

Practical Incremental Network Coding for Multimedia Content Delivery

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Abstract—Random linear network coding is a promising solution to improve network capacity by allowing intermediate node that combines incoming packets into network coded packets. Nevertheless, there are two main drawbacks: rank deficiency and processing delay. The first drawback can be solved by performing systematic network coding, in which sender transmits all uncoded packets in the first phase and coded packets in the second phase. The processing delay still remains in practical communication system and multimedia content delivery. In this paper, we propose a practical incremental network coding for application of multimedia content delivery over multi-hop network. We implement the proposed scheme using Raspberry Pi as transmission node and evaluate performance in terms of throughput and the attainable video quality (i.e., peak signal-to-noise ratio). The results demonstrate that our proposed incremental network coding outperforms conventional network coding schemes.

Keywords—Random Linear Network Coding, Systematic Network Coding, Device-to-device, Internet of Things

I. INTRODUCTION

Random linear network coding (RLNC) was firstly proposed in [1]. Authors proved that RLNC can achieve maximal capacity by allowing intermediate node that linearly and randomly combines incoming packets [2]. The most benefit of RLNC that facilitates a receiver to easily decode the transmitted packets after receiving a sufficient number of linearly independent packets. RLNC has been applied in application of video transmission [3], [4]. However, there are two main drawbacks needed to be taken under consideration: rank deficiency and processing delay. The rank deficiency is that the receiver decodes nothing if the coefficient matrix is not achieved full rank. To tackle this drawback, SNC was proposed [5]. SNC can achieve the same performance as the receiver receives a sufficient number of transmitted packets. On the other hand, receiver also can decode a partial of transmitted packets in case of rank deficiency. Nevertheless, the processing delay still remains as practical issue in video streaming.

Cisco Visual Networking Index Forecast predicts an increase in mobile data traffic to 49 exabytes per month by 2021 [6]. The video traffic would be 82 percent of all consumer traffic by 2020 [7]. To meet the fast increment of mobile data traffic growth, 5G ultra-dense cellular networks have been investigated by jointly composing small cells, macrocells and device-to-device (D2D) [8]. In this paper, we propose a practical incremental network coding (INC) for multimedia content delivery over multi-hop network, in which a source streams a video over M intermediate nodes to destination. This practical multi-hop communication can be applied in D2D



Fig. 1. Multi-hop network with $M + 1$ hops.

communication, in which a device delivers the multimedia content to another device through multiple hops. Our work also can be considered for streaming video from a small cell to another cell through multiple cells or multiple relay/base stations. Particularly, our contributions can be listed as follows:

- INC not only solves the drawback of rank deficiency but also reduces the processing delay. Hence, INC can increase the attainable video quality which requires strict time constraint.
- INC can be easily implemented in practical system. We do testbed implementation using Raspberry Pi as transmission node for performance evaluation.
- Results demonstrate that our practical INC outperforms the conventional network codes in terms of throughput and attainable video quality.

The remainder of this paper is organized as follows. We describe system model along with conventional network codes in Section II. In Section III, we present our proposed INC. Furthermore, we evaluate the system performance with testbed implementation in Section IV. Finally, we conclude this paper in Section V.

II. SYSTEM MODEL AND PRELIMINARY

A. System Model

Figure 1 depicts a multi-hop network with $M + 1$ hops, in which a source node streams video content to destination through M intermediate nodes. We provide the matricial model with mathematical entities to present communication entities. We use a bold lowercase letter to represent a vector and a bold uppercase letter for a matrix.

In our testbed implementation, we simply extract a video content into multiple frames for streaming. Let img be a frame from the video streamed from source node, each frame is partitioned into K packets. The number of packets can be different frame by frame in the video. The k^{th} packet is represented by a vector with S symbols (i.e., each symbol of 1 byte):

$$\mathbf{x}_k = [x_{k,1} \ x_{k,2} \ \cdots \ x_{k,S}]. \quad (1)$$

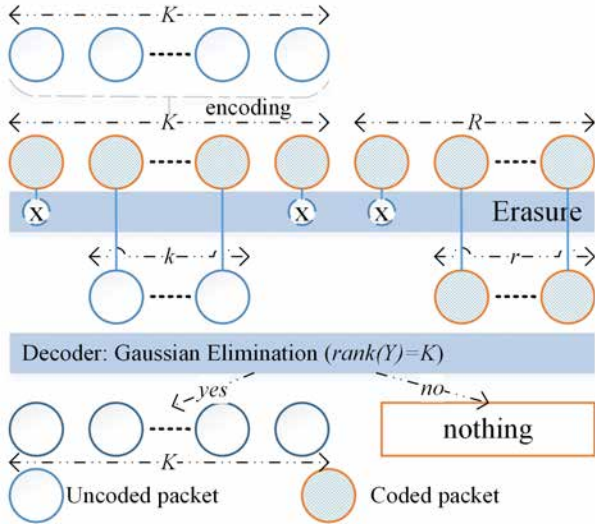


Fig. 2. Encoding and decoding processes of RLNC.

Hence, K packets of the u^{th} UE can be presented as a K -by- S matrix:

$$\mathbf{X}_u = [\mathbf{x}_1 \ \mathbf{x}_2 \ \cdots \ \mathbf{x}_K]^T, \quad (2)$$

where $(\cdot)^T$ denotes the transpose operation.

B. Random Linear Network Coding

RLNC was proved to increase the efficiency (i.e., throughput and bandwidth) compared to legacy transmission methods [12]. RLNC allows an intermediate node the capability of encoding incoming packets. Figure 2 presents the encoding and decoding processes of RLNC. A network-coded packet is a linear combination of incoming packets. The form of a coded packet [2] is presented as follows:

$$\mathbf{b}_{RLNC,n} = \mathbf{f}_n \mathbf{X} = \sum_{k=1}^K f_{n,k} \mathbf{x}_k, \quad (3)$$

where $f_{n,k}$ is a coefficient number generated randomly over a Galois field $\mathbb{F}(q)$ of size q . The sender always sends the number of SNC packets $N \geq K$ to overcome erasures on the channel; hence, $R = N - K$ is the number of redundant packets. Let $\mathbf{H}$ be a $N \times N$ diagonal transfer matrix from the sender to the receiver, in which the diagonal component is one with the probability of $1 - \epsilon$ and zeros with the probability of ϵ (i.e., erasure probability).

$$\mathbf{Y}_{RLNC} = \mathbf{H} \mathbf{F} \mathbf{X}, \quad (4)$$

where $\mathbf{F}$ is a $N \times K$ coefficient matrix over the Galois field $\mathbb{F}_q^{N \times K}$, $\mathbf{X}$ is a matrix representing the original packets over $\mathbb{F}_q^{K \times S}$, and $\mathbf{Y}_{RLNC}$ is a matrix representing the received packets over $\mathbb{F}_q^{N \times S}$. A Gaussian elimination algorithm is used to decode the original packets after receiving a sufficient number of coded packets. The decoding process is successful if and only if the coefficient matrix achieves full rank (i.e., $\text{rank}(\mathbf{Y}_{RLNC}) = K$). The receiver is able to successfully decode the transmitted data without asking for retransmission. Note that further information regarding NC can be found in [1], [2].

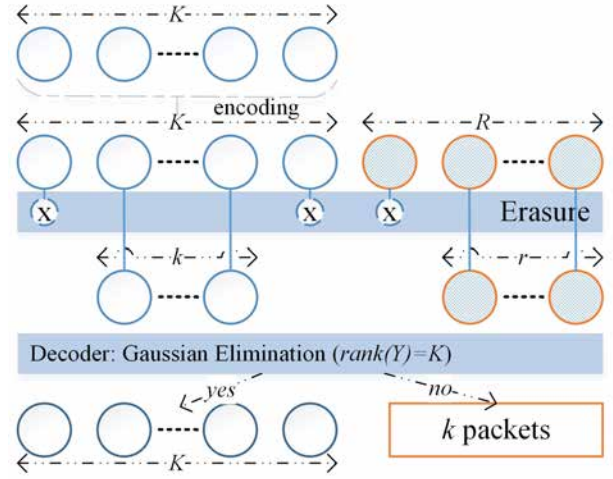


Fig. 3. Encoding and decoding processes of SNC.

C. Systematic Network Coding

The transmission of SNC consists of two stages: a sender sends original packets in the first stage; upon sending out all original packets, the sender continues to generate RLNC packets in the second stage for transmission shown in Fig. 3. Obviously, the receiver can still decode some original packets even though the receiver cannot receive a sufficient number of linearly independent packets. On the other hand, SNC can achieve the same performance as the receiver receives a sufficient number of transmitted packets. A n -th SNC packet is defined as follows:

$$\mathbf{b}_{SNC,n} = \mathbf{f}_n \mathbf{X} = \sum_{k=1}^K f_{n,k} \mathbf{x}_k, \quad (5)$$

where $f_{n,k} = 1$ with $n = k$; otherwise, $f_{n,k} = 0$ in the case of $n \leq K$. For the case of $n > K$, $f_{n,k}$ is a coefficient number generated randomly over a Galois field $\mathbb{F}(q)$ of size q .

III. PROPOSED INCREMENTAL NETWORK CODING

In this section, we present the proposed INC. One of the most important feature of network coding is the ability of recoding which is that the encoded packet is re-encoded again without encoding in advance [9]. Let $\mathbf{b}_n$ be the n^{th} encoded packet and $\mathbf{B}$ be a vector of N encoded packets, a re-encoded packet $\tilde{\mathbf{b}}_n$ is defined as follows:

$$\tilde{\mathbf{b}}_n = \tilde{\mathbf{f}}_n \mathbf{B} = \sum_{i=1}^N \tilde{f}_{n,i} \mathbf{b}_i, \quad (6)$$

Instead of decoding the encoded packets into original data, the receiver simply uses received packets and makes the new encoded packet by linear combination of received packets again. The advantage of recoding is to reduce the delay by decoding and encoding (i.e., processing time). Hence, the recoding can provide better performance in throughput. Figure. 4 presents the difference between conventional NC, recoding, and our proposed INC. As seen, the conventional encoding and decoding at intermediate node shown in Fig. 4a is a simple method to re-encode the received packets, but the delay increases as the generation size increases. The conventional recoding shown in Fig. 4b can provide better performance in

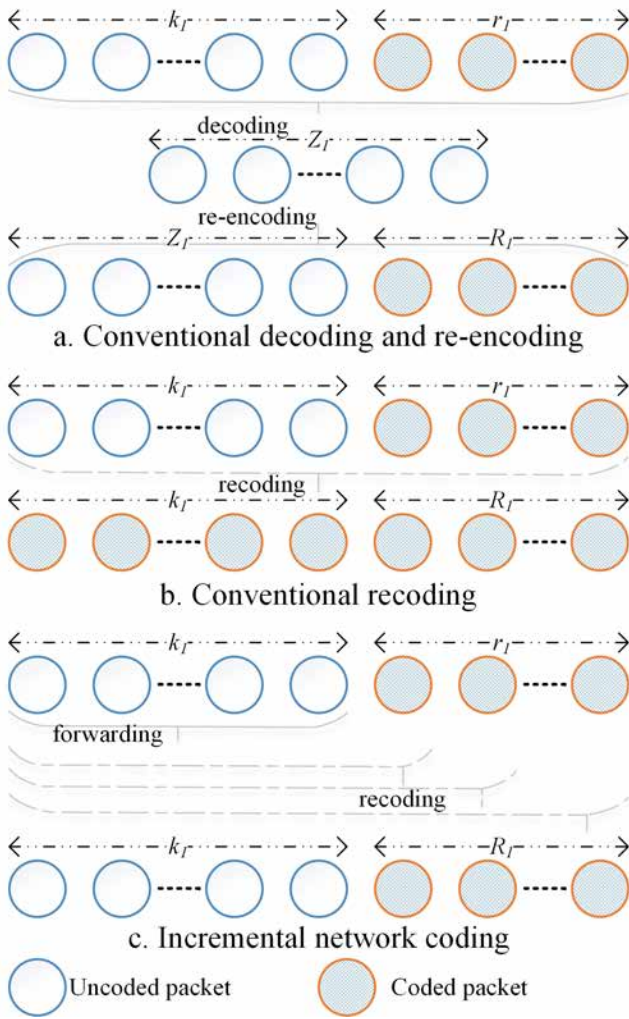


Fig. 4. The difference between conventional NC, recoding and INC.

terms of processing time, but it is not suitable for multimedia content since the receiver only can decode data after receiving enough re-encoded packets. To catch the characteristic of time constraint in multimedia content delivery, we need to design the transmission scheme in which receiver can decode the data immediately after receiving the data. And our proposed INC shown in Fig. 4c can satisfy the above requirement. Receiver distinguishes the uncoded and coded packets, if the received packet is uncoded packet, receiver simply stores in the cache and forwards to the next hop, otherwise receiver uses the coded packets with all uncoded packets in the cache for re-encoding.

IV. TESTBED IMPLEMENTATION

For performance evaluation, we implement the proposed INC using Raspberry Pi [10] as transmission node and the network coding Kodo library [11]. Raspberry Pi is a low code credit-card sized computer that can be easily for network programming. Kodo is a C++ library for implementing network codes. This library can be used for building reliable communication protocols and the practical implementation of various network codes.



Fig. 5. Diagram of testbed implementation.

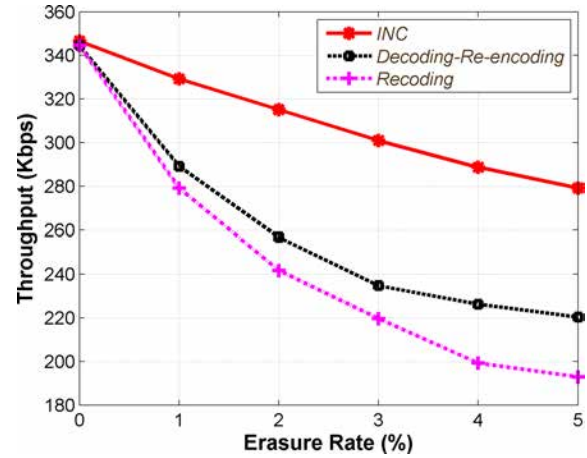


Fig. 6. Throughput performance versus erasure rate of conventional NC, recoding and INC.

Figure 5 presents the testbed implementation, in which consists three nodes: source, relay, and destination. Source transmits a video to destination through an intermediate node. We use OpenCV to extract the video frame, and perform network codes frame by frame.

The advantage of INC not only reduce the processing time but also provide the capability of decoding data immediately after receiving packets. We evaluate the performance in terms of throughput and PSNR shown in Figure 6 and Figure 7, respectively. The results demonstrate that INC outperforms the conventional recoding and decoding-re-encoding methods. The

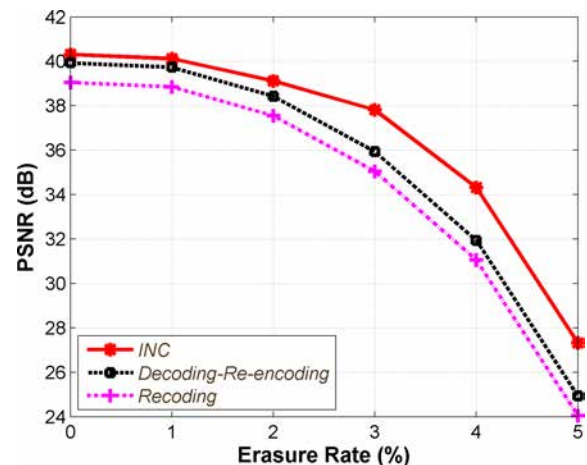


Fig. 7. PSNR performance versus erasure rate of conventional NC, recoding and INC.

performance is better as erasure rate increases. The recoding method can achieve better performance of processing time but it uses all received packets for recoding, hence, the receiver needs to wait for all received packet to decode the data. This causes the worse performance compared to others.

V. CONCLUSIONS

In this study, we proposed a practical INC for multimedia content delivery over multi-hop network. Since INC could reduce the processing delay along with rank deficiency. Furthermore, we implemented into real network using Raspberry Pi as transmission node. We proved that our proposed INC outperforms the conventional network codes in terms of throughput and attainable video quality (i.e., PSNR).

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