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Research on Congestion Management in Delay-Tolerant Networks

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Abstract. Far from the traditional network, delay-tolerant network (DTN) is a new kind of network derived by deep space communication. As congestion control is an important factor that directly affects network performance, development of DTN must rely on the perfect congestion control mechanism to ensure reliability, stability, and extensiveness of the network. If TCP widely used as core protocol in Internet is directly used in DTN, it could appear a series of problems such as fairness, stability and throughput rate, etc. Meanwhile, in order to enhance the reliability of data delivery in such challenging network, researchers have proposed the use of custody transfer protocols, which produces a lot of copies in network and sometimes even aggravates congestion in DTN. This paper shows some limitations of TCP directly applied in DTN, some undesirable effects of custody transfer, and survey of four kinds of distinctive congestion management in DTN.

Keywords: Delay tolerant networks; custody transfer; congestion management

1. Introduction

In recent years, designs about structure and protocol of delay-tolerant network have become more and more popular. DTN is a new kind of network derived by deep space communication. Differed from the traditional network, DTN network has the following several characteristics: long delay , limited resources, intermittent connectivity , asymmetric data rate, low SNR(Signal to Noise Ratio) and high error rate.Examples of DTN such as Terrestrial Mobile Networks, Exotic Media Networks, Military Ad-Hoc Networks, Sensor/Actuator Networks, Vehicular Networks, etc[1]. The Internet's success depends on many factors：the main one is TCP that provides end-to-end flow control mechanism, which can prevent congestion collapse [2]. The key point of TCP end-to-end congestion control is that each source is sensitive for resource distribution of network. End-to-end TCP- ACK is used to report arrival of source data, according to it, the source can adjust its data input rate , thus fulfilling the congestion control. Due to its end-to-end continuous path frequently interrupted, However, TCP congestion control mechanism can't be directly used in DTN. As being unable to ensure sustained end-to-end path in the network, we need to design a kind of congestion control mechanism that not rely on end-to-end connection

Development of DTN network must rely on the perfect congestion control mechanism to ensure reliability, stability, and extensiveness of the network. As some existing constraint condition of DTN network, so its congestion control problem is very different from the Internet. Meanwhile, due to many inadaptabilities, if TCP widely used as core protocol in Internet is directly used in DTN, it could appear a series of problems such as fairness, stability and throughput rate, etc[3].Therefore, in view of DTN characteristics, to study new congestion control is very important. At the same time, there are more and more researchers studying DTN in recent years. Some put forward custody transfer mechanism [7] to enhance the reliability of DTN. However,

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as a custodian could not release or transfer custody of message in face of a continuous demand, which consumes much storage resources, and prevents future flow in the outgoing connection. Meanwhile, it has caused many copy messages in the network, which sometimes aggregates congestion. In short, congestion control in DTN should be paid much attention. This paper focus on the following four distinctive kinds of DTN network congestion control: HBD (history based drop) [4], a cognitive approach to congestion control [6], migrating custodian storage strategy [5], management based on economic model [8]. And the paper makes a detailed investigation and research for their work.

2. Limitations of TCP congestion control in DTN

2.1. Assumptions that TCP are dependent on

Table 1 (refers to [8]) shows some difference between assumptions that TCP are dependent on and characteristic of DTN.

From table l, it can see that DTN does not accord with TCP basic assumptions conditions.

2.2. Requirements of transmission quality.

Internet uses "best-effort" service model of nodes to send data, so for data transmission quality it does not provide any guarantee. And intermediate node can take lost package strategy (such as FIFP, PQ, etc) to ease congestion.

Table 1. Difference between assumptions of TCP and DTN

Underlying assumptions of TCP	Characteristics of DTN
Effective continuous end-to-end path	Intermittent hop-by-hop and end-to-end connection
Short RTT	Long and variable delay
Low erroe rate	Low SNR and high error rate
Symmetric data transmission	Asymmetric data transmission
Best=effort service	Custody transfer service
Abundant energy of node	Constraint energy of node
Exchange signaling between	Coarse granularity feedback
Source and destination	Unconfirmed unicast message

On the contrary, DTN adopts custody transfer mechanism under store-and-forward mode, so it should guarantee the reliability of hop-by-hop and the intermediate nodes cannot discard the data after commitment when it cannot successfully forward data due to no opportunistic contact [1], thus congestion may behave as denial of service.

2.3. Propagation delay

TCP assumes that error rate of link is low, plus characteristics of session protocol (ACK), so it can use timeout mechanism to detect congestion, while end-to-end propagation delay of DTN can be very large, feedback information of intermediate nodes or a destination cannot promptly send to the source. Thus DTN congestion detection cannot use simple timeout mechanism.

2.4. Behavioral characteristics of routing node

Behavioral characteristics of routing node take great influence on congestion control effect. The main purpose of DTN routing is not to choose the shortest path or minimal hop count but the possibility of maximizing message transmission [10].

Accordingly, there are larger differences between DTN and traditional Internet in various aspects such as end-to-end connections, propagation delay, reliability, data flow, channel characteristic, routing mechanism, etc [8]. The most important difference is that far from traditional network that is connected and most of the time for at least one complete end-to-end communication path exists between nodes, DTN may cause interruptions of end-to-end continuous path frequently due to energy-saving mechanism, node sparse, moving beyond the scope of nodes and some other reasons. [2]The interruptions may obey a certain rule and also may be random. In view of the above situation, TCP can't be directly used in DTN, and we need to design a kind of congestion control mechanism that not rely on end-to-end connection.

3. Custody Transfer Mechanism In DTN

3.1. What is custody transfer

In DTN, continuous end-to-end connection cannot be assured, any point-to-point link may be interrupted at any time, be unable to timely monitor data rate, and buffer occupancy rate cannot dynamically change. On the contrary of TCP, DTN protocol does not include end-to-end confirm mechanism that can be as vehicle for promptly correct action at source. In view of the above characteristics, hop - hop custody transfer mechanism has been proffered to improve the reliability of the network includes custody acceptance or custody refusal [1]. Custody transfer that assumes responsibility of reliable transmission is a special kind of mobile message toward the destination in hop - by - hop way [7]. Custody transfer can guarantee reliability to some degree as the custodian node cannot discard message unless the life time expires or be transferred to another node after commitment [8]. On the other hand, one advantage of custody transfer is that custody transfer ACK can make node release buffer relatively quickly as it is likely that custody transfer occurs between relatively close nodes, which can keep its round - trip - time less than an end -to- end round-trip-time. Anyhow, the function of custody transfer is by using reliability of hop -by-hop (custodian-to-custodian) to improve end-to-end reliability and soon release the sender's retransmission space.

3.2. Flaws of custody transfer mechanism

- Poor timeliness. Due to inherent dynamics of network , signal propagation delay may be high, a CT - ACK likely are not connected with state information of the time when it arrives at source, so congestion control can't be solved[2] by custody transfer mechanism. In addition, for node that is responsible for collecting data (remotely deployed sensors) , ability of timely releasing storage space is very important, so high delay correct action can not wait until CT - ACK reach [7].
- Occupying large amount of resources. As bundle cannot be discarded before being transferred to other nodes or its life time expires, node must storage bundle for a certain time, which will occupy much buffer of node.Furthermore, during that time looking for the next trust node, it needs to copy a lot of messages in the network to improve the transmission possibility, which will also occupy a lot of network resources and make the network congestion.
- Aggravating congestion. When network is in congestion state, a node that has received a lot of bundles can not discard bundle to ease congestion. On the contrary, as custody transfer conditions it is likely to receive more bundles, which will aggravate the network congestion instead.
- Low utilization. Because the storage space is limited, if to accept any bundle custody, precious storage space will be occupied by the bundle arrives earlier, which will prevent the future more important and effective custody transfer, thus reduce the network utilization rate [8]. To sum up, due to the characteristics of DTN (global information are not often available and network status is always in dynamic change), node must execute asynchronously congestion management mechanism according to local information, and therefore to overcome some limitations of existing custody transfer mechanism it should explore some distinctive congestion management mechanism.

4. Distinctive congestion management in DTN

4.1. HBD (history based drop)

In view of the congestion phenomenon caused by excessive consumption of storage space brought by store-and-forward protocol, reference [4] proposed optimal buffer management, based on HBD, different from traditional drop - tail or drop - front [14] buffer management mechanism. This one, aiming at unavailable timely global information caused by characteristic of DTN itself such as high propagation delay, strong node mobility, limited energy, etc, and using theory of encounter - based message dissemination to obtain global information. Furthermore, by using distributed algorithm to calculate global information needed by buffer management. In order to the goal of improving the average transmission rate and reducing the average propagation delay , discarding message by judging whether it meets two proposed theoretical formulae , thus carries out buffer optimal mechanism. HBD mechanism allows DTN node to exchange information with other nodes inband to gain global network historical records. As each node includes a series of status and update information [4] of the nodes once met. Through meeting each other to exchange each other information all the node will have the same right global view to network history over a period of time. Meanwhile, if network is very big, the network history will be restricted in a period of time, thus node can gain global historical information. In addition, HBD mechanism includes a distributed algorithm that using accurate global network history does not rely on flooding time to compute locally transmission rate and delay utility to obtain value of each message, and delete those minimum value of the message to improve average transmission rate and reduce the average propagation delay.

Based on the above, the optimal management must perform the following rule (Details about Imin mi ni T_i R_i L refer to [4]): In order to improve average network transmission rate, node must discard message Imin Satisfying(1):

$$i_{min} = \underset{i}{argmin}\left[(1-\frac{m_i(T_i)}{L-1})\lambda R_i \exp(-\lambda n_i(T_i)R_i) \right] \tag{1}$$

In order to reduce average network latency, node must discard message I_{min} satisfying (2):

$$i_{min} = \underset{i}{argmin}\left[\frac{1}{n_i(T_i)^2 \lambda}(1-\frac{m_i(T_i)}{L-1}) \right] \tag{2}$$

At the same time, through NS - 2 [13] to evaluate HBD mechanism's performance of average transmission rata and sum of propagation delay in three kinds of mobile mode (a synthetic one, based on the Random Way point model , the trace was collected as part of the ZebraNet wildlife tracking experiment in Kenya described in [11] , The mobility trace tracks San Francisco’s Yellow Cab taxis [12]) to draw a conclusion that HBD outperforms (DF, DO, DL, DY, FLD [4]), and so close to the ideal mode GBD(global knowledge Drop).

In view of buffer management problems in DTN, HBD [4] introduces the distributed algorithm that obtains historical information through node encounter to estimate required global information, and based on this to execute optimization control mechanism. There are, however, many problems with this mechanism. For instance, assume that bandwidth is infinite, uncertainty of node contacts, without considering the factor of message size, complex algorithm for DTN node, and the simulation results is not general.

4.2. Cognitive approach to congestion control

On the condition of long loop, flow control information carried on bundle layer and lack of human management, reference [6] proposed a kind of congestion management based on cognitive method of machine learning (artificial intelligence) to make network operate within acceptable efficiency. Also pointed out that due to restrictions of incomplete information and high delay, node must have the ability oneself to explore a plausible scenarios (similar to the chess program) and suggest a best action plan under available information. Furthermore, in order to reduce human intervention, node needs to have the capability to learn achievements and failures, forming a diagnosis and repair mechanism [15]. Machine-learning Program (M Program) according to the following information -- local free storage size, time for buffer full, change of input number rate , input data rate ,output data rate (don't need all 5) --can detect congestion in DTN, and according to a set formula (weighted average above three measuring) to estimate a numerical size representing congestion degree, a scale from 1 (least likely) to 5 (imminent), thus to monitor network congestion. When network is in congestion state, using artificial intelligence method to search a series of possible solutions, and analyze the different effects of this solutions, to suggest a best action plan under available information to flow control, for example: by analyzing the influence of reducing sending rate to determine whether to abandon node bundles (as NACKS) requiring the sender reducing the sending rate. Also to suggest a better action plans that may require several specific senders to reduce their rates, and let other nodes continue previous rate. Through simulation results, it finds that even when the program only has the raw data (input rate, output rate and available buffer), each node predicts 30% of their test cases correctly. Change of input rate and time for buffer full values are allowed, which leads to appreciable increase in the performance. Finally, when the program has all the attributes, a peak performance of 68.43% is achieved by the decision table [6].

Aiming at conditions of DTN, it proposed a approach for "cognitive networking," which is beyond some traditional technology. Traditional technology will fail in face of a imperfect information, while so long as enough training is machine learning programs, even under the condition of incomplete circumstance, it still can by "learning" provide a highly correct result. However, short of rigorous simulation platform, and uncertainty of available data , risk of influence taken by "best plan", are all negligence of the congestion management. And the most important one is this idea is not easy to realizable and details about how to solve congestion after detection is not provided.

4.3. Migrating custodian storage strategy

Reference [5] considers that it must generally migrate its stored messages to alternative storage locations when the node is congested , and for custodian it only need keep track of where stored messages have been placed and retrieve them later at appropriate times. By separating the buffer management method from the routing selection problem, it proposed a method based on symmetric push-pull custody transfers without interfering with global routing, including Storage routing (SR) that determines which message should migrate to which node at which time., which is in full use of network resources to ease the congestion and reduces the data loss to improve the network performance. This migration employs DTN protocol mechanisms such as custody transfer requests and acknowledgments. To avoid locally modifying a global routing algorithm, it instead applied a novel operation (push-pull custody transfers) in the custody transfer mechanism. A node with available resources can claim actively to receive custody of messages from other nodes that is congested by means of push-pull custody transfers operation without disrupting the global routing system.When a DTN custodian node becomes congested, the custodian then transfers the selected messages to alternative storage locations through the push operation. And when a custodian has sufficient storage resources to retrieve custody for messages, it uses a retrieval algorithm to pull the messages that are migrated previously to other node by itself. Furthermore, SR including following algorithms [5]:

- Select which messages to migrate: based on temporal (such as tail or head), size(such as small or large),priority(such as lowest or highest).
- Select which nodes that messages should be migrated to: based on storage cost(S) that the amount of available storage used for accepting migrated message and transmission cost (T) that dependents on latency, bandwidth, and up/down schedules of the links. In addition, according to different requests of network, it can adjust the weight value to calculate S and T.
- Select which messages to retrieve and from whom: when a custodian eases congestion and has sufficient buffer to take custody, it may send a custody request which may be sent to either a single custodian (e.g. When the sender knows the location of messages it previously migrated [5]) or might instead use a form of group query to find other nearby custodians that once migrate messages to.

On the concept of the DTN architecture [18] which supports a proactive fragmentation mechanism that can divide a message into smaller fragments, each of which can be handled by custodians individually and message migration may not need to involve transferring entire messages among custodians. In addition, it proposed “Joint custody” that allows more than one custodian for a given message to enhance efficiency of algorithms. Finally, by using message completion rate (MCR) to evaluate the efficiency of SR to draw a conclusion that the efficiency is as much as 48% for some source-constrained DTN when the number of interrupted link is not big, while as the number increases to certain size, there is a drastic effect on MCR.

This solution is based on separation of routing selection and management mechanism and no more research for message priority. But to introduce the priority and routing mechanism in many situations will make this problem much more complicated especially in the circumstances of limited network resources encountering a high-capacity and higher-priority message. Meanwhile, this solution is passive approach, in very serious condition of network interruption, nodes cannot access its distributed storage system. If so, the custodian may be unable to carry out a complete custody transfer with another custodian. In addition, when the network is partitioned, message movement will be in oscillating state making little forward progress, which results in further research about taking advantage of multiple buffers of available storage to store one message and studying multiple paths towards the same destination

4.4. Management based on economic model

To maximize the overall system benefit subject to the constraints of the system resources such as delay tolerant networks and aiming at the buffer congestion problem caused by custody transfer, reference [4] applied the concept of revenue management and dynamic programming to develop an optimal congestion management strategy which show that the optimal solution is completely distributed in nature where only local information such as available storage space of a node is required. At the same time, it can accommodate different motilities as not making any assumption about the types of contacts among nodes. In other hand, far from many other economic modes, this model does not try to reach an equilibrium state based on the rationality of participant nodes or effect noncooperative behavior [4]. On the contrary, the object is to optimize the overall revenue by accepting/forwarding bundle transfer requests under the assumption of nonrational behaviors of nodes [19], which attributes congestion to the optimization problem. And using the dynamic programming and game theory method to let node itself decide whether to accept the custody transfer. Benefit function (R): can be defined according to users' request in the systems (e.g. a function of bundle size and type). For simplicity, it assumes that the bundle sizes of different priorities or types are same in size and thus indistinguishable when filling the buffer if they are accepted [4](to achieve different optimization goals can adjust benefit function).While there is no strict limitation to choose benefit function, the choice of benefit function should guarantee that the value of benefit function and opportunity cost are comparable. Opportunity cost (V): measure the value of the storage capacity, which is the benefit that may be lost by higher benefit request as a result of consumption of the above resource by the lower benefit request. Decision epochs (T): assume that requests for custody arrival at discrete points in time. Distributed Optimal Policy: as tradition revenue management with an unpractical assumption on the availability of global information and even if the global information was available, the potential large dimension of the state space would often get the solution hopeless in practice [4]. Fortunately, the unique setup of delay tolerant networks naturally provides an approach toward distributed solution based on system decomposition [1]. End-to-end path is not often continuous in delay tolerant networks so hop-by-hop forwarding and control is adopted. Once the bundle is transferred to another node, the resource previously occupied will become immediately available. Whether this transaction will be carried out will only depend on the receiving node, which therefore presents a dynamic programming for opportunity cost. Main objective: to minimize a certain cost or maximize a certain reward. Rule: if the benefit (Rt) is greater than its opportunity cost (ΔVt+1(at)) , the message shall be accepted and the decision actually is optimal [4]. Through simulation of congestion control strategy on two situations that link capability changing with time and discontinuous link connection to draw a conclusion that dynamic policy achieves better than static policy in comparison of network throughput and utilization of node buffer. Even if this solution seems plausible, its assumption that requests for custody arrival at discrete points in time is open to discussion. And the reliability of simulation is not high as it assumes each link has infinite bandwidth and limits the certain speed of mobile nodes and fixed nodes, which is not general. At the same time, it is also based on separation of routing selection and management mechanism and no more research for message priority, which should make a further study about joint design. In addition, to specify the distribution of group sizes to model and the number of demand from groups of various sizes make the value function concave. If the value function may not be concave, then it can make the optimal issue intractable [20,21].

5. Conclusion

In this work, we investigate the congestion management of delay tolerant network. First, we introduce the basic idea about DTN and some problems of congestion control in DTN. Then, we explain the limitations of applying TCP congestion control in DTN and some undesirable effects taken by custody transfer mechanism of DTN. Finally, we summarize four kinds of distinctive Congestion management in DTN.

Furthermore, Now there have been wide application prospects and many researches about DTN. However, it is still in rapid development stage, so to further research and application about DTN congestion control technology and the transmission control protocol will be the future hotspot but also key of DTN. In addition, almost all designs of congestion control fail to consider the influence of bundle protocol and various mechanisms also have not been fully tested and practiced, so how to ,based on characteristic of DTN itself, put forward relevant model of testing the performance is very meaningful work in the future.

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