Network Coded Rate Scheduling for Two-way Relay Networks

Dong Min Kim and Seong-Lyun Kim
School of Electrical and Electronic Engineering, Yonsei University
50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, Korea
Email: {dmkim, slkim}@ramo.yonsei.ac.kr

***Abstract*—We investigate a scheduling scheme incorporating network coding and channel varying information for the two-way relay networks. Our scheduler aims at minimizing the time span needed to send all the data of each source of the network. We consider three channel models, time invariant channels, time varying channels with finite states and time varying Rayleigh fading channels. We formulate the problem into a manageable optimization problem, and get a closed form scheduler under time invariant channels and time varying channel with finite channel states. For Rayleigh fading channels, we focus on the relay node operation and propose heuristic power allocation algorithm resemblant to water filling algorithm. By simulations, we find that even if the channel fluctuates randomly, the average time span is minimized when the relay node transmits/schedules network coded data as much as possible.**

***Index Terms*—Network coding, scheduling, time span, two-way relay networks.**

I. Introduction

Network coding attracted the attention in wireless networks [1]. The network coding benefit is easily represented by reducing the number of transmissions. For example, in two-way relay networks [2] of Figure 1, the traditional method requires four slots to exchange data, whereas the network coded relaying requires three slots [3]. In [4], moreover, two-slot transmission strategy is studied. In the example, the relay node should have data from both source nodes to execute network coding. This means the source nodes must transmit their data before the relay node does. Consequently, scheduling can significantly impact the performance of network coding.

The packet scheduling in multiuser communications was originally motivated by [5], where only one user that has the best channel condition should transmit to achieve the capacity. Since then, many scheduling algorithms have been proposed [6]. In [7], the authors proposed a cross layer scheme that integrates per-hop packet scheduling, network coding and congestion control. To maximize coding opportunities, they investigated the scheduling of transmissions. However, they considered only time invariant case, where all links have the identical channel gain. In [8], the authors considered a throughput optimal scheduling problem with random traffic. They showed that both digital and analog network coding outperform the plain routing. In [9], the authors pointed that if network coding and scheduling are designed separately, the expected throughput gain may not be achieved. When it comes to throughput maximization criterion, the buffers of nodes are assumed full. The full buffer assumption is not realistic though it may provide tractableness of analysis.

The network situation can arbitrarily change over time by node mobility, channel fading and the amount of data. Considering these dynamics, throughput may not be well defined. Instead, the time it takes to transfer a bunch of data volume at each source can be practical measurement of the network performance [10]. In this point of view, we consider the finite amount of initial data traffic by introducing a *time span minimization* criterion [11]. The details of time span minimization are explained later.

Scheduling in time varying channels is a difficult problem. In [12], the opportunistic scheduling, which exploits time varying nature of the radio environment, is proposed. Scheduling algorithms with consideration of energy-efficiency [13], limited channel information [14] are investigated.

In this paper, we propose a scheduling scheme incorporating network coding and channel varying information for the two-way relay networks. The provided channel information will constrain the choice of the scheduling policy. If we know the current and future instantaneous channel state information, we can adjust appropriate transmission rates. However, in practical situations, we know only the current channel information and the distribution of the channel fluctuation. Our question is how to design scheduling algorithms incorporating network coding and channel varying information. We consider three channel models, time invariant, time varying with finite states and Rayleigh fading. The first two models may less reflect practical situations than the Rayleigh fading model. However, we can obtain an optimal solution by analysis in the first two cases, which helps us understanding the relation between scheduling and network coding. In Rayleigh fading model, we propose a heuristic algorithm and obtain meaningful results by simulations.

Throughout the paper, we use the time span as the performance metric for our scheduling algorithm. The time span means the amount of time needed to send all the data in every source node in the network. The problem was first defined in uplink packet scheduling for the cellular CDMA system [11]. By minimizing the time span, we can shorten the end-to-end delay while keeping the per-node throughput reasonably high. The rationale behind is to take care of both throughput and delay.

The rest of the paper is organized as follows. In Section 2, we describe the system model. Our scheduling scheme for the

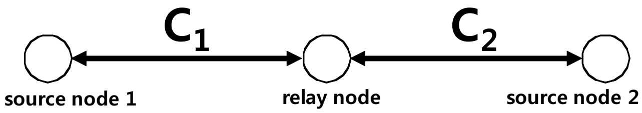


Fig. 1. The two-way relay networks employing network coding at relay node.

minimum time span is proposed in Section 3. In Section 4, we verify the performance of the proposed scheme by simulations. Section 5 concludes the paper.

II. System Model

Consider the two-way relay networks as shown in Figure 1. The source nodes at both ends communicate with each other using the relay node in the middle. The relay node carries out network coding (e.g., eXclusive OR) operations to the received data from two source nodes. C_i is the maximum data rate through the link i during a time slot. C_i is constant, but randomly varies between slots due to the time varying channel. The channel model between the two nodes is reciprocal. Then, the link is symmetric in that both directions have the same rate. We consider two models for the time varying channel model. The first one is a finite channel state model. Each data rate varies in a set of finite possible rates $\mathbf{S} = (s_1 \ \ldots \ s_n)$. Without loss of generality, we assume $0 < s_1 < s_2 < \ldots < s_n$. We represent the channel state as a vector of data rates $(C_1 \ C_2)$. In a time slot, the channel state is one of possible combinations of data rates. For example, if $n = 2$, then there are four channel states: $\mathbf{S}^{(1)} = (s_1 \ s_1)$, $\mathbf{S}^{(2)} = (s_1 \ s_2)$, $\mathbf{S}^{(3)} = (s_2 \ s_1)$ and $\mathbf{S}^{(4)} = (s_2 \ s_2)$. We denote the probability that the channel state is $\mathbf{S}^{(i)}$ as $p^{(i)}$. In a time slot, if the *assumed* channel state vector (i.e., the rates using a specific level of modulation and coding) is element-wisely less than or equal to the *actual* channel state vector, then transmissions succeed. The second model is the continuous state model of Rayleigh fading. Each channel power gain follows an exponential distribution with a mean value.

Let B_i denote the finite amount of data that source node i wants to send to the other source node. We assume only one node can transmit at any time instant, i.e., TDMA.

III. Time Span Minimization

To propose a scheduling scheme for the minimum time span, we start with the time invariant channels, and extend the result to the case of randomly varying channels.

A. Time Invariant Channels

It is a special case of the time varying channels; one of $p^{(i)}$'s is one, and the others are zero. To begin with, consider the rate region that depicts the amount of *transmittable* data in a single time slot (see Figure 2(a)). The rate region [15] is a convex set and the network coding is adopted by the relay node. In the figure, the corner point $b = (r_{nc}, r_{nc})$ represents the data rate of the (network coded) three-mode transmission. In the first fraction of a time slot, a source node sends data to the relay node. In the second fraction, the other source transmits. In the last fraction, the relay node broadcasts the network coded data to both ends. Note that r_{nc} is the maximum achievable rate by network coding to exchange data between source nodes. The network coded data rates of both end nodes are equal. This is because the network coded data rates are symmetric and bounded by the minimum of maximum transmission rates of links. Note that r_j is the maximum achievable rate by one-directional forwarding from source node j to the other source node. Two edge points $a = (0, r_2)$ and $c = (r_1, 0)$ represent one-directional forwarding. The line segment between the corner point (b) and an edge point (a or c) denotes the time multiplexing of network coding and one-directional forwarding. From Theorems 3.1 and 3.2 of [15], the maximum rates of one-directional forwarding and network coding are:

$$r_1 = r_2 = \left(\frac{1}{C_1} + \frac{1}{C_2}\right)^{-1}, \qquad (1)$$

$$r_{nc} = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{\min(C_1, C_2)}\right)^{-1}. \qquad (2)$$

To minimize the time span, we formulate the minimum time span into the following linear programming problem:

$$\begin{aligned} &\min \theta_1 + \theta_2 + \theta_3 \\ &\text{s.t. } \theta_1 \begin{pmatrix} r_1 \\ 0 \end{pmatrix} + \theta_2 \begin{pmatrix} 0 \\ r_2 \end{pmatrix} + \theta_3 \begin{pmatrix} r_{nc} \\ r_{nc} \end{pmatrix} = \begin{pmatrix} B_1 \\ B_2 \end{pmatrix} \\ &\quad 0 \le \theta_1 \le \frac{B_1}{r_1}, 0 \le \theta_2 \le \frac{B_2}{r_2}, 0 \le \theta_3 \le \frac{\min(B_1, B_2)}{r_{nc}} \\ &\quad \theta_1, \theta_2, \theta_3 \ge 0, \end{aligned} \qquad (3)$$

where θ_1 denotes the transmission time of source node 1 to source node 2 by one-directional forwarding, and θ_2 corresponds to that of source node 2. The time for network coded transmission is denoted by θ_3. The maximum network coded data size is $\min(B_1, B_2)$ because the relay node codes the same amount of received data from both source nodes. The objective is to minimize the total transmission time to send the target amount of data (B_1, B_2).

Proposition 1. *To achieve the minimum time span, the time for network coding operation should be* $\theta_3^* = \min(B_1, B_2)/r_{nc}$.

Proof. We can rewrite the first constraint of (3) in terms of θ_3 as follows:

$$\theta_1 = \frac{B_1 - \theta_3 r_{nc}}{r_1}, \theta_2 = \frac{B_2 - \theta_3 r_{nc}}{r_2}, \theta_3 = \theta_3.$$

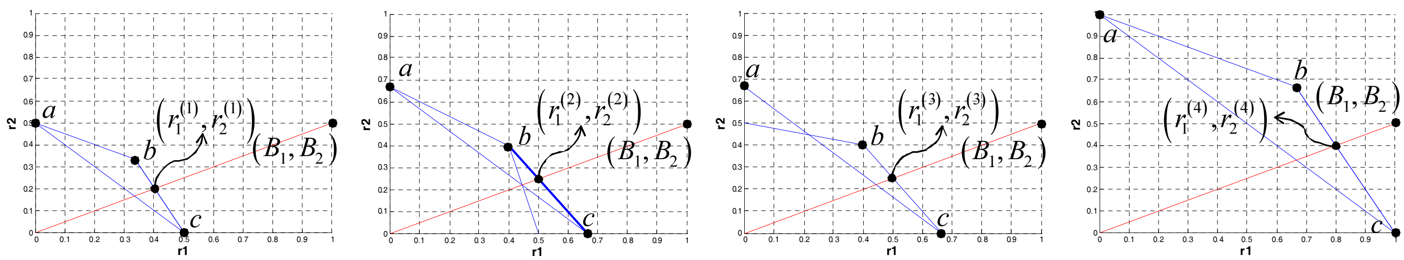
Then objective function of (3) can be rewritten as:

$$\frac{B_1}{r_1} + \frac{B_2}{r_2} + \theta_3 \left(1 - r_{nc}\left(\frac{1}{r_1} + \frac{1}{r_2}\right)\right).$$

Without loss of generality, we assume $C_1 \ge C_2$ and from (1):

$$r_{nc}\left(\frac{1}{r_1} + \frac{1}{r_2}\right) = \left(\frac{1}{C_1} + \frac{2}{C_2}\right)^{-1}\left(\frac{2}{C_1} + \frac{2}{C_2}\right) = \frac{2C_1 + 2C_2}{2C_1 + C_2}.$$

Because $\frac{2C_1+2C_2}{2C_1+C_2} > 1$, it is $\theta_3\left(1 - r_{nc}\left(\frac{1}{r_1} + \frac{1}{r_2}\right)\right) < 0$. To minimize the objective function, θ_3 should be as large as possible. Therefore, $\theta_3 = \min(B_1, B_2)/r_{nc}$. □



(a) $\mathbf{S}^{(1)} = (1\ 1)$ (b) $\mathbf{S}^{(2)} = (1\ 2)$ (c) $\mathbf{S}^{(3)} = (2\ 1)$ (d) $\mathbf{S}^{(4)} = (2\ 2)$

Fig. 2. Four instantaneous rate regions of time varying channels. Channel states are $\mathbf{S}^{(1)} = (1\ 1), \mathbf{S}^{(2)} = (1\ 2), \mathbf{S}^{(3)} = (2\ 1)$ and $\mathbf{S}^{(4)} = (2\ 2)$.

The consequence of Proposition 1 is summarized as follows: First, either node 1 or node 2 transmits its data during B_1/C_1 or B_2/C_2, respectively. Then, the relay node transmits the received data with network coding during $\min(B_1, B_2)/\min(C_1, C_2)$ and with the one-directional forwarding for flushing the remaining data during $(B_1 - B_2)/C_2$ or $(B_2 - B_1)/C_1$.

Proposition 1 explains what the solution of the time span minimization looks like but a question still remains regarding how to achieve it. We propose a rate region based scheduling to achieve the minimum time span. We draw a line segment across $(0, 0)$ and (B_1, B_2) as in Figure 2. The drawn line has the slope B_2/B_1. There is a cross point $(r_1^{(i)}, r_2^{(i)})$ between the rate region and the line. The number $r_j^{(i)}$ denotes the data rate of node j under the channel state i. To minimize the time span, each source node should transmit $r_1^{(i)}$ and $r_2^{(i)}$ under the channel state i, by time multiplexing of network coding and one-directional forwarding. Then a time slot is over. We draw another line between $(0, 0)$ and the remaining data $(B_1 - r_1^{(i)}, B_2 - r_2^{(i)})$ and repeat the same procedure. This intuitively explains how the minimum time span scheduling works.

B. *Time Varying Channels*

1) Finite State Model: Consider the channels vary randomly with channel states. For example, if the $n = 2$, we can draw four instantaneous rate regions as in Figure 2. Nodes hardly find out the current channel state, but know the probability p_i that the channel state is $\mathbf{S}^{(i)}$. Due to the randomness of the channel, the *expected* time span will depend on the scheduling policy. If a source node selects the rate region of $\mathbf{S}^{(4)}$, the transmission succeeds only when the actual rate region is $\mathbf{S}^{(4)}$. However, if the source node selects the rate region of $\mathbf{S}^{(1)}$, its transmission succeeds for all channel realizations.

We want to minimize the expected time span. For the purpose, let us consider a probabilistic scheduling policy such that the probability to select $\mathbf{S}^{(i)}$ is q_i. The expected data rate of source node j in $\mathbf{S}^{(i)}$ is defined as $\sum\limits_{k \in A^{(i)}} p_k r_j^{(i)}$, where $A^{(i)} = \left\{k | \mathbf{S}^{(k)} \preceq \mathbf{S}^{(i)}\right\}$ is the index set of transmittable channel states i. $E[r_j]$ denotes the expectation of an instantaneous data rate of node j. For two vectors $\mathbf{a}$ and $\mathbf{b}$, we define operator $\mathbf{a} \preceq \mathbf{b}$ if $\mathbf{a}$ is element-wisely less than or equal to $\mathbf{b}$. Similar to the time invariant case, the ratio of expected data rates $E[r_2]/E[r_1]$ should be B_2/B_1 to minimize the time span. We can derive expected data rate of node 1 as:

$$E\left[r_1\right] = E_{q_i}\left[E\left[r_1 | \mathbf{S}^{(i)}\right]\right] = \sum_{i=1}^{n^2}\left(\sum_{j \in A^{(i)}} p_j r_1^{(i)}\right) q_i. \quad (4)$$

We assume finite amount of data that source nodes want to send. In this case, the time span minimization problem can be solved by solving expected data rate maximization problem. To this end, we consider the following optimization problem:

$$\begin{aligned} &\max_{q_1,\ldots,q_n} \sum_{i=1}^{n^2} \alpha_i q_i \\ &\text{subject to} \quad \sum_{i=1}^{n^2} q_i = 1 \\ &\qquad\qquad\quad q_i \geq 0, i = 1, 2, ..., n., \end{aligned} \quad (5)$$

where $\alpha_i = \sum\limits_{k \in A^{(i)}} p_k \left(r_1^{(i)} + r_2^{(i)}\right) = \left(1 + \frac{B_2}{B_1}\right) \sum\limits_{k \in A^{(i)}} p_k r_1^{(i)}$ is the sum of expected data rates of source nodes 1 and 2 when channel state i is selected.

In (5), the linear programming is solved by assigning 1 to q_i that has the largest coefficient:

$$q_i^* = 1, \text{ for } i = \arg\max \alpha_i. \quad (6)$$

Each node selects the channel state using q_i^* and decides its transmission rate. Even if the channel fluctuates randomly, each source transmits/schedules its data as if the channel were fixed. Consequently, the time for network coded transmission can be find by Proposition 1. The above scheduling configuration is performed at the beginning of each time slot to decide transmission order and data rate. The node that decides scheduling policy (the relay node is favorable) must know initial data size of the other nodes. Due to the nature of two-way relay networks, the data size information of the other source nodes is readily available. We can apply the following protocol to share data size information. First, relay node requests source nodes to inform their data sizes. Source nodes send data size information to the relay node, respectively. After gathering data size information, the relay node computes the transmission rates of sources by (5). It broadcasts these scheduling information to sources.

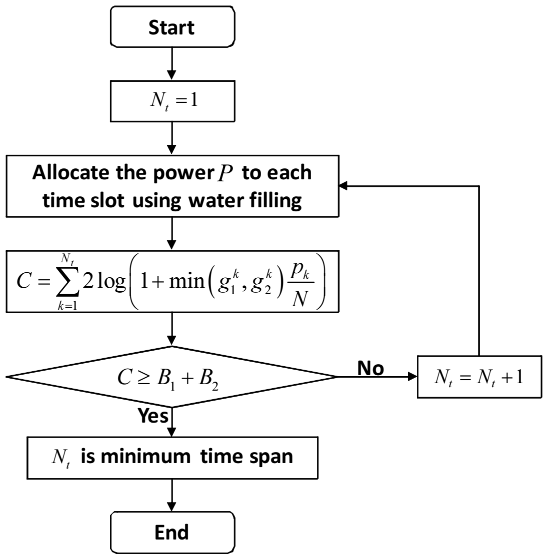


Fig. 3. Time span minimization with noncausal channel knowledge.

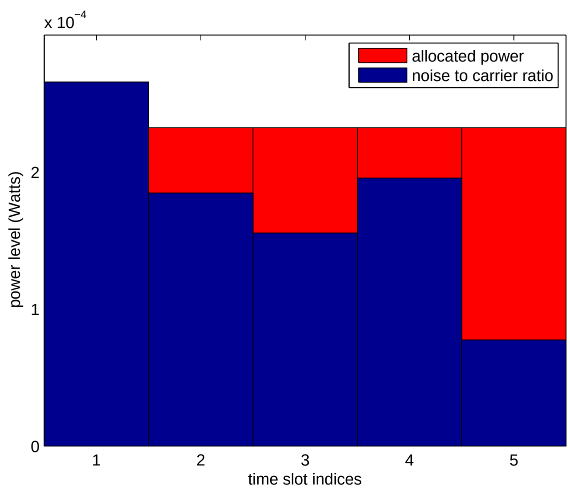


Fig. 4. Water filling power allocation with noncausal channel knowledge.

2) Rayleigh Fading Model: We assume now that channels experience the Rayleigh fading. The channel power gain g_i varies between slots following the exponential distribution with a known parameter μ. In this case, the approach in the previous subsections is inapplicable and analytical results may not be found. We introduce a total power constraint P (W), the additive white Gaussian noise power I (W/Hz) and focus on the relay node operation. We assume that the relay node has received all the data from sources. According to Proposition 1, to minimize time span, the relay node should have at least $\min(B_1, B_2)$ data from each of sources. Then the problem is reduced to the power allocation problem over slots. The water filling is known to be optimal for allocating powers to orthogonal multi-channels in throughput maximization. We have the channel information *causally* if the past and current channel information are available. On the other hand, we have the channel information *noncausally* if the future channel information is known. In the noncausal channel information case, we can regard each time slot as a orthogonal subchannel block. If the number of time slots is fixed, we can solve the throughput maximization problem by the water filling power allocation.

Given the fixed amount of data, the time span is minimized by throughput maximization at the relay node. If the amount of received data from both sources is equivalent ($B_1 = B_2$), the relay node can always transmit network coded data. We consider the following optimization problem for relay node:

$$\begin{aligned} &\min N_t \\ &\text{subject to} \quad \sum_{k=1}^{N_t} 2\log\left(1+\min\left(g_1^k, g_2^k\right)\tfrac{p_k}{I}\right) \geq B_1 + B_2 \\ &\qquad\qquad\quad \sum_{k=1}^{N_t} p_k \leq P \\ &\qquad\qquad\quad p_k \geq 0, \forall k, \end{aligned} \tag{7}$$

where, N_t is the number of required time slots to transmit the given data and g_i^k is channel power gain for link i at time slot k. The total throughput over the time slots should be greater than or equal to the received data size to flush out the data. We propose to solve the problem in the following way. The procedure is also depicted in Figure 3. First, assuming $N_t = 1$, allocate the power budget P to the first time slot. If the total throughput over the slot is greater than or equal to the remaining data size, a feasible solution is founded. If not, increase one time slot $N_t = 2$, and, apply the water filling allocation again with the power budget P. We continue this procedure until flushing out the remaining data. Figure 4 is an example of the power allocation. The total power constraint is -5 dBm and the data size is 30 MBytes. Five slots are consumed to transmit all data.

In practice, the above algorithm may not be applicable because the future channel knowledge cannot be obtained. On the other hand, if we know the channel distribution and its mean value, the following heuristic approach can be used instead. The algorithm is described in Figure 5. First, assuming $N_t = 1$ and a virtual time slot $\Delta = 1$, then virtually apply the water filling allocation with power budget P. If the total throughput over the time slots is greater than or equal to the remaining data size, a feasible solution is founded. If not, increase one virtual time slot $\Delta + 1$, assume that the future channel is the same as the mean value of the channel distribution and virtually apply the water filling allocation again. When flushing out the remaining data, the power p_{N_t} allocated the current time slot, is actually used. Recalculate the power budget and the remaining data size. We continue this procedure until the relay node has no remaining data. Figure 6 is an example of the heuristic power allocation. Total power constraint is -6 dBm and data size is 15 MBytes. Total 26 time slots are consumed to transmit the given data. The water level is not flat because actual channel information is not given. However, the power is allocated to relatively high channel quality slots. This means the heuristic power allocation works like the water filling.

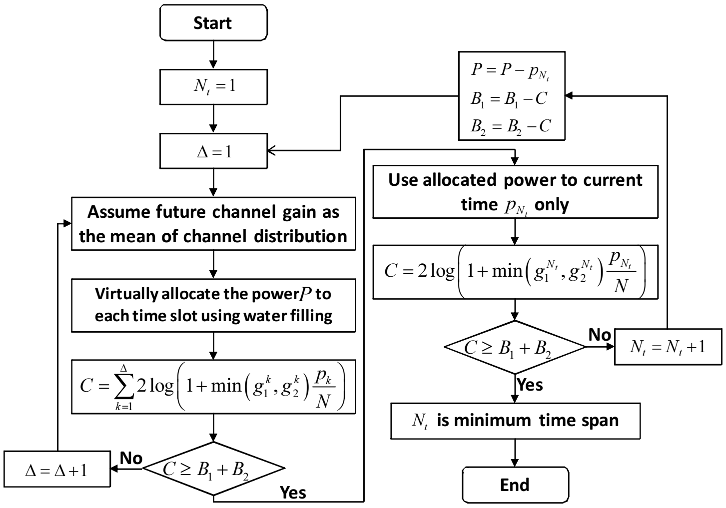


Fig. 5. Time span minimization with causal channel knowledge.

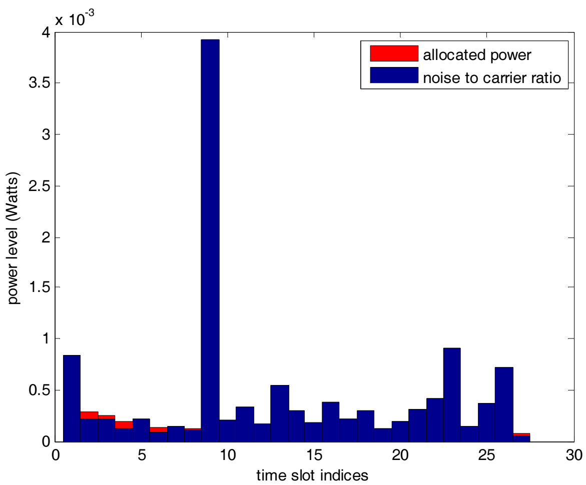


Fig. 6. Heuristic power allocation with causal channel knowledge.

The heuristic algorithm can be combined with one-directional forwarding. Before the power allocation step, the relay node compares the throughput of three cases, i.e., network coding and two one-directional forwarding transmissions, and selects the transmission scheme shown the largest throughput at each time slot. The other type of incorporation is also possible. For example, we can put high priority on the network coding. If network coding is possible at the current time slot, it is selected even though one-directional forwarding shows higher throughput. In this way, a heuristic algorithm combined with one-directional forwarding can be applied for the case that the data sizes from two sources are different. The performance of this algorithm is verified in following section.

IV. Simulation Results

We simulated our heuristic power allocation algorithms under the Rayleigh fading channel. We assume that channel power gains follow the exponential distribution with mean 1. The amounts of data to transmit are $B_1 = B_2 = 8.5$ MBytes. Channel bandwidth is 100 MHz. The noise power is fixed to 10^{-12} W/Hz. Figure 7 shows the average time span as a function of the power budget. For comparison, noncausal and causal one-directional forwarding cases are plotted together. To execute one-directional forwarding, the relay should decide to whom it should transmit, i.e., the relay node should select one of the two links. The relay node chooses the highest quality channel between the two channels. With noncausal channel knowledge, the relay node can select future channels in advance. After that, the relay node allocates power using water filling. In the causal case, the relay node can select only one of current channels and allocates power with mean valued future channel gain. As the power budget increases, the average time span decreases for all the cases. Network coding outperforms one-directional forwarding in all cases considered. The performance gap becomes bigger under a small power budget. With -10 dBm power budget, the gap between the network coding with causal channel information and one-direction forwarding with causal channel information is about 2.2 slots. However, with 0 dBm power budget, the gap is about 1. This result shows that network coding improves the power efficiency. The network coding with the causal channel information, i.e., only executing network coding at the relay node, shows almost the same performance with the network coding with the noncausal channel information as the power budget increases. However, the opportunistic network coding with causal channel information, i.e., selecting proper one between network coding and one-direction forwarding at the current time slot, shows worse performance than the network coding with causal channel information. This result means that network coding opportunity should be maximized to minimize the time span. The imbalance between two buffers can be occurred by the opportunistic network coding and it reduces network coding opportunity.

To further investigate the relation between time span minimization and network coding, we simulated opportunistic

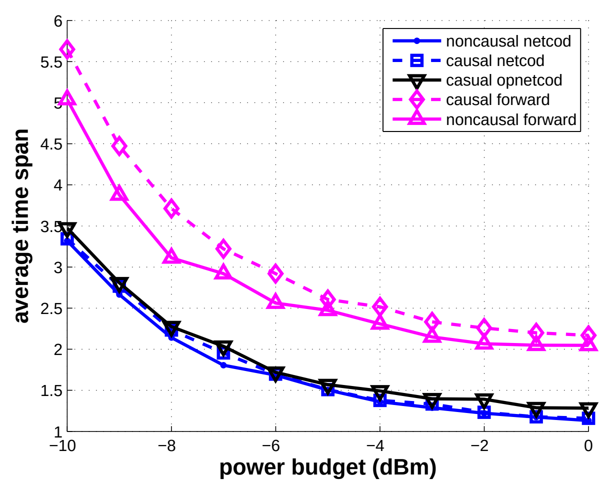


Fig. 7. The average time span as a function of the power budget.

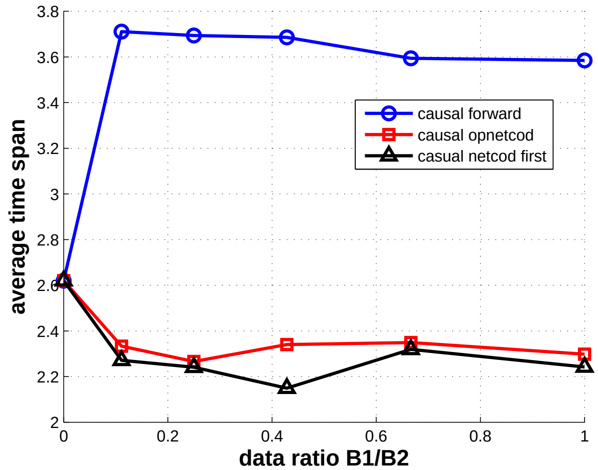


Fig. 8. The average time span as a function of data ratio (B_1/B_2).

network coding, network coding first scheme (high priority on the network coding) and one-directional forwarding with various data ratio (B_1/B_2). $B_1 + B_2$ is fixed to 17 MBytes. Due to the imbalance between buffers, one-directional forwarding should be used to flush the remaining data. Figure 8 shows the average time span as the data ratio varies. When the data ratio is zero, network coding cannot be applied and one-directional forwarding is the only option. When the data ratio becomes positive, one-directional forwarding (solid line with circle marker) shows poor performance because the relay node should transmit the both direction. In all cases, the network coding first scheme (solid line with triangle marker) outperforms the opportunistic network coding (solid line with square marker). The results mean that maximizing the network coding opportunity is a better strategy than maximizing the throughput of the current slot.

V. Concluding Remarks

We proposed a scheduling scheme incorporating network coding and channel varying information for the network coded two-way relay networks. In time varying channels with finite states, to minimize the expected time span, the proposed scheduler operates as if channels stay in the specific channel state. Even if the channel experiences a constant mean valued Rayleigh random fading, the average time span can be minimized when the relay node transmits/schedules network coded data as much as possible. A possible research direction is to find an optimal network coding scheduling under the Rayleigh fading channel and to extend the results, considering other network coding strategies (e.g., physical-layer network coding).

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2009-0088483).

References

[1] J. Y. LeBoudec, C. Fragouli and J. Widmer, “Network coding: an instant primer,” *ACM SIGCOMM Computer Communication Review*, 36 (1), pp. 63–68, 2006.

[2] B. Rankov and A. Wittneben, “Achievable rate regions for the two-way relay channel,” in *Proc. of the IEEE International Symposium on Information Theory 2006*, Seattle, Washington, USA, 2006.

[3] P. Larsson, N. Johansson and K. E. Sunell, “Coded bi-directional relaying,” in *Proc. of the Scandanavian Workshop on Wireless ad-hoc Networks 2005*, Stockholm, Sweden, 2005.

[4] T. J. Oechtering, C. Schnurr, I. Bjelakovic and H. Boche, “Broadcast capacity region of two-phase bidirectional relaying,” *IEEE Transactions on Information Theory*, 54 (1), pp. 454–458, 2008.

[5] R. Knopp and P. A. Humblet, “Information capacity and power control in single-cell multiuser communications,” in *Proc. of the IEEE International Conference on Communications 1995*, Seattle, USA, 1995.

[6] S. Shakkottai, T. S. Rappaport and P. C. Karlsson, “Cross-layer design for wireless networks,” *IEEE Communications Magazine*, 41 (10), pp. 74–80, 2003.

[7] W. Hu, B. Scheuermann and J. Crowcroft, “Near-optimal co-ordinated coding in wireless multihop networks,” in *Proc. of the ACM CoNEXT conference 2007*, New York, NY, USA, 2007.

[8] D. Guo, Y.E. Sagduyu and R. Berry, “Throughput optimal control for relay-assisted wireless broadcast with network coding,” in *Proc. of the IEEE International Workshop on Wireless Network Coding 2008*, San Francisco, CA, USA, 2008.

[9] P. Chaporkar and A. Proutiere, “Adaptive network coding and scheduling for maximizing throughput in wireless networks,” in *Proc. of the ACM International Conference on Mobile Computing and Networking 2007*, New York, NY, USA, 2007.

[10] A. Pantelidou and A. Ephremides, “The Scheduling problem in wireless networks (invited paper),” *Journal of Communication and Networks*, 11 (5), pp. 489–499, 2009.

[11] R. Jantti and S.-L. Kim, “Transmission rate scheduling for the non-real-time data in a cellular cdma system,” *IEEE Communications Letters*, 5 (5), pp. 200–202, 2001.

[12] E. K. P. Chong, X. Liu and N. B. Shroff, “A framework for opportunistic scheduling in wireless networks,” *Computer Networks*, 41 (4), pp. 451–474, 2003.

[13] J. Lee and N. Jindal, “Energy-efficient scheduling of delay constrained traffic over fading channels,” in *Proc. of the IEEE International Symposium on Information Theory 2008*, pp. 604–608, 2008.

[14] H. Asnani, P. Chaporkar, A. Proutiere and A. Karandikar, “Scheduling with limited information in wireless systems,” in *Proc. of the ACM International Symposium on Mobile Ad Hoc Networking and Computing 2009*, New York, NY, USA, 2009.

[15] C.-H. Liu and F. Xue, “Network coding for two-way relaying: Rate region, sum rate and opportunistic scheduling,” in *Proc. of the IEEE International Conference on Communications 2008*, Beijing, China, 2008.