Performance Evaluation of Routing Schemes for Energy-Constrained Delay Tolerant Networks

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***Abstract*—In order to provide communication services in Delay Tolerant Networks (DTNs) where it lacks of end-to-end paths between the communication sources and destinations, a variety of routing schemes have been proposed. Consequently it is significant to accurately evaluate their performance to show their advantages and inferiority. At the same time, the energy is very limited in a large number of DTNs, such as sparse mobile sensor networks and emergency ad hoc networks, and it impacts the routing performance significantly. However, current related works ignore the influence of the energy constraint on the routing. In this paper, we investigate the performance of routing schemes for the energy-constrained DTNs. First, we model the two-hop relaying, epidemic routing and K-hop forwarding with energy constraint based on a continuous time Markov chain. Then, we obtain the system performance of message delivery delay and delivery cost by explicit expressions. By both simulation and numerical results, we demonstrate the accuracy of our proposed model and reveal that the energy constraint can actually avoid the message storms which are harmful to the systems in term of delivery cost and transmission contention.**

I. Introduction

In Delay Tolerant Networks (DTNs), there are no end-to-end paths from communication sources to destinations during most of the time due to node mobility, wireless propagation effect, sparse node density and so on [1][2]. Examples of such networks include deep-space inter-planetary networks [3], vehicular ad hoc networks [4], underwater networks [1], military networks [5], etc. In such kind of networks, traditional ad hoc routing protocols, which rely on the end-to-end paths [6], fail to work [1]. Therefore, a new routing mechanism, called store-carry-and-forward [7][8], was proposed to provide communication. In this routing mechanism, when the next hop is not available for a node to forward a message, the node will store the message in its local buffer, carry it along on the move, and forward it to other appropriate nodes when there is a transmission opportunity.

In order to improve the message delivery probability, a variety of routing schemes have been proposed, such as two-hop relaying [9], epidemic routing [10], K-hop forwarding [8] and a family of spray routing algorithms [11]. These routing schemes try to achieve short message delivery delay and relatively low transmission cost. However, there is a tradeoff between them. Generally speaking, short delivery delay is obtained at the expense of more cost. Therefore, it is significant to accurately evaluate the performance of these routing schemes to show their advantages and inferiority. Some works use simulation method [7][12], but recently theoretical analysis frameworks, such as Markov models [13] and Ordinary Differential Equation (ODE) models [14], are also used to evaluate the performance in an immediate way. These works ignore the influence of the energy constraint on the DTN routing. Although the ONE [15] simulator specifically designed for evaluating DTN routing allows users to simulate energy consumption of nodes, proposing theoretical frameworks is important for immediate and incisive analysis.

In several DTNs, the energy is limited. For example, in wireless mobile sensor networks for environmental and wildlife behavior monitoring [16], the sensor nodes are attached to animals such as zebras [17] and deer [18]. The mobile sensor nodes form the DTN and consequently the energy will be a serious issue. Another example is human network like Pocket Switched Networking [19], where the mobile users as the networking nodes use their mobile devices, which are energy-constrained. Furthermore, even for networks such as vehicular DTN where typically energy is not an issue, unnecessary message transmissions and flooding are not good for the common welfare of the whole network since transmissions also cause contentions to other users. Therefore, energy efficient forwarding algorithms not only affect the energy consumption but also influence the overall network throughput. Therefore, it is necessary to develop a uniform analysis framework appropriately characterizes the effect of energy constraint to evaluate the DTN routing performance.

In this paper, we investigate the performance of various routing schemes for the energy-constrained DTN. By using a continuous time Markov chains to model the message dissemination, we evaluate three popular routing schemes: two-hop relaying, epidemic routing and K-hop forwarding. The main contributions of this paper can be summarized as the following aspect:

- We use a continuous time Markov chains to model the message transmission with energy constraint in DTNs, and provide a uniform framework to model the two-hop relaying, epidemic routing and K-hop forwarding. Since the proposed model appropriately characterizes both the message dissemination and energy constraint, it significantly simplifies the performance analysis.
- We derive explicit expressions for the performance of both message delivery delay and message delivery cost based on the proposed Markov model. From the aspect of

computation, since our results is matrix-based operation, it is easy to obtain by computation tools.
- We demonstrate the accuracy of our Markov model by comparing the theoretical results with simulation results. Furthermore, through extensive results, we show that in DTN routing, the energy constraint decreases the message delivery cost at the expense of increasing the delivery delay.

The rest of the paper is organized as follows. In Section II, we describe the system model, and give the analysis framework for the three routing schemes. In Section III, we derive the system performance of message delivery delay and cost based on the model. Then, we introduce the performance evaluation environment, validate the obtained system performance and investigate the numerical results in Section IV. Finally, we conclude the paper in Section V.

II. Modeling the DTN Routing

A. System Model

We model a DTN as a set of wireless mobile nodes, denoted by $\mathbb{V}$, and $|\mathbb{V}| = N + 1$ $(N > 2)$ that means the number of nodes is $N + 1$. In this paper, we consider the message transmission from the source node to the destination node, and investigate the message delivery delay and delivery cost. Since the density of the nodes is usually sparse in DTN, they can communicate only when they move into the transmission range of each other, which means a communication contact. We assume the contact rate is λ. Considering the energy consumption for delivering a message to the destination, we assume it is proportional to the expected number of transmission times during the message's lifetime, where the energy consumption of one time transmission includes both the reception energy at the receiving node and sending energy at the transmitting node. Therefore, it is reasonable to have the energy constraint, denoted by Ψ, in proportional to the expected number of transmissions. The maximum number of nodes that can be infected by the message, denoted by X, can be calculated by the following expressions $\gamma(X - 1) \leq \Psi$. Without loss of generality, we assume $\gamma = 1$, and obtain $X \leq \Psi + 1$. For simplify of explanation, we let $M = \Psi + 1$. In our model, we notice that we only consider the communication energy for message transmission and reception, which is the main energy consumption in the system [17]. Since we limit the total energy consumption but not the energy by each node for delivering a message, the number of transmissions of the whole system is constrained. Consequently, this model concerns about how to constrain the whole number of transmissions. Therefore, it is meaningful in practice.

Regarding DTN routing algorithms, we consider three most typical schemes, two-hop relaying, epidemic rouging and K-hop forwarding, which are described as follows:

- *Two-hop Relaying*: In two-hop relaying, the source node can replicate the message to any other nodes, but other nodes can only forward it to the destination. The two-hop relaying aims at limiting the number of message transmissions.

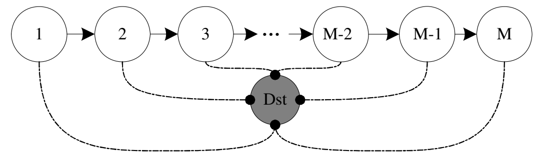

Fig. 1. The continuous time Markov model for the epidemic routing and two-hop relaying. States (0) to (M) are M transition states and state (Dst) is the absorbing state.

- *Epidemic Routing*: In epidemic routing, packets arrived at intermediate nodes are forwarded to all neighbors of the nodes. There are no constraints on the number of message copies in the network, and the messages are transmitted in a flooding way.
- *K-hop* $(k \geq 3)$ *Forwarding*: Under K-hop forwarding, a message can traverse at most K hops from the source to the destination.

Actually, the two-hop relaying scheme is a special case of K-hop forwarding when $K = 2$. However, since two-hop relaying can be modeled by a simpler model used for analyzing the epidemic routing, we separate two-hop routing from the K-hop forwarding and study K-hop $(K \geq 3)$ forwarding separately. In the following sections, we model the message dissemination process in the above three routing schemes using a continuous-time Markov model. Exactly, for the epidemic routing and two-hop relaying, we use the one dimensional Markov model, while for the K-hop forwarding, we use the two dimensional model.

B. Two-hop Relaying and Epidemic Routing

Considering the message dissemination process in the two-hop relaying and epidemic routing. After the message is generated by the source node, it will be transmitted to more and more nodes when communication contacts occur, and we model it by a one dimensional continuous time Markov chain with state $(m(t))_{t\geq 0}$, where $m(t)$ represents the number of nodes with the message at time t. Fig. 1 shows the state transition diagram. We can observe that this Markov chain is started with state (1) at the time the message is generated, and has M transient states because the energy constraint only allows the message to be transmitted to at most M nodes including the source node. In any transient state $(m(t))$, the message may be transmitted to the destination node, which means the absorbing state, denoted by state (Dst). Therefore, the number of total states is $M + 1$. At the same time, we can observe that state $(m(t))$ is related to the times of message transmissions. Therefore, by this model, we can obtain the message delivery cost. According to Fig. 1, we obtain the generator matrix $\mathbf{Q}$ as the following form:

$$\mathbf{Q} = \begin{pmatrix} \mathbf{T} & \mathbf{R} \\ \mathbf{0} & \mathbf{0} \end{pmatrix}, \quad (1)$$

where sub-matrix $\mathbf{T}$ is an $M \times M$ matrix with element $T_{i,j}, (1 \leq i, j \leq M)$ means the transition rates from transient state (i) to state (j), $\mathbf{R}$ is a $M \times 1$ matrix with element

$R_{i,Dst}$ meaning the transition rate from transient state (i) to the absorbing state (Dst). The left **0** matrix is a $1 \times M$ vector with all element 0 meaning zero transition rates from the absorbing state to transient states. The right **0** matrix degenerates to a single 0 element representing the negative sum of the left **0** vector. According to the different routing algorithms controlling the message dissemination, we obtain the transition rate $\{q_{i,j}\}$ from state i to state j as the following two subsections.

1) Two-hop Relaying: Recall the 2-hop relaying scheme, the source node can replicate the message to any other nodes, but other nodes can only forward it to the destination. We consider the message transmission process when the system is in the transient state (m). There are m nodes with the message and $N-m$ nodes without the message. When one of the nodes without the message encounters the source and receives the message, the system state turns to $(m+1)$. Since the contact rate between the source and other nodes is λ, transition rate from state (m) to $(m+1)$ is $(N-m)\lambda$. When one of the nodes with the message encounters the destination, the system turns to state (Dst), and the transition rate is $m\lambda$. Therefore, the system transition rates can be given as follows:

$$\begin{cases} T\{(m+1)|(m)\} = (N-m)\lambda, & for\ m \in [1, M-1]; \\ R\{(Dst)|(m)\} = m\lambda, & for\ m \in [1, M]; \\ T\{(m)|(m)\} = -N\lambda, & for\ m \in [1, M]. \end{cases} \quad (2)$$

2) Epidemic Forwarding: In the epidemic routing, the message arriving at the intermediate node is forwarded to all of the neighboring nodes in contact. According to the behaviors of the message transmission, we have that when the system is in state (m), the next state will be $(m+1)$ if one of the nodes without the message receives a copy or be (Dst) if one of the nodes with the message encounters the destination. Different from two-hop relaying, the nodes can receive the message from any nodes with it. It means that if one of the $N-m$ nodes that does not have the message encounters any one of the m nodes, the system state changes. Thus the transition rate from state (m) to state $(m+1)$ is $(N-m)m\lambda$. Therefore, the system transition rates is given by the following expressions:

$$\begin{cases} T\{(m+1)|(m)\} = (N-m)m\lambda, \\ \qquad\qquad for\ m \in [1, M-1]; \\ R\{(Dst)|(m)\} = m\lambda, \\ \qquad\qquad for\ m \in [1, M]; \\ T\{(m)|(m)\} = -(N-m+1)m\lambda, \\ \qquad\qquad for\ m \in [1, M]. \end{cases} \quad (3)$$

C. K-hop Forwarding

Now, we consider the K-hop forwarding. Unlike two-hop relaying and epidemic routing, K-hop forwarding has a system state about how many hops the message has been transmitted. Therefore, we need a two dimensional continuous Markov chain to model the message dissemination. The Markov model is with state $(m(t), k(t))_{t\geq 0}$, where $m(t)$ represents the number of nodes with the message and $k(t)$ represents the maximum number of hops the message has been transmitted at time t. Fig. 2 shows the state transition diagram. From it, we can see that this Markov chain starts with state $(1, 0)$ because only the source node with the message and the hop counter is 0 at the time the message is created. It has $S = NK-K(K+1)/2+1$ transient states and one absorbing state. Similar to the two-hop relaying and epidemic routing, we can obtain the same generator matrix **Q** expressed by Equation (1). Here, the sub-matrix **T** is a $S\times S$ matrix, **R** is a $S\times 1$ matrix, the left **0** matrix is a $1 \times S$ vector, and the right **0** matrix is a single 0 element, which are with the same meanings in the generator matrix of epidemic and two-hop relaying. When the system is in state (m, k), the next state will be state $(m+1, k)$ if one node except the destination receives the message and does not increase the maximum hop counts, be state $(m+1, k+1)$ if one nodes it increases the hop counts, and be state (Dst) if one of the m nodes transmits the message to the destination. According to the message dissemination controlled by K-hop forwarding, we obtain the transition rates as the following expressions.

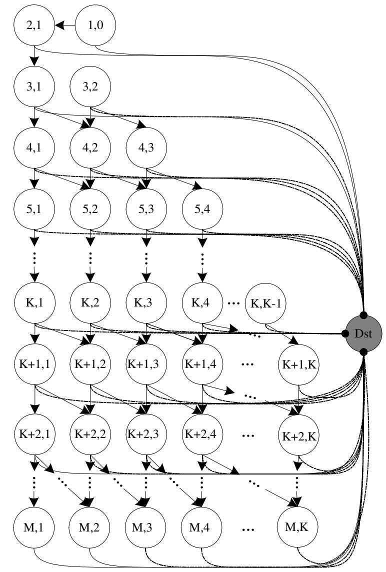

Fig. 2. The continuous time Markov chains for the K-hop forwarding scheme. States $(1, 0)$ to (M, K) are $S = NK - K(K + 1)/2 + 1$ transition states and state (Dst) is the absorbing state.

$$\begin{cases} T\{(m+1, k)|(m, k)\} = (N-m)k\lambda, \\ \qquad for\ m \in [1, M-1], k \in [0, K]; \\ T\{(m+1, k+1)|(m, k)\} = (N-m)(m-k)\lambda, \\ \qquad for\ m \in [1, M-1], k \in [0, K-1]; \\ R\{(Dst)|(m, k)\} = m\lambda, \\ \qquad for\ m \in [1, M], k \in [0, K]; \\ T\{(m, k)|(m, k)\} = -(N-m+1)m\lambda \\ \qquad for\ m \in [1, M], k \in [0, K]. \end{cases} \quad (4)$$

III. Performance Analysis

In Section II, we have model two-hop relaying, epidemic routing, and K-hop forwarding by the continuous time Markov chains with a uniform model of generator matrix **Q**, although their transition rates, denoted by $\{q_{i,j}\}$, is different. We use

S to denote the number of transient states, which is M in the two-hop relaying. Based on the model, we consider two system performance metrics. One is the *message delivery delay*, defined as average time the network spends to deliver the message to the destination. The other is the *message delivery cost*, which is defined as the average number of times that the message has been replicated before transmitted to the destination. Related to the message delivery cost, we assume that there is some mechanism to signal the network that the message has reached the destination. Therefore, the computed cost does not address the copies keeping on propagating the message needlessly. In this section, we obtain explicit expressions for these two important system performance metrics.

A. Message Delivery Delay

According to the transition matrix $\mathbf{D}$, we can derive the message delivery delay, denoted by D_d, as the following expression:

$$D_d = \mathbf{e} \cdot (-\mathbf{D}^{-1}) \cdot \mathbf{I}, \tag{5}$$

where $\mathbf{e}$ is a $1 \times S$ vector denoting the initial state probability vector $\mathbf{e} = [1, 0, \cdots, 0]$, and $\mathbf{I}$ is a $1 \times S$ all-one vector $\mathbf{I} = [1, 1, \cdots, 1]$.

B. Message Delivery Cost

In order to derive the message delivery cost, we should obtain the transition probability from the transient state (i) to the absorbing state (Dst). For this purpose, we consider the embedded Markov chain of the generator matrix $\mathbf{Q}$, denoted by $\mathbf{P}$. Its element $p_{i,j}$ is expressed as follows:

$$p_{i,j} = \begin{cases} -q_{i,j}/q_{i,i}, \ j \neq i; \\ 0, \ j = i. \end{cases}$$

$\mathbf{P}$ means the one step transition probability matrix, and consequently, the transition probability from state $(0, 0)$ to state (Dst), denoted by $\mathbf{P}_{1,S+1}$, is $\mathbf{P}_{1,S+1} = p_{1,S+1}$. $\mathbf{P}^2$ means the two step transition probability matrix. Thus, the transition probability from state $(1, 0)$ and state $(0, 1)$ to state (Dst) is $\mathbf{P}^2_{1,S+1}$. Therefore, we have the average message delivery cost as follows:

$$C_d = \sum_{i=1}^{M+K} i \cdot \mathbf{P}^i{}_{1,S+1}. \tag{6}$$

IV. Model Validation and Performance Evaluation

Now, we evaluate the accuracy of our continuous Markov model and analyze the performance of the routing schemes including the two-hop relaying, epidemic routing and K-hop forwarding.

A. Model Validation

In this section, we evaluate the accuracy of our continuous-time Markov model based performance evaluation framework. From our framework, two performance metrics, message delivery delay and message delivery cost, can be obtained by explicit expressions. To show the accuracy of our expression for the delivery delay, we compare the simulation and theoretical results. Related to the delivery cost, we compare our results with that obtained by the ODE model given by Ref. [14], which is validated to be accurate enough to model the delivery cost. Related to the simulation settings, we set $N + 1$ mobile nodes moving according to a speed chosen from a uniform distribution from 4 to 10 within a 20×20 terrain according to random direction mobility model. The transmission range of the nodes is set to 0.1. Without loss of generality, we set $M = N$ since our goal is to verify the accuracy of the model. The results for the two-hop relaying and epidemic routing are shown in Figs. 3 and 4, respectively.

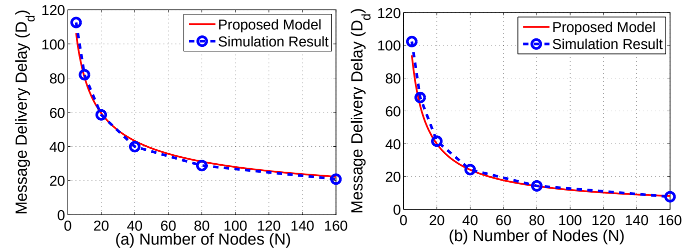

Fig. 3. Comparison between the results of message delivery delay obtained by simulation and the proposed model. (a) Two-hop relaying. (b) Epidemic routing.

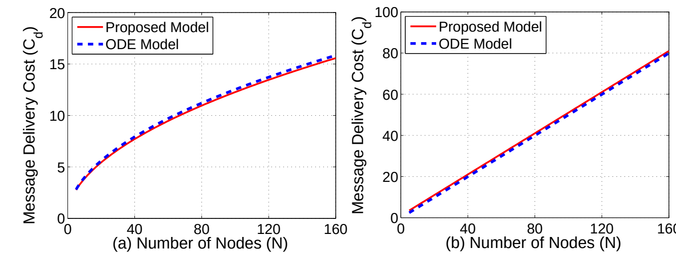

Fig. 4. Comparison between the results of message delivery cost obtained by the ODE model and our proposed model. (a) Two-hop relaying. (b) Epidemic routing.

Comparing the simulation and theoretical results shown in Fig. 3, we can see that the message delivery delay of our model is close to that obtained by simulation, and the average deviations between the simulation and theoretical results are about 5.14% and 4.68% for the two-hop relaying and epidemic routing, respectively. This demonstrates the accuracy of the derived closed form of the message delivery delay by Equation (5). Related to the delivery cost, from Fig. 4, we can observe that the results in almost the same with that obtained by ODE model, and the average deviations between ODE model and our model are about 2.32% and 4.45% for the two-hop relaying and epidemic routing, respectively, which shows the accuracy of Equation (6). These results further demonstrates the accuracy of our continuous-time Markov model. For this reason, we use the theoretical results obtained by our model in the performance evaluation of different routing schemes with energy constraint in the next subsection.

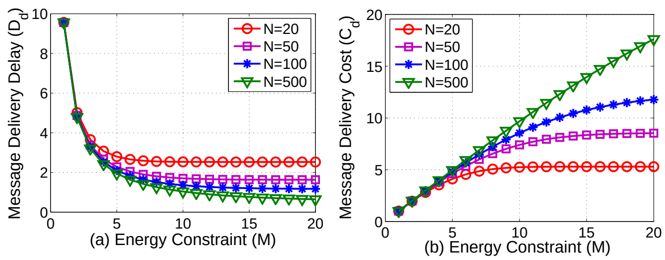

Fig. 5. Results of the two-hop relaying under different energy constraint. (a) Message delivery delay. (b) Message delivery cost.

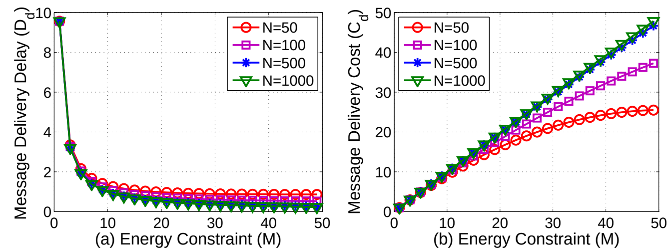

Fig. 6. Results of the epidemic routing under different energy constraint. (a) Message delivery delay. (b) Message delivery cost.

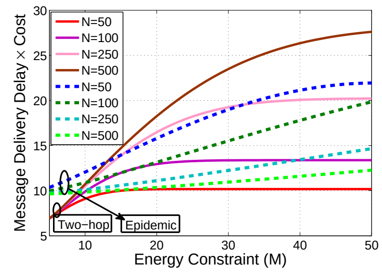

Fig. 7. Numerical results of delay-cost-product for the two-hop forwarding and epidemic routing.

B. Performance Analysis

Using the proposed performance analysis model, we evaluate the performance of the two-hop relaying, epidemic routing and K-hop forwarding with energy constraint on the aspects of message delivery delay and delivery cost. The important parameters in our evaluation include the Poisson contact rate λ, energy constraint M, the number of nodes in the network N. Regrading to the parameter λ, we use an approach similar to [20], which considers a standard Random Waypoint (RWP) mobility scenario. From Ref. [9], we can obtain that for RWP, $\lambda = \frac{8\omega r v}{\pi L^2}$, where $\omega = 1.3683$ is a constant, r is the transmission range, v is the node's scalar speed, and L is the playground size. In the numerical simulation, λ is set to $0.1046\ h^{-1}$ with $r = 20$ m, $v = 15$ m/s and $L = 100$ m. For the purpose of investigation, the number of nodes N and the energy constraint M are set as variable.

Fig. 5 presents the results of message delivery delay and delivery cost under the two-hop relaying scheme with different energy constraint M. Fig. 5(a) shows the message delivery delay with the comparison of the results with different number of nodes N. With the increase of the energy constraint M, the message delivery delay D_d is reduced. As M becomes larger, the delay tends to be a constant. For example, when $N = 20$ and M is larger than 5, the delivery delay is almost the same. Comparing the curves with different N, we can observe that the achieved constant is different, and the larger the number of nodes, the smaller the constant. This reveals that the number of nodes can reduce the delivery delay. It is because more nodes can be used as relays when N is larger. However, when the energy constraint is strict, the message delivery delay of different N is almost the same. The reason is the energy constraint only allows a small ratio of nodes to forward the message. Therefore, the number of nodes influences the message delivery little. Fig. 5 (b) shows the message delivery cost relates to the energy constraint M. It shows that the delivery cost increases with the increase of the energy constraint M and the number of nodes N. When $N = 20$, the delivery cost almost keeps the same value when the energy constraint is more than 8. However, when $N = 500$, the delivery cost keeps increasing with M linearly. Combing the results of Fig. 5 (a) and Fig. 5 (b), we come to the conclusion that the energy constraint reduces the message delivery cost at the expense of increasing the message delivery delay, while the number of nodes reduces the delivery delay at the expense of increasing the delivery cost.

Figs. 6 (a) and (b) respectively show the results of message delivery delay and delivery cost under the epidemic routing. Similar to the results under the two-hop relaying, we can obtain that in the epidemic routing, the energy constraint M decreases the message delivery delay while increasing the delivery cost. However, comparing with the two-hop relaying, we can observe that the number of nodes N influences the performance of epidemic routing less. The reason is that in the epidemic routing, message arriving at intermediate nodes are forwarded to all neighbors. Therefore, the message will infect the nodes much more quickly than that in the two-hop relaying. Consequently, the increase of the number of nodes would impact the performance less.

We obtain the conclusion that the energy constraint reduces the delivery delay by increasing the delivery cost in both the two-hop relaying and epidemic routing. But does it achieve this in an efficient way? In this aspect, we define a related metric, named *delay-cost-product*, which equals the production of message delivery delay and delivery cost. The results of delay-cost-product for the two-hop relaying and epidemic routing are shown in Fig. 7. From the results, we can see that the delay-cost-product increases with the increase of the energy constraint M for both two-hop relaying and epidemic routing. This means the energy constraint takes effect in terms of reducing the delay-cost-product. In the two-hop relaying, we can observe that the delay-cost-product converges to a constant with the increasing of M. For example, when M is larger than 15, the delay-cost-product of $N = 50$ is always 10, and when M is larger than 20, the delay-cost-product of

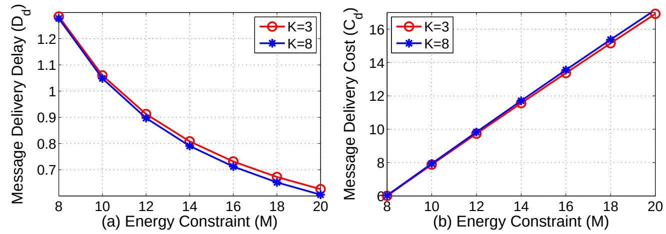

Fig. 8. Results for the performance of the K-hop forwarding with the energy constraint. (a) Message delivery delay. (b) Message delivery cost.

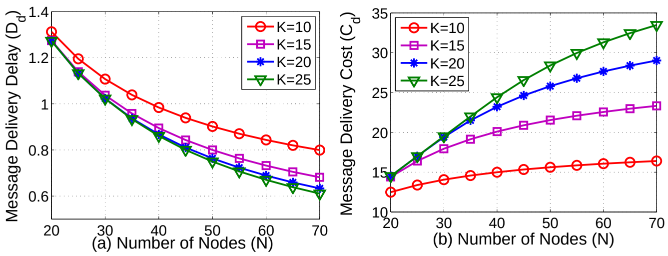

Fig. 9. Results for the performance of the K-hop forwarding when $M = N$. (a) Message delivery delay. (b) Message delivery cost.

$N = 50$ is always 14. However, the delay-cost-product for the epidemic routing always increases with M.

Fig. 8 show the results of message delivery delay and delivery cost for the K-hop forwarding. Similar to the results of two-hop relaying and epidemic routing, we can obtain the energy constraint M decreases the message delivery delay while increasing the delivery cost. At the same time, the performance of both delivery delay and delivery cost with the same hop counts K under the same energy constraint is almost the same. Therefore, we can obtain that when there is energy constraint, the setting of the hop counts would take less effect on the performance.

Since the influence of energy constraint has been investigated for the K-hop forwarding, we focus on the influence of hop count K on the performance and therefore set $M = N$. The results is shown in Fig. 9. Fig. 9 (a) shows the message delivery delay according to the number of messages N. From the four curves with different K, we can observe that the delivery delay decreases with the increase of K. When the number of nodes $N = 20$, the message delivery delay of different K almost the same, and equals to 1.3 h. However, when $N = 70$, the gap between different K becomes larger. For example, the delay is 0.8 h and 0.6 h when $K = 10$ and $K = 20$, respectively. Fig. 9 (b) shows the message delivery cost. We can obtain that the delivery cost increases with the increasing of the number of nodes N and the hop count K. Combining the results of delivery delay and cost, we come to the conclusion that the hop count K increases the message delivery delay while reducing the delivery cost.

V. Conclusion

In this paper, we focus on the performance analysis of various routing schemes, including the two-hop relaying, epidemic routing and K-hop forwarding, for the energy-constrained delay tolerant networks by focusing on the message delivery delay and delivery cost. By using a continuous Markov model, we propose a performance analysis framework for the DTN routing, and derive the explicit expressions for the message delivery delay and delivery cost. By comparing the theoretical results with simulation results, we show the accuracy of our model. Extensive results show that in the DTN routing, the number of nodes decreases the delivery delay at the expense of increasing the delivery cost, while the energy constraint decreases the message delivery cost while deteriorating the delivery delay. Therefore, we conclude that the energy constraint can avoid the message storms which are harmful to the system in term of delivery costs and transmission contention.

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