, it is very slow. An faster way to perform routing in delay tolerant networks is Epidemic Routing. The basic idea of Epidemic routing is to select all nodes in the network as relays, say to flood the message throughout the network [3]. However, as messages are flooded to all other nodes, it is extremely wasteful of resources, such as batteries energy.

Some later work studied relay selection strategies to reduce the overhead and improve the performance of epidemic routing [9] [10] [11]. A message is forwarded to another node with some probability smaller than one. A node selects relays based on the history information such as the history of past

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TABLE I: Notation and Meaning.

Notations	Meanings
$DR(t)$	delivery ratio after time t
PT	packets throughput
DP	delivery performance
n	the threshold of neighbors
N	the number of ordinary nodes
L	the length of experiment area
λ	the density of adversaries, $\lambda = N/L^2$
v	the sender's speed
v_1	the node's speed
$E[V^*]$	relative speed between nodes
r	node's transmission range
p	the pairwise meeting rate
k	delivery performance ratio
h	the probability that a node having at leat n neighbors
$\lvert X\rvert$	the number of nodes in X
$\lVert * \rVert$	the number of nodes in the area $*$

encounters. PRoPHET is a Probabilistic Routing Protocol using a History of Encounters and Transitivity [8]. PRoPHET calculates the delivery predictability at each node by using encounter history. PRoPHET can be used for intermittently connected networks, where there is no guarantee that a fully connected path between source and destination exists at any time, rendering traditional routing protocols unable to deliver messages between hosts.

Some routing schemes select some nodes with desirable mobility patterns as message ferries [9] [10]. Since node mobility patterns are hard to control [13], another strategy is social-based forwarding scheme which exploit sociological centrality metrics for relay selections [20] [21]. The BUBBLE scheme improves the forwarding efficiency significantly compared to oblivious forwarding schemes and to PROPHET algorithm based on the users' social activity[21]. Some other routing algorithms are about security and privacy in DTN [16] [17] [18].

III. Basic Epidemic Routing

If nodes forward packets by basic epidemic routing, nodes transmit packets whenever they meet a neighbor and they may transmit a packet many times. Now, we calculate the delivery ratio $DR(t)$ of basic epidemic routing. Table 1 lists all the notations we used in this study.

Let N be the total number of nodes moving within a square area L^2. If nodes move in a limited region according to common mobility models and if their transmission range is largely smaller than the length of network area, say $r \ll L$, the pairwise meeting time between nodes to be nearly exponentially distributed[11]. Define pairwise meeting rate p to be the probability that two nodes can meet.

$$p \approx \frac{2\omega r E[V^*]}{L^2} \tag{1}$$

where ω is a constant which depends on the mobility model used and $E[V^*]$ is the average relative speed between two nodes. $\omega \approx 1$ when the mobility model is random direction and $\omega \approx 1.3683$ when the mobility model is random waypoint. Assume the average speed of an ordinary node is v_1, the average relative speed $E[V^*]$ can be calculated by equation 2 [12].

$$E[V^*] = \frac{\omega}{\pi v_1^2} \int_0^{2v_1} \left(\frac{x^2}{\sqrt{1-(\frac{2v_1^2-x^2}{2v_1^2})^2}}\right) dx \tag{2}$$

Equation 3 shows the number of nodes that received a packet after time t with one initial sender, where $I(t)$ represents the number of nodes received the packet, p is the contact rate of the nodes and t is the duration from the beginning of packets sending till present [12].

$$I(t) = \frac{N}{1 + e^{-pNt}(N-1)} \tag{3}$$

Here, we do not know which node will forward the packet to the destination, so the more nodes have received the packet, the larger probability that the destination can receive the packet. We define the proportion of the nodes that have received a packet to be the delivery ratio (DR) of the packet. As we know, the delivery ratio of a packet increases with time, so it is a function of time, $DR(t)$.

$$DR(t) = \frac{I(t)}{N} = \frac{1}{1 + e^{-pNt}(N-1)} \tag{4}$$

IV. n-Epidemic Routing

A. Protocol Description

As packets are forwarded on the move, we assume a node is powered by batteries. Usually, when people are moving, it is inconvenient to charge the batteries, so the energy is a constraint in this scenario. If a node transmits packets to others whenever it meets another node, its batteries will be used up quickly and fruitlessly. For this reason, we optimize the chances that a node forwards a packet to its neighbors. Here, when other nodes are within a node's transmission range, they are this node's neighbors.

In n-epidemic routing, we assume that a node forwards a packet only when it has at least n neighbors. By n-epidemic routing, a node cannot send a packet as casually as by basic epidemic routing, so we have to determine the value of n carefully. If n is large, the probability of a node having so many neighbors is low and the chances that this packet is sent out are few. If a packet can not be spread out widely, the destination has low probability of receiving it. On the contrary, if n is very small, nodes have lots of chances to forward a packet, so the batteries energy will be used up quickly. The key step of n-epidemic routing is to determine the value of n.

B. Delivery Ratio

According to the epidemic routing scheme, when a node even has a neighbor, it transmits its packets to the neighbor, but according to the n-epidemic routing scheme, only when a node has at least n neighbors, it forwards its packets. So the rate that a node forwards packets to neighbors by n-epidemic routing is smaller than that by epidemic routing. Let the pairwise

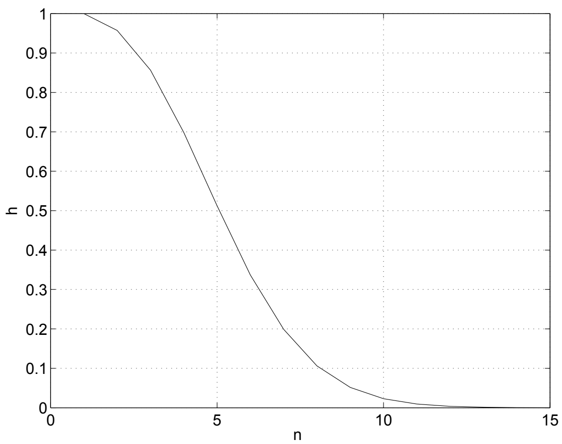

Fig. 1: The relation between h and n.

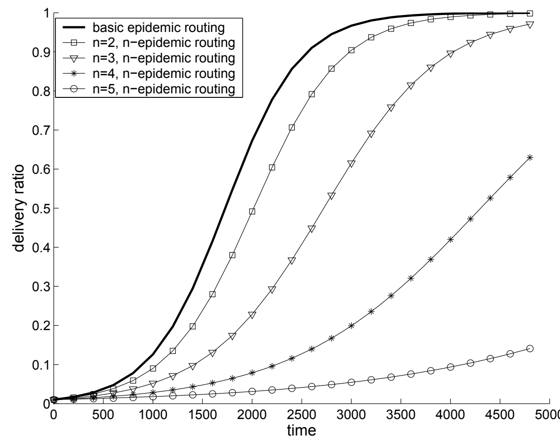

Fig. 2: The comparison of the delivery ratio of n-epidemic routing and basic epidemic routing.

meeting rate of n-epidemic routing be p_2 and the ratio of p_2 and p be h.

$$h = \frac{p_2}{p} = \frac{P(|\pi r^2| \geq n)}{P(|\pi r^2| > 0)} \tag{5}$$

As $P(|\pi r^2| \geq 0) = 1$, $P(|\pi r^2| > 0) = 1 - P(|\pi r^2| = 0)$. Then, Equation 5 can be transformed into

$$\begin{aligned} h &= \frac{P(|\pi r^2| \geq n)}{1 - P(|\pi r^2| = 0)} = \frac{1 - \sum_{i=0}^{n-1} \frac{e^{-x} x^i}{i!}}{1 - e^{-x}}, \\ x &= \frac{\pi r^2 (N)}{L^2} \end{aligned} \tag{6}$$

As we assume that a node can forward a packet only when it has at least n neighbors, the nodes meeting rate is p_2 and $p_2 = ph$. Let the delivery ratio of n-epidemic routing be $DR_n(t)$.

$$\begin{aligned} DR_n(t) &= \frac{1}{1 + e^{-p_2 N t}(N-1)} \\ p_2 = ph &= p \frac{1 - \sum_{i=0}^{n-1} \frac{e^{-x} x^i}{i!}}{1 - e^{-x}}, \end{aligned} \tag{7}$$

Figure 1 shows the relation between h and n. We can know from it that the value of h decreases with the increase of n. The larger n is, the fewer chances that nodes have so many neighbors. We restrict the value of n should ensure $h > 0.1$.

Figure 2 shows the influence of n on delivery ratio. The x-axis of it is the experiment time from the beginning and y-axis is $DP(t)$. It indicates that n-epidemic routing defers the spreading of a message and it would take all nodes longer time to receive a packet.

V. Delivery Performance Evaluation

A. Metrics

Although basic epidemic routing results in higher delivery ratio than n-epidemic routing during the beginning time, nodes also consume much more energy to transmit a packet by basic epidemic routing. As we consider the energy to be a constraint, we judge the delivery performance from both the delivery ratio and the packets throughput.

We define a metric to measure the packets throughput, packets throughput (PT), which is the amount of different packets that a node can transmit/receive during its life time. Also we define a metric to measure the delivery performance (DP) which is the product of delivery ratio and packets throughput, $DP = DR(t) \times PT$.

B. Evaluation

Assume the total energy of a node's battery is E, and the energy that a node consumes to transmit or receive a packet is W. Since a node's battery capacity is mostly consumed in receiving and transmitting packets in real experiments [14] [15], we assume that a node's battery is consumed in transmission entirely. Here, we also assume a node will forward a packet H times. Then by basic epidemic routing, the amount of packets that a node will forward is

$$PT = \frac{E}{W \cdot H} \tag{8}$$

Then the delivery performance of basic epidemic routing is given by equation 9.

$$\begin{aligned} DP &= DR(t) \cdot PT \\ &= \frac{1}{1 + e^{-pNt}(N-1)} \frac{E}{W \cdot H} \end{aligned} \tag{9}$$

On the other hand, by n-epidemic routing protocol, a node cannot send packets as casually as by basic epidemic routing protocol. As we have introduced in above section, the probability that a node has at least n neighbors is h. Then the amount of packets that a node will forward by n-epidemic routing is

$$PT_n = \frac{E}{W \cdot H \cdot h} \tag{10}$$

TABLE II: The values of parameters.

Parameters	Values	Parameters	Values
N	150	$time$	1...5000
r	100 m	L	1000 m
v	60 m/minute	v_1	60 m/minute

So the delivery performance of n-epidemic routing can be calculated by equation 11

$$\begin{aligned} DP_n &= DR_n(t) \cdot PT_n \\ &= \frac{1}{1+e^{-phNt}(N-1)} \frac{E}{W \cdot H \cdot h} \end{aligned} \tag{11}$$

Here, we compute the ratio of DP_n and DP. If the ratio is smaller than 1, the delivery performance of n-epidemic routing is worse than basic epidemic routing. if the ratio is larger than 1, the delivery performance of n-epidemic routing is better than basic epidemic routing.

$$k = \frac{DP_n}{DP} = \frac{1+e^{-pNt}(N-1)}{1+e^{-phNt}(N-1)} \cdot \frac{1}{h} \tag{12}$$

With the parameters listed in table 2, we compute the ratio of the delivery performance of n-epidemic routing to that of basic epidemic routing. Figure 3 shows the delivery performances under different values of n. We can find that when $n > 1$, the delivery performance ratio $k > 1$ during the beginning 500 minutes. It indicates n-epidemic routing has better delivery performance than basic epidemic routing in the beginning. However, after that, the ratio k becomes lower than 1 from time 500 to 1800 minutes. This is reasonable because the delivery ratio of n-epidemic routing is lower than that of the basic epidemic routing during that time duration. We can find this conclusion from Figure 2. On the other hand, after about 1800 minutes, the delivery performance ratios with $n = 2$ 5 become again larger than 1. The delivery performance ratio with $n = 6$ becomes larger than 1 after about 3200 minutes as well.

From Figure 3, we cannot get a conclusion on the delivery performance of n-epidemic routing and basic epidemic routing. So we compute the average of the delivery performance ratios. Figure 4 shows the average delivery performance ratios with different n. It indicates that in the first day, the delivery performance of n-epidemic routing is worse than basic epidemic routing. However, after 2 days, the the delivery performance of n-epidemic routing is better than basic epidemic routing. Therefore, if a device's batteries can be working on for more than 1 days, n-epidemic routing has better delivery performance.

Also we can know k reaches the maximum when $n = 5$ or $n = 6$, which is a little bit larger than the node's average number of neighbors, 4.7. So we suggest the best value of n to be a little bit larger than the node's average number of neighbors.

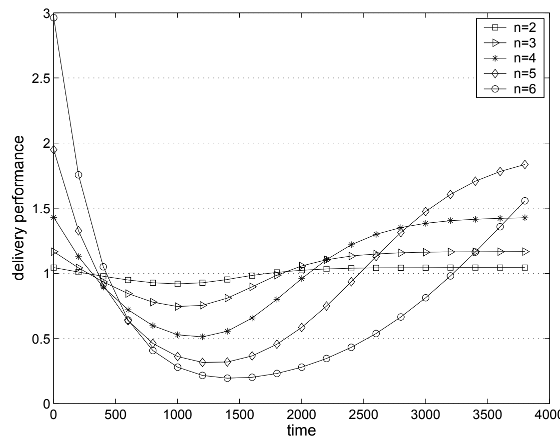

Fig. 3: The comparison of the delivery performance ratios under different n.

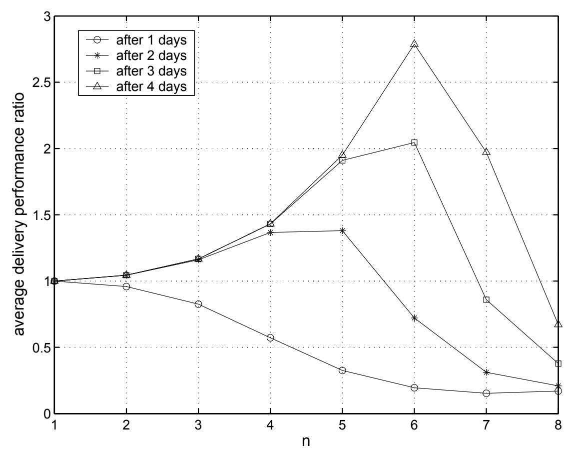

Fig. 4: The averages of the delivery performance ratios after different time.

VI. Experiment

A. Experiment Setup

As human mobility plays a key role in packet delivery in DTN [20], we checked the user contacts in the real world. We validated n-epidemic routing on a real-world experiment datasets to study the delivery performance of n-epidemic routing.

In this study, we use the experimental dataset gathered at the IEEE *Infocom* 2005 conference by the Haggle Project (www.haggleproject.org) [21]. In the experiment, the device used to collect connection data was the Intel iMotes that had the same transmission and reception range. Each participant carried a iMote that logged the beginning time and the end time of any contact with other nodes and the device's id. The iMotes sent heartbeat signals every two minutes. The format of the dataset is *(i, j,* t_b*,* t_e*)*, where t_b is the beginning time of a contact and t_e is the end time of this contact. We define a variable *contact duration* to study the relative mobility

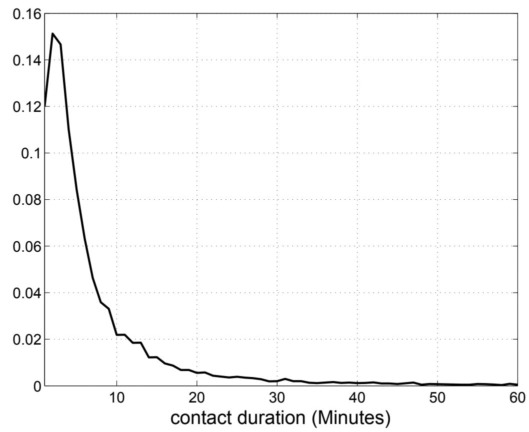

Fig. 5: Distribution of the contact durations.

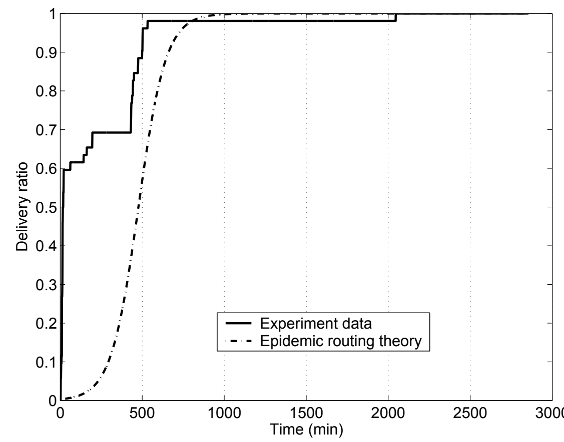

Fig. 7: An illustration of delivery ratio with time.

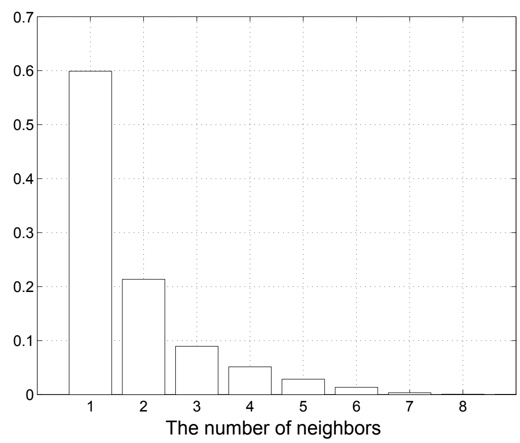

Fig. 6: Distribution of the number of neighbors

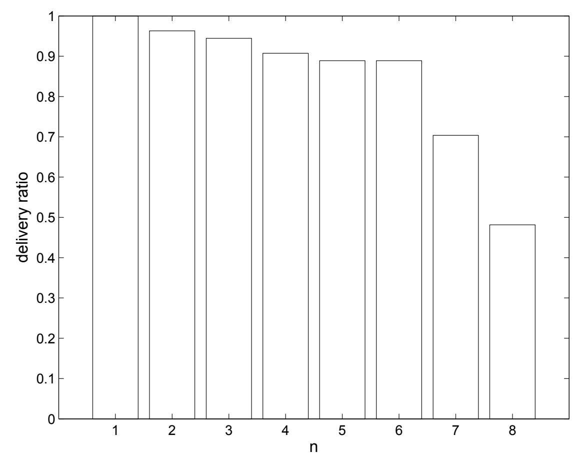

Fig. 8: The delivery ratio function of n

between nodes, $contact\ duration = t_e - t_b$.

B. Contact Analysis

Figure 5 shows the distribution of the contact durations. The statistical study of these contacts shows that more than 80 percent of the contacts are shorter than 10 minutes and more than 90 percent contacts are shorter than 20 minutes. This demonstrates that two nodes did not remain in contact for a long time. This is the feature of DTN.

Figure 6 shows the distribution of the number of neighbors. We conclude that each node has at least one neighbor with around 30 percent experiment time during the 4 days experiment time. This figure also shows that a node usually does not have too many neighbors. It is almost zero probability that a node has more than 6 neighboring nodes at one moment in this experiment.

C. Experiment Results

Figure 7 shows the theoretical delivery ratio and real delivery ratio of basic epidemic routing on the real datasets. In Figure 7, the dot-line means the theoretical packet delivery ratio of basic epidemic routing and the line means the real delivery ratio of the real world experiment. This figure shows that by basic epidemic routing, the delivery ratio can increase almost to 1.

We compute the delivery ratios of the experiment dataset after 4 days from the beginning time. Figure 8 shows the delivery ratios on experiment data with different values of n. This figure indicates that when the value of n is lower than 4, the delivery ratios are just about 0.54, which means only half of nodes received the packet. The delivery ratio reached its maximal value when the number of receivers is 6. If we restrict that each node sends a packet only when it has more that 8 neighboring nodes, this packet can not be send out.

Figure 9 shows the times that a packet to be forwarded by different routing protocols. In this figure, $n = 1$ means nodes forward packets by basic epidemic routing, and $n > 1$ means nodes forward packets by n-epidemic routing. Our study shows that each node forwards a packet average 95 times by basic epidemic routing during 4 days. The times that a packet was forwarded by n-epidemic routing decreases with the increase

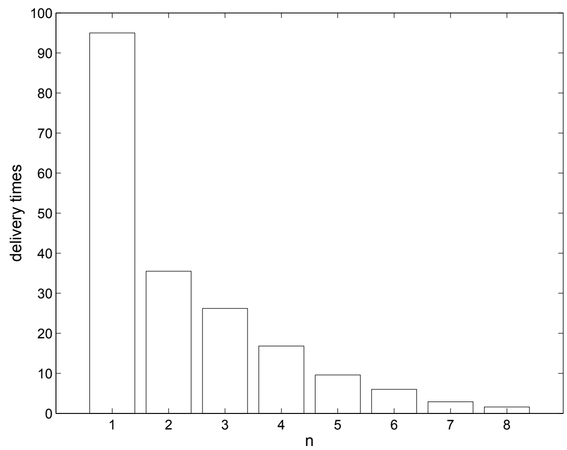

Fig. 9: A packet delivered times by n-epidemic routing and basic epidemic routing

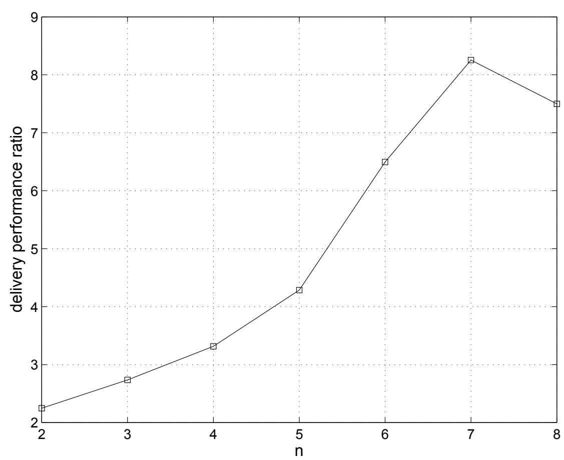

Fig. 10: The delivery performance ratio of n-epidemic routing to basic epidemic routing under different n.

of n. And the forwarding times of n-epidemic routing were much lower than that of basic epidemic routing.

Now, we will compute the delivery performance ratio, k, of n-epidemic routing to basic epidemic routing. Figure 10 indicates that the delivery performance ratios of n-epidemic routing to basic epidemic routing are larger than 1. The average of the delivery performance ratios is 4.34. It means n-epidemic routing protocol can increase the delivery performance of basic epidemic-routing by 434% average. The average number of neighbors is 5, so we set $n = 5$. When $n = 5$, n-epidemic routing protocol can increase the delivery performance of basic epidemic-routing by 430%. We can get the conclusion that n-epidemic routing has much better delivery performance than basic epidemic routing.

VII. Conclusion

Most current researches do not consider the energy issue in epidemic routing. If a node transmits packets to others whenever it meets other nodes, its batteries will be used up quickly and fruitlessly. n-epidemic routing protocol can reduce the chances that a node forwards a packet to its neighbors. We set up a delivery performance model to evaluate n-epidemic routing protocol. Also we validated n-epidemic routing protocol on a real world contact dataset. Our experiment on the real contact dataset shows that the delivery performance of n-epidemic routing is much better than that of basic epidemic routing. The experiment shows that n-epidemic routing protocol can increase the delivery performance of basic epidemic-routing by over 434 %.

VIII. Acknowledgment

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