Performance Analysis of Network Coding with Raptor Codes for IPTV

Kwangseok Noh, Sungroh Yoon, Jun Heo, *Member*, IEEE

Abstract — *Multimedia services including IPTV require huge multimedia data transmission on the internet. In order to improve a throughput of data transmission, network coding has been proposed to use network bandwidth (=throughput) efficiently with error free channel assumption. However, when the channel is not error free, network coding may not increase the throughput. In this case, effective erasure recovery codes such as Raptor codes have to be used with the network coding. We present the advantage of Raptor codes combined with network coding for high throughput multimedia data transmission services like IPTV. For the applications allowing retransmission, Hybrid-ARQ combined with network coding is also considered.*

Index Terms — Network coding, Raptor codes, HARQ, IPTV.

I. INTRODUCTION

In recent years multimedia services are booming based on the internet. Network bandwidth becomes a bottleneck for IP-based multimedia services like IPTV. Network Coding (NC) [1] increases the achievable throughput for broadcast or multicast in a network by performing a simple operation like modulo 2 addition at the intermediate nodes. Recently, Fountain codes [2][3] have demonstrated their ability to achieve high capacity over erasure channels. Raptor codes [2] are computationally efficient fountain codes, which consist of LT codes [3] and LDPC codes. Due to their low decoding complexity and rateless property, Raptor codes has been adopted by several IPTV standards, including DVB-IPTV (Digital Video Broadcasting - IPTV) [4] as well as several mobile multimedia standards including 3GPP MBMS [5] and DVB-H [6].

Auto-Repeat reQuest (ARQ) has been used for applications allowing retransmission to obtain higher reliability. Hybrid ARQ (HARQ) is a combination of a FEC (Forward Error Correction) with ARQ to reduce the number of required retransmission. Incremental Redundancy (IR) HARQ [7][8] is a kind of HARQ, which transmits different parities when previous transmission fails. It has been known that rateless property of Raptor codes is good for the IR HARQ because of its flexibility on parity generation.

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Although NC can improve network throughput, most of previous researches on NC assumes error free channels. However when the channel is an erasure channel and the erasure rate is relatively high, NC can not increase the throughput. In this paper, we compare the throughput of NC with or without Raptor codes and show that NC with Raptor codes increases channel throughput in a realistic erasure channel model. We also present that HARQ scheme based on Raptor codes on a network which requires higher reliability.

The remainder of this paper is organized as follows. We first show a brief background in Section II. We describe the problem formulation in Section III. The throughputs using the Raptor codes are derived in Section IV. In Section V, we combine NC with HARQ technique. Simulation results and discussions are provided in Section VI. Conclusions are drawn in Section VII.

II. BACKGROUND

A. Raptor codes

Raptor codes introduced by Shokrollahi et al. in [2] have been standardized for IPTV and 3GPP multimedia services. Raptor codes are a group of Fountain codes which are rateless codes. Generally, the total amount of successfully received data in order to recover the source data is only slightly greater than the size of the source data. The failure probability of Raptor codes with K (>200) number of source symbols and m number of received symbols can be modeled by the following equation [9].

$$Pf(m,K)=\begin{cases}1 & if\ m<K\\ 0.85\times 0.567^{m-K} & if\ m\geq K\end{cases} \tag{1}$$

B. Network coding (NC)

Ahlswede et al. have proposed in [1] a new concept of NC which deals with transmission of information from a set of source nodes to a set of destination nodes in a network. NC is used for not only combining but also routing the incoming data. The routing scheme can be easily operated by the coefficient of the linear network coding.

1. single-hop transmissions (=two-way relay)

Fig. 1 depicts an abstract model of the two-way relay channel for communication between user S_1 and S_2 over a intermediate node (=relay) using NC. In the two-way relay channel, two nodes exchange their information through an intermediate node. Data of source node S_1 and S_2 are delivered

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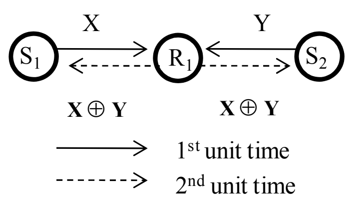

Fig. 1. NC in a single-hop transmissions example.

to intermediate node R_1 in first unit time. In Fig. 1 node R_1 performs NC with the received data from node S_1 and S_2 and broadcasts the $Z=X\oplus Y$ to both nodes S_1, S_2 in second unit time. The operation $\oplus$ denotes a mod-2 addition. In this case, the improvement of the throughput with NC is proximately 50%.

2. Multi-hop transmissions

Fig. 2 shows the butterfly structure that is often used for multi-hop schemes. The intermediate node R_1 receives packets X and Y from source node S_1 and S_2 respectively and transmits modulo 2 value $X\oplus Y$ to another intermediate node R_2 which transmits the received packets to destinations A and B respectively. This scheme is a well known example which shows the throughput with NC becomes twice as much as that without NC.

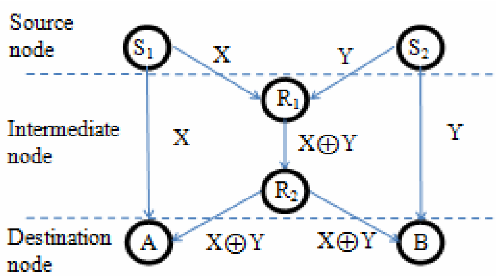

Fig. 2. An example of NC in multi-hop transmissions

C. IPTV

Fig. 3 shows a simplified IPTV architecture. In the case that several service providers and users exist in a network, Source nodes, intermediate nodes and destination nodes in Fig. 2 correspond to service providers, routers in broadband IP network, and users at home network in Fig. 3, respectively.

For IPTV the required QoS/QoE is very high because the multimedia data is transmitted through IP network and there is high correlation between the frames in H.264 which is the standard of video compression in IPTV.

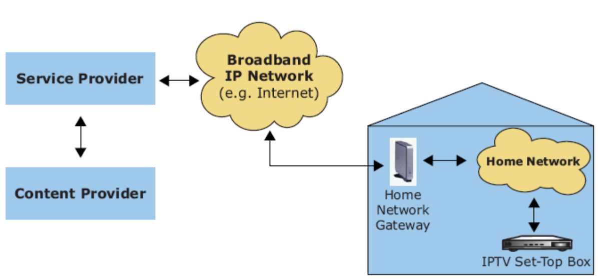

Fig. 3. Simplified IPTV Architecture [10]

There are some standpoints for measuring the QoS/QoE. Especially in IPTV, the network performance is measured based on the packet loss rate. In general, the image quality is highly influenced by the some loss of video stream when UDP is applied for the packet loss. A proper FEC scheme can be used to reduce the packet loss and enhance the QoS.

III. Problem Description

When all channels in a network are noiseless, NC can always improve the throughput of a network. However, if transmission errors occur in any channel in a network, some of transmitted IP packets may be erased either during transmission or during decoding due to CRC fail. For example in Fig. 2, if transmission errors occur in channel S_1-A (the path between source node S_1 and destination node A) and the packet $X\oplus Y$ is correctly received through the channel R_1-A (the path form intermediate node R_1 to destination node A via intermediate node R_2), none of the information can be extracted. On the other hand, if a NC is not used, the packet X can be received in first unit time and packet Y can be received in second unit time at destination node A through the channel R_1-A. It can be noted that NC decreases the throughput due to the errors in the network. Therefore NC should be used with a proper error correction code for a multimedia data streaming service. Raptor codes are good to be used with NC because it requires only small amount of overhead to recover the source data and low decoding complexity. To derive analytic expression of throughput, we need to define a set of assumptions and the terms as follows.

A. Delay

In Fig. 2, there are two values of the end-to-end delay between the nodes S_1 and A. One is the delay over channel S_1-A and the other is the delay over channel R_1-A. Two values of end-to-end delay are different. The delay of channel R_1-A is higher than that of channel S_1-A as end-to-end delay is in proportion to the number of hops over the path. When the NC and Raptor codes are applied to node R_1, the difference of delay increases due to the addition of processing delay. However, in this paper, we ignore any delay since the major point of view is with or without NC under the same condition regardless of using Raptor codes.

B. Other assumptions and terms

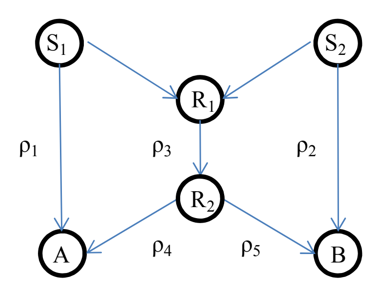

Fig. 4. A butterfly network and corresponding erasure rate ρ_i, i=1,…,5.

For analytic expression of throughput, we assume the following conditions.

- The channel S_1-A, S_1-R_1, R_2-A and S_2-B, S_2-R_1, R_2-B are symmetric structure and it is assumed that each erasure rate is same ($\rho_1=\rho_2$, $\rho_4=\rho_5$).
- Error-free between each source nodes S_1, S_2 and intermediate node R_1.
- T_i : i-th unit time. Source nodes broadcast a packet per a unit time.
- N: Packet size transmitted from node S_1(S_2).
- Throughput L is defined as

(Number of packets that are successfully transmitted)/(Total number of packets that are transmitted from the source)

- ε_1, ε_2 : overhead that is added at node S_1, S_2.
- ε_3 : Overhead that is added at node R_1.
- ρ_i : Erasure rate of each channel.
- P_i : Packet failure probability of a channel with ρ_i. The packet loss follows the Bernoulli distribution with parameter ρ_i. For example,

$$P_1 = 1-(1-\rho_1)^N$$

- Pf_i : Packet failure probability with Raptor codes of a channel with ρ_i
- Prime symbol(') is used to denote the second unit time or unit time of the retransmission.

IV. Network Coding with Raptor Codes

A. Without Raptor codes

In this subsection we consider two cases with or without NC. First, R_1 receives the packet from S_1 and S_2 and then the packet received from S_1 is broadcasted in unit time T_1 and the packet received from S_2 is broadcast in unit time T_2. Node A receives the packet X which is from intermediate node and the direct path from S_1 as well. In T_2, the packet from intermediate node is the packet Y. The throughput of A without NC can be computed as:

$$L = \frac{(1-P_1 \times P_2 \times P_1') \times N + (1-P_2') \times N}{(2 \times N) \times 2} \tag{2}$$

where

$$P_2 = 1-\prod_{i\in\{3,4\}}(1-\rho_i)\ ,\ P_2' = 1-\prod_{i\in\{3,4\}}(1-\rho_i') \tag{3}$$

In case that the NC is applied to intermediate R_1, the transmission is completed in first unit time because R_1 does mod-2 operation for the packet from S_1, S_2 and broadcasts. The packet Y recovers as $X\oplus(X\oplus Y)$ at A. Thus, if the packet loss is occurred for packet X or packet $X\oplus Y$ due to packet erasure, the whole packet cannot be recovered.

The throughput of A with NC can be computed as:

$$L = \frac{(1-P_1) \times N + (1-P_1) \times (1-P_2) \times N}{(2 \times N) \times 1} \tag{4}$$

where

$$P_2 = 1-\prod_{i\in\{3,4\}}(1-\rho_i) \tag{5}$$

B. With Raptor codes at nodes S_1, S_2, and R_1

As it was mentioned in section III, if the NC is applied to erasure channel, there is a case that the packet Y cannot be taken because the error is occurred in packet X even though the packet $X\oplus Y$ is received without error. Thus the Raptor codes are applied at source node to reduce the failure probability of packet X. The Raptor codes are also applied at R_1 due to reducing the failure probability of packet $X\oplus Y$.

The throughput of A without NC can be computed as:

$$L = \frac{(1-Pf_1 \times Pf_2 \times Pf_1') \times N + (1-Pf_2') \times N}{\{(1+\varepsilon_1)N + (1+\varepsilon_2)N\} \times 2} \tag{6}$$

Pf_2 represents the failure probability of Raptor codes due to channel loss when packet is transmitted to A through the intermediate node and it follows

$$Pf_1 = 0.85 \times 0.567^{N(1+\varepsilon_1)(1-\rho_1)-N} \tag{7}$$

$$Pf_2 = 0.85 \times 0.567^{N(1+\varepsilon_3)\prod_{i\in\{3,4\}}(1-\rho_i)-N} \tag{8}$$

Similarly, in unit time T_2, P'_1 and Pf'_2 are as follows

$$Pf_1' = 0.85 \times 0.567^{N(1+\varepsilon_1)(1-\rho_1')-N} \tag{9}$$

$$Pf_2' = 0.85 \times 0.567^{N(1+\varepsilon_3)\prod_{i\in\{3,4\}}(1-\rho_i')-N} \tag{10}$$

To apply NC in R_1, Raptor decoding, network encoding, Raptor decoding are processed in order, thus Raptor coding performed in A before network decoding. The throughput of A with NC can be computed as:

$$L = \frac{(1-Pf_1) \times N + (1-Pf_1)(1-Pf_2) \times N}{\{(1+\varepsilon_1)N + (1+\varepsilon_2)N\} \times 1} \equiv \frac{N_d}{N_n} \tag{11}$$

Pf_1 and Pf_2 are equal to (7), (8) respectively.

C. Network coding at node R1 in single-hop transmission

The single-hop transmission is the same as the butterfly structure. In Fig. 4, A is the same as S_1 and B is the same as S_2. In case that ρ_1, ρ_2 and ρ_3 are '0', it is single-hop transmission. Also, the number of needed unit time is three in without NC, and two in the case of applying network code. Thus, the throughput of applying the NC in single-hop transmission can be easily achieved using IV-A, B

V. JOINT NETWORK CODING AND HARQ

In this section, we derive the throughput of NC combined with IR (Incremental Redundancy) HARQ technique using Raptor codes for error correction. Raptor codes are appropriate for IR-HARQ technique which transmits additional parities at retransmission since Raptor codes are rateless and flexible for parity generation. Moreover low complexity decoding algorithm with additionally transmitted parities has been developed in [11]. Followings are the conditions for HARQ scheme considered in this paper.

- The number of retransmission is one
- Positive/Negative acknowledgement (ACK/NAK) are never lost
- Delay and bandwidth used by ACK/NAK are ignored.
- Stop-and-wait ARQ is applied for HARQ scheme.
- Each packet is sent in a unit time and the delay of ACK/NAK is neglected. Thus Round-Trip Time (RTT) can be unit time.

The retransmission at butterfly structure network in Fig. 4 can be determined by CRC check after Raptor decoding of a packet which is transmitted via channel S_1-A and R_1-A. At retransmission, the decoding process of the received packet at node A is shown in Fig. 5.

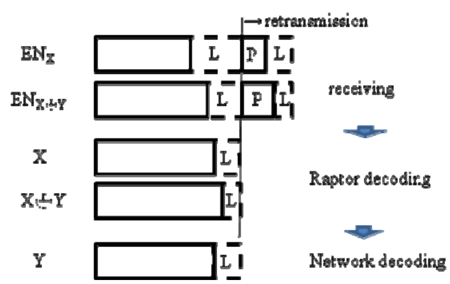

Fig. 5. Retransmission for packet X ⊕ Y

EN_i represents the encoded packet with Raptor codes, L denotes the lost symbols and P means the added parity symbols. The total throughput increases since the failure probability of the packet X and X ⊕ Y decreases by HARQ scheme. The throughput of NC with HARQ can be expressed using (11) as

$$L = \frac{N_d \times S_{RT} + \{(1-Pf_3)N + (1-Pf_3)(1-Pf_4)N\} \times (1-S_{RT})}{N_n + (N_R + N_R)(1-S_{RT})} \quad (16)$$

where N_R is the retransmitted packet size, S_{RT} represents the success probability of the first transmission. Pf_3 and Pf_4 are the failure probability of the retransmitted packet via S_1-A, R_1-A. Pf_3 and Pf_4 can be evaluated as

$$Pf_3 = 0.85 \times 0.567^{N(1+\varepsilon_1)(1-\rho_1)+N_R(1-\rho_1')-N} \quad (19)$$

$$Pf_4 = 0.85 \times 0.567^{N(1+\varepsilon_3)\prod_{i\in\{3,4\}}(1-\rho_i)+N_R\prod_{i\in\{3,4\}}(1-\rho_i')-N} \quad (20)$$

VI. NUMERICAL RESULTS AND DISCUSSION

For numerical results, we consider systematic Raptor codes (K=1536) which is a standard for 3GPP MBMS application layer FEC [12]. The performance is evaluated on the burst mode transmission scenario. The simulation parameters are shown in Table I. In the considered transmission model, the burst size is 2Mbytes and the packet size is 1024bytes. Each burst has eight blocks and each block consists of 255 packets. The retransmission packet size is 512 bytes

TABLE I
SIMULATION CONDITIONS

TRANSMISSION UNIT	SIZE
Raptor code symbol	1024 bytes (=1 Packet)
Block	255 packets
Burst	2Mbytes
Retransmission Packet	512 bytes

We assume that the transmission packet size of X and Y at source nodes S_1 and S_2 are the same, we also assume that the channel S_1-A and S_2-B, the channel R_2-A and R_2-B have the same erasure rate respectively. Therefore we only consider throughput at A.

When channel R_1-A has very low erasure rate of 0.05%, the throughputs of with or without NC are shown for various erasure rate ρ_1 in Fig.6. We observe from the results that NC without error correcting code can make the throughput worse than that without NC when the erasure rate is greater than 0.07%. In practice, the erasure rate may be greater than 0.07% in most cases, therefore it can be noted that NC should be combined with error correcting code in practical systems.

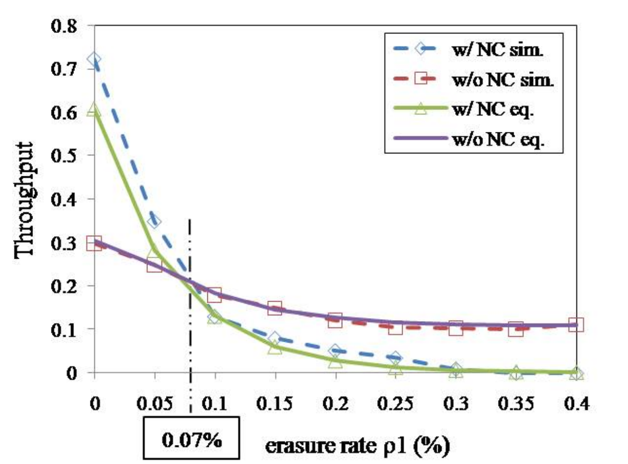

Fig. 6. Comparison of throughputs by equation and simulation without FEC

Fig. 7 shows the throughput with Raptor code. It is assumed that each erasure rate ρ_3 and ρ_4 of R_1-R_2 and R_2-A is '0.1' respectively. As the result for applying FEC, in case that the erasure rate ρ_1 is smaller than 0.245, the throughput with NC is higher than that of without NC. The threshold 0.245 erasure rate is due to the 0.25 code rate of Raptor code. Higher rate Raptor code will result in higher threshold of erasure rate.

The throughput of NC using HARQ is presented in Fig.8. As expected, it shows high throughput with a staircase shape at the retransmission point.

VII. CONCLUSIONS

In this paper we presented the needs for FEC at a lossy network with network coding. The analytic throughputs were derived with and without network coding as a function of channel erasure rates. We showed that network coding can not increase the network throughput even at a very low channel erasure rate without FEC. We also showed that Raptor code is a good FEC scheme which can be used with network coding because of its good properties. IR-HARQ scheme was also considered with network coding for a network requiring higher reliability.

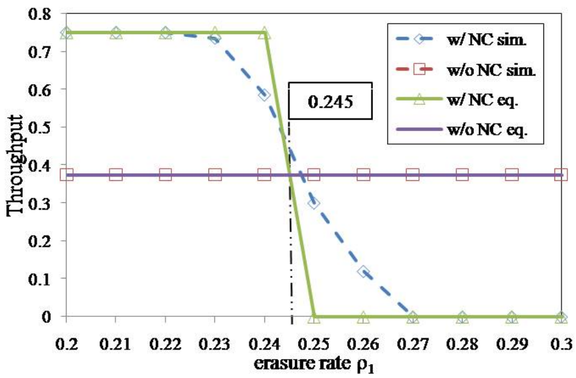

Fig. 7. Comparison of throughputs by equation and simulation with FEC

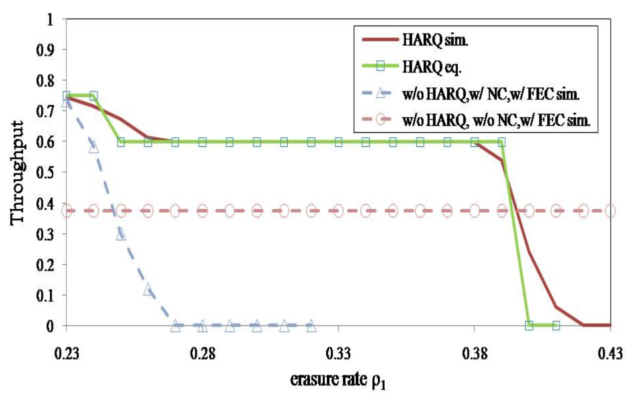

Fig. 8. Comparison of throughputs by equation and simulation, with or without HARQ

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