Physical Network Coding for OFDM in Two-Way Receiving Communications

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Abstract: This paper is related with the purpose of distributed coding in the multiple access (MA) phase for two-way relaying communication (TWRC) systems using OFDM. The error probability analysis is organized to establish the diversity and coding
Gains for three error categories in the MA phase. Then, the design decided of distributed coding to reaches the maximum diversity and coding gains are given. The frequency-grouped linear constellation precoding (F-GLCP) is first examined and shown not to be able to achieve the maximum diversity gain under type-3 errors. A novel frequency–time GLCP (FT-GLCP) that performs coding in both the frequency and time domains is then applied. It is proved that the proposed FT-GLCP is able to reaches the maximum diversity gain under type-3 errors while maintaining the maximum diversity and coding gains under type-1 and type-2 errors. To finding the theoretical analysis, simulation results are provided to show the advantage of the proposed FT-GLCP over other schemes in both Rayleigh and Rician fading channels.

I. INTRODUCTION

With the bidirectional transmission capability, two-way receiving communication (TWRC) systems has been recently secured a strong interest in research community. Different protocols are proposed and analyzed. In these papers, the two-slot protocol is shown to provide capacity advantage over the conventional four-slot protocol and the three-slot protocol, which is based on exclusive-OR (XOR) network coding. In the first slot of the two-slot protocol, the terminal nodes send their information to the receive node. This is also known as the multiple access (MA) phase. In the second slot, which is also called the broadcast (BC) phase, the receive node transmits the processed information back to the terminal nodes. In designing the two-slot protocol, there are two problems that need to be addressed. One problem is how to combine the discovered signals at the receive node. In particular, the authors in extend the decode *and forward* (DF) in one-way receive communications to TWRC in such a way that the relay broadcasts a linear combination of the discovered signals. In two versions of partial DF (PDF) relaying are studied. Since the activity of this paper is not on the design of a combining scheme, XOR-based network coding is assumed for its simplicity. The second problem is how to warrantee good detection quality in the MA phase. Two factors that influence the detection quality are MA interference and channel fading. To manage MA interference, denoise and forward (DNF) is applied, which maps the close constellation pair in the MA phase to the same constellation point in the BC phase and thus stops the influence of MA interference. Although, DNF has two main disadvantages: 1) high overhead in the BC phase to inform the denoising maps to the terminal nodes and 2) irregular constellation may need to be used in the BC phase, which would cause performance condition. Although, all of the schemes recently discussed are mainly designed to manage MA interference, and they do not work well when one or more channels from the terminal nodes to the receiving node are in deep fade. Exploiting diversity is an efficient way to minimize the influence of deep fading. In frequency-selective fading channels, multipath diversity is an important source of diversity gain. On the other hand, OFDM is often used in systems with frequency-selective fading channels because it is effective to combat inter symbol interference caused by frequency-selective fading. In point-to-point communication systems using OFDM, schemes exact multipath diversity gains have well examined. Among these schemes, coding-based schemes are simple to implement and able to reaches higher spectral efficiency compared with other schemes. The objective of this paper is to design a coding based scheme to efficiently exact the multipath diversity in TWRC systems using the two-slot protocol and OFDM. The design can also obtain cooperative diversity gain, which is effective to make less severe impact of the MA interference on the detection performance.

II. MODELLING OF THE SYSTEM

The TWRC system under consideration has two terminal nodes, denoted as nodes T1 and T2, which interchange their information by the help of receive node R. These information interchange happens in two phases. In the MA phase, both terminal nodes send their signal frames to the receive node. After processing the relayed signals, the receive node broadcasts a new signal frame in the BC phase. In the MA phase, the several path channel from terminal node Ti to relay node R is represented by vector $\boldsymbol{hi} = [hi(1), \ldots, hi(Li)]T$, where Li is the number of channel taps, $i = 1, 2$.The components of a channel vector follow a joint complex Gaussian distribution with mean $\boldsymbol{\mu hi}$ and covariance matrix Rhi . The square root of matrix $\boldsymbol{Rhi}$, which is denoted by $\boldsymbol{Bhi}$, is assumed to be full rank. Suppose that there are N subcarriers and M OFDM symbols in each signal frame. Let the mth OFDM symbol from terminal node Ti before coding be $\boldsymbol{si,m} = [si,m(1), \ldots, si,m(N)]T$ where each element belongs to a constellation set S. The whole information frame is expressed as $\boldsymbol{Si} = [\boldsymbol{si},1, \ldots, \boldsymbol{si},M]$], which contains $N \times M$ complex symbols. After coding is performed on the whole information frame, the mth OFDM symbol is expressed as $\boldsymbol{xi,m} = [xi,m(1), \ldots, xi,m(N)]T$. At the receive node, the mth received OFDM symbol in the frequency domain is denoted as $\boldsymbol{ym} = [ym(1), \ldots, ym(N)]T$. By letting $\boldsymbol{Xi,m} = \mathrm{diag}(\boldsymbol{xi,m}),\boldsymbol{Xi} = [\boldsymbol{Xi},1, \ldots, \boldsymbol{Xi},M]T$, and $\boldsymbol{y} = [\boldsymbol{y}T1, \ldots, \boldsymbol{y}TM]T$, one has

$$\boldsymbol{y} = \boldsymbol{X}1\boldsymbol{W}1\boldsymbol{h}1 + \boldsymbol{X}2\boldsymbol{W}2\boldsymbol{h}2 + \boldsymbol{\Omega}\mathrm{r} \quad (1)$$

where $\boldsymbol{\omega}\mathrm{R} \sim CN(\mathbf{0}MN, N0\mathbf{I}MN)$ is the additive white Gaussian noise vector at the receive node, and $\boldsymbol{Wi}$ is the $N \times Li$ truncated discrete Fourier transform (DFT) matrix with elements $\boldsymbol{Wi}(n, l) = \exp((-j2\pi(n-1)(l-1))/N)$. As usually, $N0$ is
the one-sided power spectral density of thermal noise at the terminal and receive nodes. By defining $\boldsymbol{X} = [\boldsymbol{X}1$ $\boldsymbol{X}2]$, $\boldsymbol{h} =$
$[\boldsymbol{h}T1\boldsymbol{h}T2]\ T$, then (1) can be rewritten as

$$y = XWh + \omega\mathrm{R}. \quad (2)$$

Let $X(\boldsymbol{S}1,\boldsymbol{S}2) = \boldsymbol{X}$ denote the mapping from the information frames $(\boldsymbol{S}1,\boldsymbol{S}2)$ to $\boldsymbol{X}$, which includes coding, diagonalization,
and combination of both terminal nodes signals, as recently described. Before closing this section, it is pointed out that the difficult of the ML detection in occurs to be high in general, but it is not the case when practical coding of OFDM signals is implemented. This is because with OFDM transmission, coding can be done jointly with subcarrier grouping. Specifically, the total N subcarriers are divided in $V = N/K$ disjoints groups such that each group has only K subcarriers, where K can be as small as the maximum number of multipath channel components, i.e., much smaller than N. coding is then performed independently across subcarriers in each group. For our presented FT-GLCP scheme, the search space of the ML detection minimizes to $SK{\times}2 \times SK{\times}2$.

III.PERFOMANCE ANALYSIS

As described in the previous section, precoding is performed in both the MA and BC phases. This section focuses on performance analysis of precoding in the MA phase. There are two reasons for this. First, in the MA phase, the detection quality is influenced not only by fading but also by MA interference due to simultaneous signal transmissions from two terminal nodes. MA interference causes the phenomenon of *distance shortening* and deteriorates the detection performance Therefore, the error probability in the MA phase is typically much higher than that in the BC phase since the latter is only
affected by fading. Second, as far as transmitting and detecting the network-coded signals are concerned, signal processing
in the BC phase is almost the same as that in point-to-point communication systems. As such, precoding design for the BC
phase can directly follow existing designs for point-to-point communication systems.

Referring to (2), let $\boldsymbol{e} = \{(\boldsymbol{S}1,\boldsymbol{S}2) \rightarrow (\boldsymbol{S}\_1,\boldsymbol{S}\_2)\}$,where $(\boldsymbol{S}1,\boldsymbol{S}2) = (\boldsymbol{S}\_1,\boldsymbol{S}\_2)$, denote the error event that the relay node decodes $(\boldsymbol{S}1,\boldsymbol{S}2)$ erroneously to $(\boldsymbol{S}\_1,\boldsymbol{S}\_2)$. Focusing on the case of Rayleigh fading, i.e., $\boldsymbol{\mu hi} = \mathbf{0}Li$, the channel response vector can be expressed as $\boldsymbol{h} = \mathrm{Bh}.\ \boldsymbol{H}$ where elements in $.\boldsymbol{h}$ are independent and identically distributed (i.i.d.) zero mean
Complex Gaussian variables with unit variance. By letting $X(\boldsymbol{S}1,\boldsymbol{S}2) = \boldsymbol{X}$, $X(\boldsymbol{S}\_1,\boldsymbol{S}\_2) = \boldsymbol{X}\_$, and $\boldsymbol{\Lambda e} = \boldsymbol{X} - \boldsymbol{X}\_$, the following upper bound on the conditional pair wise error probability (PEP) can be obtained .

IV. PRECODING DESIGN IN TWO WAY RECEIVING COMMUNICATION SYSTEMS

A. F-GLCP

In point-to-point communication systems with OFDM, F-GLCP was proposed to achieve the maximum diversity
and coding gains while maintaining acceptable complexity of the receiver. In F-GLCP, all N subcarriers are equally divided
into V disjoint groups with K subcarriers in each group. Linear constellation precoding (LCP) is performed separately in each group by using the following $Q \times Q$ rotation matrix as the precoding matrix.

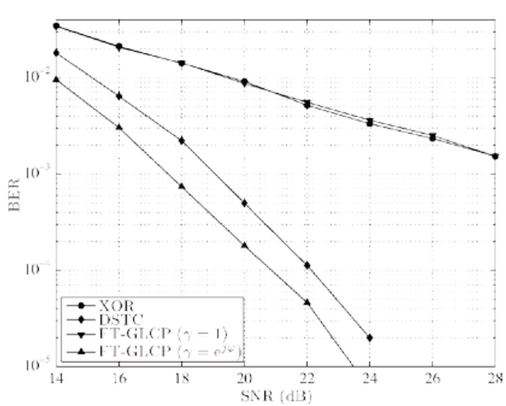
. If Q is a Euler number, i.e., $Q \in Q1 := \{\eta(Z) : Z = 0 \bmod 4\}$, where $\eta(Z)$ is the number of positive integers less than Z and relatively prime to Z, then $\{\alpha q\}$ are the roots of $\eta(x) =\_z{\in}Z(x - \exp(j2\pi z/Z))$, and $Z := \{1 \leq z \leq Z : \gcd(z,Z) = 1\}$.
• If Q is a power of 2, i.e., $Q \in Q2 := \{2z : z \text{ is an integer}\}$, then $\{\alpha q\}$ are the roots of $xQ - \sqrt{-1} = 0$.
• If $Q \in Q = Q1 \cup Q2$, then $\{\alpha q\}$ are the roots of $xQ - (1 + \sqrt{-1}) = 0$.
It is proved in [14] that if Q is larger than the number of channel taps, the maximum diversity gain is achieved. Furthermore,
.if $Q \in Q$, the maximum coding gain is achieved. Otherwise, if $Q \in Q$, at least 70% of the maximum coding gain is achieved.
In addition, to guarantee the maximum diversity and coding gains in a point-to-point Communication system, the indices of the K subcarriers belonging to the vth group are $Iv = \{v, V + v, \ldots, (K - 1)V + v\}$, i.e., *interleaved* subcarrier grouping.

V. Simulation Results

This section provides various simulation results to validate the analysis in previous sections. In all simulations, the size of fast Fourier transform is $N = 128$, the length of cyclic prefix is $Nc = 16$, and the number of OFDM symbols is $M = 2$. In addition, QPSK is taken as the modulation scheme for all nodes. All channels are assumed to be quasi-static fading and have the same number of channel taps. Both cases of flat fading ($Li = Pi = 1$) and frequency-selective fading with $Li = Pi = 2$
are tested, and the average norms of the channel vectors for all links are assumed to be unity. The size of the subcarrier group is set to be $K = 2$ for the case of frequency-selective fading channels. Let the transmitted power values of both terminals and the relay be the same as Pt. Given that the average power gains of all channels are set to unity, the received SNR is the same as the transmitted SNR, and it is defined as $Pt/N0$, where $N0$ is the one-sided power spectral density of thermal noise at the terminal and relay nodes. In addition, the performances are calculated in terms of both the terminal-to-terminal frame error rate (FER) and bit error rate (BER), which means that both the MA and BC phases are included in the simulation. For the MA phase, four schemes, namely, F-GLCP, FTGLCP, no coding, and DSTC, are compared. As previously explained, for the BC phase, the system model and signal processing is almost the same as that in the point-to-point communication system. As such, the F-GLCP scheme is applied in the BC phase of TWRC. It is pointed out that, with subcarrier grouping, only K instead of total N subcarriers are jointly coded.

Table: Diversity gains of physical coding schemes in the MA phase

	no pre.	DS TC	F-GLCP	FT-GLCP ($\gamma = 1$)	FT-GLCP ($\gamma = e^{j\varphi}$)
$\delta_{d,1}$	1	1	L_1	L_1	L_1
$\delta_{d,2}$	1	1	L_2	L_2	L_2
$\delta_{d,3}$	1	2	$\max(L_1, L_2)$	$\max(L_1, L_2)$	$L_1 + L_2$
	no pre.	DS TC	F-GLCP	FT-GLCP ($\gamma = 1$)	FT-GLCP ($\gamma = e^{j\varphi}$)
$\delta_{d,1}$	1	1	L_1	L_1	L_1
$\delta_{d,2}$	1	1	L_2	L_2	L_2
$\delta_{d,3}$	1	2	$\max(L_1, L_2)$	$\max(L_1, L_2)$	$L_1 + L_2$



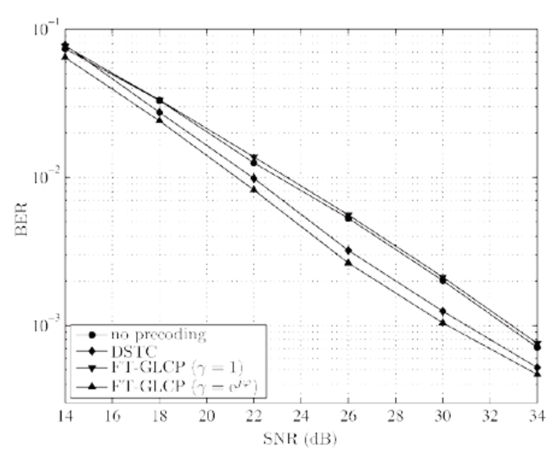
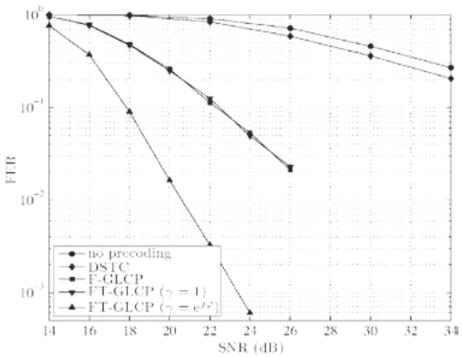


Fig1: BER performance for flat Rician fading channels channel

Fig2: BER performance for Rayleigh fading



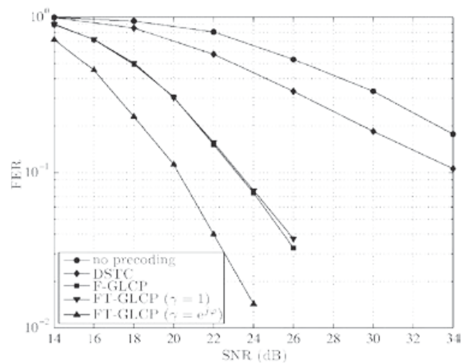


Fig3:FER performance frequency-selective Rician fading Rayleigh channel

Fig4:FER performance frequency-selective fading channel

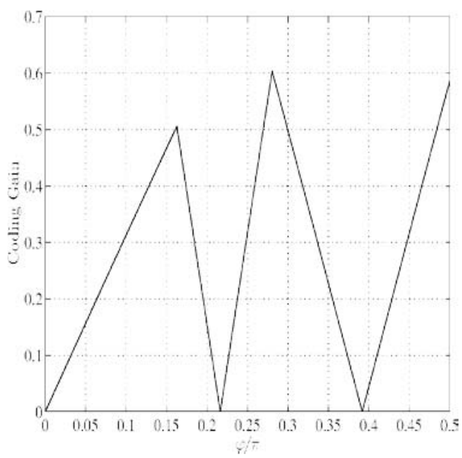


Fig5: Coding gain of flat Rayleigh fading channel

Fig1 shows the BER performances in the flat fading case1 ($L_i = P_i = 1$). According to Table I, in this case, all schemes have the same diversity gain of 1 under type-1 and type-2 errors. Under type-3 errors, DSTC and FT-GLCP ($\gamma = e^{j\phi}$) can achieve a higher diversity gain of 2, whereas no coding and F-GLCP schemes still have a diversity gain of 1. This is because in flat-fading channels, no multipath diversity gain is available. However, DSTC and FT-GLCP ($\gamma = e^{j\phi}$) can obtain extra diversity gain by combating MA interference using coding in the time domain. The modeling of the system in the MA phase can be viewed as a system with two antennas at the transmitter. By using DSTC or FT-GLCP ($\gamma = e^{j\phi}$), the maximum spatial diversity gain of 2 is achieved. Since this spatial diversity gain is actually obtained via the cooperation of the two terminal nodes, it can be considered as cooperative diversity gain. It is important to point out that the ability of FT-GLCP to provide cooperative diversity gain is only possible by using proper values for γ. For example, with $\gamma = 1$, FT-GLCP has the same diversity gain as that of using no coding. Figs.2 show that under Rayleigh fading channels, the advantage on diversity gain achieved by DSTC and FT-GLCP ($y=e^{j\phi}$) over other schemes is not exact. In contrast, as shown in Fig.3, under Rician fading channels, the diversity advantage reached by DSTC and FT-GLCP ($\gamma= e^{j\phi}$) is very clear. It is useful to summarize in Table I the diversity gains achieved by all schemes in the MA phase under comparison. Finally, simulation results are also provided for correlated channels. Specifically, the following correlation matrix is assumed for two-tap frequency-selective Rayleigh fading channels As expected, the FER and BER plotted in Figs.3 and 4 show that channel correlation will cause performance degradation. In addition, the performance superiority of the proposed FTGLCP ($\gamma = e^{j\phi}$) method over all other methods is also clearly observed for correlated frequency-selective Rayleigh fading channels.

V. CONCLUSIONS

The design of distributed precoding in TWRC systems using OFDM have studied in these paper. A novel FT-GLCP has been presented by minimizing the error probability in the MA communications phase. Compared with the no-precoding

scheme and the precoding scheme based on distributed space–time coding, the proposed scheme successfully utilizing multipath diversity gain to alleviate the influence of deep fading. In addition, compared with the scheme that employs
the conventional F-GLCP, the proposed scheme was shown to reaches the cooperative diversity gain under type-3 errors,
Whereas the F-GLCP cannot. Simulation results validated the theoretical analysis and showed the performance advantage of
the proposed scheme over other schemes.

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