Abstract—In Delay Tolerant Networks (DTN), as disconnections between nodes are frequent, establishing the routing paths from the source node to the destination node may not be possible. Messages are forwarded in DTN similarly to an infective disease spreading among humans. This paper sets up an evolving model of message delivery. Also, in this paper, we propose the 'crash' issue. Because large part of persons will turn off their mobile phones and discard the messages received, the 'crash' could happen in DTNs. The 'crash' in DTN means large part of the copies of messages are discarded within a short time duration. The evolving model is validated by a message forwarding simulation among mobile nodes. In the simulation, we study the influence of 'crashes' on the delivery ratio and delay of Epidemic routing, SprayAndWait and PROPHET routing protocols.

I. INTRODUCTION

The increasing popularity of wireless mobile communication devices (e.g., Bluetooth and BlueSky) have made wireless networks to be the most convenient solution for interconnection in many scenarios. When these mobile devices are carried by persons or mobile agents, the connections between devices are not stable and disconnections between nodes are frequent. A large number of routing protocols for wireless ad hoc networks have been proposed in the past. However, traditional ad hoc routing protocols are not appropriate for networks with high mobility. The common assumption behind existing ad hoc routing techniques is that there is always at least a connected path from the source to the destination. However, if nodes move unpredictably with high speed, the end-to-end path between any node-pair may not be always possible, thus, source-based techniques are expected to be inappropriate since the calculated path will most likely be invalid before it is used [1] [2]. Such a kind of mobile wireless network is referred to as a Delay or Disruption Tolerant Network (DTN) [1].

In DTNs, messages are delivered from the source to the destination through a totally different way from the ad hoc networks. Like infectious diseases spreading in human being when people meet each other, mobile nodes in DTNs can forward packets in the same way. Nodes send messages to encounter nodes and then these encounter nodes relay this packet to other encounter nodes. Such packet delivery is analogous to the spread of infectious diseases [3] [4] [5]. If a copy of the packet reaches the destination node, the transmission is successful.

Many other routing protocols have been developed for DTN [6] [7] [8]. For example, by epidemic routing protocol, when a relay meets another node, it sends its messages to the encounter. Thus, a node may send a packet to different encounters lots of times. Since the mobile devices are in general powered by batteries and are not able to charge batteries expediently, energy is a major constraint in some mobile scenarios [9] [10]. If a 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.

Just as the delivery of a message is like the spreading of a infectious disease, we believe the process of spreading a message in DTN can be considered as the evolving of a infectious disease. Secondly, when we study the evolving of a species, we can also find the crash phenomenon, which means the number of a species decrease rapidly in a short time. In fact, crashes in the evolving of species are not rare [11], the most famous crash in the history is the depopulation of dinosaurs.

In computer networks, a router stores and relays packets, and then all the packets stored in its buffer will be cleaned up after the router is turned off. Usually, when a mobile device, such as a mobile phone works for the DTN, it runs a DTN engine which is a software to receive messages and relay them. When a user turn off the software, the user can determine whether clean up all the messages it receives or not. A DTN software user can turn off the software at anytime during a day. Also, we assume larger part of all users will
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
carry the message all the way to the destination [13].
Although this scheme performs only one transmission, it is
very slow.

An faster way to perform routing in DTN is Epidemic rout-
ing. The basic idea of Epidemic routing is to select all nodes
in the network as relays, say Epidemic routing being flooding-
based in nature, as nodes continuously replicate and transmit
messages to newly discovered contacts that do not already
possess a copy of the message [3]. However, as messages are
flooding to all other nodes, it is extremely wasteful of resources,
such as batteries energy. More sophisticated techniques can be
used to limit the number of message transfers.

Some later work studied relay selection strategies to reduce
the overhead and improve the performance of epidemic routing
[7] [8] [12].

SprayAndWait is a routing protocol that attempts to gain
the delivery ratio benefits of replication-based routing as well
as the low resource utilization benefits of forwarding-based
routing [14]. SprayAndWait routing protocol consists of two
phases: spray phase and wait phase. In the spray phase, the
source of a message initially starts with L copies; any node
A that has \( n > 1 \) message copies (source or relay), and
encounters another node B (with no copies), hands over to B
\( \lceil n/2 \rceil \) and keeps \( \lfloor n/2 \rfloor \) for itself; when it is left with only one
copy, it switches to direct transmission. If the destination is
not found in the spraying phase, each of the L nodes carrying
a message copy performs direct transmission.

PRoPHET is a Probabilistic Routing Protocol using a His-
tory of Encounters and Transitivity [15]. PRoPHET uses an
algorithm that attempts to exploit the non-randomness of real-
world encounters by maintaining a set of probabilities for
successful delivery to known destinations in the DTN (delivery
predictabilities) and replicating messages during opportunistic
encounters only if the node that does not have the message
appears to have a better chance of delivering it.

MaxProp is flooding-based in nature, in that if a contact is
discovered, all messages not held by the contact will attempt to
be replicated and transferred [16]. The intelligence of MaxProp
comes in determining which messages should be transmitted
first and which messages should be dropped first. Some routing
schemes select some nodes with desirable mobility patterns [7]
[8]. Another strategy is social-based forwarding scheme which
exploit sociological centrality metrics for relay selections [17]
[18]. The BUBBLE scheme improves the forwarding effi-
ciency significantly compared to PRoPHET algorithm based
on the users’ social activity [18].

III. REALITY IN DTN ROUTING

Routing in DTN is totally different from routing in ad hoc
networks because the disconnections are frequent in DTN.
When we design a routing protocol for DTN, we must face
the following realities.

A. Energy Constraint

Goldsmith et al. pointed out that energy constraints is not
inherent in all ad hoc networks, as some nodes may charge
their batteries timely. However, many if not most, mobile
nodes will be powered with batteries and their lifetime are
limited. Forman et al. believed limited power to be the greatest
constraints in designing algorithms for mobile devices [20].
Part of current DTN routing protocols do not consider the
energy constraint, such as Epidemic routing protocol. The
problem of Epidemic routing is that if a 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. Many DTN routing protocols
have been designed to decrease the overhead of Epidemic
routing as well. For example, SprayAndWait routing protocol
is a routing protocol that limits the number of replication of
a message to reduce the overhead of delivering a message.

B. Human Behavior Habit

Current DTN routing protocols study does not consider the
human behavior habit impact on the spreading of messages. In
fact, most mobile phone users shutdown their mobile phones
before sleeping. Before these mobile phone users turn off their
phones, the DTN engine that is a software runs on the mobile
phones will indicate whether to discard all the messages whose
destinations are not itself. So, the number of the replications of
a message toboggans because most of the message are deleted
after mobile devices are turned off. We call it to be a ‘crash’.

Researches showed that SprayAndWait routing protocol
can get high delivery ratio with low overhead. However,
SprayAndWait routing protocol does not consider the crash
issue. How is the delivery performance of SprayAndWait
routing protocol after a crash?

C. Opportunism and Privacy

In fixed infrastructure networks, link failures are relatively
rare, but the rate of link failure is the primary obstacle to rout-
ing in mobile ad hoc networks due to node mobility. In DTN,
user may move freely and organize themselves arbitrarily, thus
the network’s topology may change rapidly and unpredictably.
It means that any topology information may become stale after a short period of time and is ineffective for use in forwarding decisions. As a result, most DTN routing protocols are opportunistic, which means a sender sends messages if it gets a chance to send messages.

To improve the probability of delivering a message to its destination successfully, many DTN routing protocols make use of nodes’ history knowledge to select available relays. However, the history knowledge of a node is the privacy of the node. Not all nodes want to provide their routing messages. If there are un-trusted nodes in the network, a node does not share its information with others for the security reason [21] [22]. In this assumption, lots of routing protocols, such as ProPHET and BUBBLE protocols, cannot work because they need encounter nodes to tell the sender their history knowledge.

IV. EVOLVING IN DTN

A. Evolving Model

We study the messages spreading based on the disease spreading [23] study. We divides all nodes into three groups: Susceptible (S), Infective (I) and Received (R). We indicate the number of nodes in each group at time \( t \) as \( S(t), I(t) \) and \( R(t) \), respectively. The total number of \( S(t) \) and \( I(t) \) is \( N \).

In our evolving model of a message, we consider a message as an infective disease.

Assumption 1: When a device is turned off, its user can determine whether to discard its messages.

Assumption 2: Before sleeping, a large part of users turn off their mobile devices.

Definition 1: Susceptible nodes are nodes that have not received the message.

Definition 2: Infective nodes are nodes that receives a message and the node’s DTN routing engine works.

Definition 3: Received nodes of a message are nodes that have received the message.

If a node has received a message, it is the infective node of this message. If this node discards this message, then this node is a received node but not a susceptible node.

Definition 4: Crash means that a large part of users turn off their mobile devices within a short time duration simultaneously, and all the messages that they received are discarded.

Assume the number of the infective nodes at time \( t \) is \( I(t) \), and let the probability of a node catching the infective disease be \( p \). If an user is in the \( S \) state at time \( t \), and one of its neighbors is in the \( I \) state, then it moves into the \( I \) state with the probability \( p \) and stays in the \( S \) state with probability \( 1 - p \). In addition to this, each infective agent can move into the \( S \) state with probability \( \mu \). If we do not consider crashes in the evolving of infective disease, the evolving model of delivering a infective disease is equation 1.

\[
\begin{align*}
S(t+1) &= S(t) - pS(t) + \mu I(t) \\
I(t+1) &= I(t) + pS(t) - \mu I(t) \\
R(t+1) &= R(t) + p(S(t) - \frac{\mu I(t)}{S(t)})
\end{align*}
\]  

(1)

where \( p \) is the probability of a susceptible node becomes a infective node, and \( \mu \) is the probability of an infective node becomes a susceptible node.

We assume one node is in the infective group at \( t = 0 \), and all other nodes are in the susceptible group at \( t = 0 \). Figure 1 shows the \( I(t) \) function of time. \( I(t) \) increases in the beginning phase and reaches the largest value soon, and then, \( I(t) \) keeps the largest value until the message’s TTL equals zero. We divide the total experiment time into two phases: growing phase and balance phase. In the growing phase, the number of receivers of a message increases and reaches the maximum. In the balance phase, the number of receivers of a message keeps the same.

Figure 1 shows the variation of the number of receivers of a message. However, in DTNs, there are not only one message. Here, we suppose that a new message will be generated periodically and a message is considered to be delivered to its destination when \( I(t) \) of a message is larger than a threshold, such as 40% of all nodes. Figure 2 shows the variation of the number of delivered messages. It is easy to find that the number of all delivered messages increases almost linearly.

The values the parameters in Equa. (1) and Equa. (2) are listed in table 1.

B. Evolving Model With ‘Crashes’

In the evolving of infective disease, ‘crashes’ happen sometimes. Suppose part of users turn off their devices at night and
When a crash happens, large part of infective nodes discard the messages. Let \( I \) be the proportion of the users who will turn off their devices and determine to discard all its messages, a 'crash' happens. Let the proportion of the users who will turn off their devices and discard the messages is \( \mu_1 \).

\[
\begin{align*}
S(t+1) &= S(t) - pS(t) + \mu_1 I(t) \\
I(t+1) &= I(t) + pS(t) - \mu_1 I(t) \\
R(t+1) &= R(t) + p(S(t) - \frac{\mu_1 I(t)}{S(t)}), t_0 < t + 1 < t_1 \\
S(t+1) &= S(t) - pS(t) + \mu_1 l(t), t_0 < t + 1 < t_1 \\
I(t+1) &= I(t) + pS(t) - \mu_1 l(t), t_0 < t + 1 < t_1 \\
R(t+1) &= R(t) + p(S(t) - \frac{\mu_1 I(t)}{S(t)}), t_0 < t + 1 < t_1
\end{align*}
\]  

(2)

In above evolving model, we did not add energy constraint for the simplification reason. Figure 3 shows the development of \( I(t) \) when crashes happen at different times without energy constraint. It indicates that \( I(t) \) increases again after a crash. When a crash happens, large part of infective nodes discard the messages they received. However, there are still some users who do not turn off their mobile devices at night. So, these mobile devices can spread their message continue after the crash. On the other hand, those mobile devices who have discarded all their messages have large free buffer to receive the messages that may be a new message or an old message they have discarded. So, the number of the susceptible nodes increases after a crash, and the number of the infective nodes increases again after the crash and can reaches the 'balanced' \( I(t) \) value again.

V. Evaluation

A. Simulation Setup

To validate the evolving model, we evaluated different DTN routing protocols. We do a simulation by THEONE. THEONE is a popular DTN simulator and has been used in DTN study widely. Table 2 lists all the values of the parameters used in THEONE. The mobile nodes' mobility model in THEONE is Shortest Path Map-Based Movement because it shows the trait of mobile agents' movement in a city. We compare the message delivery ratio, delivered messages and delay of Epidemic routing, SprayAndWait and PRoPHET. Delivery ratio is the proportion of delivered messages over all created messages.

B. Delivered Messages

A delivered message means the message's destination has received this message. Obviously, the number of delivered messages will not decrease theoretically. Figure 4 shows the increasing of delivered messages. We can find that the function of delivered messages of Epidemic routing reported by THEONE increases almost linearly, which is very similar to the Figure 2. This indicates that the evolving model we proposed is reasonable.

The increasing of delivered messages of Epidemic routing is faster than SprayAndWait and PRoPHET as SprayAndWait routing protocol limits the number of the copies of a message and PRoPHET routing protocol selects the relay nodes strictly. We can find that the total number of the delivered messages of PRoPHET is larger than that of Epidemic routing. We believe the reason is that by Epidemic routing a node will generate more copies of a message so that it’s buffer saves lots of copies.

### Table II

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![Fig. 2. The variation of delivered messages](image1)

![Fig. 3. I(t) function of time with crashes happening at different time.](image2)
of different messages. When a node’s buffer is not enough to receive a new message, it deletes some oldest messages to get free buffer space no matter whether the deleted messages have been delivered to the destinations or not. Thus, after a long time, most nodes’ buffer are full and they have to discard many messages to receive a new message so that lots of messages that have not been delivered to their destinations are discarded.

C. Delivery Ratio

Figure 5 shows the comparison of delivery ratio of Epidemic, SprayAndWait and PRoPHET when there is no crashing and there is a crash. We find that the delivery ratio of Epidemic routing and PRoPHET increases when a crash happened at time=2500 compared with there is no crash. We think the reason is that when a crash happens, about 50% messages copies stored by all nodes are dropped so as to they can have free buffer to receive and relay new messages. In DTNs, when a destination receives a message, it will not response to the source node or other nodes, so actually most copies of messages are useless after some time. This is the first time that we find a crash can help nodes to get free buffer space and increases the delivery ratio of the DTN routing protocol that have no copies limitation. On the contrary, the delivery ratio of SprayAndWait decreases when a crash happened. As the number of the copies of a message is fixed in SprayAndWait protocol, the buffer constrain is not a pivotal factor of the routing performance. The number of the copies of a message is the pivotal factor of the routing performance. So, when a crash happens, about 50% messages copies are discarded and the routing performance of SprayAndWait decreases heavily.

D. Delay

Figure 6 shows that the delay of all the three DTN routing protocols decrease. If there is no crash, the delay of SprayAndWait is largely higher than that of Epidemic and PRoPHET. This is reasonable because the copies of a message is limited in SprayAndWait. So, with SprayAndWait, each copies of a message has to wait for longer time to reach its destination. If there was no crash, 111 messages were delivered to the destinations. But when a crash happens at time=2500, large part of messages copies are dropped and only 80 messages are delivered to the destinations. The reason of the decreasing of the delay is that the crash divided the simulation into two time parts. As the crash happened at half of the whole simulation time, the simulation time of each part was just half of the total simulation time so that the lifetime of some messages shortened. therefore, the average delay of all messages shortened in result.

VI. CONCLUSION

We consider the delivering a message according to opportunistic routing protocols in DTN as the spreading of an infectious disease. In this paper, we study the development
of the receivers of a message from the disease evolving viewpoint. Firstly, we propose the crash issue in the delivering of a message in DTNs.

We validated the evolving model by simulating messages being delivered among mobile nodes in THEONE. The experiment results validate the correctness of the proposed evolving model. Also, we compared the delivered messages, delivery ratio and delay of Epidemic routing, SprayAndWait and PROPHET. The simulation results indicate that the delivery ratio of Epidemic routing and PROPHET increase if there was a crash. But the delivery ratio of SprayAndWait decreases when there was a crash. Also, the delay of the three routing protocols decrease when a crash happens.

VII. ACKNOWLEDGMENT

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