A New Deterministic Linear Network Coding and Its Application on Multicast Network

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***Abstract*- Network coding is a promising technique to improve the resource efficiency and reliability for multicast networks. With network coding, each node of the multicast network is able to generate and transmit encoded data of information. This paper proposes a deterministic linear network coding scheme. This scheme exploits a special type of network topology called uniform network. This network structure is proved that it can achieve higher network coding gain with network coding. The scheme can accommodate dynamic membership and construct a much simple overlay network topology. The system performance is further improved, whether in throughput or in reliability. Our simulation results show that the new scheme can improve throughput, compared to the traditional multicast system, by at most 10% to 15%. Moreover, it achieves good reliability and robustness to dynamic peer arrival or leave.**

Keywords-network coding; deterministic linear coding; uniform network; multicast network

I. INTRODUCTION

In traditional networks messages were usually transmitted by routing directly, that is, by having intermediate nodes store and forward messages. Recently, network coding technique arises as a promising generalization of routing. It refers to a scheme where a node is allowed to generate forwarding messages by encoding its received messages. Thus, network coding allows mixing the information, in contrast to the traditional routing approach where each node simply forwards received messages.

Network coding is a promising technology that is employed to improve system throughput and reliability. Ahlswede has generally proved that if network coding is allowed in network nodes, then multicast capacity can be achieved [1], in other words, network capacity can be fully utilized in multicast. With network coding, every transmitted packet is a linear combination of all or a subset of the packets available at the sender. Observe that encoded packet can be further combined to generate new linear combination. The original information can be reconstructed after receiving enough linearly independent packets. Compared to traditional approaches, network coding makes optimal use of the available network resource without the need for sophisticated scheduling algorithms and provides a high degree of robustness, even if nodes suddenly depart the system[2].

Most existing works on network coding in the literature focusing on linear network coding. In [3], linear network coding was applied to application layer multicast, but this paper did not discuss how to process dynamic joining or leaving of peers, while dynamic membership is a common phenomenon in multicast networks. [4] presented a random linear network coding approach, in which nodes generate edge vectors randomly. In [2] random network coding was applied to content distribution, in which nodes encode their received messages with random coefficients. The advantage of random network coding is that there is no control overhead to construct and maintain a linear coding scheme among nodes. However, the edge vectors of a receiver's incoming edges may not be linearly independent. A receiver may not recover the original messages. To reduce the probability of failing to decode messages, it is required to encode over a very large field. In contrast to the random network coding, Jaggi et al. proposed a polynomial deterministic algorithm in [5] which can construct deterministic liner network coding schemes for multicast networks.

In this paper, we want to provide a simply and reliable deterministic linear network coding scheme–DLNC. We utilize a special type of network with a regular topology called uniform network. When the network size increases, this type of network can achieve higher network coding gain with network coding [6]. The basic idea of our scheme is to construct a multicast network over the source and the receivers that it can be decomposed into multiple uniform networks. Our network coding scheme is deterministic, which means that the validity of the coding scheme is guaranteed. Moreover, we considered the dynamic joining or leaving of peers.

The rest of the paper is organized as follows. In section II, we design a simple deterministic linear network coding scheme for the uniform network. In section Ⅲ, we describe how the multicast network based on deterministic network coding works. In section Ⅳ, we conduct extensive simulations and discuss the simulation results. Finally, section Ⅴ.concludes this paper.

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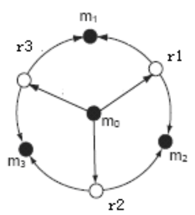
II. DETERMINISTIC LINEAR CODING ALGORITHM

In this section, we describe the uniform network and deterministic linear network coding over it. The uniform network is a multicast network with a regular topology and it can achieve higher network coding gain with network coding. The deterministic linear coding algorithm is efficient.

A. The Uniform Network Model

The uniform network is a 3-layer single source node multicast network. The first layer consists of the source node, where n message consisting of a number of symbols is generated. The second layer consists of n nodes, where each of them receives a single incoming edge from the source node, we call them relay nodes. The third layer consists of $\binom{n}{m}$ sink nodes, where each of them receives incoming edges from a unique set of m out of the n intermediate nodes on the second layer. The capacity of each edge is equal 1, one symbol can be transmitted in each edge, and all links have a capacity of 1.Fig.1 shows a uniform network where n=3, m=2, m_0 is a source node, $r_1\ r_2\ r_3$ are relay nodes, and $m_1\ m_2\ m_3$ are sink nodes, usually denoted as $A\binom{3}{2}$. [6] proved m can be arbitrarily large, we come to the conclusion that network coding gain can be higher.



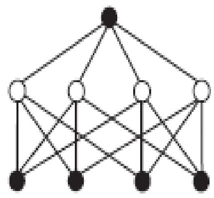


Fig 1 The uniform network for n=3, m=2 Fig 2 The uniform network A_3^4

B. The Deterministic Network Coding Algorithm

As we know, constructing a valid linear network coding scheme is equivalent to assigning each edge an edge vector such that the vectors of the incoming edges of a receiver are linearly independent. In other words, the edge vector of a receiver node must be linearly independent if it wants to decode the original data. In a $A\binom{\text{n}}{\text{m}}$ uniform network, there are a total of $n + mc_n^m$ edges. The first n edges connect the source node to relay nodes with edge vectors $V_1, V_2, \cdots V_n$. For each relay node, there are mc_n^m / n outgoing edges connecting it to mc_n^m / n receiver nodes. Thus each receiver has m incoming edges whose edge vectors are m vectors out of the n vectors $V_1, V_2, \cdots V_n$. For a receiver node to decode the original messages, the m edge vectors must be linearly independent. Our network coding scheme is deterministic, which supposed GF(q) is a given Galois field[7], where |GF(q)|=q, GF={0,1,2,……q-1}, q≥n. We give the rules for our linear network coding scheme construction for $A\binom{n}{m}$ uniform networks as follow:

The deterministic linear network coding scheme for $A\binom{n}{m}$ uniform network is to assign vectors [7] $\left(1, a_1, a_1^2, a_1^3, \ldots\ldots a_1^{m-1}\right), \left(1, a_2, a_2^2, a_2^3, \ldots\ldots a_2^{m-1}\right)$, $\left(1, a_n, a_n^2, a_n^3, \ldots\ldots a_n^{m-1}\right)$, where $a_1, a_2, \ldots. a_n$ are different symbols in GF(q), to n edges connecting to n relay nodes as edge vectors.

Proof:

For any m vectors $\left(1, a_1, a_1^2, a_1^3, \ldots\ldots a_1^{m-1}\right)$, $\left(1, a_2, a_2^2, a_2^3, \ldots\ldots a_2^{m-1}\right)$ and $\left(1, a_m, a_m^2, a_m^3, \ldots\ldots a_m^{m-1}\right)$, where $a_1 \neq a_2 \neq \ldots. \neq a_m$, the determinate of matrix $\begin{pmatrix} 1 & a_1 & a_1^2 & \cdots. & a_1^{m-1} \\ 1 & a_2 & a_2^2 & \cdots & a_2^{m-1} \\ 1 & a_3 & a_3^2 & \cdots & a_3^{m-1} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & a_m & a_m^2 & \cdots & a_m^{m-1} \end{pmatrix}$ is

$$\begin{vmatrix} 1 & a_1 & a_1^2 & \cdots & a_1^{m-1} \\ 1 & a_2 & a_2^2 & \cdots & a_2^{m-1} \\ 1 & a_3 & a_3^2 & \cdots & a_3^{m-1} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & a_m & a_m^2 & \cdots & a_m^{m-1} \end{vmatrix} = \prod_{1 \le i \prec j \le m} (a_j - a_i)$$

Since $a_1 \neq a_2 \neq \ldots. \neq a_m$, the determinate is not equal to 0.We conclude that the m vectors are linearly independent.

III. A MULTICAST NETWORK BASED ON DETERMINISTIC LINEAR NETWORK CODING

In this section, we describe the idea of constructing the multicast network composed of multiple uniform networks, and discuss the processes of peer dynamic arrivals, departures and transmission control with network coding.

A. Construction of Multicast Network

We construct the multicast network based on the idea of uniform network. The server encodes the file into n different messages using the deterministic network coding scheme. The peers are divided into disjoint n groups. Each group of peers is responsible for relaying one of the n encoded messages. In the same group peers are connected by some loose rules. Each peer in a group is connected to at least other m-1 peers which are in m-1 different groups [7]. Thus any m message out of the n message can be used to decode the original file. As any m different messages can be used to decode, we only need to find m-1 peers in different groups, and connect the peer to m-1 random peers in different groups. A peer is a receiver node in a uniform network may be a relay node in another uniform network. Different uniform network may overlap. The linear network coding scheme is deterministic and easy to implement. There is no requirement for peers to collaborate to construct the linear coding scheme on demand. All the peers are mapped on the encoding function. And this mapping does not change with time

Fig.2 shows an example of the overlay network based on uniform network where n=4 and m=3. There are four groups. We can see that each peer has at least three links pointed to itself. All the peers are able to decode the received message.

B. Dynamic Arrivals and Departures

The population of nodes in a multicast network is extremely dynamic with nodes joining and leaving the network. In this section we discuss the scheme that node dynamic arrivals and departure.

a) Node Joining

When nodes arrive at different times, newly arriving nodes have different download objectives with the nodes that have been in the system for sometimes. The server keeps track of the number of peers in each group and maintains a list of existing peers in the group. When a node wants to download data from the server, it sends a joining request to the server. After the request is received, the server assigns the node to a group such that the numbers of peers in different groups are balanced. It is required that each peer is connected to at least m-1 nodes in m-1 different groups respectively. We first connect the peer to m-1 random peers in different groups. Then a local topology adjustment is performed to find the m-1 peers in order to minimize the average latency between the peer and m-1 peers. Then the server sends the list of peers of that group to the joining peer and updates the number of peers in that group.

b) Node Departure

All nodes are allowed to leave the system at any time. When a node leaves the system, it will send LEAVE message to its neighbors (in the same group or not). The leaving of the node may impair the connectivity between peers in the same group. When receives a LEAVE request, the server rebuild the connectivity between peers in the same group. After receiving the LEAVE message from the leaving peer, the peer's neighbor (not in the same group) will ask one of its neighbors in the same group to replace the leaving one. In addition, the server will update the number of peers in the group.

The leaving peer may leave the system without any notification due to link crash or computer crash. Peers send Hello messages to its neighbors periodically and maintain a Hello timer for each neighbor. When the timer is timeout, the neighbors detect the abruptly departure of peers. One of the neighbors is chosen to send a LEAVE message to the server so that the server can update the number of the peers in the group.

C. Transmission Control

When the server sent out the data, the data is divided into multiple blocks. The first m blocks are encoded and then the second m blocks, and so on. In the case that there are not enough blocks to encode, zero string is padded. Each m blocks are encoded into n different messages using the DLNC given in Section II, any m message can be used to decode the original m blocks. In order to improve transmission efficiency, the peer forward all the messages they receive based on the follow rules [7]:

a) If the message comes from the server, the peer forwards it to all its neighbors.

b) If the message comes from one of its neighbors in the same group, the peer forwards it to other neighbors that in the same group except for the sender.

c) If the message comes from one of its neighbors in different group, the peer does nothing

A peer forwards message, which means that the messages are forwarded under the three rules. A peer decodes the messages right after it receives m different messages.

IV. PERFORMANCE EVALUATIONS

We have conducted extensive simulations to evaluate the performance of the proposed algorithms when the deterministic linear coding is employed. In this section, we present our simulation results and compare different approach. We use NS-2 as the network simulator. NS-2 is a modular and extensible network simulator framework that we can add our new protocol by defining the behavior of the node and communication rules between the nodes. In our experiment, we add the DLNC in the application layer. We used the NS socket API for data transmission and the time handling mechanism for the control of connection between peers and selection of messages. (Shown in Fig.3) The network topologies are generated by GT-ITM software [8] which is a degree-based Internet structural topology generator. Both the source nodes and the receiver nodes are selected randomly. Any node can not be a source node and a receiver node at the same time. Each data packet carries an additional 16 byte header to hold the encoding vector. Peers have uniform link capacities. The simulation is divided into two steps, including overlay construction period and data transmission period: the server sends the data to the multicast network peers based on the DLNC.

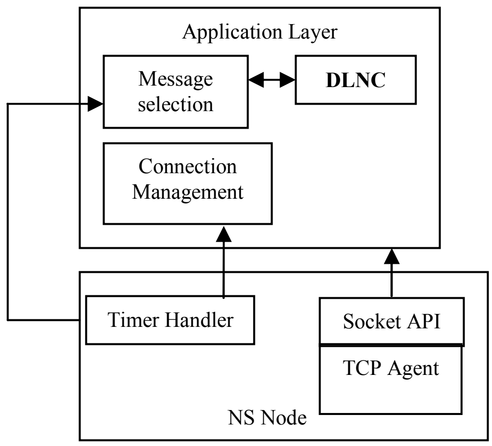


Fig.3 simulation code structure

A. *Throughput*

Throughput is defined as the service provided in one time unit. It is represented by the number of delivered messages in one time unite. We plot the throughput curves of deterministic linear network coding algorithm and traditional multicast in Fig4. We simulate DLNC with different m values as shown in the figure. It can be seen that the throughput of DLNC is 10%-15% higher than that of traditional multicast network. From the figure we can see that the throughput of DLNC is higher for m=4 than that for m=3. This can be explained by the fact that when m=4, each peer is connected to more peers. Thus the download capacity of peers can be better utilized.

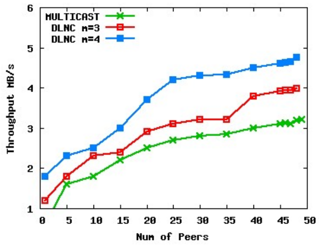


Fig. 4 The performance comparison of throughput

B. *Bandwidth Consumption*

We defined the network bandwidth as bandwidth consumption that used to deliver the message. A data message going through one link contributes 1 unit to the bandwidth consumption. Fig.5 shows the bandwidth consumption evaluation. As the figure shows, the bandwidth consumption increases with the increase of the network size.

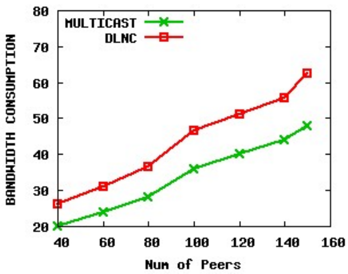


Fig. 5 The performance comparison of bandwidth

C. *Dynamic arrivals and departures*

In this section, peers are allowed to join and leave the system during the data transmission in a smooth way. Peers may still stay in the system even after they finish receiving the message, while they may also leave the system before they finish receiving the message. Fig.6 shows the throughput comparison between DLNC and traditional multicast. We can see that the throughput both schemes decrease compared to the Fig.4. Compared to the curves of Fig.4, the throughput of traditional multicast decreases by about 26%, while DLNC decreases by about 17%, which indicates that DLNC is more robust under dynamic peers join or leave.

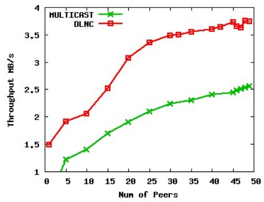


Fig.6 Thoughput of the dynamic peer arrive or leave

V. CONCLUSION

Network coding is a promising technique to improve the resource efficiency for multicast networks. In this paper, we have investigated the deterministic linear network coding for multicast network. The contribution of this paper is two folds. First, we propose a deterministic linear network coding arithmetic that can be used to decode the original file. This scheme exploits a special type of network topology called uniform network. The scheme can accommodate dynamic membership and construct a much simple overlay network topology. Second, we studied the performance of network coding from the deterministic coding. Compare to other network coding scheme, the advantage of DLNC can be summarized as follows. (a) Efficiency. The linear network coding scheme is deterministic and easy to implement. All the peers are mapped on the encoding function. Compared to random network coding, the receiver can always recover the original message after receiving m different messages. (b) Reliability. Our simulation results show DLNC has higher throughput under dynamic peer join or leave. Our future work includes how to optimize the system under unstable network status.

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