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비대칭 채널에서의 네트워크 코딩 기반 양방향 릴레이 전송 기법

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Network-Coded Bi-Directional Relaying Over an Asymmetric Channel

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요약

본 논문에서는 양방향 링크의 채널 상태와 트래픽 부하가 비대칭적인 채널에서 네트워크 코딩을 적용하는 기법과 그 방식에 따른 성능에 대해서 살펴본다. 이러한 양방향 링크의 비대칭성을 반영하기 위해 패딩후 네트워크 코딩(Network Coding after Padding: NaP) 방식과 분할 후 네트워크 코딩(Network Coding after Fragmentation: NaF) 방식을 고려한다. NaP 방식은 지금까지 트래픽 부하의 비대칭성만을 반영하기 위해 고려된 바 있으며, 본 논문에서는 실제로 채널의 상태를 동시에 고려할 경우에는 NaP 방식이 갖는 기존의 이득이 오히려 열화되는 것을 보인다. 또한, NaF 방식이 일반적인 양방향 링크 기법뿐만 아니라 NaP 방식보다 항상 성능이 좋다는 것을 보인다.

Key Words : Cooperative Diversity, Mutually Cooperative Relay, Coordinate-Interleaved Orthogonal Design (CIOD)

ABSTRACT

In this paper, we consider network-coded bi-directional relaying (NCBR) schemes over an asymmetric channel, in which bi-directional links have the different channel quality, as well as the asymmetric traffic load. In order to deal with asymmetric nature, two different types of NCBR schemes are considered: network coding after padding (NaP) and network coding after fragmentation (NaF). Even if NaP has been known as only a useful means of dealing with the asymmetry in traffic load up to now, our analysis shows that its gain can be significantly lost by the asymmetry in channel quality, under the given bit error performance constraint. Furthermore, it is shown that NaF always outperforms NaP, as well as traditional bi-directional relaying scheme.

Ⅰ. Introduction

Network coding is emerged as a promising solution to achieve higher bandwidth efficiency in both wired[1-3] and wireless networks[4-6]. Especially in wireless network, a network-coded bi-directional relaying (NCBR) has been proposed to improve system throughput[5]. The key features of NCBR are that packets from the mobile station (MS) and base station (BS) are jointly encoded through bit-wise network coding, e.g., XOR, and then the composite packet is broadcasted back to each

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station. Based on these features, NCBR can reduce the number of transmissions and consequently, enhances the throughput up to 33.3% as compared with TBR (traditional bi-directional relaying). On the hand, another type of network coding which is referred to as physical-layer network coding (PNC) has been proposed[4]. The main idea of PNC is that network-coding arithmetic can be realized with electromagnetic signal reception and modulation. In other words, through a proper modulation-and-demodulation technique at the relay station (RS), additions of electromagnetic signals can be mapped to GF (Galois Field) additions of digital bit streams (i.e., XOR). By this approach, PNC can achieve 50% and 100% improvement in throughput over NCBR and TBR schemes, respectively.

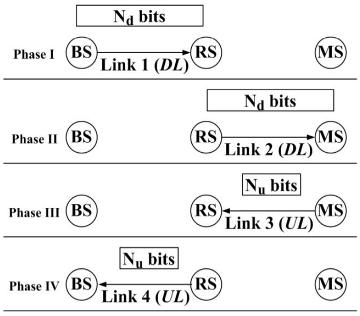
However, these gains can only be guaranteed when a packet size to be transmitted through downlink (*DL*) and uplink (*UL*) as well as the link qualities between bi-directional links are symmetric. In a typical broadband access scenario, however, *DL* traffic load tend to be dominant over *UL*. Thus, the size of packet to be transmitted through *DL* and *UL* may be asymmetric. The packet lengths can be a critical factor that governs the overall system throughput of NCBR scheme, simply because the asymmetry in the packet length involves some means of equating the number of bits to be network-coded. On the other hand, the different link conditions in *DL* and *UL* also incur a similar type of inefficiency, because the different number of network coded symbols can be broadcasted via bi-directional links. In other words, if the channel qualities conservatively with the lower-order modulation to guarantee the minimum performance of the relatively worse link. It may incur a typical bottleneck problem and consequently, reduce the throughput performance of NCBR scheme.

Meanwhile, it is generally accepted that the means of dealing with the asymmetry in the packet length is to insert a redundancy, such as zero padding or repetition[4-9]. which is referred to as network coding after padding (NaP) hereafter. Especially, NaP is a useful means for turbo coded systems, since the more channel coding gain can be achieved as the longer size of turbo-encoder packet is[10]. Due to this feature, NaP can improve the performance of NCBR scheme with turbo code in the sense of minimum error rate[7]-[9]. However, those works have mainly focused on the system with symmetric channel quality, which means the link conditions between bi-directional links are the same. Even whilst NaP is a useful means of dealing with asymmetry in traffic load, it may not be true in case that there is an asymmetry in the link quality due to the bottleneck problem. Thus, it is required to simultaneously consider the asymmetry in traffic load and link quality.

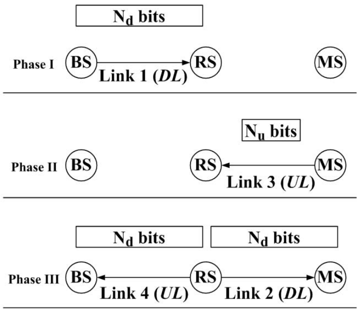
In this paper, we propose a NCBR scheme to handle the bottleneck problem over an asymmetric channel. As opposed to NaP, our proposed scheme is based on Packet fragmentation. In other words, the RS constructs the network-coded packet by fragmentation based on shorter size between the received packets through *DL* and *UL*. And after, the remaining bits which are not subject to network coding are separately transmitted to the destination e.g., MS or BS. Our scheme is referred to as network coding after fragmentation (NaF) hereafter.

To analyze the effect of asymmetry in both traffic load and link quality on the performance of average spectral efficiency, we consider uncoded system, because its analysis is simple yet useful to gain an insight. For uncoded system, we show that NaF always outperforms NaP as well as TBR scheme over the asymmetric channel.

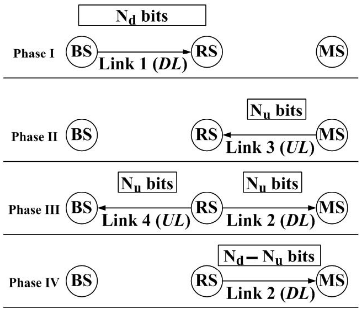
This paper is organized as follows. In Section II, we describe the asymmetric channel model. In Section III, we present the bi-directional relaying schemes, including the proposed one. We analyze a number of channel uses and the average spectral efficiency in Section IV. We show some numerical examples in Section V. Finally, conclusions are given in Section VI.



(a) Traditional Bi-directional Relaying (TBR)



(b) Network coding after Padding (NaP)



(c) Network coding after Fragmentation (NaF)

Fig. 1. Bi-directional relaying schemes over an asymmetric channel for the case of $\alpha > 1$
그림 1. $\alpha > 1$인 비대칭 채널에서의 양방향 릴레이 기법들

Ⅱ. System Model

The different types of two-hop bi-directional relaying schemes are illustrated in Fig. 1, in which BS and MS mutually communicate with each other via RS that exploits decode-and-forward processing. We assume that each station is equipped with a single antenna, operating in a half-duplexing mode. Furthermore, all links are ideally synchronized with each other.

2.1. Asymmetry in Link Quality

In the two-hop bi-directional relay system, four different links are involved: downlinks (*DLs*) in BS-to-RS and RS-to-MS direction, and uplinks (*ULs*) in MS-to-RS and RS-to-BS direction. We employ adaptive modulation and coding scheme over each link, so as to increase the spectral efficiency of relay system while still satisfying a required link quality, e.g., a target bit error rate (BER) or frame error rate (FER)[12]. In other words, different modulation order and coding rate can be applied by taking the link condition between *DL* and *UL* into account.

Suppose that the link l employs M_l-QAM modulation where $M_l = 2^{n_l}$, $n_l \in \{2,3,4\}$ and $l =$ 12,3,4. We assume that all links are independent with each other and subject to block Rayleigh fading. i.e., M_l does not change until the whole transmission of a block over each link. Even whilst we consider the uncoded system in the current analyses and numerical examples, our results can be extended to the coded systems using the adaptive-coded schemes in[11].

2.2. Asymmetry in Traffic Load

In a typical broadband access scenario, *DL* traffic load tends to be dominant over *UL*. Thus the size of packet to be transmitted through *DL* and *UL* may be asymmetric. More specifically, let N_d and N_u bits denote the size of *DL* and *UL* packets for uncoded system, respectively. In order to characterize the traffic asymmetry, the asymmetric ratio can be defined as $\alpha = N_d / N_u$ (e.g., $\alpha > 1$ for the *DL*-dominant traffic).

Ⅲ. Bi-directional Relaying Schemes over an Asymmetric Channel

3.1. Traditional Bi-directional Relaying (TBR)

In the traditional bi-directional relaying (TBR) scheme for uncoded system (see Fig. 1(a)), the BS transmits N_d bits to the RS in *DL*, which is decoded in the RS and then forwarded to the MS in *DL*. Similarly, the same process can be applied in *UL*. In other words, a complete round of bi-directional relaying requires four transmission phases in TBR system.

3.2. Network-coded Bi-directional Relaying (NCBR)

When there is an asymmetric traffic load, i.e., $\alpha > 1$, two types of network coding schemes can be implemented at the RS; network coding after padding (NaP) and network coding after fragmentation (NaF).

3.2.1. Network coding after Padding (NaP)

The concept of NaP is that the RS jointly encodes the packet based on longer size, i.e., with a length of $\max(N_d, N_u)$ as shown in Fig. 1(b), by zero-padding or repetition.

3.2.2. Network coding after Fragmentation (NaF)

As opposed to NaP, NaF is that the RS constructs the network-coded packet based on shorter size, i.e., with a length of $\min(N_d, N_u)$ (Fig. 1(c)) by fragmentation. And after, the remaining $(N_d - N_u)$ bits which are not subject to network coding will be separately transmitted to the MS. Even whilst NaP requires one less transmission opportunity (phase) than NaF and TBR, we will show that the asymmetries degrade the bandwidth efficiency of NaP.

Ⅳ. Performance Analysis

Since we consider the packet-level transmission rather than symbol-by-symbol transmission, we analyze a normalized number of channel uses (NNCU) and compare the average spectral efficiency (ASE) for each scheme. Suppose that the link l employs M_l-QAM modulation where $M_l = 2^{n_l}$ ($n_l \in \{2,4,6\}$, $l = 1,2,3,4$). Furthermore, let μ_A denote a total number of channel uses for the specific bi-directional relaying scheme A in the uncoded system. Then we define the NNCU as $\widetilde{\mu_A} = \mu_A / N_u$.

4.1. Normalized Number of Channel Use (NNCU)

As shown in Fig. 1(a), taking the number of channel uses over each link into account, a NNCU for TBR is given as

$$\widetilde{\mu_{TBR}} = \alpha\left(\frac{1}{n_1} + \frac{1}{n_2}\right) + \frac{1}{n_3} + \frac{1}{n_4} \tag{1}$$

Referring to Fig. 1(b), the NNCU for NCBR with NaP is given as

$$\widetilde{\mu_{NaP}} = \frac{\alpha}{n_1} + \frac{1}{n_3} + \frac{\max(\alpha,1)}{n_b} \tag{2}$$

where n_b is the instantaneous spectral efficiency of network-coded symbols and given by $n_b = \min(n_2, n_4)$.

In NCBR with NaF, $N_d - N_u$ bits are transmitted as a separate block after the network-coded N_u bits are broadcast. Thus, referring to Fig. 1(c), the NNCU of NaF is given as

$$\widetilde{\mu_{NaF}} = \frac{\alpha}{n_1} + \frac{1}{n_3} + \frac{\min(\alpha,1)}{n_b} + \frac{\alpha - 1}{n_2} \tag{3}$$

It is obvious from (1) to (3) that if $n_2 \le n_4$, $\widetilde{\mu_{TBR}} > \widetilde{\mu_{NaP}} = \widetilde{\mu_{NaF}}$; otherwise, $\widetilde{\mu_{TBR}} > \widetilde{\mu_{NaF}}$ and $\widetilde{\mu_{NaP}} > \widetilde{\mu_{NaF}}$. Meanwhile we note that $\widetilde{\mu_{TBR}} > \widetilde{\mu_{NaP}}$ can be guaranteed as long as $\alpha < n_2/(n_2 - n_4)$. Thus NaF always outperforms NaP and TBR in terms of the NNCU.

4.2. Average Spectral Efficiency (ASE)

The ASE of TBR is given by

$$\overline{R_{TBR}} = \sum_{n_1}\sum_{n_2}\sum_{n_3}\sum_{n_4} \frac{\alpha + 1}{\widetilde{\mu_{TBR}}} p(n_1)p(n_2)p(n_3)p(n_4) \tag{4}$$

where $p(n_l)$ is the probability that the instantaneous output SNR, γ_l of the link l falls in the n_l-th region[10],[12], i.e.,

$$p(n_l)=\begin{cases}F_{\Gamma_l}\left(\gamma_{th}^{(n_l+2)}\right)-F_{\Gamma_l}\left(\gamma_{th}^{(n_l)}\right), & n_l=2,4\\ 1-F_{\Gamma_l}\left(\gamma_{th}^{(n_l)}\right), & n_l=6\end{cases} \tag{5}$$

where $F_{\Gamma_l}(\bullet)$ is the cumulative density function (CDF) of γ_l. Especially, for the Rayleigh fading channel, $F_{\Gamma_l}(\gamma_l)=1-\exp\left(-\gamma_l/\overline{\gamma_l}\right)$ where $\overline{\gamma_l}=E[\gamma_l]$. Meanwhile, $\gamma_{th}^{(n_l)}$ is the switching threshold for M_l-QAM at a given target BER, η_{th}. It can be bound by solving the inverse BER expression[10],[12], i.e.,

$$\gamma_{th}^{(n_l)}=\frac{2^{n_l}-1}{3}\left[Q^{-1}\left(\frac{\sqrt{2^{n_l}}\bullet\eta_{th}}{2\left(\sqrt{2^{n_l}}-1\right)}\right)\right]^2 \tag{6}$$

For the NCBR with NaP, the ASE is given as

$$\overline{R_{NaP}}=\sum_{n_1}\sum_{n_3}\sum_{n_b}\frac{\alpha+1}{\widetilde{\mu}_{NaP}}p(n_1)p(n_3)p(n_b) \tag{7}$$

where $p(n_b)$ is the probability that the instantaneous spectral efficiency of the broadcast channel is n_b, which is given by

$$p(n_b)=\begin{cases}p(n_4=2)\sum\limits_{n_2=2,4,6}p(n_2)\\ +p(n_4=2)\sum\limits_{n_4=4,6}p(n_4), & n_b=2\\ p(n_2=4)p(n_4=6)\\ +p(n_4=4)\sum\limits_{n_2=4,6}p(n_2), & n_b=4\\ p(n_2=6)p(n_4=6), & n_b=6\end{cases} \tag{8}$$

For NCBR with NaF, meanwhile, we assume that n_2 in the transmission phase IV is the same as that in phase III, which is usually true for block fading. Thus, the probability of n_2 in phase IV depends on n_b used in phase III, which is given by the conditional probability $p(n_2|n_b)$. Then, the ASE for NCBR with NaF is given by

$$\overline{R_{NaF}}=\sum_{n_1}\sum_{n_3}\sum_{n_b}\sum_{n_2}\frac{\alpha+1}{\widetilde{\mu}_{NaF}}p(n_1)p(n_3)p(n_b)p(n_2|n_b) \tag{9}$$

where $p(n_2|n_b)$ can be represented by the Bayes' rule as follows:

$$p(n_2|n_b=2)=\begin{cases}\dfrac{p(n_2)\sum\limits_{n_4=2,4,6}p(n_4)}{p(n_b=2)}, & n_2=2\\ \dfrac{p(n_2)p(n_4)}{p(n_b=2)}, & n_2=4,6\end{cases} \tag{10}$$

$$p(n_2|n_b=4)=\begin{cases}0, & n_2=2\\ \dfrac{p(n_2)\sum\limits_{n_4=4,6}p(n_4)}{p(n_b=4)}, & n_2=4\\ \dfrac{p(n_2)p(n_4=4)}{p(n_b=4)}, & n_2=6\end{cases} \tag{11}$$

$$p(n_2|n_b=6)=\begin{cases}0, & n_2=2\\ 0, & n_2=4\\ \dfrac{p(n_2)p(n_4=6)}{p(n_b=6)}, & n_2=6\end{cases} \tag{12}$$

V. Numerical Results

In this section, numerical example are provided to demonstrate the ASE of the bi-directional relaying schemes. For all the results, we set η_{th} to 10^{-3}.

The plots in Fig. 2 illustrate ASE for the symmetric channel condition $\left(\overline{\gamma_1}=\overline{\gamma_2}=\overline{\gamma_3}=\overline{\gamma_4}=\overline{\gamma}\right)$ as the traffic asymmetric ratio, α varies. In this scenario, the average SNR, $\overline{\gamma}$ varies with 25, 30 and 50dB. We note that our simulation results for each scheme closely coincide with the analysis ones. Meanwhile, it is clear from Fig. 2 that the best possible performance of NCBR schemes is achieved only when the packet length is the same for both direction, i.e., $\alpha=1$, which corresponds to 33% gain over the TBR scheme. Furthermore, the ASE of NCBR schemes is significantly degraded as α increases. For the sufficiently large $\overline{\gamma}$, e.g., $\overline{\gamma}=50\text{dB}$, we observe $\overline{R_{TBR}}=\overline{R_{NaP}}=\overline{R_{NaF}}\rightarrow 3$ as $\alpha\rightarrow\infty$ from (4), (7) and (9), which implies that NCBR schemes would not be useful any more. Meanwhile, the NCBR with NaP

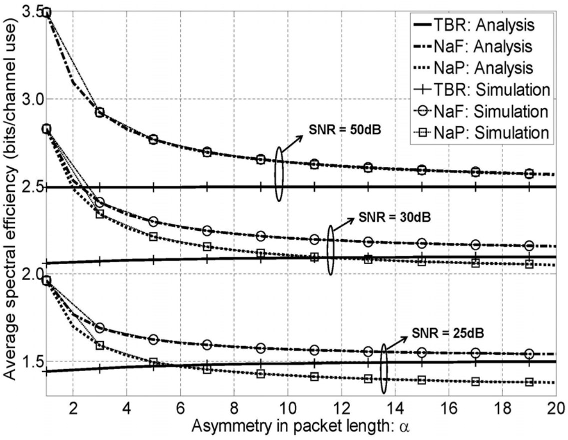


Fig. 2. Average spectral efficiency as the function of α when the link qualities are symmetric ($\overline{\gamma_1}=\overline{\gamma_2}=\overline{\gamma_3}=\overline{\gamma_4}=\overline{\gamma}$).
그림. 2. 링크 품질이 대칭일 때 α에 따른 평균 대역 효율성 성능의 비교

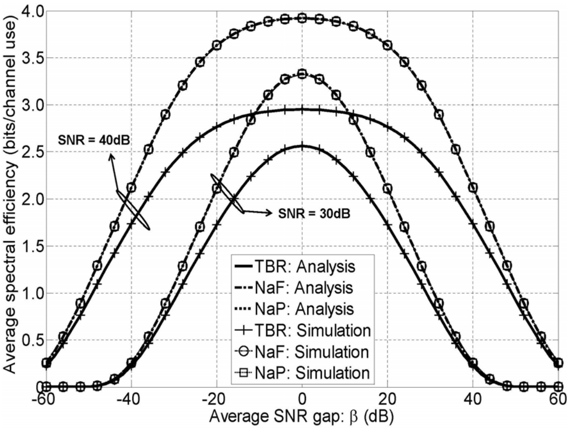


Fig. 3. Average spectral efficiency as the function of β when $\alpha=1$ and $\alpha=4$
그림 3. $\alpha=1$과 $\alpha=4$일 때, β에 따른 평균 대역 효율성 성능의 비교

could suffer more than TBR, depending on the asymmetry in packet length, e.g., $\alpha > 6$ when $\overline{\gamma}=25$dB. We note that the lower SNR is, the more significant the effect of asymmetry is for NaP. However, we find NaF always outperforms TBR at any degree of asymmetry in the packet length in the case of symmetric channel quality.

In Fig. 3, the ASE with the different traffic asymmetry ratio (i.e., $\alpha=1$ and $\alpha=4$, respectively) is shown as the asymmetry in the link condition varies. To represent the asymmetric channel condition, we consider the average SNR gap of β between $\overline{\gamma_1}$ and $\overline{\gamma_2}$ in dB scale, e.g., $\overline{\gamma_1}=\overline{\gamma}-\beta/2$ and $\overline{\gamma_2}=\overline{\gamma}+\beta/2$. For the simplicity of exposition, we assume $\overline{\gamma_1}=\overline{\gamma_4}$ and $\overline{\gamma_2}=\overline{\gamma_3}$. It is clear from Fig. 3 that our simulation results for each scheme are exactly identical to the analysis ones. More specifically, Fig. 3 shows that both NaP and NaF have the same performance. It implies that the asymmetry in link quality does not affect the ASE performance of both schemes as long as packet length to be transmitted over bi-directional links is symmetric. However, when there exists asymmetry in packet length as shown in Fig. 3, the ASE performance of NaP degraded as compared to NaF and TBR for the different degree of channel asymmetry. Furthermore, we find that there exists a threshold in the average SNR gap, beyond which NaP performs worse than TBR when $\beta \geq 0$. In fact, this threshold varies with SNR, which implies that NaP is more vulnerable to the link quality when the traffic asymmetry becomes significant. This observation can be explained by (2) and (3). Meanwhile, it is clear that the traffic asymmetry has more effects on the ASE performance between TBR and NCBR schemes than the asymmetry in link quality. Finally, there is no much difference between NaP and NaF in the efficiency when $\beta < 0$. This is attributed to the fact that the less reliable access link can be a bottleneck for both NaP and NaF.

Ⅵ. Conclusion

In this paper, we have shown that the asymmetries in the bi-directional traffic load and channel conditions can incur a significant degradation in the spectral efficiency of the network-coded bi-directional relaying (CBR) schemes. We have analyzed how this asymmetry affects the average spectral efficiency performance of NCBR schemes. It has been shown that network coding after fragmentation (NaF) is more efficient than the exisiting network coding scheme, i.e., network coding after padding (NaP) in the asymmetric channel. As we find that channel coding may have some other implication in the current issue, e.g., packet length matters for the performance of turbo code[13], both channel coding and network coding must be jointly investigated in the future work.

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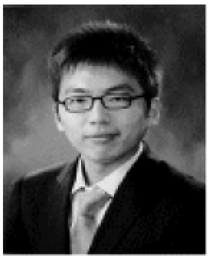

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