Exact Outage Probability of Two Nodes for Cooperative Networks using GF(4)

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***Abstract*—In wireless networks, advanced communication techniques exploited network coding and cooperative schemes have attracted considerable attention as ways to enhance power efficiency as well as to achieve high throughput and spectral efficiency. In this paper, we consider a cooperative wireless network with two nodes and one base station, and investigate the impact of using nonbinary network coding. We derive the exact and general outage probability in our network coding schemes, and obtain the approximation of the outage probability. We compare outage probabilities between exact and approximate results. We show that a full diversity order can be obtained using a nonbinary network code with GF(4) in the considered network.**

***Index Terms*—outage probability, nonbinary network coding, cooperative networks**

I. Introduction

Wireless fading is one of the underlying causes of performance degradation in wireless networks. One approach to overcome the fading problem is to increase the transmit power. A more advanced way is to exploit diversity techniques such as time, frequency, and space. Cooperative networking is a state-of-art technology that utilizes the spatial diversity via user cooperation. Each user takes a part in collaboration and shares the benefit of using a virtual antenna array in transmitting its information to a receiver that is available through another user's antenna [1].

In [2], Ahlswede et al. proved that the use of simply routing or replicating data in a single-source multicast scenario is not optimal approaches in terms of the flow rate. And they proposed network coding to enhance the flow rate. Many studies have since been performed to clarify that network coding provides advantages over the existing cooperative network schemes [3]-[6].

There are many studies about the analysis of outage probability in cooperative networks in [1], [7]-[12]. In [8], Chen et al. showed that binary network coding (BNC), based on the arithmetic of size 2 of a Galois Field, viz. GF(2), provides improved diversity gains and bandwidth efficiencies in wireless networks, where each user employs a simple decode-and-forward scheme with a perfect inter-user channel assumption. In practice, there exists a channel noise between users, as presented in [9], where the authors proposed an adaptive decode-and-forward scheme with BNC. It was recently shown in [10] that BNC is not optimal for achieving full diversity in a system of multiple users and relays. Using nonbinary network coding (NBNC) with GF(q) for $q > 2$, it was shown that a full diversity order can be achieved [10] and [11]. In addition, for aspects of power efficiency techniques, a couple of benefits of the use of NBNC has been found in [12] as expansion of deployment of source nodes without increasing transmit power.

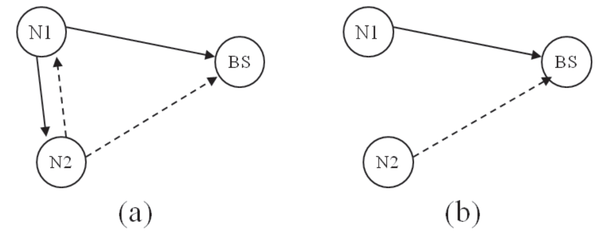


Fig. 1. Cooperative scheme; (a) broadcasting phase, (b) relay phase.

In this paper, we consider a cooperative wireless network, where there are two source nodes and one base station (BS) as shown in Figure 1. We investigate the impacts of using network coding. In [10], although Xiao and Skoglund have showed that the diversity order of NBNC is higher than that of BNC, their outage probability was obtained from a number of approximations: *i*) they did not consider all possible outage scenarios (for a full consideration see [7]), *ii*) all channel outages are treated the same with the same transmit powers, the same average channel gains, and thus the same average channel SNRs. In this work, however, we derive a general and an exact outage analysis framework with which we can investigate the impacts of field sizes in network coding, i.e., GF(2) vs. GF(4), transmit powers, transmission rates, and network topologies on the outage performance of the network. We thereby investigate the impact of different channel environments according to the different variances of channel gains. In addition, we show the approximation of the exact outage probability for both network coding schemes, and compare outage probabilities between exact and approximate results. We show that our approximations are well matched the exact ones in the high SNR region.

II. System Description

A. Cooperative Schemes

We consider a cooperative scheme for wireless networks as shown in Figure 1. There are two source nodes, called as node 1 (N1) and node 2 (N2), and two phases in the cooperative scheme, the broadcasting and the relay phase. In the broadcasting phase, source nodes N1 and N2 transmit their messages, S_1 and S_2, respectively. In the relay phase, when both nodes successfully recover the transmitted messages, the messages are re-encoded and then forwarded to the base station (BS). When a node does not achieve successful decoding, it instead repeats its message in the relay phase. When receiving repeated messages, the BS as a destination performs maximum ratio combining (MRC) of these messages, and recovers the transmitted messages. In this paper, we make the assumption that the transmission rate is selected to be sufficiently smaller than the capacity of each channel so that near perfect decoding of messages can be made with the use of a channel code. Thus, for all wireless channels, the received messages are either completely corrupted and not available at the receiving end, or considered error-free.

At the BS, the set of all possible received messages is $\{S_1,S_2,Z_1,Z_2\}$, where the subscript denotes the index of the transmit node. The first two messages are received in the first phase, and the two latter ones are the messages linearly combined and sent from the sources in the relay phase. The alphabet of the combined message, Z_1 and Z_2, is selected to be a finite field. The two finite fields considered in this paper are GF(2) and GF(4). In this paper, the combined messages Z_1 and Z_2 are generated for each network scheme as follows: *i*) for GF(2) as called *BNC*, $Z_1 = S_1 + S_2$ ad $Z_2 = S_1 + S_2$, *ii*) for GF(4) as called *NBNC-4*, $Z_1 = S_1 + S_2$ and $Z_2 = S_1 + 2S_2$, respectively. All arithmetic operations are performed over finite fields.

B. Channel Model

Our system consists of a multiple access channel network. In the broadcasting and relay phases, all source nodes transmit signals through orthogonal channels using time division multiple access or frequency division multiple access. The channels used in this paper are assumed to be spatially independent, flat faded, and perturbed by Additive White Gaussian Noise (AWGN). We further assume that the channel gains in both the broadcasting and the relay phase are mutually independent. The received signal at the *j*-th node is,

$$y_{i,j,k} = \sqrt{P_i} h_{i,j,k} x_{i,j,k} + n_{i,j,k}, \tag{1}$$

where k denotes the transmission phase, such as the broadcasting and relay phase, $k \in \{1, 2\}$, i denotes the transmitted node, i.e. $i \in \{1, 2\}$, namely N1 and N2. Let j denote the received node for $j \in \{1, 2, 0\}$, where "0" denotes the BS. The transmitted and received signals are given as $x_{i,j,k}$ and $y_{i,j,k}$ with $i \neq j$. P_i denotes the transmit power at the i-th node. The channel gain is represented by $h_{i,j,k}$, which consists of the fading term $p_{i,j,k}$ and the path-loss coefficient $q_{i,j,k}$, i.e., $h_{i,j,k} = p_{i,j,k} q_{i,j,k}$. Here, we assume that the fading term $p_{i,j,k}$ is random and the path-loss coefficient $q_{i,j,k}$ depends on the distance between nodes i and j. The noise $n_{i,j,k}$ is AWGN with a normal distribution $\mathcal{N}(0, N_0)$ with a zero mean and power spectral density N_0. The path-loss coefficient is modeled as $q_{i,j,k} = (d_0/d_{i,j})^{\alpha/2}$, where $2 \leq \alpha \leq 6$ is the path-loss exponent, $d_{i,j}$ is the distance between nodes i and j, and d_0 is the reference distance. In this paper, we use $d_0 = 1$ and $\alpha = 3$, $|h_{i,j,k}|$ is assumed to be Rayleigh distributed such that the channel energy of power $|h_{i,j,k}|^2$ is exponentially distributed. We assume that the fading term $p_{i,j,k}$ is complex valued Gaussian, independent and identically distributed Gaussian in each dimension with a zero mean and 1/2 variance. The average power of $h_{i,j,k}$ is then represented by the average power of $q_{i,j,k}$, which depends on the distance between the transmitter and the receiver. All channel gains are assumed to be reciprocal, i.e., $h_{i,j,k} = h_{j,i,k}$. The instantaneous SNR (signal-to-noise ratio) of each channel is denoted as $\gamma_{i,j,k} = |h_{i,j,k}|^2 P_i/N_0$, where P_i/N_0 is the transmit SNR at the source node i.

C. Outage Probability

The channel capacity as a function of the received SNR at the node j is given by

$$C_{i,j,k} = \log_2 (1 + \gamma_{i,j,k}), \tag{2}$$

where $C_{i,j,k}$ denotes the channel capacity from nodes i to j at the k-th transmission phase. In this paper, we use the single channel capacity as $C_{i,j,k} = \frac{1}{2} \log (1 + \gamma_{i,j,k})$ for each transmission phase since a factor of 2 is considered as the bandwidth expansion for each node in the cooperative scheme. A channel outage event occurs if the capacity is less than the transmission rate R, where R is the desired spectral efficiency in bits/s/Hz. For the Rayleigh fading channel, the outage probability is given and approximated at a high SNR in the following manner,

$$\begin{aligned} P_{out}(\gamma_{i,j,k}, R) &= \Pr\left\{\gamma_{i,j,k} < \left(2^R - 1\right)\right\} \\ &= 1 - \exp\left(-\frac{2^R - 1}{\Gamma_{i,j}}\right) \\ &\approx \frac{2^R - 1}{\Gamma_{i,j}}. \end{aligned} \tag{3}$$

where $\Gamma_{i,j} = \sigma_{i,j}^2 P_i/N_0$, is the average SNR at the receiver j, $\sigma_{i,j}^2$ is the variance of the channel gain $h_{i,j,k}$ which only depends on the distance such that $\sigma_{i,j}^2 = \sigma_{i,j,1}^2 = \sigma_{i,j,2}^2$ The outage probability $P_{out}(\gamma_{i,j,k}, R)$ is a function of the average SNR and the transmission rate. It is assumed that MRC is used at the BS for combining identical transmissions. For the case of MRC, the probability of an outage event is a function of two exponentially distributed random variables, which denote the instantaneous SNR for each channel. Thus, the outage probability for MRC at the BS is represented as $\Pr\left\{\gamma_{s,0,k} + \gamma_{r,0,k} < 2^{2R} - 1\right\}$, for $s, r \in \{1, 2\}$. The outage probability with two random variables is obtained from the following cumulative distribution function (CDF). Let $w := u + v$, where u and v are independent exponential random variables with parameters λ_u and λ_v. The CDF of the

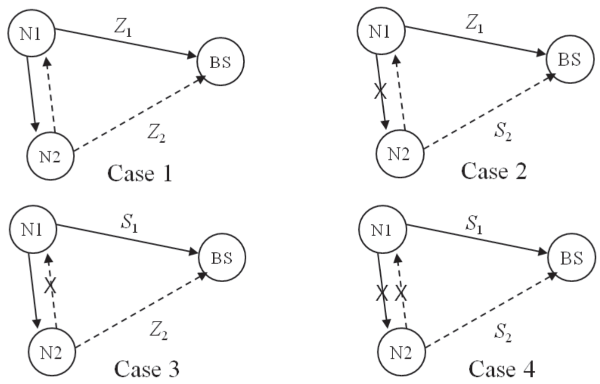


Fig. 2. Four cooperative scenarios for relay phase transmission based on the decoding results in the broadcasting phase.

random variable w is given by

$$P_w(w) = \begin{cases} 1 - \left(\left(\frac{\lambda_v}{\lambda_v - \lambda_u}\right) e^{-\lambda_u w} + \left(\frac{\lambda_u}{\lambda_u - \lambda_v}\right) e^{-\lambda_v w}\right), \\ 1 - (1 + \lambda w) e^{-\lambda w}, \quad \text{if} \quad \lambda_u = \lambda_v = \lambda. \end{cases} \tag{4}$$

III. Derivation on Outage Probability

In this section, we aim to derive the exact outage probability that allows us to investigate the impacts of different outage events, transmit power, channel gains, and field sizes in network coding, viz. BNC $vs.$ NBNC-4.

A. Outage Events in the Cooperative Network

In the broadcasting phase, both source nodes transmit their messages to the BS in an orthogonally multiplexed manner, and they can listen to each other's message. In the relay phase, the two source nodes conduct independently with no knowledge of whether their own broadcasted message was successfully decoded or not by their neighbor node. No feedback channel is assumed between the two nodes. As such, there are four possible cooperation scenarios depending on whether the decoding of messages was successful or not in the broadcasting phase. These four outage events are shown in Figure 2, and the four cooperative scenarios to each of the four outage events are denoted as Case 1, 2, 3, and 4, respectively.

In Case 1, both nodes successfully decode the partner's message. In the relay phase, each node linearly combines the neighbor's message with a network coding, and forwards the encoded message to the BS, resulting in a fully cooperative scenario. In Case 2, N1 successfully decodes the message from N2, but N2 does not successfully decode the message from N1. Hence, N1 combines the N2's message and forwards the re-encoded message to the BS in the relay phase in the same manner as in Case 1. However, N2 repeats its message in the relay phase. At the BS, the repeated messages are decoded by using the MRC strategy. Case 3 is similar to Case 2 where the only change is that the role of N1 is switched with that of N2. In Case 4, no node successfully decodes its neighbor's message in the broadcasting phase, and hence each node uses the available channel in the relay phase to just repeat its own message made in the broadcast phase. Thus, in this case, the system automatically reverts to a non-cooperative case. In our cooperative schemes, we assume that the base station knows which case out of the four cases has occurred. Next, we derive and evaluate the outage probability for the NBNC-4 scheme for each scenario.

B. Outage Probabability for NBNC-4 and BNC

In the following, we focus on the derivation of outage probability for the NBNC-4 scheme. First, network coding in the relay phase is performed. Message transmission consists of two phases as described in the previous subsection. We analyze the outage event based on MRC. In this work, we assume that the instantaneous SNRs for the broadcasting and for the relay phase are mutually independent. We consider the outage probability for N1, which is identical to that for N2 using the symmetric argument. We define the transmission rate for each node as R_1 and R_2.

Case 1: In this case, both nodes correctly decode each other's messages. Correct decoding events are defined as follows:

$$\{C_{1,2,1} > R_1\} \cap \{C_{2,1,1} > R_2\}. \tag{5}$$

We consider the outage events for Case 1. Suppose that transmitted messages in the broadcasting phase from N1 and N2 are not decoded successfully at the BS. This amounts to an outage event except when both of the combined messages with rates R_1 and R_2, respectively, are successfully decoded in the relay phase. In this case, the outage event can be determined as

$$\{C_{1,0,1} < R_1\} \cap \{C_{2,0,1} < R_2\} \cap \Big(\{C_{1,0,2} < R_1\} \cup \{C_{2,0,2} < R_2\}\Big). \tag{6}$$

In addition, consider the case where the transmitted message in the broadcasting phase from N1 is not decoded successfully, but the transmitted message in the broadcasting phase from N2 is decoded successfully. An outage occurs only when decoding of both messages in the relay phase fails. This outage event can be written as

$$\{C_{1,0,1} < R_1\} \cap \{C_{2,0,1} > R_2\} \cap \{C_{1,0,2} < R_1\} \cap \{C_{2,0,2} < R_2\}. \tag{7}$$

As a result, the outage probability of N1 for Case 1 can be obtained as

$$\begin{aligned} P^1_{NBNC-4} = {} & \Pr\{\gamma_{1,2,1} > r_1\} \cdot \Pr\{\gamma_{2,1,1} > r_2\} \cdot \\ & \Big(\Pr\{\gamma_{1,0,1} < r_1\} \cdot \Pr\{\gamma_{2,0,1} < r_2\} \cdot \\ & (1 - \Pr\{\gamma_{1,0,2} > r_2\} \cdot \Pr\{\gamma_{2,0,2} > r_2\}) \\ & + \Pr\{\gamma_{1,0,1} < r_1\} \cdot \Pr\{\gamma_{2,0,1} > r_2\} \cdot \\ & \Pr\{\gamma_{1,0,2} < r_1\} \cdot \Pr\{\gamma_{2,0,1} < r_2\}\Big) \end{aligned} \tag{8}$$

where we denote $r_1 = 2^{2R_1} - 1$ and $r_2 = 2^{2R_2} - 1$.

Case 2: In this case, N1 correctly decodes the message S_2 from N2, but N2 does not correctly decode the message S_1 from N1. This corresponds to the following events:

$$\{C_{1,2,1} < R_1\} \cap \{C_{2,1,1} > R_2\}. \tag{9}$$

According to the transmission protocol, the BS receives N2's message S_2 twice, and decoding is performed by MRC. Hence, the outage probability of N2 for MRC is obtained as

$$\begin{aligned}\Pr\{MRC_2\} &= \Pr\left\{\gamma_{2,0,1} + \gamma_{2,0,2} < 2^{2R_2} - 1\right\} \\ &= 1 - \left(1 + \frac{r_2}{\Gamma_{2,0}}\right)\exp\left(-\frac{r_2}{2\Gamma_{2,0}}\right).\end{aligned} \tag{10}$$

This outage event for the conditional case is

$$\Big(\{C_{1,0,1} < R_1\} \cap \{C_{1,0,2} < R_2\}\Big) \cup \Big(\{C_{1,0,1} < R_1\} \cap \{C_{1,0,2} > R_1\} \cap \{MRC_2\}\Big). \tag{11}$$

Thus, the overall outage probability for Case 2 is

$$\begin{aligned}P^2_{NBNC-4} = &\Pr\{\gamma_{1,2,1} < r_1\} \cdot \Pr\{\gamma_{2,1,1} > r_2\} \cdot \\ &\Big[\Pr\{\gamma_{1,0,1} < r_1\} \cdot \Big(\Pr\{\gamma_{1,0,2} < r_2\} + \\ &\Pr\{\gamma_{1,0,2} > r_1\} \cdot \Pr\{MRC_2\}\Big)\Big].\end{aligned} \tag{12}$$

Case 3: In this case, N2 correctly decodes N1's message S_1, but N1 cannot decode node 2's message S_2. The corresponding event is

$$\{C_{1,2,1} > R_1\} \cap \{C_{2,1,1} < R_2\}. \tag{13}$$

Using the same approach for Case 2, we obtain the overall outage probability as follows

$$\begin{aligned}P^3_{NBNC-4} = &\Pr\{\gamma_{1,2,1} > r_1\} \cdot \Pr\{\gamma_{2,1,1} < r_2\} \cdot \Pr\{MRC_1\} \\ &\cdot \Big(\Pr\{\gamma_{2,0,1} < r_2\} + \Pr\{\gamma_{2,0,1} > r_2\} \cdot \Pr\{\gamma_{2,0,2} < r_2\}\Big).\end{aligned} \tag{14}$$

The outage probability with MRC employed for N1 is

$$\begin{aligned}\Pr\{MRC_1\} &= \Pr\left\{\gamma_{1,0,1} + \gamma_{1,0,2} < 2^{2R_1} - 1\right\} \\ &= 1 - \left(1 + \frac{r_1}{\Gamma_{1,0}}\right)\exp\left(-\frac{r_1}{2\Gamma_{1,0}}\right).\end{aligned} \tag{15}$$

Case 4: Neither node decodes the message in the broadcasting phase correctly. The overall outage probability for Case 4 is

$$P^4_{NBNC-4} = \Pr\{\gamma_{1,2,1} < r_1\} \cdot \Pr\{\gamma_{2,1,1} < r_2\} \cdot \Pr\{MRC_1\}. \tag{16}$$

Next, the exact outage probability with NBNC-4 for N1 is obtained by adding the results so far, i.e., (8), (12), (14), and (16), as follows:

$$P_{NBNC-4} = P^1_{NBNC-4} + P^2_{NBNC-4} + P^3_{NBNC-4} + P^4_{NBNC-4}. \tag{17}$$

Using the high SNR approximation, the one given at the last line of (3), the outage probability can be approximated as follows:

$$P_{NBNC-4} \approx \frac{A_1}{P_1^2 P_2} + \frac{A_2}{P_1 P_2^2} + \frac{A_3}{P_1^3}, \tag{18}$$

where $A_1 = \frac{2r_1^2 r_2 N_0^3}{\sigma^4_{1,0}\sigma^2_{2,0}} + \frac{r_1^2 r_2 N_0^3}{2\sigma^2_{1,2}\sigma^2_{1,0}\sigma^2_{2,0}} + \frac{r_1^2 r_2 N_0^3}{2\sigma^2_{1,2}\sigma^2_{2,1}\sigma^2_{1,0}}$, $A_2 = \frac{r_1 r_2^2 N_0^3}{\sigma^2_{1,0}\sigma^4_{2,0}} + \frac{r_1 r_2^2 N_0^3}{\sigma^2_{2,1}\sigma^2_{1,0}\sigma^2_{2,0}}$, and $A_3 = \frac{r_1^2 r_2 N_0^3}{\sigma^2_{1,2}\sigma^4_{1,0}}$.

Similar to the analysis done in the NBNC-4 scheme, the outage probability analysis for BNC is done, which shows that the outage probabilities for BNC remain identical to those for NBNC-4, except for the first case, i.e., $P^2_{BNC} = P^2_{NBNC-4}$, $P^3_{BNC} = P^3_{NBNC-4}$, and $P^4_{BNC} = P^4_{NBNC-4}$. The reason for this is that the outage events, in each case of Case 2, Case 3, and Case 4, for the BNC scheme are identical to those of NBNC-4. The only difference comes from Case 1.

The outage probability of BNC for Case 1 is given by

$$\begin{aligned}P^1_{BNC} = &\Pr\{\gamma_{1,2,1} > r_1\} \cdot \Pr\{\gamma_{2,1,1} > r_2\} \cdot \Pr\{\gamma_{1,0,1} < r_1\} \\ &\cdot \Big(\Pr\{\gamma_{2,0,1} < r_2\} + \Pr\{MRC_1\} \cdot \Pr\{\gamma_{2,0,1} > r_2\}\Big).\end{aligned} \tag{19}$$

The exact outage probability of the BNC scheme is as again obtained by collecting the results

$$P_{BNC} = P^1_{BNC} + P^2_{BNC} + P^3_{BNC} + P^4_{BNC}. \tag{20}$$

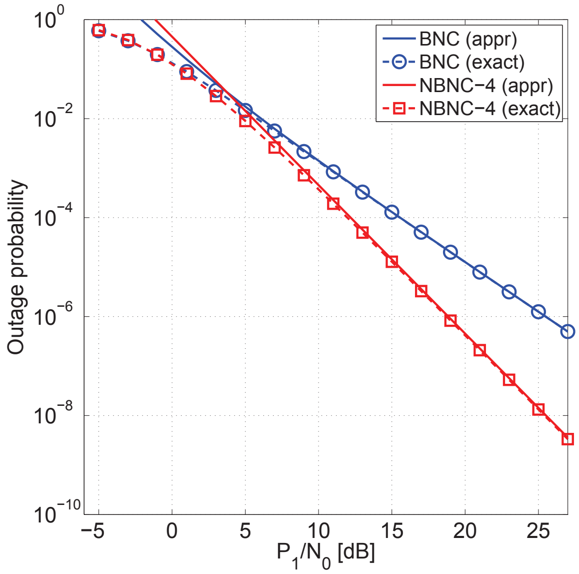
High SNR approximation is then given by

$$P_{BNC} \approx \frac{B_1}{P_1 P_2} + \frac{B_2}{P_1^2 P_2} + \frac{B_3}{P_1 P_2^2} + \frac{B_4}{P_1^3}, \tag{21}$$

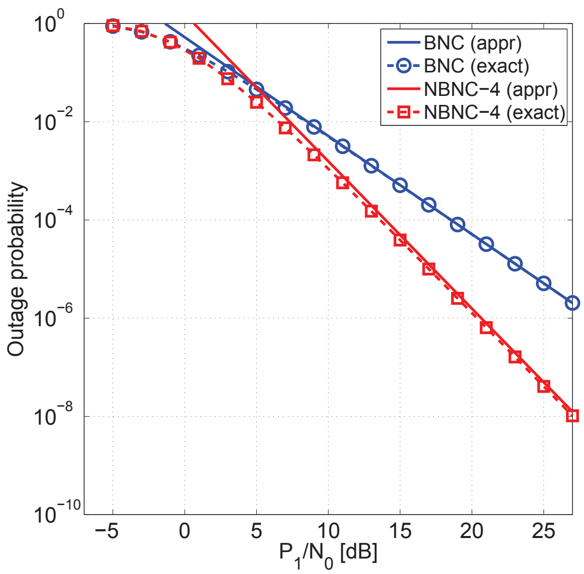
where $B_1 = \frac{r_1 r_2 N_0^2}{\sigma^2_{1,0}\sigma^2_{2,0}}$, $B_2 = \frac{r_1^2 r_2}{2\sigma^2_{1,2}\sigma^2_{1,0}\sigma^2_{2,0}} + \frac{r_1^2 r_2}{2\sigma^2_{1,2}\sigma^2_{2,1}\sigma^2_{1,0}}$, $B_3 = \frac{r_1 r_2^2 N_0^3}{\sigma^2_{2,1}\sigma^2_{1,0}\sigma^2_{2,0}}$, and $B_4 = \frac{r_1^2 r_2 N_0^3}{\sigma^2_{1,2}\sigma^4_{1,0}}$.

We evaluate the outage probability of N1 for both BNC and NBNC-4 schemes in terms of the average SNRs and the transmission rates R_1 and R_2. We show that the use of NBNC-4 provides improved outage probabilities compared to BNC for different channel environments. In Figure 3, we show evaluation results for which the benefits of network coding can be obtained at mid to high SNR regions. We compare the approximation version of outage probabilities and the exact ones in Figure 3. The both approximations (18) and (21) well match with the exact outage probabilities (17) and (20) in the high SNR region.

In order to investigate the impact of different channel gains, we assume that the transmit powers of both nodes are equal, $P_1 = P_2$, and use the same transmission rates $R_1 = R_2 = 1$ b/s/Hz. As shown in Figures 3, we investigate the effect of the noise variances. We can observe that the NBNC-4 scheme achieves a diversity order of 3, whereas a diversity order for the BNC scheme is 2. In Figure 3 (a), we set all noise variances as $\sigma^2_{1.0} = 1, \sigma^2_{1.2} = 8, \sigma^2_{2.0} = 8$. This means that the link quality between N2 and BS is better than N1-BS. Since the noise variance of the channel gain depends on the distance, the case of Figure 3 (a) reflects the channel environment where N2 is the middle of N1 and BS. In Figure 3 (b), we consider the case where N2 is located closer to N1, by setting $\sigma^2_{1.0} = 1$, $\sigma^2_{1.2} = 125$, and $\sigma^2_{2.0} = 2$ with the equal power allocation. Note that the diversity order for the three different schemes still holds.



(a)



(b)

Fig. 3. Outage probablities of two nodes for cooperative wireless networks with equal transmit power, i.e., $P_1 = P_2$, (a) $\sigma^2_{1,0} = 1, \sigma^2_{1,2} = 8, \sigma^2_{2,0} = 8, \sigma^2_{1,0} = 1, \sigma^2_{1,2} = 125, \sigma^2_{2,0} = 2$; (b) $\sigma^2_{1,0} = 1, \sigma^2_{1,2} = 8, \sigma^2_{2,0} = 8, \sigma^2_{1,0} = 1, \sigma^2_{1,2} = 125, \sigma^2_{2,0} = 2$

IV. Conclusions

In this paper, we investigated the impact of the size of finite fields for the linear network coding, GF(2) vs. GF(4). To evaluate the benefits of the increase of the field size, we derived the exact outage probability for the considered network coding schemes. We also obtained the approximation of the exact outage probabilities for both BNC and NBNC-4 schemes, showed that our approximation expressions are well matched the exact ones in the high SNR region. We then analyzed the diversity order for the both network coding schemes. Our results indicate that the diversity order using NBNC-4 is three, but that using BNC is only two. For future work, it will be meaningful to see if the proposed NBNC scheme can be extended to a larger scale network where a more number of nodes are involved in cooperative networks.

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