Dynamic Beaconing Control in Energy-Constrained Delay Tolerant Networks

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***Abstract*—Due to the uncertainty of network topology and intermittent connectivity among nodes in Delay Tolerant Networks (DTNs), beaconing is used to detect probabilistic contacts. However, it causes the following new problem: beaconing frequency not only influences the probability of message transmission, but also affects the consumption rate of energy. Thus, putting forward a beaconing control strategy in energy-constrained DTNs becomes the key point. In this paper, we propose an efficient and dynamic beaconing control method DBCEC in energy-constrained DTNs based on the time-continuous Markov Model. A linear decline strategy (i.e. DBCEC-L) and exponential decay strategy (i.e. DBCEC-E) are respectively applied to control the beaconing frequency. Simulations based on the synthetic mobility model and real mobility traces are conducted in ONE, and results show that DBCEC-E achieves a better delivery rate without influencing average delay and the overhead ratio, compared with other beaconing control strategies.**

***Keywords*—DTNs, Energy-constrained, Markov, Beaconing.**

I. INTRODUCTION

Delay-tolerant networks (DTNs) [1], are a type of challenged network in which end-to-end transmission latency may be arbitrarily long due to occasionally connected links. A traditional TCP/IP protocol suite is no longer applicable. Therefore, a bundle layer including the storage-carry-forward and custody transfer strategies is added between the transport layer and application layer. Typical application scenarios of DTNs are interplanetary networks [2], military field networks, rural countryside networks [3], wildlife monitoring, tracking networks [4], and pocket-switched networks [5, 6], etc.

The store-carry-forward approach requires that routing nodes keep a bundle while the next reliable hop is determined, unless the time to live (TTL) of the bundle expires. Thus, choosing the next nodes to which the messages can be forwarded is critical in such an approach [7], however, the effective utilization of energy in such environment is ignored. Frequent beaconing and message transmission result in quick energy depletion, and make the node stop working. Thus, the connectivity of the whole network is undermined and the delivery rate is bound to be decreased. This makes it difficult to apply the existing scheduling policies and the routing protocols in the real energy-constrained delay tolerant networks, especially in wildlife monitoring, tracking networks and PSNs, where nodes' energies cannot be timely supplied.

Consumption of energy resources in DTNs mainly includes two aspects: beaconing energy for contact detection, and communication energy for message transmission. Note that the node always stays in the beaconing state for most of its lifetime, waiting for an available contact. Only when the proper next-hop node for the stored message is within communication range will the nodes enter the transmission state. Therefore beaconing frequency not only affects beaconing energy consumption but also influences communication energy consumption. To optimize the network performance, we propose a dynamic and self-adapting beaconing control strategy, which can avoid the following two situations: (1) Because the beaconing frequency is too high, the nodes will consume excessive energy. (2) Because the beaconing frequency is too low, the nodes will miss some contacts.

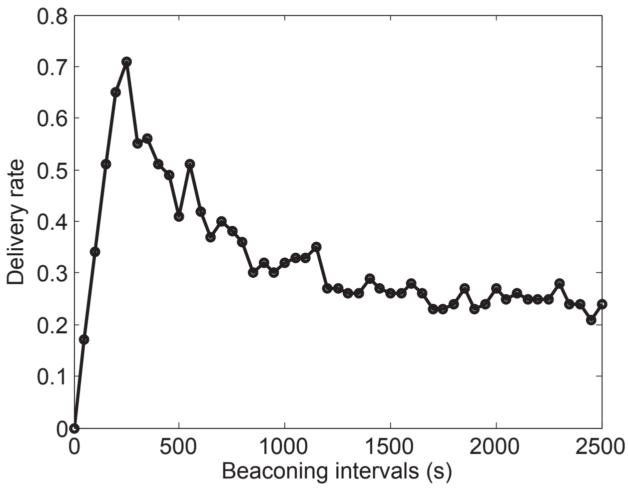


Fig. 1. The relationship between delivery rate and beaconing intervals.

Actually, as shown in Fig. 1 we believe that there is a similar relationship between delivery rate and beaconing intervals in the energy-constrained DTNs; the short beaconing intervals lead to more communication opportunities and rapid energy consumption, so the delivery rate increases as the beaconing intervals increase. However, the excessively long beaconing intervals also result in the waste of communication opportunities, and causes the descent of delivery rate. It is important to trade off the beaconing frequency in order to maximize the delivery rate; so, the optimal beaconing control is to find out the peak point in Fig. 1.

The main contribution of this paper is as follows. Aiming to maximize delivery rate, we propose a dynamic beaconing control strategy DBCEC, based on which we get the DBCEC-L and DBCEC-E by applying linear decline and exponential decay to beaconing frequency. Simulation results show that, compared with other beaconing control strategies, DBCEC-E significantly improves delivery rate without undermining average hops and overhead ratio.

The rest of this paper is organized as follows. We introduce the related work in Section II. In Section III, we model the network system and point out the assumptions. Based on the model and the assumptions, our beaconing strategy is proposed in Section IV. In Section V, performance evaluations are given. We conclude the paper in the last section.

II. RELATED WORK

Some scholars have conducted a study of energy optimization in DTNs, and some achievements have been made, especially in communication energy and beaconing energy. Eitan Altman proposed an ideal control strategy for node activation and message transmission in [8], and properly handled two problems: when to activate the node and how to beacon. Tarek Abdelzaher et al. in [9] proposed a multi-copy interactional routing protocol for energy-constrained disaster networks and ensured that the routing protocol is still able to achieve a better delivery rate when energy is extremely limited. Panayiotis Kolios et al. in [10] presented a routing protocol and a scheduling strategy to maximize the utilization rate of energy and analyzed the trade-off between energy efficiency and average delay in detail. Yong Li et al. studied the energy issues in [11] and [12] successively. In [11], they proposed an ideal opportunistic forwarding strategy to minimize energy consumption and studied the strategy from a static and a dynamic view. In [12], aiming to maximize delivery rate in energy-constrained DTNs, they proposed an energy control method. Shengbo Yang in [13] presented a contact detection method based on social properties and cooperation relationships between nodes for PSNs (pocket switched networks), which can ensure an excellent delivery rate when energy is limited. Aiming to minimize the communication energy consumption for disaster response networks where energy cannot be supplied in a timely manner, Uddin et al. in [14] proposed a multi-copy routing protocol to maximize the delivery rate and reduce the average delay by efficiently using the existing energy.

In this paper, aiming to optimize delivery rate, we propose a dynamic beaconing control strategy DBCEC based on the continuous-time Markov model. The strategy trades off the delivery rate and the energy consumption through controlling beaconing frequency. Then the linear decline strategy (i.e. DBCEC-L) and exponential decay strategy (i.e. DBCEC-E) are respectively studied.

III. SYSTEM MODEL

We consider the following delay tolerant network environment in this paper. N mobile nodes exist in the network. When a new message is generated, it randomly selects two nodes as the source and the destination. Only when the system is initialized will the messages be generated. The initial time to live for a message is denoted by TTL. A message disappears from the network when the TTL becomes zero. Besides, the local buffer size and the transmission rate are high enough to store and forward all messages. In other words, messages can be successfully transmitted when contacts exist and are successfully detected. We use Epidemic [15] routing to route messages. In Epidemic routing, messages are forwarded by all possible contact opportunities, so it can achieve the best performance in delivery rate and average delay if the network resources are sufficient. However, when the network is energy-constrained, how to control beaconing frequency reasonably becomes a hot potato. If the beaconing frequency is too low, some contacts are bound to be missed. If we increase the beaconing frequency, excessive energy consumption will be caused. To solve the above question, we propose a dynamic beaconing control strategy DBCEC for Epidemic routing. Then we present DBCEC-E by applying exponential decay to the beaconing frequency. Simulation results show that DBCEC-E can significantly improve the delivery rate.

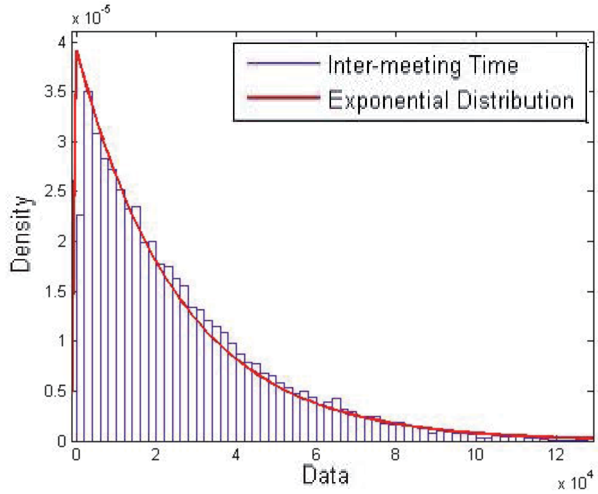


Fig. 2. Inter-meeting time distribution for a random-waypoint scenario.

In this paper, we make the following assumptions regarding the network environment. No node has an immunization strategy or a mechanism to send acknowledgments to confirm the receipt of packets. Bandwidth and local buffer sizes are large enough to transmit and store messages. A node will disappear from the network when its energy is depleted. Nodes move independently of each other under the popular mobility scenarios, such as random walk, random waypoint, and random directions, and the intermeeting times between nodes tail off exponentially [16].

In DTNs, messages are forwarded through mutual contacts. Thus, the inter-meeting time between nodes will influence the delivery ratio. Here, we define the intermeeting time as follows: intermeeting time is the time elapsed from the end of the previous contact to the start of the next contact.

The latest research shows that inter-meeting times are exponentially distributed under many popular scenarios such as random walk, random waypoint, and random direction. Our simulation is based on random waypoint. Thus, we first simulate the distribution of inter-meeting times in Fig. 2 and then fit it to exponential distribution. As illustrated in Fig. 2, we see that the inter-meeting times appropriately follow an exponential distribution: $f(x) = \lambda e^{-\lambda x}$ (x>0).

Assume that λ is the parameter for the exponential distribution of inter-meeting time, and E denotes the mathematical

TABLE I. MAIN NOTATION USED THROUGHOUT THE PAPER

Symbol	Meaning
N	Total number of nodes in the network minus one
M	Total number of distinct messages in the network
TTL	Initial time to live for messages
R	Remaining time to live for messages
t	Elapsed time for messages since they are generated
$m(t)$	Number of nodes with the message after t
$F(t)$	Beaconing frequency after elapsed time t
E	Average inter-meeting time between nodes
λ	Parameter in the inter-meeting time distribution
α	Energy consumption of each transmission
β	Energy consumption of each beaconing
Ω	Maximum energy constraint to deliver a message
$P_c(t)$	Probability that nodes can communicate at time t
$P(t)$	Probability that messages can be delivered at time t

expectation value; then $\lambda = \frac{1}{E}$. The notations used in this paper are shown in Table I.

IV. DYNAMIC BEACONING CONTROL STRATEGY

We first consider how to calculate $P_c(t)$ in Table I. Since inter-meeting time follows an exponential distribution (with parameter λ), the probability that nodes can contact at a certain time is λ. $P_c(t)$ can be written as Eq.1.

$$P_c(t) = F(t)\lambda \tag{1}$$

Then we consider a simple case in which only one distinct message exists in the network. Considering the above assumptions, our analysis and conclusion are still applicable when there is more than one distinct message. $m(t)$ is defined as the number of nodes that keep a copy of the message after elapsed time t and $m(0) = 1$. We use S to denote the set of $m(t)$, then $S = \{m(t) \mid 0 \le t \le TTL\} = i_k = \{1, 2, 3, 4...N\}$, $0 \le t_0 < t_1 < \cdots < t_{n+1} \le TTL$. Thus, we have Eq. 2.

$$\begin{aligned} P\{m(t_{n+1}) = i_{n+1} | m(t_k) = i_k; 0 \le k \le n\} \\ = P\{m(t_{n+1}) = i_{n+1} | m(t_n) = i_n\} \end{aligned} \tag{2}$$

From the above equation, we see that the next state of $m(t)$ depends only on the current state and not on the sequence of states that precedes it. So the sequence of $m(t)$ is a continuous-time Markov chain. Thus, we can use the Markov model to predict the changes of $m(t)$.

Next the derivative of $m(t)$ is considered. At time t, there are $m(t)$ nodes holding the message and the remaining $N - m(t)$ nodes have not seen the message. The increment of $m(t)$ depends on how many nodes of the remaining $N - m(t)$ nodes will be infected by the message within the next short period. Moreover, the probability that the node pair can contact and communicate with each other is $P_c(t)$ and there are $(N - m(t))m(t)$ node pairs whose contacts can lead to message replication. Consequently, we have Eq. 3. By combining Eq. 1 and Eq. 3 and $m(0) = 1$, $m(t)$ can be expressed as Eq. 4.

$$\frac{\mathrm{d}m(t)}{\mathrm{d}t} = P_c(t)(N - m(t))m(t) \tag{3}$$

$$m(t) = \frac{N}{(N-1)e^{-N\lambda \int_0^t F(t)\mathrm{d}t} + 1} \tag{4}$$

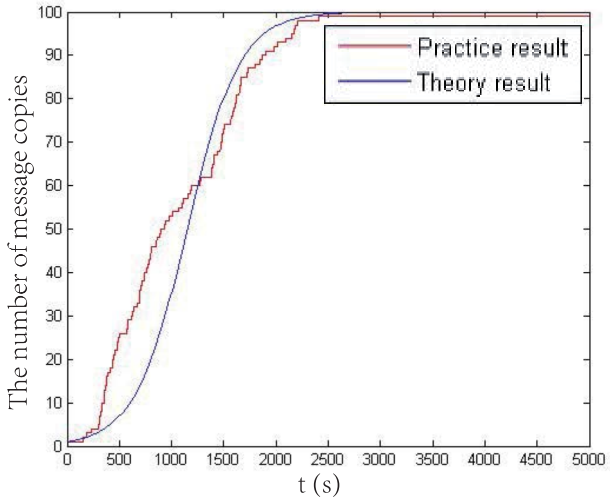


Fig. 3. Values of $m(t)$ as a function of time t.

To further verify the accuracy of $m(t)$ predicated by the Markov model, we plot the figure of $m(t)$ under a random waypoint scenario and compare it with the predicted results, as shown in Fig. 3, which shows that the theory results of $m(t)$ predicted by the Markov model can fit the practice results well, indicating that Eq. 4 can be used to calculate $m(t)$ precisely. Then the delivery rate at time t can be expressed as Eq. 5.

$$P(t) = \frac{m(t)}{N} = \frac{1}{(N-1)e^{-N\lambda \int_0^t F(t)\mathrm{d}t} + 1} \tag{5}$$

Note that the energy consumption of each message transmission and beaconing are α and β, respectively. Thus, the system energy constraint at time t can be expressed as Eq. 6.

$$\alpha(m(t) - 1) + \beta N \int_0^t F(t)\mathrm{d}t \le \Omega \tag{6}$$

Now we discuss the following problem: how to determine the beaconing frequency with energy constraints so that we can get the maximum delivery rate. The above problem can be expressed as the following optimization problem:

$Max\ P(TTL)$

$s.t. \quad \alpha(m(TTL) - 1) + \beta N \int_0^{TTL} F(t)\mathrm{d}t \le \Omega$

According to Eq. 5, we can get following equation: $P(TTL) = \frac{1}{(N-1)e^{-N\lambda \int_0^{TTL} F(t)\mathrm{d}t} + 1}$ and $P(TTL)$ increases as $\int_0^{TTL} F(t)\mathrm{d}t$ increases. From the energy constraint: $\alpha(m(TTL) - 1) + \beta N \int_0^{TTL} F(t)\mathrm{d}t \le \Omega$, we can see that $\alpha(m(TTL) - 1)$ and $\beta N \int_0^{TTL} F(t)\mathrm{d}t$ also increase as $\int_0^{TTL} F(t)\mathrm{d}t$ increases. Consequently, in order to maximize the delivery rate, $\int_0^{TTL} F(t)\mathrm{d}t$ must satisfy Eq. 7.

$$\alpha(m(TTL) - 1) + \beta N \int_0^{TTL} F(t)\mathrm{d}t = \Omega \tag{7}$$

By solving Eq. 7 using matlab, we get the approximate solution of $\int_0^{TTL} F(t)\mathrm{d}t$ as Eq. 8, where lambertw(c) is the solution of $xe^x = c$ (x is the variable and c is the constant).

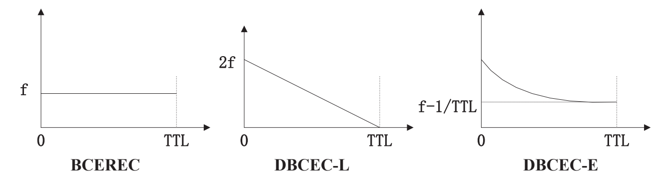


Fig. 4. Three beaconing control strategies.

$$\int_0^{TTL} F(t)\mathrm{d}t = \frac{(-\beta \cdot \mathrm{lambertw}(\frac{1}{N-1}\lambda\frac{\alpha}{\beta}e^{\frac{(\Omega+\alpha)\lambda}{\beta}}) + (\Omega+\alpha)\lambda)}{\lambda\beta N} \quad (8)$$

In summary, when the beaconing frequency satisfies Eq. 8, the delivery rate of the whole network is optimized. Because $F(t)$ affects the rate of energy consumption, how to find an optimal $F(t)$ to maximize the delivery rate becomes important.

By analysis, we can see that the number of nodes which hold packets in local buffers show an increasing trend, and the contact opportunities among those nodes show a decreasing trend. Thus, we define $F(t)$ as constant function (BCEREC), linear decline function (DBCEC-L), and exponential decay function (DBCEC-E), respectively, as shown in Fig. 4. We will verify the merits and demerits of the three beaconing strategies by conducting experiments.

When $F(t)$ is defined as a constant function, i.e. $F(t) = f$, according to Eq. 8, we can get the optimal beaconing frequency as shown in Eq. 9, and we call this BCEREC.

$$f = \frac{(-\beta \cdot \mathrm{lambertw}(\frac{1}{N-1}\lambda\frac{\alpha}{\beta}e^{\frac{(\Omega+\alpha)\lambda}{\beta}}) + (\Omega+\alpha)\lambda)}{TTL \cdot \lambda\beta N} \quad (9)$$

According to Eq. 9, we can get the information that optimal beaconing frequency is related to following parameters: number of nodes, intermeeting time, and TTL of messages. However, intermeeting time is determined by the node density in the fixed network area, so in reality the optimal beaconing frequency is decided by the node density and TTL of messages. Furthermore, optimal beaconing frequency is used as an inverse proportional function of both node density and TTL of messages. In energy-constrained DTNs, the larger node density means lower initial energy of each node; the larger TTL of messages also means longer survival time, so the lower beaconing frequency will get the optimal solution.

Then we consider that $F(t)$ is defined as a linear decline function, i.e. $F(t) = at + b$, where a is a negative constant. Combining Eq. 8 and $F(TTL) = 0$, we get the expressions of a and b as shown in Eq. 10 and Eq. 11, and obtain our dynamic beaconing control strategy DBCEC-L.

$$a = \frac{-2(-\beta \cdot \mathrm{lambertw}(\frac{1}{N-1}\lambda\frac{\alpha}{\beta}e^{\frac{(\Omega+\alpha)\lambda}{\beta}}) + (\Omega+\alpha)\lambda)}{TTL^2 \cdot \lambda\beta N} \quad (10)$$

$$b = \frac{2(-\beta \cdot \mathrm{lambertw}(\frac{1}{N-1}\lambda\frac{\alpha}{\beta}e^{\frac{(\Omega+\alpha)\lambda}{\beta}}) + (\Omega+\alpha)\lambda)}{TTL \cdot \lambda\beta N} \quad (11)$$

Lastly, we consider that $F(t)$ is defined as an exponential decay function, i.e. $F(t) = \lambda e^{-\lambda t} + d$. According to Eq. 8, we can get the approximate solution of d as shown in Eq. 12 and obtain the dynamic beaconing control strategy DBCEC-E.

$$d = (\frac{(-\beta \cdot \mathrm{lambertw}(\frac{1}{N-1}\lambda\frac{\alpha}{\beta}e^{\frac{(\Omega+\alpha)\lambda}{\beta}}) + (\Omega+\alpha)\lambda)}{TTL^2 \cdot \lambda\beta N} - \frac{1}{TTL}) \quad (12)$$

Simulation results show that, compared to other beaconing control strategies, DBCEC-E achieves the best delivery rate without undermining average delay and overhead ratio.

TABLE II. SIMULATION PARAMETERS UNDER RANDOM-WAYPOINT SCENARIO

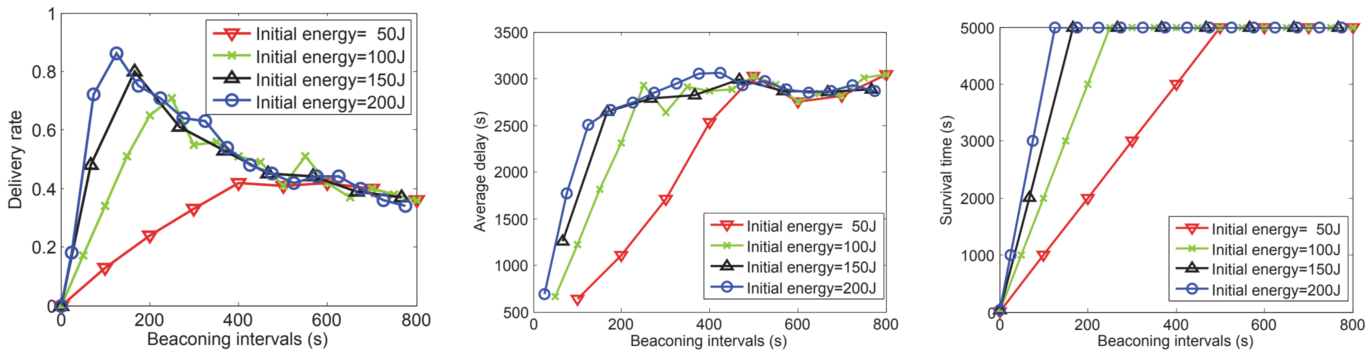
Parameter	Value
Simulation time	5000s
Simulation area	4500m×3400m
Number of nodes	100
Moving speed	2m/s
Transmission speed	250kBps
Transmission range	100m
Buffer size	500M
TTL	5000s
Message size	250kB
Transmission consumption	1J
Beaconing consumption	5J
Energy constraint for each node	50J, 100J, 150J, 200J

V. PERFORMANCE EVALUATION

A. Evaluation Settings

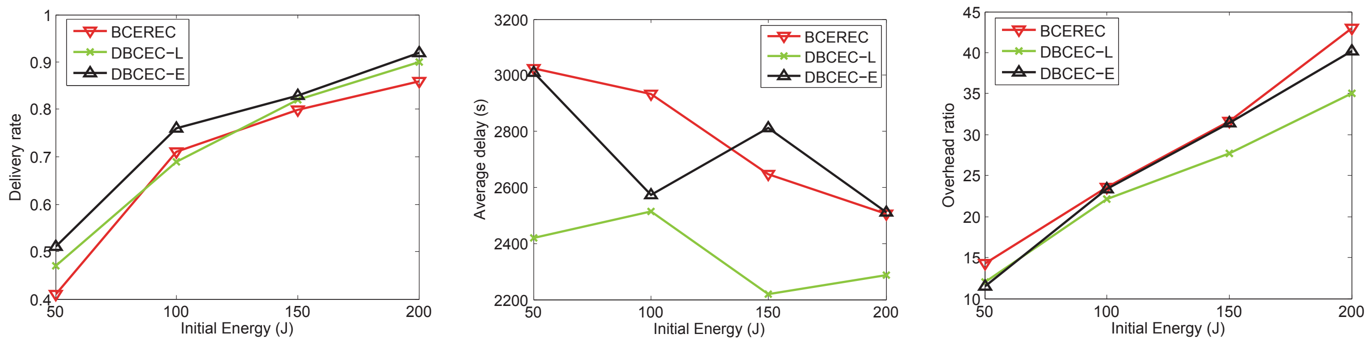
In order to compare the performances of the three beaconing control strategies, i.e. BCEREC, DBCEC-L and DBCEC-E, we used the opportunistic network simulator ONE and conducted experiments under (1) random-waypoint scenario: an existing mobility model in which each node chooses its destination randomly and walks along the shortest path to the destination; then repeats its behavior. (2) Epfl scenario [17]: it contains GPS data from 500 San Francisco taxis acquired over 30 days. To evaluate the performance of different beaconing control strategies, we configured the random-waypoint experiment environment as follows: 100 distinct messages are generated when the system is initialized, after which messages are no longer generated; The TTL is 5000s; Messages are routed under Epidemic; The initial energy of each node in random-waypoint scenario (i.e. the energy constraint) are set to 50J, 100J, 150J and 200J; and the initial energies in Epfl are set to 100J, 200J, 300J. Other parameters are given in Table II and III. Four metrics are used to evaluate the performance.

(1) Delivery ratio is the number of messages successful delivered to the destination node divided by the total number of messages generated in the network.
(2) Average delay is the average time elapsed for the successful delivery of messages.
(3) Overhead ratio (load ratio) is the ratio of the difference between the number of messages successfully forwarded and the number of messages successfully delivered to the number of messages successfully delivered.
(4) Survival time is the time interval from which the system is initialized to that in which all nodes' energy is run out.



(a) Delivery rate (b) Average delay (c) Survival time

Fig. 5. Delivery rate, Average delay, and Survival time as a function of beaconing intervals under random-waypoint scenario.



(a) Delivery rate (b) Average delay (c) Overhead ratio

Fig. 6. Delivery rate, Average delay, and Overhead ratio as a function of initial energy.

TABLE III. SIMULATION PARAMETERS UNDER EPFL SCENARIO

Parameter	Value
Simulation time	5000s
Number of nodes	200
Transmission speed	250kBps
Transmission range	100m
Buffer size	500M
TTL	5000s
Message size	250kB
Transmission consumption	1J
Beaconing consumption	5J
Energy constraint for each node	100J, 200J, 300J

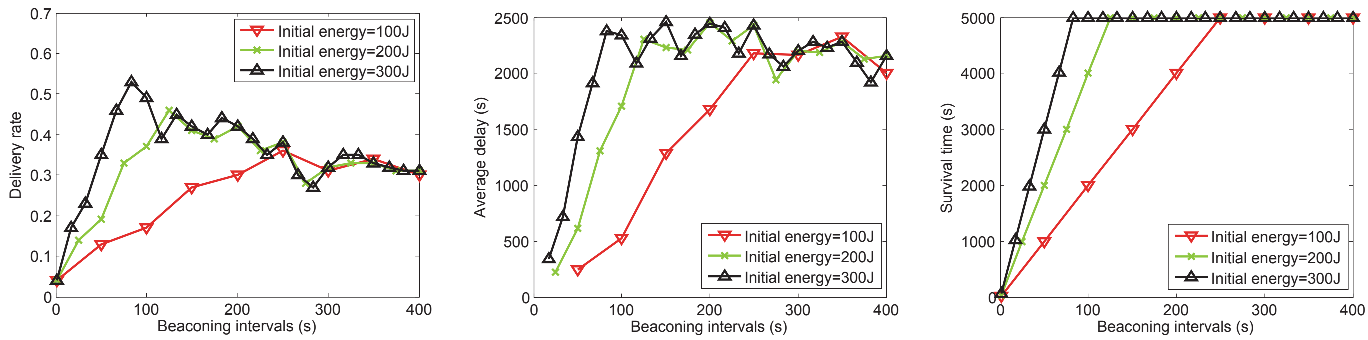
B. Simulation Analysis Under Random-Waypoint Scenario

We set the mobility model to random waypoint in ONE and set the number of nodes to 100 by default in an area of 4500m$\times$3400m. The transmission speed and buffer size are big enough. The initial energy of each node (i.e. energy constraint) is 50J, 100J, 150J and 200J, respectively. We evaluate the performance of BCEREC by changing the beaconing interval.

Firstly, the energy constraint is set to 50J, 100J, 150J and 200J, respectively. Using Eq. 9, we get that the optimal beaconing frequencies are $\frac{1}{500}$, $\frac{1}{250}$, $\frac{1}{167}$, $\frac{1}{125}$, i.e. the beaconing intervals are 500s, 250s, 167s, 125s, respectively. Simulations were done under different beaconing intervals. The delivery rate and survival time are plotted in Fig. 5.

Fig. 5-(a) shows that delivery rate first increases and then decreases as the beaconing interval increases under different initial energies. Besides, the peak point is close to the value calculated by the Eq. 9. So we can see that beaconing control strategy BCEREC has high precision: Beaconing frequency calculated by Eq. 9 can maximize delivery rate. Moreover, we can see that when beaconing interval is less than the optimal value, excessive energy is consumed due to high beaconing frequency. Thus, the survival time of the network is not long enough to support message delivery. But when the beaconing interval is larger than the optimal value, some contact cannot be detected, thus resulting in a low delivery rate. Fig. 5-(b) shows that as the beaconing interval increases, average delay also increases, which is a phenomenon that illustrates that larger beaconing intervals result in lower communication opportunities. Thus, it will consume a longer period of time to deliver from the source to the destination. Fig. 5-(c) shows that as the beaconing interval increases, survival time of the whole network increases linearly. That is because beaconing energy occupies a major portion of the whole energy, and the beaconing control strategy has a direct impact on the survival time. Moreover, we can see that the optimal beaconing interval maximizes the survival time, which further demonstrates the accuracy of BCEREC.

In summary, the beaconing control strategy BCEREC under the random-waypoint mobility model can improve the delivery rate and survival time without undermining the average delay. To further compare the three beaconing control strategies BCEREC, DBCEC-L and DBCEC-E, we conducted experiments under a different initial energy and plotted delivery rate, average delay and overhead ratio in Fig. 6. Simulation results show that, compared with other beaconing control strategies, DBCEC-E achieves the best delivery rate without undermining



(a) Delivery rate

(b) Average delay

(c) Survival time

Fig. 7. Delivery rate, Average delay, and Survival time as a function of beaconing intervals under Epfl scenario.

average delay and overhead ratio.

C. Simulation Analysis Under Epfl Scenario

In a real environment, the movement of the taxis lacks regularity and the nodes cannot contact each other as frequently as nodes do in the random-waypoint mobility scenario. As a result, some messages cannot be delivered. Thus, the delivery ratio obtained in the real scenario differs significantly from that obtained for the synthetic random-waypoint scenario. However, Fig. 7-(a) also shows that delivery rate first increases and then decreases as the beaconing interval increases under Epfl scenario. At the same time, the peak point of the curve precisely the value calculated by Eq. 9. So we can see that beaconing control strategy BCEREC still works under real mobility traces and has high precision: Beaconing frequency calculated by Eq. 9 can maximize delivery rate. Fig. 7-(c) shows that as the beaconing interval increases, survival time of the whole network increases linearly. Moreover, we can see that the optimal beaconing interval maximizes the survival time.

VI. CONCLUSION

In DTNs, high node mobility and a changing topology result in intermittent connections between node pairs. Under this scenario, routing methods always adopt the store-carry-forward strategy to transmit messages, and a message always has multiple copies. Moreover, frequent beaconing is required to detect the possible contacts (i.e. communication opportunities) and a large number of message copies are required to be forwarded ceaselessly. However, this is bound to result in the rapid consumption of energy. So efficient use of energy becomes the key point, especially when energy is limited. In this paper, aiming to maximize delivery rate, we propose our dynamic beaconing control strategy based on a continuous-time Markov model under a energy-limited environment. Furthermore, simulation experiments are conducted under the random-waypoint mobility model and results show that compared to DBCEC and DBCEC-L, DBCEC-E can significantly improve delivery rate without undermining average hops and overhead ratio.

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