Quasi Fair Forwarding Strategy for Delay Tolerant Networks

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SUMMARY Existing forwarding strategies for delay tolerant networks aim at network throughput maximization. They provide forwarding opportunities to more reachable destinations. This results in the long end-to-end delay and low throughput of less reachable destinations. In this paper, we propose two forwarding strategies to improve the throughput of less reachable nodes with little throughput degradation of more reachable nodes. Evaluation results show that the proposed forwarding strategies can control the levels of fairness among the destinations while maintaining high throughput, compared with the legacy forwarding strategies.

key words: delay tolerant network, fairness, forwarding strategy, delivery probability

1. Introduction

In a delay tolerant network (DTN), the premise of path existence may not be valid at any instant in time, and it is difficult to apply traditional mobile ad hoc routing protocols [1]. Thus, rather than determining a route, a node simply forwards messages whenever it is connected to another node. It is known that the forwarding strategy influences the network performance, such as end-to-end delay and throughput, remarkably [2]–[8].

The probabilistic routing protocol using the history of encounters and transitivity (PRoPHET) [3] was proposed to improve the routing performance in a DTN. It uses probabilistic metric called delivery predictability. The delivery predictability indicates how likely a node \(X\) will be able to deliver a message to its own destination node \(Y\) [2], [3], GRTRMax [7], a default forwarding strategy of PRoPHET, forwards the messages destined to those with higher delivery predictability. As a result, messages destined to nodes with low delivery predictability have rare forwarding opportunities. Thus, the some destinations will suffer very low message reception ratio or, furthermore, will not receive any messages at all. This is unfair from the aspect of the message reception ratio per destination. This unfairness is a serious problem in DTN applications that must update data or code in multiple destinations.

In this paper, we propose two fair message forwarding strategies for a predictable DTN. The mobility of nodes is predictable over a finite time or indefinitely put off due to periodicity in the node motion [1]. Unlike GRTRMax, our strategies aim at not only high throughput but also high fairness in terms of the message reception ratio.

2. Fair Forwarding Strategies for DTN Routing

2.1 Max-Fair Forwarding Strategy

We assume that the encounter pattern of DTN nodes is almost regular over a finite time and predictable. The total amount of available network resources between nodes \(j\) and \(k\) is denoted as \(R_{jk}\). As an outstanding example of network resource, we consider the average number of available time slots. To estimate the message delivery probability from node \(j\) to \(k\), we use the reception ratio at node \(k\) of messages that has passed node \(j\). The reception ratio is measured by counting the sequence number of arrived messages. As shown in Fig. 1, every node represented as node \(j\) allocates a message queue for any node destined to by any single message in that node. The amount of messages arrived into the queue for the node \(i\) is represented as \(a_i\). According to the forwarding strategy, node \(j\) determines the network resource per message queue, which is denoted as \(s_j\) and may be different depending on the encountered node.

We first propose a Max-Fair forwarding strategy, which aims to support the nodes the same message reception ratio. We define the fairness index as (1) based on [9].

\[
G(x_1, x_2, \ldots , x_n) = 1 - \frac{n}{n-1} \sum_{i=1}^{n} \left( \frac{x_i}{\sum_{j=1}^{n} x_j} - \frac{1}{n} \right)^2
\]  

(1)

Fig. 1 Node model for the proposed forwarding strategies.
where \( x_i \) is the message reception ratio to destination \( i \), and \( n \) is the total number of message queues. It is infeasible to have any central node in a DTN to monitor and enforce such fairness requirements in a network-wide manner. Therefore, we propose that each node try to optimize the message forwarding schedule locally for a fairness index of 1.

Let’s consider how node \( j \) determines the resource when it encounters another node \( k \). Nodes \( j \) and \( k \) exchange and update the delivery probability information first. Then, node \( j \) determines what amount of network resource is allocated to each message queue (denoted as \( s_i \)). The amount of resources allocated to each message queue is used as the weight of the queue for the weighted fair queue (WFQ) scheduler.

With the Max-Fair strategy, when node \( j \) encounters node \( k \), node \( j \) selects which messages to forward with the constraint that the resource allocation should make the fairness index of (1) to be equal to 1 (i.e., \( G = 1 \)). For each destination node \( i \), the resulting message reception ratio of node \( i \), denoted as \( x_i \), can be estimated as in (2) from this resource allocation \( s_i \).

\[
x_i = \frac{p_{kj} \cdot s_i}{a_i}
\]

where \( p_{kj} \) is the known delivery probability between the node \( k \) and the node \( i \). The dividend of (2) represents the expected number of messages actually delivered to node \( i \).

To have \( G = 1 \), all \( x_i \) should be the same. By letting \( x_i = c \), we obtain \( s_i = c \cdot a_i / p_{kj} \). In other words, the resources should be allocated proportionally to \( a_i \), and inversely proportionally to \( p_{kj} \), to have a high fairness index. Thus, we define the gravity of destination node \( i \) as in (3).

\[
g_i = \frac{a_i \cdot p_{kj}^{-1}}{\sum_{i=1}^{n} a_i \cdot p_{kj}^{-1}}
\]

where \( n \) is the number of message queues in node \( j \). The available network resource between nodes \( j \) and \( k \) is limited to \( R_{jk} \), and resource is temporarily allocated as \( t_i = g_i \cdot R_{jk} \) to the message queue corresponding to node \( i \). However, there can be a gap between \( t_i \) and \( a_i \) and the resource allocation is rearranged to reduce the gap.

If \( t_i \) is greater than \( a_i \), in other words, more resource is allocated than the required, \( s_i \) is finalized as \( a_i \) and the difference between \( t_i \) and \( s_i \) is put aside as residual resource \( r_{jk} \). If \( t_i \) is less than \( a_i \), in other words, less resource is allocated than the required, \( s_i \) is finalized as the sum of \( t_i \) and a portion of the residual resource \( r_{jk} \). In summary, the resource allocation process is finalized as in (4) until there is no more residual resource.

\[
s_i = a_i, \quad r_{jk} = r_{jk} + (t_i - s_i) \quad \text{if} \quad (t_i \geq a_i).
\]

\[
s_i = t_i + r_{jk} \times g_i \quad \text{if} \quad (t_i < a_i).
\]

2.2 Quasi-Fair Forwarding Strategy

The Quasi-Fair forwarding strategy is different from the Max-Fair strategy from the aspect that it has more relaxed fairness requirement. Instead of pursuing \( G = 1 \), we use fairness index threshold \( \left(G_{th} < 1\right) \), which represents the minimum fairness requirement. The basic motivation of the Quasi-Fair forwarding scheme is that network-wide throughput can be improved if allowing more messages to be forwarded to more reachable destinations.

As far as the minimum resource requirement \( r_{min} \) per node to have \( G \geq G_{th} \), is guaranteed, the resources of less reachable nodes are distributed to more reachable nodes. After the resources are temporarily allocated as \( t_i = g_i \cdot R_{jk} \) like the Max-Fair strategy, the resource \( s_i \) and \( s_i \) to nodes \( u \) and \( v \), respectively, is rearranged as in (5) for any node \( u \) with \( t_u < a_u \).

\[
s_u = t_u + \delta, \quad s_v = t_v - \delta, \quad \text{if} \quad p_{k,u} > p_{k,v} \quad \text{and} \quad s_v > r_{min}
\]

Let us consider how large \( \delta \) can be. We denote the resource allocation change as \( x_i' = x_i + \delta y_i \) and \( x_j' = x_j - \delta y_j \), where \( y_i \) and \( y_j \) are the message reception ratio that could be derived from \( t_u \) and \( t_v \), respectively. Both \( y_i \) and \( y_j \) are the addition and reduction caused due to \( \delta \), respectively. The maximum allowable gap in the fairness index is expressed as \( \Delta G = G(x_1, \ldots, x_n) - G_{th} \). The final resource allocation should satisfy the condition expressed in (6).

\[
G(x_1, \ldots, x_n) - G(x_1', \ldots, x_n') \leq \Delta G,
\]

where all values of \( x_i' = x_i \) for \( i \neq v \) and \( i \neq u \).

The condition is represented by substituting (1) into (6) as:

\[
\left[ \frac{1}{n} \sum_{i=1}^{n} x_i'^2 \right] - \left[ \frac{1}{n} \sum_{i=1}^{n} x_i^2 \right] \leq \Delta G \cdot \frac{n - 1}{n}.
\]

Then, (7) is expanded with \( y_u \) and \( y_v \), such that,

\[
\left[ \frac{1}{n} \sum_{i=1}^{n} (y_u - y_i + \sum_{j=1}^{n} x_j')^2 \right] - \left[ \frac{1}{n} \sum_{i=1}^{n} x_i^2 \right] \leq \Delta G \cdot \frac{n - 1}{n}.
\]

We can simplify (8) with a quadratic inequality of \( \delta \), which indicates the amount of resource that can be taken from nodes with lower delivery probability by replacing \( y_u \) and \( y_v \) with \( (p_{k,u} / a_u) \cdot \delta \) and \( (p_{k,v} / a_v) \cdot \delta \), respectively. This forwarding strategy will take the maximum \( \delta \) that satisfies (9).

\[
A \cdot \delta^2 + 2B \cdot \delta + C = 0,
\]

where

\[
A = \left( \frac{p_{k,u}}{a_u} \right)^2 + \left( \frac{p_{k,v}}{a_v} \right)^2 - K \cdot \left( \frac{p_{k,u}}{a_u} - \frac{p_{k,v}}{a_v} \right)^2,
\]

\[
B = \left( \frac{p_{k,u}}{a_u} \right) \left( x_u - K \sum_{i=1}^{n} x_i \right) - \left( \frac{p_{k,v}}{a_v} \right) \left( x_v - K \sum_{i=1}^{n} x_i \right),
\]

\[
C = x_u - x_v.
\]
the predefined routes between R1 and Dff from 0.6 to 6.4 Mbps. The bu-

"strategy. The other nodes use GRTRMax as the forwarding

nodes do not have such neighbors in our simulation sce-

ferent delivery probability to each destination but the other

ate nodes (R1 and those from N1 to N15). Figure 2 shows

The distance of D4 from source is longer than that of D1, which means that D4 is less

with 66 nodes which are a single source node (denoted as S), four desti-

nodes (denoted as from D1 to D4), and 61 intermediate

ior size of each node is set

varies from 0.5 to 0.9 by 0.2.

We compared the proposed forwarding strategies and

We build a network from simulation with 66 nodes

Our proposed forwarding strategies run on S only since

The distance of D4 from

source is longer than that of D1, which means that D4 is less

many intermediate nodes to make the delivery probabilities
diverse.

Our proposed forwarding strategies run on S only since its neighbor R1 encounters the intermediate nodes with different delivery probability to each destination but the other

do not have such neighbors in our simulation scenario. The other nodes use GRTRMax as the forwarding strategy.

The message generation rate per destination varies

from 0.6 to 6.4 Mbps. The buffer size of each node is set

as 610 kbytes which is the minimum size not to cause buffer over- flow when the data generation rate is 0.6 Mbps. Thus,

small buffer size will affect the throughput as well as forwarding strategy like in the real world situation. Fairness threshold $G_{th}$ varies from 0.5 to 0.9 by 0.2.

The simulation is divided into two stages. During the first stage, the nodes collect the message reception reports of the other nodes. In this simulation, it lasts one fourth of the simulation time. Initially, we assume that the delivery probabilities are the same. However, as the source sends messages, the intermediate nodes count the incoming messages and records own identifier into messages. The destination calculates how many messages are received from each intermediate node and broadcasts the message that reports the message counts per each intermediate node. From these messages and its own message counts, every intermediate node calculates its delivery probability to each destination node. In the second stage, the nodes use the delivery probability obtained in the first stage to determine which message to forward to which neighbor. The node mobility pattern remains the same during the whole simulation time.

We simulated 10 times with different random seeds and got the average. We measured the fairness index $G$ as defined in (1), as well as the total throughput of each destination node. The total throughput of a node is the total number of bytes received per second. Figures from Fig. 3 to Fig. 5 show the simulation-based evaluation results. The results of GRTRMax are labeled as MaxThr. Those of Quasi-Fair forwarding strategies and Max-Fair are labeled as Quasi-

Fair ($G_{th}$) and MaxFair, respectively.

Figure 3 shows the total throughputs of four destinations while changing the source’s data generation rate. The left-topmost figure shows the result of Max-Thr strategy. Since the messages destined to D1 have the highest priority, D1 (blue bar) has the highest total throughput. The resulting total throughputs of the other destinations in the order of D2 (cyan), D3 (yellow), and D4 (red) in the same order of delivery probability. Under relatively light traffic load (0.6 Mbps generation rate), the gaps between the D1 and the others are not so significant. However, the discrepancies is intensified noticeably after the generation rate gets larger than 2 Mbps, and D3 and D4 show almost zero total throughputs. We can hardly estimate when all the destinations complete data reception since the discriminated destinations has almost zero throughput.

The other three figures in Fig. 3 show the results of Quasi-Fair strategy. The right topmost figure shows the results of Quasi-Fair strategy with $G_{th}$=0.5. We still observe there are discrepancies in the total throughputs. How-
ever, it is designed to guarantee the minimum resource $r_{\text{min}}$ even in the worst case. Thus the discrepancy between the largest and the smallest ones gets relieved compared with the Max-Thr case.

We can see that as $G_{th}$ increases from 0.5 to 0.7 and 0.9, the discrepancies among the total throughputs are relieved regardless of the source’s data generation rate. The maximum throughput is much lower than the data generation rate, which means that the messages are dropped and even the delivered messages have experienced extraordinary long delay at the intermediate nodes. One interesting observation is that once the data rate increases higher than 2 Mbps, the discrepancies get more relieved and, to the contrary to the result of MaxThr case, higher data generation rate results in fairer resource allocation. With Quasi-Fair strategy, we can estimate when all the destinations complete data reception since they are guaranteed with minimum resource.

Figures 4 and 5 show the average fairness index and total throughput of the destination nodes, respectively. QuasiFair(0.5), QuasiFair(0.7) and QualiFair(0.9) represent the results of Quasi-Fair forwarding scheme with $G_{th}$ = 0.5, 0.7, and 0.9, respectively. Max-Fair represents the results of Max-Fair forwarding strategy.

When the data generation rate is less than 2 Mbps, every strategy supports the fairness index of 1. As expected, the MaxThr shows the maximum average throughput. However, the fairness index of MaxThr strategy reduces noticeably as the generation rate increases. It means that there is significant discrepancy in the throughputs. Some nodes are provided with very high throughput whereas some nodes are suffering from almost zero throughputs as shown in Fig. 3. When generation rate is larger than 15 Mbps, the fairness index seems to be stabilized. This is because the messages are lost at the intermediate nodes due to message queue overflow and, thus, the message reception ratio of the most reachable node increases slowly.

The proposed fairness-based forwarding schemes support lower throughputs than MaxThr because fairness sacrifices the throughput of the most reachable nodes. However, we believe that the fairer data delivery is more meaningful in case that a source wants to send data to multiple destinations. When the data generation rate is 26 Mbps, the average throughput of MaxThr is 2.42 Mbps whereas that of MaxFair is 1.82 Mbps which is 75.2% of MaxThr. Moreover, QuasiFair(0.5) supports 2.15 Mbps which is 88.8% of MaxThr. We conclude that the proposed fairness-based forwarding schemes can accomplish fair message delivery with cost of little performance degradation compared with MaxThr.

4. Conclusion

Focusing on fairness in terms of message reception ratio, we proposed two message forwarding strategies for delay tolerant networks. The first scheme, the Max-Fair strategy, can achieve a fairness index of approximately 1, but offers low throughput. The second scheme, the Quasi-Fair forward strategy, supports high throughput as well as a high fairness index. It is because this strategy relaxes the fairness requirement and introduces the fairness index threshold to control the fairness level.

To the best of our knowledge, this is the first paper to address the fairness issue in DTNs. We will improve our strategies to consider more dynamic network environments and the method of measuring the delivery probability more precisely.

References


