Adaptive Optimal Buffer Management Policies for Realistic DTN

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Abstract—Delay Tolerant Networks (DTNs) are able to provide communication services in challenged networks where the end-to-end path between the source and destination does not exist. In order to increase the probability of delivery, DTN routing mechanisms may require nodes in the network to store and carry messages in their local buffer and replicate many copies. When the limited buffer is consumed, choosing the appropriate messages to drop is critical to maximizing the system performance. Current methods for this are sub-optimal or assume unrealistic conditions. In this paper, we propose an adaptive optimal buffer management scheme for DTN in the situations where the bandwidth is limited and messages vary in size. In our proposal, the mobility model is adjusted according to the nodes’ historical meeting information, and the message dropping policies are designed to optimize certain network performance goals, such as maximizing the average delivery rate or minimizing the average delivery delay. Furthermore, we theoretically prove that the designed message dropping policies are optimal to achieve the best system performance.

I. INTRODUCTION

Modern computer communication networks have been developed based on modeling networks as connected graphs, over which end-to-end paths need to be established [1]. This approach is carried over to wireless networking [2]. However, it might be not appropriate for some types of existing and emerging wireless networks, such as sparse sensor networks for wildlife tracking and habitat monitoring [3], deep-space interplanetary networks [4], vehicle ad hoc networks [5] and military networks [6], where the assumption that there is a contemporaneous end-to-end path between any source and destination pair may not be true due to sparse coverage, wireless propagation phenomena, power management, malicious attacks, etc. Even if such an end-to-end path exists, it may either come at a high cost or be unstable because of the instability of network topology caused by the mobility of mobile nodes.

In order to provide communication services in challenged wireless networks where there is only intermittent connectivity, researchers have proposed the Delay/Disruption Tolerant Networks (DTN) [3][7], which exploit opportunistic connectivity and node mobility to relay and carry messages respectively around the networks [2]. This approach is called store-carry-forward routing. In store-carry-forward routing, if the next hop is not immediately available for the current node to forward a message, the node will store the message in its buffer, carry it along while moving, and forward it to other appropriate nodes until the node gets a communication opportunity which helps to forward this message further. Therefore, the nodes must be capable of buffering messages for a considerable time. Moreover, to increase the probability of delivery, the messages will be replicated many times in the network due to the lack of complete information about other nodes. For example, in Epidemic routing [8], packets arriving at the intermediate nodes are forwarded to all of their neighbors. Therefore, the limited buffer in each node is likely to be consumed rapidly by storing these flooding messages. When the buffer is full, choosing the appropriate messages to discard is necessary.

Recent papers such as [9] and [10] demonstrate that the buffer constraints and management policies affect the performance of DTN routing significantly. [11] shows that Epidemic routing performs poorly when the buffer size of nodes is limited. In [9], authors demonstrate that widely used traditional buffer management policies, such as Drop Tail and Drop Front, perform poorly in the DTN networking environment. Aruna Balasubramanian et al. [12] propose a utility maximization based intentional DTN routing and buffer management protocol under limited bandwidth, but it use a sub-optimal per-packet utilities policy. Amir Krifa et al. [10][13] propose efficient optimal buffer dropping policies based on the global knowledge of the network. However, this method assumes that the nodes’ mobility model is statically known, the bandwidth is unlimited and the message length is the same, which are uncommon in practice. Therefore, the value of this approach is severely limited.

In this paper, we propose an adaptive optimal buffer management scheme to match node mobility characteristic for the realistic DTN. Using the historical mobility information of all nodes in the network, the nodes’ mobility model is adjusted adaptively. In our proposal, the bandwidth and the capability for one communication contact are both limited, and the messages vary in size. Based on these realistic conditions, we obtain and theoretically prove the optimal message management policies, which can optimize specific performance metrics, such as average delivery rate and average delivery delay. Based on the message management policies, we design a message dropping protocol by explaining the details of control
The outline of this paper is given as follows: Section II present the system model, the designed buffer management protocol and its optimal proof. Section III and Section IV present the design of utility functions and the protocol details. Finally, Section V concludes the paper.

II. THE BUFFER MANAGEMENT PROTOCOL

A. System Model and Problem Statement

We model a DTN as a set of wireless mobile nodes. In each node, says $i$, we assume that there are $N_i(t)$ messages in its buffer at the time $t$. $PK_i(t)$ is the message set in node $i$, denoted by $\{P_{i1}^i, P_{i2}^i, P_{i3}^i, ..., P_{iN_i(t)}^i\}$. For message $j$, says $P_j^i(t) \in PK_i(t)$, is denoted by a tuple $(Sou_i^j(t), Dist_i^j(t), T_i^j(t), s_i^j(t), n_i^j(t), C_i^j(t))$, which represent the source, destination, remaining time, size, the number of copies and transmission opportunity of message $j$, respectively. $C_i^j(t)$ means the opportunity for packet $j$ to be transmitted to the destination $Dist_i^j(t)$ by all nodes in the network including $i$, denoted by $C_i^j(t) = \{(u_1, l_1), (u_2, l_2), ..., (u_{n_i^j(t)}, l_{n_i^j(t)})\}$ where the $k$th tuple represents that there is a copy of message $j$ in the buffer of node $u_k$ and in the front of the buffer there are $l_k$ Bytes other messages.

With the control plane proposed in [12], we track the information of network resources to collect a local view of global network statuses. This approach uses an in-band control channel to exchange the network information among the nodes [12]. In our buffer management scheme, we use this control channel to exchange additional metadata including the parameters of the mobility model and the transmission opportunity for messages. Although this information may be delayed and inaccurate, this mechanism with our adaptive optimal buffer management policies can enhance the system performance compared with other approaches.

We assume that the nodes are moving independently in the networks, and their mobility models are independent identical distribution (i. i. d), which is very common in the DTN. We define two important properties of the mobility model, inter-meeting time and contact time in Definition 1 and 2, respectively [14].

**Definition 1 (Inter-meeting time):** The Inter-meeting time of node $i$ and node $j$ ($MT_{ij}$) is defined as the time it takes them to come within the range of each other ($R$) again from the last time ($t_0$) when they move out range of each other, that is, $MT_{ij} = min(t - t_0) : ||X_i(t) - X_j(t)|| \leq R, t > t_0$.

**Definition 2 (Contact Time):** Assume that node $i$ and node $j$ come within the range of each other at time 0. The contact time of them is defined as the time they are keeping in contact with each other before moving out of the range of each other ($R$), that is $CT_{ij} = min(t : ||X_i(t) - X_j(t)|| > R)$.

Recently studies focusing on both well-known mobility models, such as Random Waypoint and Random Direction [14], and real-life mobility traces [15][16] find that the distributions of inter-meeting time and contact time are exponential. Therefore, the inter-meeting time in this paper is assumed to be exponentially distributed with parameter $\lambda_1$, which equals $1/MT$, and the contact time is assumed to be exponentially distributed with parameter $\lambda_2$, where parameters $\lambda_1$ and $\lambda_2$ are adjusted and updated according to the historical mobility information of all nodes in the network.

B. Protocol Design

In this subsection, we design our Adaptive Optimal Buffer Management Policies (AOBMP). Two nodes transfer messages when they are within the range of each other according to the routing protocol. When any node detects the fullness of its buffer, it performs AOBMP to choose a message to discard. We note that our buffer management policies are independent of the routing protocol. The AOBMP protocol is described as follows, and its optimal is proved in Theorem 1.

**Protocol: AOBMP**

1) **Initialization:** Obtain the metadata from the currently communicating node, which is described in Section IV-A, and update the information including transmission opportunity of messages and parameters of mobility model (Detailed in Section IV).

2) **Utilization computation:** For each message $j$ in node $i$ ’s local buffer, including the newly received message, compute its utilization according to a certain system performance metric (Detailed in Section III), denoted by $U_i^j(t)$. Therefore, the utility function for all messages in node $i$, denoted as $U_i(t)$, is as follows:

$$U_i(t) = \sum_{j \in PK_i(t)} U_i^j(t).$$

3) **Discarding message:** Discard the message, says $j_{\text{min}}$ satisfying:

$$j_{\text{min}} = \arg\min_j \frac{\partial U_i(t)}{\partial n_i^j(t)}.$$  (2)

**Theorem 1:** To maximize the utilization, the local optimal buffer management policy is to discard the message $j_{\text{min}}$ satisfying Equation (2).

**Proof:** The utility function $U_i(t)$ is system utility of all messages in the local buffer of node $i$. When the buffer is full, node $i$ should make a dropping decision, which aims to achieve a best gain in $U_i(t)$. To get the optimal dropping policy, we differentiate and discretize $U_i(t)$ with respect to the number of copies of message $j$, $n_i^j(t)$, that is:

$$\Delta U_i(t) = \frac{\partial}{\partial n_i^j(t)} \left( \sum_{j \in PK_i(t)} U_i^j(t) \right) \ast \Delta n_i^j(t).$$

In order to maximize the utility $U_i(t)$, the best decision is to discard the message which makes $\Delta U_i(t)$ decrease least. On the other side, if we choose to discard a message, says 978-1-4244-4148-8/09/$25.00 ©2009 This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM" 2009 proceedings.
The number of copies of message \( k \) in the network decreases by 1, that is \( \Delta n_i^k(t) = -1 \). Thus, the optimal buffer dropping policy, which maximizes the network utility, is to discard messages, say \( j_{\min} \), that has the smallest value in the utility related function:

\[
\partial ( \sum_{j \in P_k} U_i^j(t) ) \over \partial n_i^{j_{\min}}(t) .
\]

That is to say, choosing message \( j_{\min} \) satisfying Equation 2.

### III. The Design of Utility Function

In this section, we get different utility functions and dropping policies with respect to specific system performance metrics, including the average delivery rate and the average delivery delay.

#### A. Maximizing the average delivery rate

**Theorem 2:** Let us assume that the buffer of node \( i \) is full at the time of \( t_0 \), and the number of the messages in the buffer is \( N_i(t_0) \). To maximize the average delivery rate, the node should discard the message \( j_{\max} \) satisfying:

\[
\arg \max_{j \in [1, N_i(t_0)]} \left( \sum_{n=1}^{n-1} \frac{\lambda_2 R_i^j}{(n-1)!} \sum_{k=0}^{n-1} \frac{(\lambda_1 T_i^j)^k}{k!} \right) e^{-\lambda_2 R_i^j - \lambda_1 T_i^j}.
\]

where \( T_i^j \) and \( R_i^j \) are the remaining time and additional time needed to transmit message \( j \) respectively, \( \lambda_1 \) and \( \lambda_2 \) are the parameters of exponential distribution of inter-meeting time and contact time respectively.

**Proof:** We first consider one message, say \( j \), in the node’s buffer. Let \( MT_k \) and \( CT_k \) denote the inter-meeting time and contact time of the \( k \)th times for any node which contains a copy of message \( j \) meeting its destination, \( Dist(j) \). Let \( I_i^j(t_0) \) denotes the average Bytes waiting to be sent before message \( j \). Thus \( I_i^j(t_0) = (l_1 + l_2 + ... + l_i(t_0))/l_i(t_0) \). Therefore, The total time needed to successfully transmit message \( j \), denoted as \( R_i^j \), can be expressed as \( R_i^j = (I_i^j(t_0) + s_i^j(t_0))/B \), where \( B \) is the bandwidth when the two nodes are within the range of each other. The probability for message \( j \) having not been transmitted until the \( n \)th meeting with its destination can be expressed as:

\[
P(0 < \sum_{k=1}^{n} MT_k < T_i^j, 0 < \sum_{k=1}^{n} CT_k < R_i^j, \sum_{k=1}^{n} CT_k > R_i^j),
\]

where \( MT_k \) is assumed. Therefore, The probability for successfully transmitting message \( j \), denoted as \( P_i^j \), can be expressed as follows:

\[
P_i^j = \sum_{n=1}^{\infty} P(0 < \sum_{k=1}^{n} MT_k < T_i^j, 0 < \sum_{k=1}^{n} CT_k < R_i^j, \sum_{k=1}^{n} CT_k > R_i^j).
\]

Due to the independence of \( MT_k \) and \( CT_k \), we can obtain that

\[
P_i^j = \sum_{n=1}^{\infty} P(0 < \sum_{k=1}^{n} MT_k < T_i^j) P(0 < \sum_{k=1}^{n} CT_k < R_i^j)
\]

As the \( i, i, d \) of \( MT_k \), the distribution function for \( MT_k \), denoted as \( f_1(x) \), is expressed as \( f_1(x) = \lambda_1 e^{-\lambda_1 x} \). Therefore:

\[
P(0 < \sum_{k=1}^{n} MT_k < T_i^j)
\]

Similarly, as the \( i, i, d \) of \( CT_k \), the distribution function for \( CT_k \), denoted as \( f_2(t) \), is expressed as \( f_2(t) = \lambda_2 e^{-\lambda_2 t} \).

Therefore, \( P(0 < \sum_{k=1}^{n} CT_k < R_i^j, \sum_{k=1}^{n} CT_k > R_i^j) \)

where \( T_i^j \) and \( R_i^j \) are the remaining time and additional time needed to transmit message \( j \) respectively, \( \lambda_1 \) and \( \lambda_2 \) are the parameters of exponential distribution of inter-meeting time and contact time respectively.

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\[
P(0 < \sum_{k=1}^{n} MT_k < T_i^j, 0 < \sum_{k=1}^{n} CT_k < R_i^j, \sum_{k=1}^{n} CT_k > R_i^j),
\]

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\[
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\]

Due to the independence of \( MT_k \) and \( CT_k \), we can obtain that

\[
P_i^j = \sum_{n=1}^{\infty} P(0 < \sum_{k=1}^{n} MT_k < T_i^j) P(0 < \sum_{k=1}^{n} CT_k < R_i^j)
\]

\[
\sum_{k=1}^{n} CT_k < R_i^j, \sum_{k=1}^{n} CT_k > R_i^j).
\]

As the \( i, i, d \) of \( MT_k \), the distribution function for \( MT_k \), denoted as \( f_1(x) \), is expressed as \( f_1(x) = \lambda_1 e^{-\lambda_1 x} \). Therefore:

\[
P(0 < \sum_{k=1}^{n} MT_k < T_i^j)
\]

Similarly, as the \( i, i, d \) of \( CT_k \), the distribution function for \( CT_k \), denoted as \( f_2(t) \), is expressed as \( f_2(t) = \lambda_2 e^{-\lambda_2 t} \).

Therefore, \( P(0 < \sum_{k=1}^{n} CT_k < R_i^j, \sum_{k=1}^{n} CT_k > R_i^j) \)

where \( T_i^j \) and \( R_i^j \) are the remaining time and additional time needed to transmit message \( j \) respectively, \( \lambda_1 \) and \( \lambda_2 \) are the parameters of exponential distribution of inter-meeting time and contact time respectively.

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\[
P(0 < \sum_{k=1}^{n} MT_k < T_i^j, 0 < \sum_{k=1}^{n} CT_k < R_i^j, \sum_{k=1}^{n} CT_k > R_i^j),
\]

where \( MT_k \) is assumed. Therefore, The probability for successfully transmitting message \( j \), denoted as \( P_i^j \), can be expressed as follows:

\[
P_i^j = \sum_{n=1}^{\infty} P(0 < \sum_{k=1}^{n} MT_k < T_i^j, 0 < \sum_{k=1}^{n} CT_k < R_i^j, \sum_{k=1}^{n} CT_k > R_i^j).
\]

According to Theorem 1, we can obtain that in order to maximize the average delivery rate, we should discard the message that satisfies Equation (5).

**Proof:** According to the proof of Theorem 2, we get that the probability of message \( j \) having not been transmitted to the destination until the \( n \)th meeting, denoted as \( P_j^n(X) \), is as follows:
Due to the independence of $\sum_{k=1}^{n-1} CT_k < R^i_j$, $\sum_{k=1}^{n} CT_k > R^i_j$

Therefore, the average delivery delay of message $j$, denoted as $DE^i_j$, is expressed as follows:

$$P^n_j(X) = \left[ 1 - \sum_{k=0}^{n-1} \frac{\lambda_1 T^i_j}{k!} e^{-\lambda_1 T^i_j} \right] \left( \frac{\lambda_2 R^i_j}{n!} \right)^{n-1} e^{-\lambda_2 R^i_j}.$$  

where $X$ denotes the event that message $j$ has not been successfully transmitted to the destination until the $n$th meeting, that is, $X = \{ 0 < \sum_{k=1}^{n} MT_k < T^i_j, 0 < \sum_{k=1}^{n-1} CT_k < R^i_j, \sum_{k=1}^{n} CT_k > R^i_j \}$

Then, the utility function of message $j$ can be expressed as follows:

$$U^j_i = - \sum_{k=1}^{n} E(DE^i_j) = -n^i_j(t_0) \sum_{n=1}^{\infty} \frac{n}{\lambda_1} \left( 1 - \sum_{k=0}^{n} \frac{(\lambda_1 T^i_j)^k}{k!} e^{-\lambda_1 T^i_j} \right) \left( \frac{\lambda_2 R^i_j}{n!} \right)^{n-1} e^{-\lambda_2 R^i_j}.$$  

According to Theorem 1, we can obtain that in order to minimize the average delivery delay, we should discard the message that satisfies Equation (6).

IV. PROTOCOL DETAILS

A. Control Channel

We use in-band control channel for nodes to exchange metadata including the messages’ transmission opportunity. This information propagation may be delayed and induce network overhead. However, in [12], authors confirm that this inaccurate information is sufficient to achieve system performance gains and the overhead for metadata is minimal.

In the step 1) of AOBMP, we need to exchange the following information.

1) The incremental historical information of inter-meeting time and contact time until the exchange.

For every node in the network, it saves the inter-meeting time and contact time as historical information when it is in the communication range of other nodes. In the step 1) of AOBMP, the nodes exchange the incremental historical information, which has been saved since their last meeting.

2) The transmission opportunity for the common messages. For example, when node $i$ and node $j$ are within each other’s range, if they have the same copy of a message, they exchange and update its transmission opportunity with each other, which is described in Fig. 1. Before the exchange, in node $i$, the transmission opportunity for messages $a$, $b$, $c$ and $d$ are $C_{1i}$, $C_{2i}$, $C_{3i}$ and $C_{4i}$ respectively. The common messages for node $i$ and $j$ are messages $a$, $c$, $d$. Therefore, after the exchange of transmission opportunity, the transmission opportunity for messages $a$, $c$ and $d$ are $C_{1i}C_{1j}$, $C_{3i}C_{2j}$ and $C_{4i}C_{3j}$, respectively.

B. Mobility Characteristic Adaption

The mobility characteristic of nodes in the DTN affects the system performance significantly. For example, if the inter-meeting time and contact time can be predicted, the performance of routing and resource management protocol
can be enhanced by utilizing these information. However, in practice, it is difficult to achieve this. Some of current research on DTN focuses on the understanding of mobility characteristic such as human and wildlife mobility patterns [15][16]. In our adaptive buffer management protocol, we adapt the mobility characteristic according to the historical information of all nodes in this network. Due to the i. i. d of mobility models and exponential distribution of inter-meeting time and contact time, we can adapt the mobility characteristic through adjusting the mean of exponential distribution with the help of the information exchanged by the control channel.

When node \( i \) and node \( j \) meet at time \( t_1 \), which means they are within the range of each other, the meeting information includes inter-meeting time and contact time, denoted as \( M_{i,j}(t_1), C_{i,j}(t_1) \), respectively. By the information exchange through the control channel in Section IV-A, each node can get almost the global meeting information. Based on the i. i. d of mobility model of each node, we predict the distribution of the inter-meeting time and contact time. We assume that the historical meeting information set of nodes \( i \) and \( j \), denoted by \( T_{meeting} \), including \( n \) items, is expressed as follows:

\[
T_{meeting} = \{ (M_{i,j}(t_1), C_{i,j}(t_1)), (M_{i,j}(t_2), C_{i,j}(t_2)), ..., (M_{i,j}(t_{n-1}), C_{i,j}(t_{n-1})), (M_{i,j}(t_n), C_{i,j}(t_n)) \}.
\]

Then, the parameter \( \lambda_1 \) of inter-meeting time of node \( i \) and \( j \) \( (MT_{i,j}) \), can be obtained as follows:

\[
\lambda_1 = \frac{1}{E(MT_{i,j})} \approx \frac{1}{\frac{1}{n} \sum_{k=1}^{n} M_{i,j}(t_k)}
\]

(7)

The parameter \( \lambda_2 \) of contact time of node \( i \) and \( j \) \( (CT_{i,j}) \), can be obtained as follows:

\[
\lambda_2 = \frac{1}{E(CT_{i,j})} \approx \frac{1}{\frac{1}{n} \sum_{k=1}^{n} C_{i,j}(t_k)}
\]

(8)

The historical information becomes more with the elapse of time, and the mobility characteristic will be adapted more precisely. The reason is that when the number of items of historical information is infinite, we can get the following expressions:

\[
E(MT_{i,j}) = \lim_{n \to \infty} \frac{1}{n} \sum_{k=1}^{n} M_{i,j}(t_k)
\]

\[
E(CT_{i,j}) = \lim_{n \to \infty} \frac{1}{n} \sum_{k=1}^{n} C_{i,j}(t_k)
\]

(9)

V. CONCLUSION

In this work, we investigate the buffer management problem in the Delay Tolerant Networks. We use the control channel in [12] to help the nodes to get the global network statuses, such as transmission opportunity of messages, inter-meeting time and contact time of nodes, as much as possible. When the buffer of a node is full, our buffer management scheme AOBMP is able to determine which message to discard to optimize a certain performance goal, such as maximizing the average delivery rate or minimizing the average delivery delay, based on the collected network statuses.

In the theoretical proof, we prove that the designed two utility functions are the optimal buffer dropping policies to maximizing the delivery rate and minimizing the delivery delay, respectively. However, how to design other message dropping policies that optimize system performance such as minimizing maximum delay under our system model is also important. We leave this as future research work.

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REFERENCES