무선 네트워크에서 네트워크 코딩 재전송 기법의 점근적 이득

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Asymptotic Gain of Network-Coded Retransmission in Wireless Networks

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요 약

본 논문에서는 무선 네트워크에서 네트워크 코딩을 재전송에 사용했을 때 얻을 수 있는 이득을 계산했다. 먼저 무선 네트워크에서 네트워크 코딩을 재전송에 활용했을 때 얻을 수 있는 전송 실패 확률을 수학적으로 구했고 이에 따른 다이버시티 차수를 노드 숫자와 수신 확률에 따라 변함을 보였다. 전송 실패 확률을 이용하여 전송 실패 확률 ϵ을 만족시키는 ϵ-용량 (ϵ-outage capacity) 을 구하였고, 네트워크 코딩을 사용했을 때와 안 했을 때의 ϵ-용량의 비율을 네트워크 코딩 이득이라 정의하였다. 그리고 네트워크 코딩 이득이 다이버시티 차수의 함수로 표현됨을 보였다. 노드 숫자가 무한하게 많아지게 되면 네트워크 코딩 이득이 점근적으로 $0.25\epsilon^{-1}$을 달성할 수 있음을 보였다.

Key Words : Network coding, outage probability, diversity order, ϵ-outage probability, network-coding gain.

ABSTRACT

In this paper, we derive the gain of network coding when it is utilized for retransmission in wireless networks. To the end, we derive the outage probability of the network-coded transmission and express the diversity order as a function of the number of nodes and the node's listening probability. From the outage probability, we formulate the ϵ-outage capacity. The network-coding gain is the ratio of the ϵ-outage capacities between network-coded and non-coded transmissions. Under our system model, we find that the network-coding gain is a function of the diversity order. Moreover, when there are infinitely many nodes, we show that the network coding gain approaches $0.25\epsilon^{-1}$.

Ⅰ. Introduction

There are many obstacles that prevent reliable wireless communications, which limit the system performance severely. On the other hand, people have started to exploit the characteristics of wireless communications, a representative example being the use of broadcasting. Wireless signals propagate in all directions, and nodes within the transmission range can overhear the signal. Such a phenomenon enables each node to transmit its signal in multiple destinations.

A protocol that utilizes the broadcasting characteristics is network coding[1]. The idea of

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network coding was motivated by the opportunity to enhance the throughput of multicast wired network [2], [3]. Since then, researchers have tried to quantify the gain of network coding in wireless networks. In two studies [4] and [5], the authors calculated the diversity order of network coding in a two-way relay channel. In [6], the authors proposed a network-coded cooperation scheme and numerically showed the superiority of network coding over repetition or space-time coded transmission schemes. In [7] and [8], the authors analyzed the throughput of network-coded ALOHA scheme in a two-hop relay system and compared it to the slotted ALOHA scheme. In [9], Katti et al. suggested practical protocols that implement network coding in real wireless networks. In [10], Hwang and Kim analyzed the performance of the network coding in CSMA/CA based wireless networks.

In most earlier works in this area, wireless network coding is utilized to save transmission time slots [9], [10] or to distribute large content files to multiple nodes [11]. On the other hand, network coding can be combined with retransmission (e.g., ARQ). Two papers, [12] and [13], dealt with this issue with one source and n destinations. In [12], the authors showed that the gain when using network-coded retransmission increases with the number of nodes. The authors in [13] proved that the expected number of retransmissions scales down on the order of $\Theta(\log n)$ by network coding.

The main purpose of this paper is to derive the gain of network coding, when it is used for retransmissions. Compared to earlier work [11] and [12], we take into account the outage probability requirement as a constraint. To this end, we start by deriving the outage performance of the network-coded system and then analyzing the diversity order as a function of the number of nodes. In [14], the authors proved that the maximum diversity order of a network-coded retransmission is $m+1$, where m is the number of nodes. However, we find that the maximum diversity order is achieved only when full overhearing arises, in which all nodes should take part in overhearing the transmitted signal. On the other hand, if a node can choose whether or not to listen, the diversity order is reduced to 2. From the outage probability, we analyze the ϵ-outage capacity, the maximum achievable throughput guaranteeing the ϵ-outage probability. The network-coding gain is defined as the ratio of the ϵ-outage capacity between network-coded and non-coded transmissions. We derive upper and lower bounds of the network-coding gain. We find that the upper bound is a function of the number of nodes and the outage probability constraint ϵ. Moreover, as the number of nodes increases, the upper bound finally converges to $0.25/\epsilon$. On the other hand, the lower bound is $1/2$.

The rest of this paper is organized as follows: In Section II, our system model is introduced. In Section III, we derive the outage probability, diversity order and the gain of network-coded transmissions. Finally, we conclude the paper in Section IV.

Ⅱ. Introduction

Consider a wireless network with m active nodes, from N_1 to N_m and one terminal T.[1)] We assume a single-frequency radio network, where each node shares a common channel. Nodes cannot transmit and receive packets simultaneously. The system is time-slotted, in which a slot is allocated to one node at a time and where nodes access the wireless channel one after another. The size of one packet is R bits.

We focus on two consecutive time units, t and

1) The model is interpreted as the wireless system in which multiple nodes try to transmit their information to one destination.

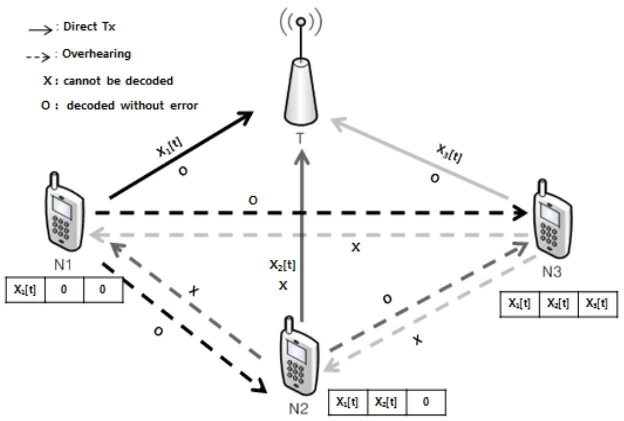

Fig. 1. An example of network-coded tran smissions ($m=3$) at the first time unit t. Each node transmits its packet to Terminal T (solid lines). When one node transmits, the others decide whether or not to overhear the signal according to the listening probability LP (dotted lines). Even if they overhear the signal according to the LP, it cannot be decoded when the channel condition is poor. Packets decoded without errors are stored in the buffer individually.

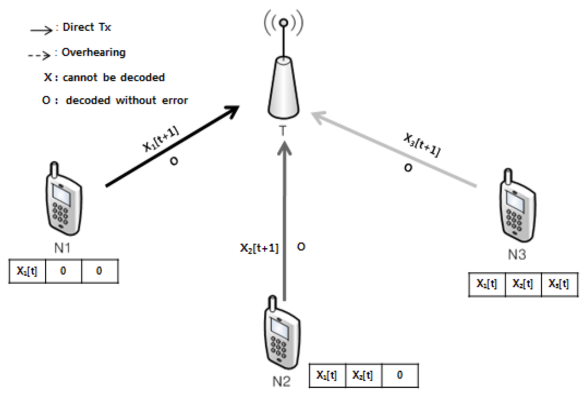

Fig. 2. An example of network-coded transmissions ($m=3$) at the second time unit $t+1$. The random coding vectors for each nodes are $[a_1, a_2, a_3]$, $[b_1, b_2, b_3]$ and $[c_1, c_2, c_3]$. Each node generates a random network-coded packet and transmits it to T. The terminal T constructs a set of linear equations, which is solvable when the rank of the C matrix is three (m).

$t+1$. Within each time unit, all m nodes transmit to T in a TDMA pattern. Figures 1 and 2 illustrate an example of a network-coded transmission for two consecutive times t and $t+1$. During the first time slot t, a node (excluding the transmitting node) $j \in \{N_1, \ldots, N_m, T\}$ receives

$$y_{i,j}[t] = h_{i,j}[t]x_i[t] + n_{i,j}[t], \qquad (1)$$

where $h_{i,j}[t]$, $x_i[t]$ and $n_{i,j}[t]$ denote the channel coefficient, the signal and the noise from transmitter i. We assume that every distance between any two nodes is identical to one and the term $|h_{i,j}[t]|^2$ is exponentially distributed with a mean of 1. The noise $n_{i,j}[t]$ is AWGN with $N(0, N_0)$. Whether each node in $\{N_1, \ldots, N_m\}$ (except thetransmitting node) overhears the transmitted packet or not is determined by the listening probability LP. Each node decides to listen to the signal with probability LP and to shut down with probability $1-LP$. Even if one node decides to overhear the signal with probability LP, the transmitted signal cannot be decoded due to the poor channel condition. If nodes decode the overheard packet without errors, they will store it in their buffers.

In the second time unit $t+1$, each node retransmits multiple received packets simultaneously by utilizing the network coding. The node, $j \in \{N_1, \ldots, N_m\}$ linearly combines the decoded packets and its own transmitted packet in time unit t using a random coding vector [13]. The random coding vectors of all nodes are obtained from a finite Galois field $GF(v)$ of the order v. In the header of the coded packet, the reception results at time t and the index of the random coding vector are contained. Then, each node transmits the network-coded packets to terminal node T. Terminal node T constructs a linear equation, which is represented by a $2m$ by m matrix C, composed of ones, zeros and the coefficients of the random coding vectors. In the matrix, the first m lows are for the direct transmissions at time unit t, constituting a m by m diagonal sub-matrix, in which the diagonal elements are either zero (error) or one (success) depending on reception results at time slot t. The last m lows are for the network-coded transmission at time $t+1$, where the elements are zero (error) or the coefficient of the random coding vectors (success) depending on overheard results of each node at time t, which are contained in each header and the reception results at time $t+1$. Let us define $[a_1, a_2, a_3]$, $[b_1, b_2, b_3]$ and $[c_1, c_2, c_3]$ as the random coding vectors of N_1, N_2 and N_3 in Figure 2. The following equation denotes the C matrix of the example shown in Figures 1 and 2:

$$\begin{bmatrix} 0\,0\,0 \\ 0\,0\,0 \\ 0\,0\,1 \\ a_1\ 0\ 0 \\ b_1\ b_2\ 0 \\ 0\ c_2\ c_3 \end{bmatrix} \begin{bmatrix} x_1[t] \\ x_2[t] \\ x_3[t] \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ x_3[t] \\ a_1 x_1[t] \\ b_1 x_1[t] + b_2 x_2[t] \\ c_2 x_2[t] + c_3 x_3[t] \end{bmatrix}$$

The terminal T obtains packets from $\{N_1, \ldots, N_m\}$ by solving linear equations, when the matrix C has the full rank. Otherwise, a system outage occurs. In other words, a system outage occurs when an un-decoded packet exists.

It is known that the network coding enhances the network capacity by reducing the number of transmissions [9], [10]. In our system, however, the number of transmissions rather increases because network coding is utilized for error recovery. Errors that may occur during a direct transmission at time t are recovered by the network-coded transmission at time $t+1$.

Ⅲ. OUTAGE PROBABILITY ANALYSIS OF NETWORK-CODED TRANSMISSION

3.1. System Outage Probability

Let us define the link success probability, p, as the probability that a transmission is successful given the target data rate R:

$$\begin{aligned} p &= \Pr\left[\frac{1}{2}\log_2\left(1+|h_{i,j}|^2 SNR\right) \geq R\right] \\ &= \exp\left[-\frac{2^{2R}-1}{SNR}\right], \end{aligned} \qquad (2)$$

where the term $1/2$ represents the time delay by two transmissions and SNR denotes the transmission power divided by the average received noise power N_0.

Let us assume that the order v of $GF(v)$ is high enough so that each row in C is independent according to the results in an earlier study [14]. With this assumption, a system outage does not occur when there are at least m non-zero rows and there is no zero column in C. The outage probability $P_{out}(m, LP, p) = \Pr[rank(C) < m]$ can be derived by $f(k;n,p)$ and $F(k;n,p)$, the probability mass function (PMF) and the cumulative distribution function (CDF) of a binomial distribution with parameters k, n and p:

$$\begin{aligned} &P_{out}(m, LP, p) = F(m-1; 2m, p) \\ &+ \sum_{k=m}^{2m} \sum_{i=k-m}^{m} \sum_{j=0}^{m-i} f(i;m,p) f\left(j; m-i, 1-(1-LP \cdot p)^i\right) \\ &\left\{ f(k-i;m,p) - \binom{i+j}{k-m+a} p^{k-i}(1-p)^{m-k+i} \right\} \end{aligned} \qquad (3)$$

The exact derivation of the outage probability (3) is in Appendix.

From numerical results, we find that the outage probability can be approximated by the CDF of the binomial distribution $F(m-1; 2m, p)$ when LP is one. Futhermore, when SNR is high enough $(p \approx 1)$, the CDF is approximated as follows:

$$\begin{aligned} F(m-1; 2m, p) &\approx f(m-1; 2m, p) \\ &= \binom{2m}{m-1}(1-p)^{m+1} \end{aligned} \qquad (4)$$

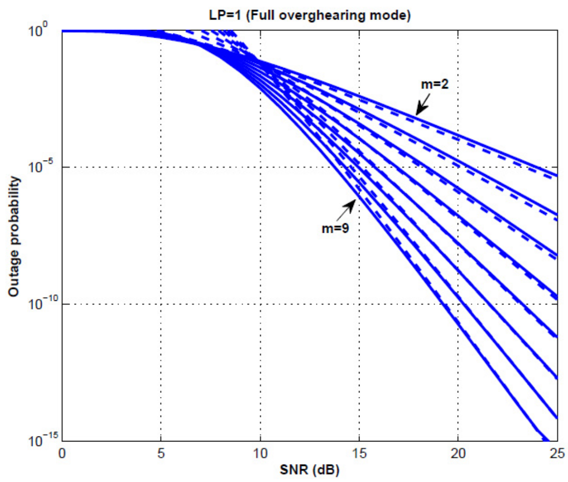

Fig. 3. The outage probability of network-coded transmission when there are various nodes ($2 \le m \le 9$) in the system. Solid lines here denote the exact outage probabilities and the dotted lines are the approximated outage probabilities (4).

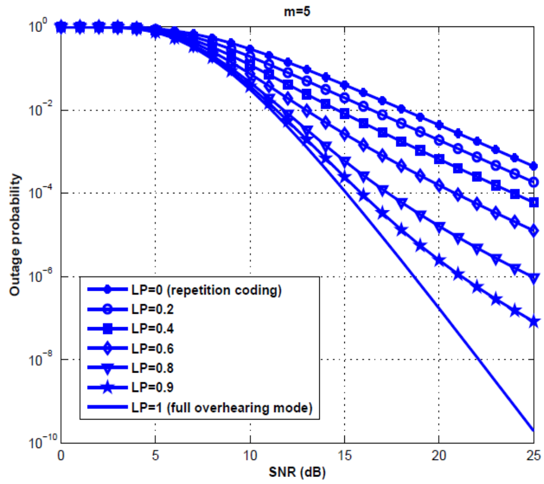

Fig. 4. The outage probability of an opportunistic network-coded transmission when LP varies from 0 to 1 $(m=5)$

3.2. Diversity Order of a Network-Coded Transmission

In [15], the authors defined the diversity order as a measure how fast the outage probability decreases when the SNR is high enough:

$$d \equiv -\lim_{SNR \to \infty} \frac{\log_2 P_{out}(m, LP, p)}{\log_2 SNR} \quad (5)$$

The diversity order is determined by the dominant SNR order of the outage probability. We make the following proposition:

Proposition 1. With full overhearing $(LP=1)$, the diversity order of the network-coded transmission is $m+1$.
Proof. See Appendix.

Fig. 3 shows the outage probabilities of the network-coded transmissions when LP is one. In the figure, the outage performance improves when m increases. In particular, we see that the slope of each curve is $m+1$. The diversity order is determined by the number of related links. The maximum number of links related to one packet is $m+1$ (two direct transmissions and $m-1$ network-coded transmissions). Our next question is how the diversity order is affected by LP.

Proposition 2. The diversity order of the network-coded transmission is 2 except for the full overhearing mode $(LP=1)$.
Proof. See Appendix.

Figure 4 shows how the outage probabilities when LP varies between zero and one. This figure shows that the diversity order of the full overhearing mode $(LP=1)$ is $m+1$, whereas for the others it is two. When LP is less than one, one packet on average receives an amount of help, represented by $(m-1)LP$ from the others. Some nodes may receive more than $(m-1)LP$ while others may receive less than $(m-1)LP$. That is, one node is likely not to receive any help from the others. Such a node has bad influence on the system outage probability, as those packets have only two related links.

3.3. The Gain of the Network-Coded Transmission

One question concerns whether utilizing

network coding is beneficial even though there is time-consuming caused by the two-phase transmissions (See Figures 1 and 2). To this end, we introduce the ϵ-outage capacity [16], the maximum transmission rate R under the constraint that outage probability is less than ϵ:

$$C_\epsilon(m,LP,\epsilon)=\max\{R: p_{out}(m,LP,p)\leq \epsilon\} \quad (6)$$

To analyze the ϵ-outage capacity, we utilize the approximated outage probability of (4). The condition that the outage probability (4) satisfies the outage constraint ϵ is:

$$p \geq 1-\sqrt[m+1]{\frac{\epsilon}{\binom{2m}{m-1}}} \quad (7)$$

We can find a sufficient condition of the target rate R, which satisfies the ϵ-outage capacity from (2) and (7):

$$R \leq \frac{1}{2}\log\left[1-SNR\ln\left(1-\sqrt[m+1]{\frac{\epsilon}{\binom{2m}{m-1}}}\right)\right] \quad (8)$$

Hence, ϵ outage-capacity of the full overhearing mode, $C_\epsilon(m,1,\epsilon)$ of (6) is:

$$C_\epsilon(m,1,\epsilon)=\frac{1}{2}\log\left[1-SNR\ln\left(1-\sqrt[m+1]{\frac{\epsilon}{\binom{2m}{m-1}}}\right)\right] \quad (9)$$

Note that the ϵ outage-capacity of the direct transmission $C_d(\epsilon)$ is:

$$C_d(\epsilon)=\log_2[1-SNR\ln(1-\epsilon)] \quad (10)$$

From (9) and (10), we make the following definition.

Definition 1. (Network-coding gain) The network-coding gain is the ratio between the ϵ-outage capacity of network-coded and direct transmissions:

$$G=\frac{C_\epsilon(m,1,\epsilon)}{C_d(\epsilon)} = \frac{1}{2}\frac{\log_2\left[1-SNR\ln\left(1-\sqrt[m+1]{\frac{\epsilon}{\binom{2m}{m-1}}}\right)\right]}{\log_2[1-SNR\ln(1-\epsilon)]} \quad (11)$$

The term $\frac{1}{2}$ in (11) represents the time loss due to the network-coded retransmissions. In the following proposition, we find that the network-coding gain G (11) is a function of the number of nodes m and the outage probability constraint ϵ. The proof is in Appendix.

Proposition 3. The upper bound of the network-coding gain G are:

$$\sqrt[m+1]{\frac{1}{\binom{2m}{m-1}}}\frac{\sqrt{\epsilon}}{\epsilon} \quad (12)$$

As the number of nodes m increases, it asymptotically converges to $0.25\epsilon^{-1}$. On the other hand, the asymptotic lower bound is $\frac{1}{2}$.

Figures 5 and 6 show the network-coding gain G (11). When the quality of each wireless link is bad (low SNR), there is a significant gain even though the network-coded retransmission needs the twice of slots. In the direct transmission, the performance depends on each individual link. In the network-coded transmission, even when one node fails to transmit its packet, the others deliver it instead. When SNR becomes high, on the other hand, the network-coded retransmissions cannot improve the

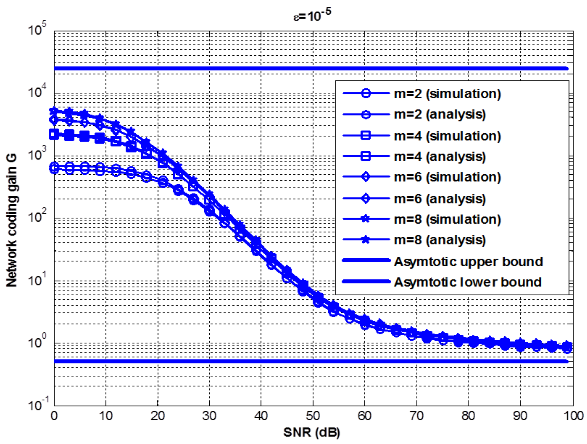

Fig. 5. The network-coding gain as a function of m

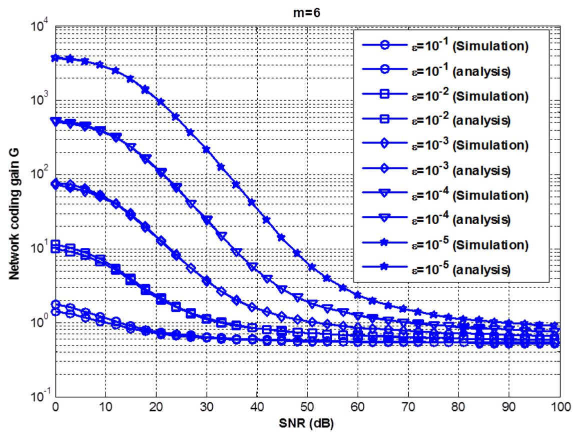

Fig. 6. The network-coding gain as function of ϵ

performance of the system (G is less than one). Without help from network coding, the quality of each direct link is good enough to decode the its packet without error.

According to Proposition 3, given the outage probability constraint ϵ, the upper-bound of network-coding gain (12) is a non-decreasing function of the number of nodes m (see Figure 5). As m increases, the maximum diversity order increases (Proposition 1). Due to the enhanced diversity order, terminal T can decode more packets and the system outage probability is reduced.

The outage probability constraint ϵ is another factor to explain the gain of network coding. The tighter the outage constraint is, the larger the network-coding gain is (See Figure 6). Due to the diversity effect, the network-coded system can achieve the outage probability requirement more easily than the direct transmissions.

Ⅳ. Concluding Remarks

In this paper, we utilized the network coding as a retransmission scheme for a random wireless network. To quantify the merit of the retransmission scheme, we defined the network-coding gain G as a measure how much network coding enhances the capacity of the wireless network for a given outage constraint. We derive theoretical upper and lower bounds of the network-coding gain G. Moreover, we found that G approaches to $0.25\epsilon^{-1}$, where the outage probability is less than ϵ and there are infinite nodes employing network coding. Despite the fact that network coding uses additional time resource, it can enhance the capacity by recovering errors efficiently.

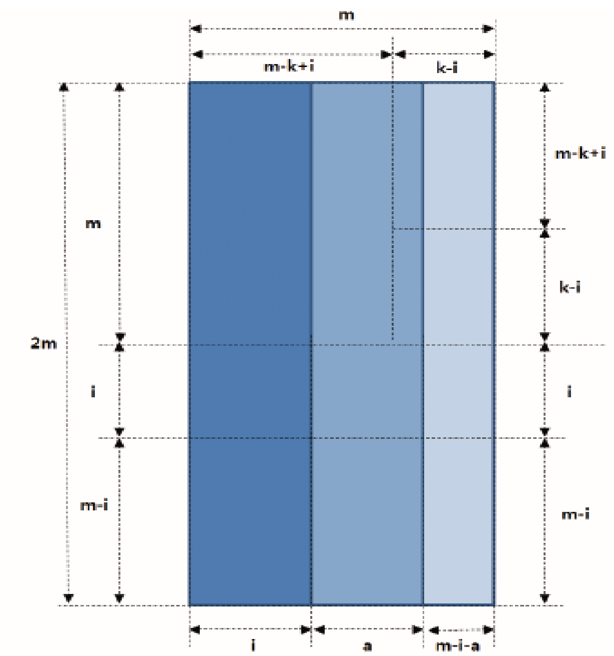

Fig. 7. A graphical presentation of the C matrix

V. Appendix

5.1. Derivation of the outage probability of a network-coded transmission

Within two consecutive units, there are $2m$ transmissions, out of which let us assume k transmissions are successfully received by the terminal, T. A necessary condition for the rank to be smaller than m is that k must not be less than m. This probability can be expressed by the CDF of the binomial distribution:

$$F(m-1;2m,p) \tag{13}$$

Given $m \le k \le 2m$, the full rank is achievable when there is no zero column in C. Figure 7 is a graphical presentation of the C matrix. Let us consider the last m rows in the C matrix. The event during which there are i successful transmissions in the second time unit, $t+1$, is equivalent to the event in which there are at least i non-zero columns in C (darkest box), as each transmission contains own packet with no overlap as regards any other transmissions in the second time slot. Due to the network-coding operation, these i transmissions can create additional non-zero columns. We denote a as the number of additional non-zero columns (light dark box).

$$f(i;m,p)f(a;m-i,1-(1-LP \cdot p)^i) \tag{14}$$

When at least one of the $m-i-a$ remaining columns is zero, the C matrix is not a full-rank matrix. Because there are $k-i$ successful transmissions in the first time unit, there are $\binom{m}{k-i}$ cases for the first time unit. The number of cases containing the remaining $m-i-a$ columns is as follows:

$$\binom{m-(m-i-a)}{k-i-(m-i-a)} = \binom{i+a}{k-m+a} \tag{15}$$

Therefore, the probability C does not have the full rank is:

$$\left\{\binom{m}{k-i} - \binom{i+a}{k-m+a}\right\} p^{k-i}(1-p)^{m-k+i} \tag{16}$$

The overall outage probability is obtained by multiplying (15) and (16) and adding the product to (14).

5.2. Proof of Proposition 1

Using the Taylor series extension, the link success probability (2) p is rewritten as follows:

$$p = 1 - \lambda \frac{2^{2R}-1}{SNR} + O(SNR^{-1}) \tag{17}$$

Using (17), the approximated outage probability (4) is expressed by

$$\binom{2m}{m-1}\left(\lambda \frac{2^{2R}-1}{SNR}\right)^{m+1} \tag{18}$$

Therefore, the diversity order of the full overhearing mode is derived as

$$\begin{aligned} d &= -\lim_{SNR\to\infty} \frac{C_1 - \log_2 SNR^{m+1}}{\log_2 SNR} \\ &= \lim_{SNR\to\infty} (m+1)\frac{\log_2 SNR}{\log_2 SNR} = m+1, \end{aligned} \tag{19}$$

where C_1 is $\log_2\left[\binom{2m}{m-1}\{\lambda(2^{2R}-1)\}^{m+1}\right]$.

5.3. Proof of Proposition 2

In the high-SNR regime, the outage probability (3) with opportunistic listening $(0 < LP < 1)$ is approximated as follows:

$$P_{out}(m,LP,p) \approx \sum_{r=0}^{m-1}\binom{2m}{r}(1-p)^{2m-r} + \sum_{k=m}^{2m}\sum_{i=k-m}^{m}\sum_{a=0}^{m-i} C_2\{(1-LP)^i\}^{m-i-a} \{1-(1-LP)^i\}^a(1-p)^{2m-k} \quad (20)$$

where C_2 is $\binom{m}{i}\binom{m-i}{a}\left\{\binom{m}{k-i}-\binom{i+a}{k-m+a}\right\}$. The dominant order of the first term is $m+1$. In the second term, when $k=2m-2$, the dominant order is 2. Therefore, the diversity order of $P_{out}(m,LP,p)$ is 2.

5.4. Proof of Proposition 3

For small ϵ, the asymptotic network-coding gain G (11) can be expressed as follows:

$$G \approx \frac{\frac{1}{2}\log_2\left[1+SNR\sqrt[m+1]{\frac{\epsilon}{\binom{2m}{m-1}}}\right]}{\log_2[1+SNR\epsilon]} \quad (21)$$

At small SNR, the network-coding gain is approximated as follows:

$$G \approx \frac{\frac{1}{2}SNR\sqrt[m+1]{\frac{\epsilon}{\binom{2m}{m-1}}}}{SNR\epsilon} = \sqrt[m+1]{\frac{1}{\binom{2m}{m-1}}}\frac{\sqrt{\epsilon}}{\epsilon} \quad (22)$$

When the number of nodes m increases to infinity, (22) converges to $0.25\epsilon^{-1}$. On the other hand, when SNR becomes higher, the network coding gain G is:

$$G = \frac{\frac{1}{2}\log_2(SNR)+\log_2\left(\sqrt[m+1]{\frac{\epsilon}{\binom{2m}{m-1}}}\right)}{\log_2(SNR)+\log_2\epsilon} \approx \frac{1}{2} \quad (23)$$

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