Power Control for Physical-Layer Network Coding in Fading Environments

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Abstract—In a three-node wireless relay network, two nodes, BS1 and BS2, exchange information through a relay node, RL. Suppose time division duplex is used, Physical Network Coding (PNC) uses two time slots for the information exchange instead of four time slots needed by the conventional method. In the first time slot, both BS1 and BS2 transmit simultaneously to RL. The relay node, RL does a PNC mapping based on the received signal and broadcast the mapped signal back to BS1 and BS2 simultaneously during the second time slot. The nodes, BS1 and BS2 are able to decode their desired information based on the received mapped signal and the signal which they had transmitted during the first time slot. In this paper, we analyze the average BER of the information exchanged between the two nodes in Rayleigh fading environments. We also derive the average BER of the mapped signal at the relay during the first time slot. With the derived BER of the mapped signal at RL, we propose to use power control at BS1 and BS2 to minimize the instantaneous BER of the mapped signal at RL. The proposed technique improves the BER of the desired information decoded at the two nodes. The solution turns out to be channel inversion based power control at both BS1 and BS2. The proposed power control technique improves both the average BER of the mapped signal at RL and the desired information at BS1 and BS2.

I. INTRODUCTION

In a three-node wireless network as shown in Fig. 1, two nodes, BS1 and BS2, have information to exchange. However, these two nodes may not have a direct link due to distance, shadowing etc. so that they have to use a relay node, RL, to transmit information to each other. There are various methods for the information to be exchanged and these methods can be classified based on the number of time slots each method uses. The most conventional way of getting the information exchanged is to use four time slots: Assume BS1 has modulated signal $S_1(n)$ to transmit to BS2 and BS2 has modulated signal $S_2(n)$ to transmit to BS1, we let BS1 transmits $S_1(n)$ to RL during the first time slot and then RL transmits $S_1(n)$ to BS2 at the second time slot. The node BS2 then transmits $S_2(n)$ to RL at the third time slot and RL transmits $S_2(n)$ to BS1 at the fourth time slot.

Network coding [1], which was first developed for wireline network, has been applied to wireless networks and is able to reduce the number of time slots used from four to three [2], [3]. This is done by transmitting $S_1(n)$ from BS1 to RL at the first time slot where RL decodes and demodulates $S_1(n)$ to its corresponding bit stream, $b_1(n)$. At the second time slot, BS2 transmits $S_2(n)$ to RL where RL decodes and demodulates $S_2(n)$ to its corresponding bit stream, $b_2(n)$. The relay node, RL combines $b_1(n)$ and $b_2(n)$ by a XOR operation: $b_r(n) = b_1(n) \oplus b_2(n)$. The bit stream $b_r(n)$ is then modulated to $S_r(n)$ where $S_r(n)$ is transmitted to both BS1 and BS2 simultaneously at the third time slot. Both BS1 and BS2 receive and decode $S_r(n)$ and subsequently demodulate it to $b_r(n)$. At BS1, the desired information $b_2(n)$ can be extracted from $b_r(n)$ by using $b_2(n) = b_r(n) \oplus b_1(n)$, where $b_1(n)$ is known at BS1. Similarly at BS2, $b_1(n)$ can be extracted from $b_r(n)$ and $b_2(n)$. Thus, the whole information exchange process only requires three time slots.

Wireless network coding can make use of the natural additive property of the electromagnetic waves to further reduce the number of time slots used to two. There are a few schemes to achieve that, namely Amplify-and-Forward (AF) [4], Denoise-and-Forward (DNF) [5] also known as Physical Network Coding (PNC) in [6], and Analog Network Coding (ANC) [7] etc. We briefly explain how wireless network coding can achieve the information exchange within two time slots by using the AF scheme. Both BS1 and BS2 transmit $S_r(n)$ and $S_r(n)$ respectively and simultaneously during the first time slot so that the received signal at RL is given by

$$y_r(n) = h_1 \sqrt{E_1} S_1(n) + h_2 \sqrt{E_2} S_2(n) + u_r(n), \quad (1)$$

where $h_1$ is the fading coefficient from BS1 to RL and vice versa, similarly, $h_2$ is the fading coefficient from BS2 to RL and vice versa. The transmission energies of BS1 and BS2 are $E_1$ and $E_2$ respectively and $u_r(n)$ is the additive white Gaussian noise at RL. The relay, RL, amplifies $y_r(n)$ by a factor $\beta$ and transmits $\beta y_r(n)$ to both BS1 and BS2 simultaneously during the second time slot. The received signal at BS1 is given by

$$y_{BS1}(n) = \beta h_1^2 \sqrt{E_1} S_1(n) + \beta h_1 h_2 \sqrt{E_2} S_2(n) + \beta h_1 u_r(n) + u_1(n), \quad (2)$$
where $n_1(n)$ is another additive white Gaussian noise at BS1. Since BS1 knows $S_1(n)$ and assuming it also knows $h_1$, $h_2$ and $\beta$, it is able to decode $S_2(n)$. Similarly, BS2 is able to decode $S_1(n)$ and the whole process only requires two time slots.

In [8], Denoise-aNd-Forward (DNF) has the highest achievable rates compared to the other schemes. Hence, in this paper, we will investigate the average BER performance of the DNF scheme in fading environments. We first derive the average bit error rate (BER) for using DNF under Rayleigh fading environments and then propose to minimize the instantaneous BER by power control. In the rest of the paper, we follow the terminology of [6] and use the term Physical-layer Network Coding (PNC) instead of DNF.

This paper is organized as follows. In Section II, we review the working principles of PNC. The analysis of the average BER performance of PNC is given in Section III. In Section IV, we propose a power control scheme to minimize the instantaneous BER of PNC. Section V gives the analysis of the average BER performance of PNC after using the proposed power control method. Performance evaluations are provided in Section VI and some conclusions are drawn in Section VII.

II. PHYSICAL-LAYER NETWORK CODING

This paper focuses on PNC and hence in this section, we give a brief review of the concept of PNC and how it achieves information exchange in two time slots. In the first time slot, both BS1 and BS2 transmit their information, $S_1(n)$ and $S_2(n)$, simultaneously to the relay, RL. The received signal of RL is given in (1) which is similar to the AF scheme. Let us consider the case in which BPSK modulation is used so that $S_1(n), S_2(n) \in \{-1, 1\}$, which correspond to $b_1(n), b_2(n) \in \{0, 1\}$. We assume the phases of the transmitted signals $S_1(n)$ and $S_2(n)$ are synchronized at the relay and also $|h_1| > |h_2|$ so that the signal constellation of the received signal $y_r(n)$ at the relay is the same as shown in the Fig. 2.

The parameter $\gamma$ in Fig. 2 denotes the decision boundary for mapping $S_r(n)$ where $S_r(n)$ is the information the relay transmits to both BS1 and BS2 during the second time slot. In this example, the mapping is performed as follows. When the received signal $y_r(n)$ falls within the decision boundary $[-\gamma, \gamma]$, we map $S_r(n) = 1$ and when $y_r(n)$ falls outside the decision boundary $[-\gamma, \gamma]$, we map $S_r(n) = -1$. Take note that the operation at the relay for PNC is a symbol level operation, where $S_r(n)$ is mapped symbol by symbol depending on $y_r(n)$, $h_1$ and $h_2$. This is different from conventional network coding which the operation at the relay is a bit level operation.

After $S_r(n)$ is mapped at the relay, the relay transmits the mapped signal $S_r(n)$ to both BS1 and BS2 simultaneously at the second time slot. We use $S_r(n)$ instead of $S_1(n)$ because, the mapping is done based on $y_r(n)$ which contains fading and noise terms, hence the mapped signal $S_r(n)$ can contain errors. We denote $S_r(n)$ as the desired error-free mapped signal at the relay while $S_r(n)$ is the actual mapped signal. Both BS1 and BS2 receive and decode $S_r(n)$ during the second time slot. The decoded signal, $S_r(n)$ at the BS nodes are used to obtain the desired information ($S_2(n)$ for BS1 and $S_1(n)$ for BS2). For example, BS1 is able to decode the signal $S_2(n)$ from $S_r(n)$ and $S_1(n)$ where $S_1(n)$ is known to BS1. We denote $S_2(n)$ as the desired error-free signal while $S_r(n)$ is the actual decoded signal at BS1. $S_2(n)$ is obtained by the following decision rules.

$$
S_2(n) = -1 \text{ when } \left(\hat{S}_r(n) = -1 \text{ and } S_1(n) = -1\right) \text{ or } \left(\hat{S}_r(n) = 1 \text{ and } S_1(n) = 1\right),
$$

$$
S_2(n) = 1 \text{ when } \left(\hat{S}_r(n) = 1 \text{ and } S_1(n) = -1\right) \text{ or } \left(\hat{S}_r(n) = -1 \text{ and } S_1(n) = 1\right).
$$

BS2 can obtain $S_1(n)$ in a similar way. The whole information exchange process using PNC is completed within two time slots.

III. BER PERFORMANCE OF PNC

We proceed to analyze the average BER performance of PNC. At BS1 (or BS2), we are interested in finding the average BER performance of the decoded signal $S_2(n)$ (or $S_1(n)$), under Rayleigh fading environments. In PNC, the decoded signal $S_2(n)$ at BS1 is extracted from the decoded signal $S_r(n)$ at BS1 using $S_1(n)$. Since $S_1(n)$ is completely known at BS1, the errors in $S_2(n)$ totally depend on $S_r(n)$. Hence, the average BER performance of the decoded signal $S_2(n)$ at BS1 is equivalent to the average BER performance of the decoded signal $S_r(n)$ at BS1.

There are two possible scenarios for an error to occur in the decoded signal $S_r(n)$ at BS1. In the first scenario, after the first time slot, errors occur during the mapping of $S_r(n)$. When this $S_r(n)$ is transmitted to BS1 at the second time slot, these errors are propagated to the decoded signal $S_r(n)$ at BS1. In the second scenario, the mapped signal $S_r(n)$ at the relay is error-free but the errors are introduced during the transmission of $S_r(n)$ to BS1 during the second time slot. The BER performance of the decoded signal $S_r(n)$ have to include errors from both scenarios and therefore, before we can derive the average BER performance of the decoded signal $S_r(n)$, we need to derive the average BER performance of the mapped signal $S_r(n)$ at the relay, which is shown in the next subsection.

$$
\begin{align*}
\langle S_r(n) = (-1, 1), (1, -1), (1, 1), (-1, -1) \rangle
\end{align*}
$$

Fig. 2. Signal constellation of received signal at the relay node.
A. BER Performance of \( \hat{S}_r(n) \) at the Relay Node

We analyze the average BER performance of \( \hat{S}_r(n) \) at the relay when the transmissions are done using BPSK modulation. We assume that the fading coefficients \([h_1]\) and \([h_2]\) follow Rayleigh distribution with \( \text{E}([h_1]^2) = P_1 \) and \( \text{E}([h_2]^2) = P_2 \). The transmission energies at BS1, BS2 and RL are denoted as \( E_1, E_2 \) and \( E_r \), respectively. In the first time slot, both BS1 and BS2 transmit their signals simultaneously and the received signal at RL is given by

\[
y_r(n) = h_1 \sqrt{E_1} S_1(n) + h_2 \sqrt{E_2} S_2(n) + u_r(n),
\]

where \( u_r(n) \) is the additive white Gaussian noise denoted as \( N(0, \sigma_r^2) \). We consider slow fading in our system model so \( h_1 \) and \( h_2 \) remain constant within the two time slots. When \([h_1] > [h_2]\), the signal constellation of \( y_r(n) \) is shown in Fig. 2 whereas for \([h_2] > [h_1]\), the symbols \((−1, 1)\) and \((1, −1)\) in Fig. 2 are exchanged. This however, will not change the mapping of \( S_r(n) \) since both \((−1, 1)\) and \((1, −1)\) map \( S_r(n) \) to ‘1’.

Next, we need to find out the value of the decision boundary \( \gamma \) for the mapping. The optimal boundary \( \gamma \) which minimizes bit errors is found by solving

\[
\exp(-\frac{1}{\sigma_r^2}(\gamma - A)^2) + \exp(-\frac{1}{\sigma_r^2}(\gamma + A)^2) = \exp(-\frac{1}{\sigma_r^2}(B - \gamma)^2) + \exp(-\frac{1}{\sigma_r^2}(B + \gamma)^2),
\]

which is equivalent to

\[
\frac{\cosh(\frac{A}{\sigma_r^2})}{\cosh(\frac{B}{\sigma_r^2})} = e^{\frac{1}{2}B - B^2}. \tag{5}
\]

It is clear that (5) is not in closed form. However, at high SNRs where both \( A \) and \( B \) are greater than \( 3\sigma_r^2 \), the value of \( \gamma \) will approach \( \frac{A + B}{2} \). Using \( \gamma = \frac{A + B}{2} \) as the decision boundary, the average BER caused by PNC mapping, which maps \( S_r(n) \) given \( y_r(n) \) at the relay is given by

\[
\text{BER}_{RL} \triangleq P_r(\hat{b}_r \neq b_r|y_{BS1}(n)) = \text{E}_{\lambda_{min}}[Q(\lambda_{min})] + \frac{1}{2} \text{E}_{\lambda_{min}, \lambda_{max}}[Q(2\lambda_{max} - \lambda_{min})] - \frac{1}{2} \text{E}_{\lambda_{min}, \lambda_{max}}[Q(2\lambda_{max} + \lambda_{min})]. \tag{6}
\]

where

\[
\lambda_{min} = \min\left([h_1] \sqrt{\frac{2E_1}{N_0}}, [h_2] \sqrt{\frac{2E_2}{N_0}}\right), \tag{7}
\]

\[
\lambda_{max} = \max\left([h_1] \sqrt{\frac{2E_1}{N_0}}, [h_2] \sqrt{\frac{2E_2}{N_0}}\right). \tag{8}
\]

The notation \( \min(x_1, x_2) \) (or \( \max(x_1, x_2) \)) denotes the smaller (or larger) value between \( x_1 \) and \( x_2 \). The notation \( b_r \) (or \( b_r \)) is the bit corresponding to the modulated signal \( S_r(n) \) (or \( \hat{S}_r(n) \)). \( \text{E}_x[\cdot] \) denotes the expectation operation over random variable \( x \) and \( Q(\cdot) \) denotes the Q-function.

We can simplify the equation for \( \text{BER}_{RL} \) by approximating it with the dominant Q-function term.

\[
\text{BER}_{RL} \approx \frac{1}{2} \left(1 - \frac{P_1P_2\gamma_1\gamma_2}{P_1P_2\gamma_1\gamma_2 + P_1\gamma_1 + P_2\gamma_2}\right). \tag{9}
\]

where \( \gamma_1 = \frac{E_1}{N_0} \) and \( \gamma_2 = \frac{E_2}{N_0} \). We will later show by simulation that removing the other two Q-function terms in (6) have little impact on the \( \text{BER}_{RL} \) since

\[
Q(\lambda_{min}) > \frac{1}{2}\{Q(2\lambda_{max} - \lambda_{min}) - Q(2\lambda_{max} + \lambda_{min})\}. \tag{10}
\]

B. BER Performance of \( \hat{S}_1(n) \) and \( \hat{S}_2(n) \)

After \( \hat{S}_r(n) \) has been mapped using PNC at the relay, it is broadcast to both BS1 and BS2 simultaneously at the second time slot. Both S1 and S2 decode \( \hat{S}_r(n) \) and the average BER performances of the decoded signal \( \hat{S}_1(n) \) at BS1 and BS2 in closed form are given in [9] which are

\[
\text{BER}_{S_1} \triangleq P_r(\hat{b}_r \neq b_r|y_{BS1}(n)) = \text{E}_{h_{min}}[Q(\lambda_{min})] \tag{11}
\]

\[
\text{BER}_{S_2} \triangleq P_r(\hat{b}_r \neq b_r|y_{BS2}(n)) = \frac{1}{2} \left(1 - \sqrt{\frac{P_1E_r}{N_0 + P_1E_r}}\right). \tag{12}
\]

As mentioned previously, the amount of errors in the decoded \( \hat{S}_2(n) \) is directly dependent on the amount of errors in \( \hat{S}_r(n) \). Hence, the average BER of the decoded \( S_2(n) \) at BS1 is given by

\[
\text{BER}_{S_1} \triangleq P_r(\hat{b}_r \neq b_r|y_{BS1}(n), y_r(n)) = \text{BER}_{RL} + \text{BER}_{S_1} - 2\text{E}[\text{BER}_{RL}\text{BER}_{S_1}]. \tag{13}
\]

Similarly, the average BER of the decoded signal \( \hat{S}_1(n) \) at BS2 is given by

\[
\text{BER}_{S_2} \triangleq P_r(\hat{b}_r \neq b_r|y_{BS2}(n), y_r(n)) = \text{BER}_{RL} + \text{BER}_{S_2} - 2\text{E}[\text{BER}_{RL}\text{BER}_{S_2}]. \tag{14}
\]

Fig. 3 shows the average theoretical BER performances given by (9) and (14) and their corresponding curves obtained from
The objective of (17) is maximized when $|h_1|\sqrt{E_1} = |h_2|\sqrt{E_2}$. Therefore, the corresponding solutions for $E_1$ and $E_2$ for the problem in (17) are given by

$$E_1 = \frac{2|h_2|^2\pi}{|h_1|^2 + |h_2|^2},$$

$$E_2 = \frac{2|h_1|^2\pi}{|h_1|^2 + |h_2|^2}.$$  

The above results turn out to be channel inversion based power control at both BS1 and BS2 nodes. It implies that $BER_{RL}$ can be reduced if we allocate the energies at BS1 and BS2 such that their received SNRs at the relay are equal.

Referring back to Fig. 2, the value of $B$ in the figure is zero given that $|h_1|\sqrt{E_1} = |h_2|\sqrt{E_2}$ after applying power control. There are now three possible received symbols instead of four as shown in the figure, with the symbol at zero having twice the prior probability compared to the symbols at $\pm A$. With this, we find the optimal boundary $\gamma$ again, by solving

$$\exp\left(-\frac{1}{2\sigma^2}(\gamma - A)^2\right) + \exp\left(-\frac{1}{2\sigma^2}(\gamma + A)^2\right) = 2\exp\left(-\frac{1}{2\sigma^2}\gamma^2\right),$$

and a closed form solution for $\gamma$ can be obtained as

$$|\gamma| = \frac{\sigma^2}{A} \cosh^{-1}\left(\exp\left(\frac{1}{2\sigma^2}A^2\right)\right).$$

V. BER PERFORMANCE OF PNC WITH POWER CONTROL

We now analyze the average BER performance of $\hat{S}_r(n)$ after applying the proposed power control with (18) and (19) and the optimal boundary (21). As mentioned in the previous section, the signal constellation has three possible received symbols after power control with $B = 0$ and $A = 2|h_1|\sqrt{E_1} = 2|h_2|\sqrt{E_2}$. The decision boundary has a closed-form representation but it looks complex with an inverse hyperbolic cosine function. However, when $A > 3\sigma^2$, the optimal boundary $\gamma$ is approximated as $\frac{\sigma^2}{A} \ln 2 + \frac{A}{2}$. Since we are more concerned with the BER at high SNR, we use $\gamma = \frac{\sigma^2}{A} \ln 2 + \frac{A}{2}$ in our BER analysis for $\hat{S}_r(n)$ with power control. We will later show by simulation that using the optimal boundary (21) does not result in deviations from the BER analysis which uses $\gamma = \frac{\sigma^2}{A} \ln 2 + \frac{A}{2}$ at the interested SNR regions.

The average BER caused by PNC mapping at the relay with power control using (18) and (19) with $\gamma = \frac{\sigma^2}{A} \ln 2 + \frac{A}{2}$ is found to be

$$BER_{RLp} = E_{h_1,h_2} \left[ Q\left(|h_1|\sqrt{\frac{2E_1}{N_o}} + \ln 2 \sqrt{\frac{N_o}{8E_1}}\right) + \frac{1}{2} E_{h_1,h_2} \right] + \frac{1}{2} E_{h_1,h_2} \left[ Q\left(|h_1|\sqrt{\frac{2E_1}{N_o}} - \ln 2 \sqrt{\frac{N_o}{8E_1}}\right) - \frac{1}{2} E_{h_1,h_2} \right] \left[ Q\left(|h_1|\sqrt{\frac{18E_1}{N_o}} + \ln 2 \sqrt{\frac{N_o}{8E_1}}\right) \right] \right].$$

Fig. 3. Theoretical and simulated BER performances of PNC.

IV. MINIMIZING BER OF PNC

In this section, we propose to minimize the instantaneous BER caused by PNC mapping at the relay through power control at BS1 and BS2. Since the received signal’s energy at the relay is a combination of the transmit energies of both BS1 and BS2, we investigate if controlling the value of $E_1$ and $E_2$ can give a better $BER_{RL}$ at the relay, and if it does, the amount of improvement it can offer. Obviously, the $BER_{RL}$ approaches zero when both $E_1$ and $E_2$ approach infinity. Hence, we constrain the total transmit energy to some finite value, $2\varepsilon$. Our aim is to

$$\min_{E_1, E_2} \quad BER_{RL}$$

$$s.t. \quad \frac{E_1 + E_2}{2} = \varepsilon. \quad (15)$$

From (9), the instantaneous $BER_{RL}$ can be approximated by $Q(\lambda_{min})$. Hence, we minimize $Q(\lambda_{min})$ in order to minimize $BER_{RL}$ and therefore (15) can be reduced to

$$\min_{E_1, E_2} \quad Q\left(\min\left(|h_1|\sqrt{\frac{2E_1}{N_o}}, |h_2|\sqrt{\frac{2E_2}{N_o}}\right)\right)$$

$$s.t. \quad \frac{E_1 + E_2}{2} = \varepsilon. \quad (16)$$

The $Q$-function is a monotonically decreasing function of its argument, hence the minimization of a $Q$-function is equivalent to maximizing the argument of the $Q$-function. The problem (16) is now equivalent to

$$\max_{E_1, E_2} \quad \min\left(|h_1|\sqrt{E_1}, |h_2|\sqrt{E_2}\right)$$

$$s.t. \quad \frac{E_1 + E_2}{2} = \varepsilon. \quad (17)$$

computer simulations. Both $E[|h_1|^2]$ and $E[|h_2|^2]$ are set to unity and we let $E_1 = E_2 = E_r = E_r$. It can be seen that the simulated BER performances match the theoretical results provided by (9) and (14) very well even though an approximation is made in (9).
Therefore, the average BER of the decoded signal \( \hat{S}_2(n) \) at BS1 with power control is then given by
\[
\text{BER}_{S2p} = \text{BER}_{RLp} + \text{BER}_{S_{1,2}} - 2E[\text{BER}_{RLp} \text{BER}_{S_{1,2}}].
\]  
(23)

Similarly, the average BER of the decoded signal \( \hat{S}_1(n) \) at BS2 with power control is given by
\[
\text{BER}_{S1p} = \text{BER}_{RLp} + \text{BER}_{S_{1,2}} - 2E[\text{BER}_{RLp} \text{BER}_{S_{1,2}}].
\]  
(24)

Figure 4 shows our theoretical BER results of (22) and (24) together with the simulation results. The optimal boundary (21) is used in the simulation with \( E_p = \varepsilon \). From the figure, the theoretical results match the simulation results very well and it proves the correctness of (22).

VI. PERFORMANCE GAIN

We now compare the average BER performance of \( \hat{S}_1(n) \) at BS2 with and without power control. We plot out the theoretical BER\( S_1 \) in (14) and BER\( S_{1p} \) in (24) in Fig. 5 with fading coefficients \( |h_1|^2 \) and \( |h_2|^2 \) having Rayleigh distributions with \( E[|h_1|^2] = E[|h_2|^2] = 1 \). The transmission energies of BS1 and BS2 are equal in the case without power control so that \( E_1 = E_2 = E_p = \varepsilon \), while the transmission energies for the power control case are given in (18) and (19) with \( E_p = \varepsilon \). From Fig. 5, we observe that there is around 1dB gain in the average BER by employing power control in the BS1 and BS2 nodes. This is because the errors caused by mapping \( S_r(n) \) at the relay has been reduced by the proposed power control scheme.

VII. CONCLUSION

In this paper, we have derived the BER performance of PNC under Rayleigh fading channels and its corresponding optimal boundary for the PNC mapping. We have proposed to minimize the instantaneous BER of the PNC by power control and derived the equations for the transmission energies of BS1 and BS2 in order to achieve that. The average BER performance of PNC under the suggested instantaneous power control are derived. We find that an improvement of about 1dB gain can be achieved by using the instantaneous channel inversion based power control.

REFERENCES