Capacity-Aware Routing Using Throw-Boxes

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***Abstract*—Deploying the static wireless devices (throw-boxes) at certain locations can help message dissemination among mobile nodes in delay tolerant networks. The mobile nodes traveling between throw-boxes form network links that carry the temporally stored messages at one box to another. However, the aggregated mobility between pairs of boxes reveals a time-dependent nature on its link delay (travel time) and link loading capacity (buffer size). The state-of-art DTN routing protocols do not address the challenge of combined delay and capacity with time-dependent links. In this paper, we tackle this challenge by introducing a capacity-aware routing protocol that is able to search the shortest path that considers the time-varying delay and capacity of the virtual links. We use a Markov Chain to model the evolution of the real-time link delay and capacity, and use the Markov Chain states to help derive the forwarding decision and routing policy. In evaluating the capacity-aware routing scheme, we use a network graph with the virtual links extracted from the contact trace. The simulations validate the advantages of the proposed routing strategy.**

I. INTRODUCTION

Deploying throw-boxes as static nodes can help message dissemination among mobile nodes in delay tolerant networks (DTNs) [11] [3]. This approach is especially helpful when mobility is localized, i.e. mobile nodes may only move within a region of the network field, and the entire network field lacks a global movement of most nodes. In this network scenario, communicating through pure encountering of mobile nodes may be ineffective due to the reduced chances of encountering. Careful deployment of the throw-boxes can enhance the network connectivity and decrease the transmission delay. There are usually two message relay patterns in the throw-box based message dissemination. One relay pattern is that the message is exchanged between the message sender and the receiver when they are at the same location. The other is that the message will be relayed across multiple throw boxes and the sender and the receiver communicate with difference boxes at different locations. For the former, the issue of searching the optimal location for boxes and latency analysis are studied in [11] [3]. For the latter, the messages left at a box could be carried by one or more mobile nodes to other boxes in order to increase the probability for being collected by the receiver. A routing scheme must be developed for the latter case.

Various routing strategies have been proposed for DTN, such as PROPHET [5], SPRAY [8], EPIDEMIC [9], scheduled based routing [4][6] [10], and multicast [2]. Yet, routing through throw-boxes is quite different from these previous works in that it has to address additional challenges. The challenges come from the characteristics of the potential links between two boxes. Such a link is formed by various mobile nodes that travel from one node to another at different times and with different moving speeds. The traveling time of mobile nodes between two boxes reflects the *link delay*. Thus, a routing protocol must address the time-varying nature of the link delay between two boxes. In addition, the mobile nodes travel between two boxes may have different *loading capacity* in terms of its buffer sizes. A node with large buffer size can take more messages from one box to another. Different mobile nodes that formalize a link also reveal a time-varying nature of link capacity. Thus a routing scheme must consider jointly the time-dependent link delay and link capacity. In this study, we redefine link "bandwidth" to present this joint consideration of delay and loading capacity over a link. Thus the *link bandwidth* in this paper denotes the ratio of *loading capacity* to *link delay*. In this paper, we introduce a novel routing scheme that searches the path with the highest expected link bandwidth from source to destination over time-dependent multiple links. The routing decision is affected by node velocity, occurrence frequency of nodes and loading capacity.

In the paper, we introduce a Markov Chain model to describe the time-dependent link delay and capacity between neighboring boxes (Section II). The various link bandwidths can be approximately classified into different states in the Markov model and the dynamic behavior is described through the state transition probability. The capacity-aware routing strategy includes forwarding link decision and optimal path selection based on dynamic states of the links in the network of boxes (Section III). In our scenario, we assume a message sender and a receiver frequently visit a throw-box which allows the sender to leave a message and the receiver to pick up a message. Thus, in routing, we use a source box and a destination box. The routing action for each state at a box is either sending the message to a specific box when a mobile node arrives, or waiting for another forwarder with higher bandwidth. The simulation is performed using time-varying link delay dynamics extracted from UMassDieselNet trace [1] (Section IV). In evaluation, we compare the proposed routing scheme with two representative DTN routing protocols to show the advantages and trade-off in using the proposed routing strategy. The paper is concluded in Section V.

II. NETWORK AND LINK MODELS

Due to the dynamic feature of mobile node, the same link could have time-varying delay (the traveling time between two

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boxes), and loading capacity (buffer sizes). Furthermore, we assume the static throw boxes have large storage compared to the mobile nodes. So only the buffer constraint of mobile nodes is considered in our routing protocol. The routing decision is affected by the velocity, the occurrence frequency of mobile nodes at the boxes and the loading capacity of a mobile node. We further redefine "link bandwidth" (the ratio of *loading capacity* to *link delay*) to present the joint consideration of delay and loading capacity over a link what is formed by movement. The symbols for modeling the dynamic links, the network and routing are given in Table I.

TABLE I
TABLE OF SYMBOLS

V	Set of throw-boxes
E	Set of links formed by mobile nodes between a pair of boxes
S_i	Set of link states for box i
S	Set of link states, $S = \{S_1, S_2, ..., S_{\|V\|}\}$
e_{ij}	Time-varying link from box i to box j
$\{C, D\}$	Link state, C is the loading capacity and D is the link delay
$c_{ij}(s_k)$	Loading capacity at state $s_k \in S_i$ for link e_{ij}
$d_{ij}(s_k)$	Delay at state $s_k \in S_i$ for link e_{ij}
s^i_m	Link state of box i, $m \in [1, N_i]$, total N_i states
$V_i(s^i_m)$	Minimum value of bandwidth inverse at state s_m of box i
$p_{s_k s_l}$	Transitional probability from state $s_k \in S_i$ to state $s_l \in S_i$
$\pi(s^i_k)$	Stationary probability at state s^i_k for box i
T_i	Expected link inter-arrival time for box i
q_i	Message amount in the sending queue of box i
$b_{ij}(s^i_m)$	Link bandwidth of e_{ij} at state s^i_m

According to the network scenario, each link between a pair of boxes could be formed by mobile nodes with various velocities, occurrence time and loading capacity, so a stochastic model is suitable to model the time-dependent link. In this paper, we propose a Markov Chain to describe the link evolution where the states have the corresponding delay and capacity varying according to the state transition matrix. We describe the network as $G(V, E, S)$ according to Tbl.I.

Taking two boxes and the incident link as example, the state diagram on time dependent link e_{12} is shown in Fig.1 where e_{12} is the link connecting box 1 and box 2. There are two delay states s_1 and s_2 in S_1 transmitting based on probability p_{ij},$i, j = 1, 2$ and the corresponding states are $\{c_{12}(s_1), d_{12}(s_1)\}$ and $\{c_{12}(s_2), d_{12}(s_2)\}$.

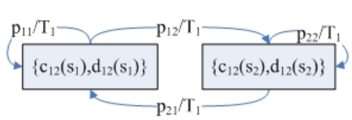


Fig. 1. Time dependent link with capacity and delay

III. ROUTING STRATEGY

The proposed capacity-aware routing scheme (called CA) uses one single copy of a message during its delivery. The CA routing protocol runs at the boxes and makes forwarding decisions and corresponding actions when a mobile node arrives. Each box also has a background agent that changes its link state according to the Markov model. During the current state, multiple links could occur when mobile nodes arrive. Thus, CA consists of three main components: forwarding decision for the current state, path selection given a positive forwarding decision, and forwarder selection considering the potential of multiple links during the current state for the selected path. The first component is to determine whether the messages should be forwarded through the current link. If the current link has relatively larger bandwidth, then it could be adopted for delivering messages. Otherwise, the box will ignore the current link and wait for the next link with larger bandwidth. After that, based on the forwarding decision at each link, the function of path selection helps to find the path with the expected highest bandwidth from the current node to destination. The last component forwarder selection involves the mapping between a link and a mobile node since the traveling nodes produce the links between two boxes. The mobile node with suitable velocity and desired moving direction will be chosen as the message forwarder.

A. Forwarding Decision

The objective of forwarding decision is to deliver messages to the other end of the link (a neighboring box) as many as possible within a given time period, so at each link state the box with outgoing messages has to decide whether to use the current link. If the bandwidth of the current link is small, the box could wait for the next state with larger bandwidth to accelerate the transmission. So the decision depends on the comparison result of bandwidth between the current link and subsequent link considering the waiting cost.

The decision model can be formalized as follows. For any link starting from box i, we assume it has total N_i states which are $s^i_m, m \in [1, N_i]$. Let $V_i(s^i_m)$ denote the minimum value of bandwidth inverse at state s_m of box i. The current box at state s_m either adopts current link to send message or waits to transmit until next state is available. The decision relies on the comparison between $V_i(s^i_m)$ and the bandwidth inverse $\frac{1}{b_{ij}(s^i_m)}$. If $V_i(s^i_m) \geq \frac{1}{b_{ij}(s^i_m)}$, then the sender will use the link e_i immediately, otherwise it waits for next state. The equation for deriving $V_i(s^i_m)$ is given below.

$$V_i(s^i_m) = \min \left\{ \frac{1}{b_{ij}(s^i_m)}, \sum_{k=1}^{N_i} \frac{(d_{kj}(s^i_k) + T_i) p^i_{mk}}{d_{kj}(s^i_k)} V_i(s^i_k) \right\}, \quad (1)$$

where $b_{ij}(s^i_m) = \frac{\min\{c_{ij}(s^i_m), q_i\}}{d_{ij}(s^i_m)}$, q_i denotes the message amount in the queue of box i and T_i is the expected link inter-arrival time for box i.

When $c_{ij}(s^i_m) < q_i$, it denotes that the current link will be saturated with all the messages from box i. The capacity of the current link will have an impact on the forwarding decision. However if the minimum value equals to q_i, the current link has enough capacity to transmit all the messages from box i, so the decision only depends on the link delay. These above two cases correspond to two general network scenarios: heavy-loaded network and light-loaded network. The transmission prefers the links with larger bandwidth in heavy-loaded network, while chooses the links with shorter delay in the light-loaded network.

The notation $DECISION(s_m^i)$ denotes the decision at state s_m^i. If $DECISION(s_m^i)$=ACCEPT, the sender will use the link at this state immediately. $DECISION(s_m^i)$=WAIT means the sender will wait for the next state. Policy iteration can be used to find the forwarding action and the time complexity is $O({N_i}^4)$ [7].

B. Path Selection

The objective of path selection is to find the link with the highest link bandwidth for message delivery. If the box decides to transmit message in the current link state and the multiple links exist, the link with the expected highest bandwidth should be chosen. Suppose box i has total N_i delay states which are $s_m^i, m \in [1, N_i]$ and $Adj(i)$ denotes the neighboring box set of box i. $V_i(s_m^i)$ denotes the minimum value of bandwidth inverse that box i has at state s_m. We derive the following equation to find the optimal link starting from box i.

$$V_i(s_m^i) = \min\left\{\min_{j\in Adj(i)}\left\{\frac{1}{b_{ij}(s_m^i)} + \sum_{k=1}^{N_j}\pi(s_k^j)V_j(s_k^j)\right\}\right. \left., \sum_{k=1}^{N_i}\frac{(d_{kj}(s_k^i)+T_i)p_{mk}^i}{d_{kj}(s_k^i)}V_i(s_k^i)\right\} \quad (2)$$

Please note if the box decides to wait, waiting time must be considered. In the Eq.2, the immediate cost will be the expected waiting value multiplied by be $\frac{d_{kj}(s_k^i)+T_i}{d_{kj}(s_k^i)}$. For each neighboring box $j \in Adj(i)$, the expected cost includes the delay $\frac{1}{b_{ij}(s_m^i)}$ at current state s_m^i and the expected values of $V_j(s_k^j), s_k^j \in S_j$. If the box decides to transmit, the neighboring box having the minimum expected value will be chosen as the next hop. The concrete procedures for path selection are introduced in Algorithm 1 where we assume the network is modeled as an acyclic directed graph.

C. Forwarder Selection

Since mobile nodes form the time-dependent links by traveling among boxes, the routing decision boils down to the forwarder selection. When a box having outgoing messages is visited by a mobile node, firstly the box has to decide whether the current mobile node can be chosen as message forwarder. Based on the inquiry result of vehicular information, the travel delay to next box and load capacity of the current mobile node can be derived or estimated in the current link state. According to the routing table, the forwarding decision of that state can be determined. If the decision is WAIT, then the current node is ignored. If the decision is ACCEPT, we have to further check the routing direction and moving direction of the current node. If the two directions are the same, then the message is transmitted from the box to the encountered mobile node. Otherwise, the current node is ignored. In this study, we focus on the routing in time-dependent network and assume the expected travel delay and load capacity of mobile

Algorithm 1 Derive the highest bandwidth path to box u

STEP 1.
Set $i = u, V_i(s_m^i) = 0, m \in [1, N_i]$. Derive the box list in the reverse order of topological sorting according to the network.
STEP 2.
Visit box i according to the reverse topological order.
STEP 3.
for $m = 1$ to N_i **do**
  $F_{ij}(s_m^i) = \frac{1}{b_{ij}(s_m^i)} + \sum_{k=1}^{N_j}\pi(s_k^j)V_j(s_k^j)$ where $j \in Adj(i)$
  find j that minimizes $F_{ij}(s_m^i)$
  $NEXT_i(s_m^i) = j$
end for
STEP 4.
Obtain $DECISION_i(s_m^i)$ based on Equ.1 where $\frac{1}{b_{ij}(s_m^i)}$ is replaced by $F_{ij}(s_m^i)$.
STEP 5.
if all the boxes are visited **then**
  GO TO STEP 6.
else
  GO TO STEP 2.
end if
STEP 6.
Assume at box i at state $s_m^i, m \in [1, N_i]$, the optimal path to box u is:
if $DECISION_i(s_m^i) = ACCEPT$ **then**
  GO TO box $NEXT_i(s_m^i)$
else
  wait time T_i
end if

node between two boxes are obtainable. The approach about how to derive the travel delay and the destination of mobile node will be studied in future work.

IV. Simulation

The simulation uses UMassDieselNet trace [1] as the mobility model. The trace includes the contact information between the buses and the access points. In the simulation, the buses are viewed as the mobile nodes and the access points become the locations where the throw-boxes are deployed. Since there is no routing protocol specially designed for the targeted throw-box based network architecture, we employ epidemic routing [9] and first contact routing(FC) [4] for comparison. Epidemic routing uses multiple copies of messages to spread throughout the network. As the performance benchmark, the shortest latency and the largest overhead are expected. In FC routing, only one message copy is used and message carrier hands over the data to the first encountered node.

We consider the following metrics for evaluation. The first metric *message delivery ratio (MDR)* denotes the ratio of the number of successfully delivered messages to the amount of all messages generated by mobile nodes up to the current time. The second metric *cumulative MDR* relies on the total generated message in the simulation and increases as the simulation proceeds. The cumulated ratio is the ratio of the number of successfully delivered messages to the total amount of generated message during the simulation. The third metric of *transmission overhead* calculates the ratio of the number of messages forwarding to the number of delivered messages.

A. Analysis of UMassDieselNet Trace

The contact information in UMassDieselNet trace bears similarity with the throw-box based network. We treat the access points(APs) in UMassDieselNet as the throw-boxes because they are usually deployed at hot locations as throw-boxes would. Naturally, the buses become the mobile nodes which generate the time-varying links when they move around.

A network graph and the related link properties derived from the data set are shown in Fig.2. The vertex values in the rectangles represent the IDs of the access points and the expected link inter-arrival time. The moving buses among these APs create the edges in graph and the arrow denotes the moving direction. The link properties are shown close to the edge, including the expected delay and the number of occurrences during the simulation time. From the links distribution shown in Fig.3, we observe that not all the links appear every hour and the occurrence frequency of the links is different during the same interval. For example, link $6-7$ can be found in every time slot, but link $5-7$ only appear in the last hour. Further when a link appears multiple times during the same time slot, the corresponding delays can be different. The 8-hour trace is used repeatedly and expanded to 24-hour trace for intensive simulation.

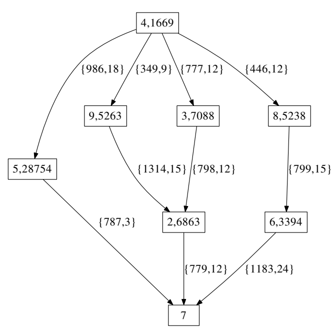


Fig. 2. Network graph

For the simulation, node 7 is selected as the message destination. The other nodes generate messages destination to node 7 in every certain time interval. Different intervals of message generating is chosen to simulate various network scenarios. Since the information of storage capacity of mobile is not given in the trace, we assign different message buffers to buses for simulating the heterogeneous capacity in realistic scenario. Specifically, there are total five buffer types for the buses which sizes are 5M, 10M, 20M, 50M and 100M. We also assume all the APs have infinite buffer and each message has 1MB.

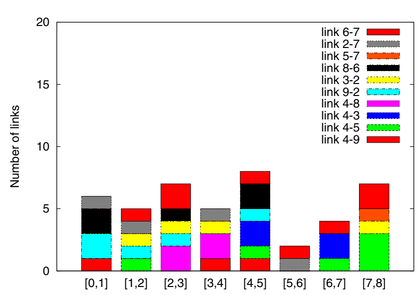


Fig. 3. Link distribution

B. Simulation Results

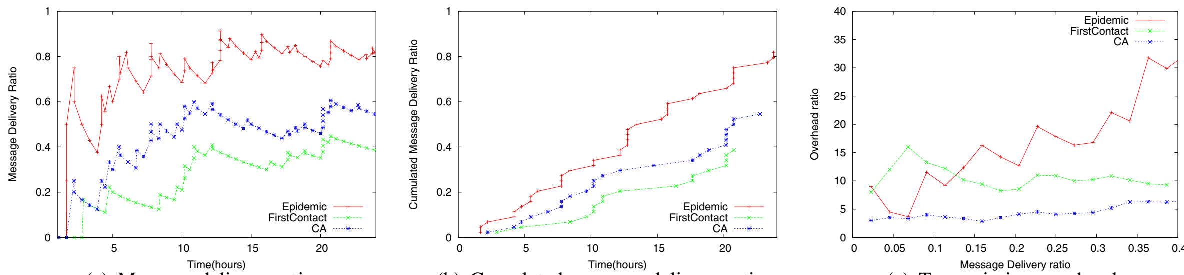
We first focus on the message delivery ratio (MDR). It measures instant successful delivery at each time interval. In simulation, messages are generated continuous every 2000 seconds. This is shown in Fig.4(a) where X-axis denotes the simulation time and Y-axis represents the message delivery ratio. The wavelike curve comes from the factor that the messages are generated incrementally in every time interval of 2000s, but the delivery of the messages is delayed in waiting for virtual links to occur. The declined segment of the curves shows the fact that the number of delivered messages in this time slot are less than the number of newly generated messages. The rising segments of the curves correspond to the case that the delivered messages during the time intervals are more than the messages generated. We also observe that the epidemic routing achieves higher MDR due to the fact of flooding. CA considers the link frequency and link capacity to select better message forwarders for routing, thus it achieves the higher message delivery ratio than the first contact routing protocol.

The cumulative MDR measures the accumulated successful deliveries up to the proceeding simulation time. Thus the curves become non-decreasing. The comparison result in Fig.4(b) shows that the ratio of CA is higher than that of FC most of time and CA needs shorter time than FC for achieving the same ratio. Epidemic routing achieves the highest cumulated MDR as expected.

Fig.4(c) shows the results measuring transmission overhead. The figure is generated to let x-axis be the accumulated delivery ratio and the y-axis be the overhead. The figure shows fluctuations of the curves. This is due to the same reason as explained in Fig.4(a), mainly, due to the periodic incremental message generation and the delayed delivery. As expected, Epidemic routing shows higher overhead than the other two protocols because of its multiple-copy strategy. More message relays thus are produced. As more messages are delivered, the overhead of the epidemic routing increases due to the redundant message copies and relays. CA and FC only make use of one message copy for delivery, so their overheads are small and relatively stable. In fact, given same delivery ratio, CA achieves the lowest overhead ratio through its efficient relay and forwarding decision.

Further, we study the routing performance given different message generating rates. The message generating intervals range from 200s to 2000s to create offered load from heavy to light. Under heavy load, the buffer of mobile nodes would not be large enough to carry all the outgoing messages from boxes. In Fig.5(a), the results show that CA can achieve higher delivery ratio than FC. In other words, given the simulation time, more messages are delivered by the capacity-aware routing with only one message copy. Besides that, the curves in Fig.5(a) show an initially increasing trend when load decreases. This is caused by higher message dropping rate when the network is overloaded. The curves become more stable when load becomes lighter. The result suggests that CA performs better than FC.

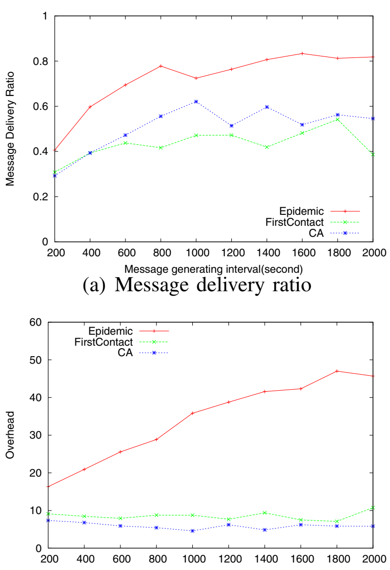
Fig.5(b) shows the comparison results of transmission over-



(a) Message delivery ratio (b) Cumulated message delivery ratio (c) Transmission overhead

Fig. 4. Protocol comparison

head. Note that the transmission overhead is calculated as the ratio of the total number of messages forwarded over the total number of messages delivered for each given message delivery ratio. This explains that when offered load is heavy, more messages are dropped instead of being forwarded in Epidemic routing. This factor results in the lower overhead when the intervals are small. The overhead of Epidemic routing increases when offered load becomes lighter due to less buffer overflow. More messages can be forwarded by the mobile nodes. In contrast, the single copy protocols of FC and CA is less impacted by the offered heavy load. It is clear that CA has the smallest overhead.



(a) Message delivery ratio

(b) Transmission overhead

Fig. 5. Protocol comparison with various intervals of message generating

V. Conclusion

In this paper, we introduced a routing strategy that captures and utilizes the time varying feature of link delay and loading capacity for message dissemination with the help of throw-boxes in DTN. The time-varying links are created by the various mobile nodes travel between pairs of throw-boxes. A Markov Chain model is presented to define the evolution of the link dynamics at each box and the policy iteration based algorithm is proposed to find the routing and forwarding logic. The protocol is evaluated using a network model extracted from the real mobility trace. The results validate the advantages of the proposed capacity-aware routing protocol with comparisons to Epidemic routing and First Contact routing.

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