PLNC USING A MULTICHANNEL DFE RECEIVER AT THE RELAY FOR SHALLOW-WATER ACOUSTIC COMMUNICATIONS

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Abstract: *Two-way relay networks typically require three time slots to complete an end-to-end packet exchange. In contrast, utilizing physical layer network coding (PLNC) in such systems results in a capacity improvement since only two time slots are required for the same information exchange. However, using PLNC in underwater acoustic networks poses a challenge due to the frequency-selective nature of the underlying channels. In this paper we propose a denoise-and-forward (DNF) approach at the relay in conjunction with a linear antenna array and a pair of optimum decision-feedback equalizers to compensate for the channel dispersion. Simulation results show that for a relatively small number of antennas, the bit error rate performance is almost identical to that of a point-to-point frequency-selective channel system with one DFE equalizer and outperforms orthogonal frequency division multiplexing (OFDM) PLNC based systems under the same channel conditions.*

Keywords: *Underwater communications, Physical layer network coding, Frequency selective multipath channels, Optimum combining.*

1. INTRODUCTION

In underwater communication systems, the introduction of physical layer network coding (PLNC) results in not only a simpler design but also doubles the amount of packets transmitted. In PLNC, we aim at exchanging data packets between two end nodes through the aid of a relay. For this to happen in two time slots, the two signals need to be physically added and processed at the relay. In the second time slot or downlink phase, the sum is broadcasted back to the end nodes. Each end node can extract the desired message by subtracting its own stored data packet. Underwater channels are known to be frequency selective. In practice, there are two types of PLNC systems, amplify-and-forward (AF) and denoise-and-forward (DNF). In AF systems, the collected message at the relay is amplified and broadcasted back to the end nodes. In DNF systems on the other hand, the received signal is decoded and mapped to give an estimate of the exclusive OR (XOR) summation of the transmitted bits from both end nodes. By doing this, we are avoiding noise amplification that happens in AF-based system, and therefore, improved performance is obtained. However, the direct implementation of the DNF system is not possible in a frequency-selective environment. In this paper, we propose using a linear antenna array at the relay using optimum combining (OC). Using a multiple antenna relay for PLNC was proposed in [1] but for flat fading channels. OC uses space diversity to reduce interference by multiplying the signals from the antenna array by a set of coefficients. These are optimized to give the maximum signal-to-interference-plus-noise ratio (SINR). For equalization, the decision feedback equalizer (DFE) is used both in the end nodes and the relay, since it outperforms linear equalizers such as the minimum mean square error (MMSE) equalizer. Another implication of frequency-selective channels is the need for channel estimation. This requires the transmission of additional symbols or pilots. Perfect channel estimation is assumed for simplicity in this paper. After combining, equalizing and proper mapping, the signal at the relay is broadcasted back to the end nodes. At the end nodes, equalization is once again required due to frequency selectivity of the downlink channels. This is accomplished with one DFE at each end node.

2. SYSTEM MODEL

Consider a PLNC network consisting of a relay and two end nodes. End nodes are equipped with a single antenna, while the relay has a linear antenna array. The packet exchange cycle requires two phases, the uplink phase and the downlink phase. For both OC and null steering techniques, the antenna array consists of N elements with a constant distance d between them. The received signals at the antenna array will arrive at different time instants depending on the angle of arrival θ, which is measured between the direction of arrival and the broadside. If the signal is modulated with quadrature phase shift keying (QPSK), then these delays can be represented as phase shifts.

A. UPLINK PHASE

Let $\boldsymbol{U_1}$ and $\boldsymbol{U_2}$ be the signal propagation vectors from nodes 1 and 2, respectively, and let $\boldsymbol{W(k)}$ be the additive white Gaussian noise (AWGN) vector representing the random uncorrelated noise at each antenna. For simplicity, the signals are assumed to have equal power. Then the received signal vector at the relay $\boldsymbol{Y(k)}$ at time k will be

$$\boldsymbol{Y}(k) = \boldsymbol{U}_1 a(k) + \boldsymbol{U}_2 b(k) + \boldsymbol{W}(k), \tag{1}$$

where $a(k)$ and $b(k)$ are the received symbols from nodes 1 and 2 respectively. Let $\boldsymbol{A}(k)$ and $\boldsymbol{B}(k)$ represent the data symbol vectors received at time k from nodes 1 and 2, respectively. Then $\boldsymbol{A}(\mathrm{k}) = \boldsymbol{U}_1 a(\mathrm{k})$ and $\boldsymbol{B}(k) = \boldsymbol{U}_2 b(k)$.

For flat fading channels, the received signal at antenna i will be $y_i(k) = a_i(k)+b_i(k)+w_i(k)$. This can be written in matrix form as $\mathbf{Y}(k) = \mathbf{A}(k)+\mathbf{B}(k)+\mathbf{W}(k)$. Let $\boldsymbol{h}_1$ and $\boldsymbol{h}_2$ represent the two tapped delay-line channel vectors of length L_1 and L_2 respectively. These channels that arise from a multipath environment are assumed to be frequency selective. Then the received signal at antenna i will be

$$\mathrm{y}_i(k) = \sum_{m=0}^{L_1-1} h_1(m) a_i(k - m) + \sum_{m=0}^{L_2-1} \mathrm{h}_2(m) \mathrm{b}_i(k - m) + w_i(k). \tag{2}$$

This can also be written in matrix form as $\boldsymbol{Y}_i(k) = \boldsymbol{A}'(k) + \boldsymbol{B}'(k) + \boldsymbol{W}_i(k)$, where $\boldsymbol{A}'(k)$ is a vector collected from the first term of equation 2 for all values of i in a similar fashion to $\boldsymbol{A}(k)$. Similarly for $\boldsymbol{B}'(k)$, which is the collection of samples from the second term in equation 2. At the relay, OC is applied using vectors $\boldsymbol{V}_1$ and $\boldsymbol{V}_2$ as shown in figure 1.

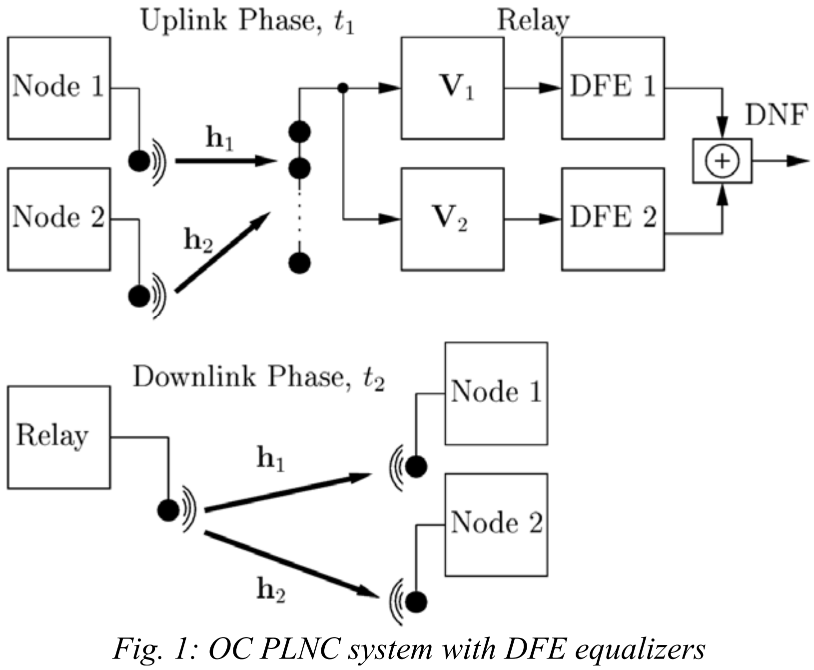

Fig. 1: OC PLNC system with DFE equalizers

B. RELAY OPERATION

Here we discuss the processing at the relay when either OC or null steering is used. OC is the method of choice in this paper and is used to design both $\boldsymbol{V}_1$ and $\boldsymbol{V}_2$. These vectors depend on the two direction of arrival angles θ_1 and θ_2 as explained in the following subsection. The next step is to remove the effect of multipath from each individual channel. One of the most efficient ways to do that is by using the optimum DFE equalizer. A separate DFE is placed for each channel. Although perfect channel estimation is assumed, the estimation error is small and can be neglected. A separate time overhead is required for each channel estimation and this is unavoidable. The input to DFE1 at time k will be the dot product between $\boldsymbol{Y}(k)$ and $\boldsymbol{V}_1$. The two estimated signals are then added. The whole uplink side is depicted in the upper side of figure 1.

B.1 *Optimum Combining:* OC uses space diversity to reduce multipath fading of the original signal and lower the power of interfering signals. This is done with the help of a linear antenna array. The received interference plus noise correlation matrix for the signal from the first node is

$$\boldsymbol{R}_{ww} = E[(\boldsymbol{W} + \boldsymbol{U}_2)^*(\boldsymbol{W} + \boldsymbol{U}_2)^T], \quad (3)$$

where (.)* denotes complex conjugate and $(.)^T$ denotes transpose. The normalized weighting vector for maximum SINR is then found to be [2]

$$\boldsymbol{V}_1 = \boldsymbol{R}_{ww}^{-1}\, \boldsymbol{U}_1^* \, . \quad (4)$$

The weighting vector for the second user $\boldsymbol{V}_2$ can be calculated similarly.

B.2 *Null Steering:* For the sake of comparison, the performance of null steering as a way of suppressing interference is investigated. In this technique, the weighting vector is designed so that the null is steered in the direction of the interference. The four most important techniques to achieve this are: null steering by real weight control (NSWC), null steering by controlling the element positions (NSEP), the CLEAN technique and null steering based on direction of arrival estimation (NSDOA) [3]. The most suitable of these for PLNC is the (NSWC) for many reasons including low computational complexity and the small number of required antennas amongst other things. It is also the method of choice in [3] where detailed comparisons are made. The NSWC method assumes all the weights to be real valued. For the purposes of comparison, we choose the number of elements to be $N = 3$ because we only need to steer one null. It is worth mentioning that $N = 7$ elements will be required to steer 3 nulls and it is clear that this is of no use in the case of PLNC under consideration. For 3 elements, the array factor F_a will be

$$F_a = (Z - Z_1)(Z - Z_1^*) = 1 + \beta Z + Z^2, \quad (5)$$

where β is the real weight that steers the null in the desired direction θ_r. β can be calculated as follows [3]

$$\beta = -(Z + Z_1^*) = -\cos\left(\alpha + \frac{2\pi}{\lambda} d \cos(\theta_r)\right), \quad (6)$$

where λ is the wavelength and α is the progressive phase shift [3].

B.3 *DFE Equalization:* In this section we will only consider the design of DFE1 as DFE2 can be designed in a similar way by replacing $\boldsymbol{h}_2$ instead of $\boldsymbol{h}_1$. Moreover, if the channels change in the downlink phase, then the DFE at each end node can be redesigned using the new estimated channel vector instead of $\boldsymbol{h}_1$. The DFE for each end node consists of a feedback FIR filter $\boldsymbol{f}$, of length N_{FF} whose taps are $[f(0), f(1), \ldots, f(N_{FF}-1)]$ and a feedback filter, $\boldsymbol{q}$ of length N_{FB} whose taps are $[q(1), q(2), \ldots, q(N_{FB})]$. Let $\boldsymbol{y}$ and $\boldsymbol{v}$ be the output observation vector and noise vector respectively. The observation covariance matrix $\boldsymbol{R}_y$ will be

$$\boldsymbol{R}_y = \sigma_s^2 \boldsymbol{H}\boldsymbol{H} + \sigma_v^2 \boldsymbol{I}_{Lp}, \tag{7}$$

where σ_s^2 and σ_v^2 are the signal and noise variances respectively and L_p is the length of the data packet. The toeplitz matrix $\boldsymbol{H}$ can be written as

$$\boldsymbol{H} = \begin{bmatrix} h_1(1) & h_1(2) & \cdots & h_1(L_1) & \cdots & 0 & 0 \\ 0 & h_1(1) & h_1(2) & \cdots & h_1(L_1) & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & 0 \\ 0 & 0 & \ldots & h_1(1) & h_1(2) & \ldots & h_1(L_1) \end{bmatrix}. \tag{8}$$

The desired feedback and feedforward filter coefficients will be

$$\boldsymbol{q}_{opt} = \frac{\boldsymbol{e}_0\, \boldsymbol{R}_d^{-1}}{\boldsymbol{e}_0\, \boldsymbol{R}_d^{-1} \boldsymbol{e}_0}, \tag{9}$$

$$\boldsymbol{f}_{opt} = \boldsymbol{q}_{opt} \boldsymbol{R}_{sy}\, \boldsymbol{R}_y^{-1}, \tag{10}$$

The full design equations can be found in [4]. It is worth noting that the uplink and downlink DFEs are both designed using (7)-(10).

C. DOWNLINK PHASE

One antenna at the relay is enough to broadcast the signal from the relay back to end nodes. This signal will once again suffer from the effect of the frequency-selective channels $\boldsymbol{h}_1$ and $\boldsymbol{h}_2$. For simplicity and without loss of generality, the channels are assumed to be fixed and have the same values from the uplink phase but this is not a necessary condition for the system to work. The lower part of figure 1 depicts the downlink phase. QPSK modulation and demodulation are used but they are omitted from the figure for simplicity. We will show in the coming section that a small number of elements N is required. This makes the computational cost of OC negligible and the overall complexity is approximately twice that of a single DFE at the relay.

3. SIMULATION RESULTS

Two underwater channels measured in the North Sea are used in the simulations. With the selection of these channels, the parameter values for the DFE design can be set starting with $L_1 = 29$ and $L_2 = 49$. In this case $N_{FF} > L$, where $L = \max(L_1, L_2)$ and $N_{FF} = 256$ taps was selected. For selecting N_{FB} and Δ, the following inequality must be satisfied [4]

$$\Delta + N_{FB} < N_{FF} + L_2. \quad (11)$$

Then N_{FB} is chosen to be 22 taps and Δ = 170. Extensive simulations using many different channels show that 4 antennas give a BER performance curve which is asymptotic to a single-hop channel with one DFE for the proposed OC-PLNC system.

Figure 2 shows the BER performances of OC-PLNC and NSWC-PLNC methods at the relay. For this, the following values were used, θ_1= 45, θ_2 = 135 and N = 3. The resulting BER curves in figure 3 show that OC at a BER of 10^{-3} has a better performance of approximately 2.2 dB over NSWC.

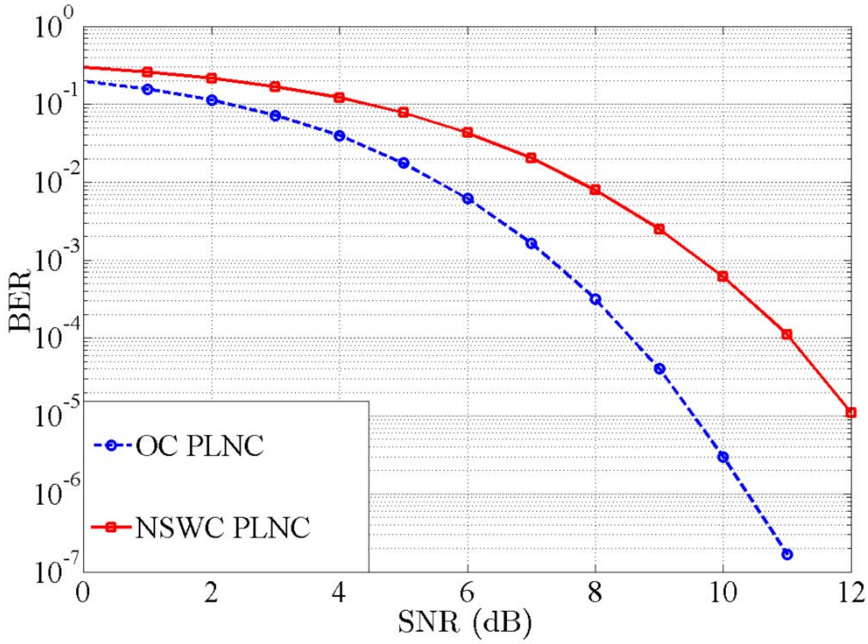

Fig. 2: Performances of OC-PLNC and NSWC-PLNC methods at the relay

4. CONCLUSIONS

In this paper, we propose a DNF PLNC to work in underwater environments. The design employs an antenna array containing a low number of elements with OC at the relay. The overall design is simple with low computational complexity as it uses FIR filters with a straight forward and non iterative design. Simulation results show that the OC PLNC clearly outperforms the null steering SNWC PLNC by at least 2 dB. The proposed DF PLNC has better performance than AF PLNC because it doesn't suffer from noise amplification.

4. REFERENCES

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