Performance Comparison of Cooperative OFDM and SC-FDE Relay Networks in A Frequency-Selective Fading Channel

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Abstract— **Cooperative networking schemes provide spatial diversity gain (named cooperative diversity gain) using the antennas of spatially distributed users. Consistent research has been focusing on cooperative networks using orthogonal frequency division multiplexing (OFDM) and single carrier with frequency domain-equalization (SC-FDE). Coherent detection and frequency-domain equalization (FDE) require accurate channel estimation. In this paper, we present a performance comparison of cooperative OFDM relay network and cooperative SC-FDE relay network with pilot-assisted channel estimation. We consider a joint diversity combining and FDE in order to obtain a larger frequency diversity gain. When channel coding is used, cooperative OFDM relay network performs similarly to cooperative SC-FDE relay network in a frequency-selective fading channel.**

Keywords: cooperative relaying, SC-FDE, OFDM, channel estimation, MMSE.

INTRODUCTION

Wireless channel is characterized by multipath propagation environments which causes an inter-symbol interference (ISI). The ISI significantly degrades the system performance if it's left uncompensated. To cope with multipath propagation two techniques are available: (i) orthogonal frequency division multiplexing (OFDM) and (ii) single carrier with frequency domain equalization (SC-FDE) [1]. However, in wireless systems, the distance-dependent path loss and shadowing loss are present and they degrade the transmission performance significantly for the power limited systems. The use of multi-antenna techniques offers spatial diversity gain. Their application often encounters practical implementation problems when a larger number of antennas are to be deployed [2]. To overcome this problem, cooperative relaying was proposed [3]-[4]. Two transmission protocols have been studied: amplify and forward (AF) and decode-and forward (DF). In AF protocol, the relay amplifies the received signal and retransmits it without decoding, while in DF, the relay decodes, encodes and sends the signal to the next terminal.

In AF based transmissions, the direct channels from the source to the destination as well as the channels from the source to the relay and relay to the destination need to be estimated for coherent detection and frequency domain equalization of both OFDM and SC-FDE schemes. To date, there has been some work on cooperative schemes with pilot-assisted channel estimation (CE) [5]-[8], but the performance of both OFDM and SC-FDE with pilot assisted CE has not been presented. In [5], pilot-assisted CE schemes are investigated using linear minimum mean squared error estimation (LMMSE). In [6], a pilot-assisted CE scheme for the general case of AF relay networks with *N* relays is presented, where a small number of short pilot symbols are used. In [7], expectation-maximization (EM) based maximum a posteriori (MAP) CE is developed and compared with comp-type pilot-aided CE based maximum likelihood (ML) and LMMSE for space-time block coded OFDM systems. Least square (LS) algorithm and minimum mean square error (MMSE) algorithm are compared in [8]. However, to the best of author's knowledge a comprehensive performance comparison of cooperative relay network with practical CE based on OFDM and SC radio access using joint cooperative combining and equalization has not been presented yet.

In this paper, we present a performance comparison of cooperative relay network with practical CE based on OFDM and SC radio access using joint cooperative combining and equalization in a frequency-selective fading channel. At the destination terminal, a joint diversity combining and FDE is done to further exploit the spatial and frequency diversity gains. We evaluate the BER performance with pilot-assisted CE performed both at the destination and the relay terminals. We assume that the channel estimates are transmitted from the relay to the destination through higher layer protocol. The BER performances of both cooperative OFDM and SC-FDE relay networks with pilot-assisted CE are evaluated by computer simulation.

The remainder of this paper is organized as follows. Section II presents the network model. In section III, we present the pilot-assisted CE scheme. Simulation results and discussions are presented in Sect. IV. Section V concludes the paper.

NETWORK MODEL

In this paper, we will discuss the impact of channel estimation error and therefore, a frequency selective transmission channel, with no shading and no path loss is assumed. The channel is half duplex therefore the source-relay/destination and relay-destination transmissions must occur in different time slots, as illustrated in Fig.1. Throughout this paper, T_c spaced discrete-time signal representation is used, where T_c represents FFT sampling period. The transmission system model is illustrated in Fig. 2.

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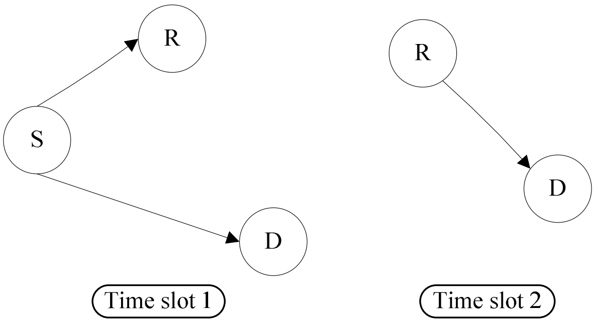


Fig. 1. Relay model.

A. Transmission System Model

The information bit sequence is channel coded and the encoded sequence is mapped to a complex-valued finite constellation such as quadrature phase shift keying (QPSK) modulation. The data-modulated symbol sequence is divided into a sequence of N_c-symbol blocks and fed to SC or OFDM modulator. Below, without loss of generality, we consider the transmission of one block of $\{d(n);\ n=0\sim N_c-1\}$ from the source to destination using cooperative relaying, having the property of $E|d(n)|^2=1$. The transmitted signal can be expressed using the equivalent low-pass representation as

$$s(t)=\begin{cases}\sqrt{P}d(t),\ SC\\ \sqrt{P}\frac{1}{\sqrt{N_c}}\sum_{n=0}^{N_c-1}d(n)exp\left(j2\pi t\frac{n}{N_c}\right),\ OFDM\end{cases}\tag{1}$$

for $t=0\sim N_c-1$, where P denotes the source transmit power. The cyclic prefix (CP) of length N_g samples is inserted into the guard interval (GI) placed in front of the data block and the signal is transmitted over a frequency selective fading channel.

The channel impulse response $h_{mn}(\tau)$ can be written as

$$h_{mn}(\tau)=\sum_{l=0}^{L-1}h_{mn,l}(\tau)\delta(\tau_l-n),\tag{2}$$

where $h_{mn,l}(\tau)$ and τ_l are respectively the path gain and time delay of the l-th path of the channel between the transmitter of node m and receiver of node n, where m and n are either s (source node), r (relay node), or d (destination node).

Time slot 1: The received signal at the destination can be expressed, using the frequency-domain representation, as

$$R_d^1(n)=\begin{cases}\sqrt{P}D(n)H_{sd}(n)+N_{sd}(n),\ SC\\ \sqrt{P}d(n)H_{sd}(n)+N_{sd}(n),\ OFDM\end{cases}\tag{3}$$

where $D(n)$ is the n-th subcarrier component of $\{d(n');\ n'=0\sim N_c-1\}$ for SC, $H_{sd}(n)$, is the channel gain between the source and destination, and $N_{sd}(n)$ is the noise component characterized by zero-mean complex-valued Gaussian variable having variance of N_0/T_c (N_0 is the single-sided AWGN power spectrum density).

The received signal at the relay can be expressed as

$$R_r^1(n)=\begin{cases}\sqrt{P}D(n)H_{sr}(n)+N_{sr}(n),\ SC\\ \sqrt{P}d(n)H_{sr}(n)+N_{sr}(n),\ OFDM\end{cases}\tag{4}$$

where $H_{sr}(n)$ is the channel gain between the source and relay, and $N_{sr}(n)$ is the noise component characterized by zero-mean complex-valued Gaussian variable having variance of N_0/T_c.

Time slot 2: The relay is assumed to amplify the received signal by a factor of $1/\sqrt{E[|R_r(n)|^2]/P}$ and forwarding it to the destination during the second time slot, where the transmit power at the relay is equal to the source transmit power.

At the destination, the received signal, in the frequency domain, can be given for both SC and OFDM as

$$R_d^2(n)=\sqrt{\frac{P}{1+N_0/PT_c}}\,H_{rd}(n)R_r(n)+N_{rd}(n),\tag{5}$$

where $H_{rd}(n)$ is the channel gain between the relay and destination, and $N_{rd}(n)$ is the noise component characterized by zero-mean complex-valued Gaussian variable having variance of N_0/T_c.

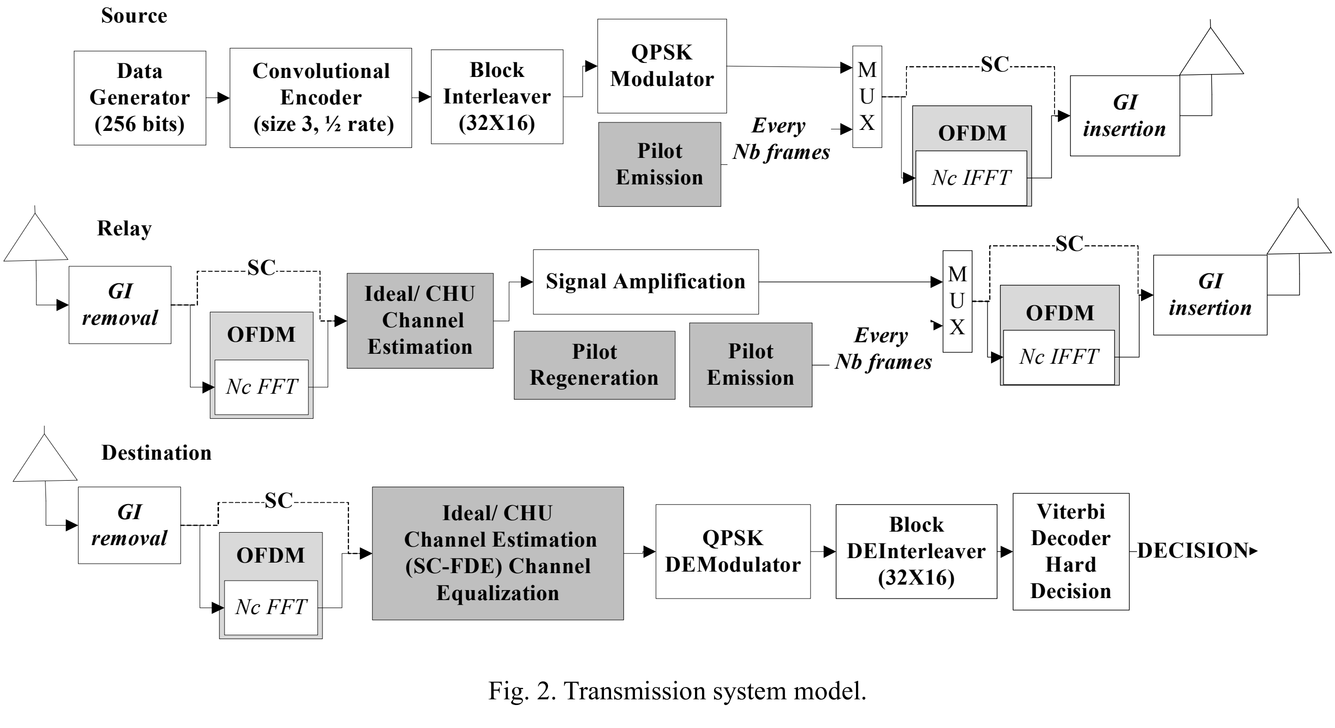


Fig. 2. Transmission system model.

B. Joint Diversity Combining and FDE

Joint diversity combining and FDE is used at the destination node to obtain a larger diversity gain. The destination combines the received signals during the two time slots based on MMSE criterion for SC (similar to [9]) and maximum ratio combining (MRC) for OFDM. The resulting frequency domain signal is represented as

$$R(n) = R_{sd}^{1}(n)w_1(n) + R_{rd}^{2}(n)\, w_2(n), \tag{6}$$

where $R_{d,j}(n)$ denotes the received signal and $w_j(n)$ the equalization weight for the received signal in the j-th time slot. These weights are given by

$$w_1(n) = \begin{cases} \frac{H_{sd}^{1*}(n)}{\left|H_{sd}^{1}(n)\right|^2 + \frac{N_0}{E_s}}, & SC \\ H_{sd}^{1*}(n), & OFDM \end{cases} \tag{7}$$

$$w_2(n) = \begin{cases} \frac{H_{sr}^{1*}(n)H_{rd}^{2*}(n)}{\left|H_{sr}^{1}(n)\right|^2\left|H_{rd}^{2}(n)\right|^2 + \left(\left|H_{sr}^{1}(n)\right|^2 + \left|H_{rd}^{2}(n)\right|^2 + 1\right)\frac{N_0}{E_s}}, SC \\ H_{sr}^{1*}(n)H_{rd}^{2*}(n), OFDM \end{cases} \tag{8}$$

where $()^*$ denotes the complex conjugate operation and E_s/N_0 the average data symbol energy to AWGN power spectrum density ratio, with $E_s = PT_c$.

The received combined signal is demodulated and the decision variables are decoded using Viterbi algorithm. We note here that channel gain estimates are required in Eqs. (7) and (8) to perform joint diversity combining and FDE. The channel gains are estimated as follows.

CHANNEL ESTIMATION

In this section we present a pilot-assisted CE scheme suitable for cooperative relay network.

Time slot 1: The source transmits the data to the relay and destination. Every N_b data blocks, a pilot sequence $p(t)$ is inserted between the data frames as shown in Fig. 3. The guard interval is added and the sequence is transmitted using SC or OFDM technique.

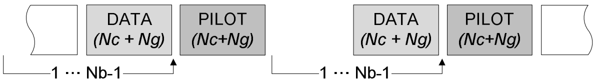


Fig. 3. Data and pilot frame insertion.

The relay receives the pilot $P(n)$, transmitted every N_b frames, and performs the estimation of the source-relay channel $H_{sr}^{1}(n)$ as

$$\widehat{H}_{sr}^{1}(n) = R_r^{1}(n)/P(n). \tag{9}$$

The noise power estimation can be done as

$$\sigma_{sr}^{1} = \frac{1}{N_c}\sum_{n=0}^{N_c-1}\left|\widehat{N}_{sr}^{1}(n)\right|^2 \tag{10}$$

where

$$\widehat{N}_{sr}^{1}(n) = R_r^{1}(n) - \widehat{H}_{sr}^{1}(n)P(n). \tag{11}$$

The destination receives the pilot sequences during the first time slot and performs channel and noise estimation respectively for the source-destination transmission

$$\widehat{H}_{sd}^{1}(n) = R_d^{1}(n)/P(n), \tag{11}$$

$$\widehat{N}_{sd}^{1}(n) = R_d^{1}(n) - \widehat{H}_{sd}^{1}(n)P(n). \tag{12}$$

The channel estimate and noise power estimate need to be forwarded to the destination to compute the FDE weights given by Eqs. (7) and (8).

Time slot 2: The relay is transmitting to the destination. The relay regenerates the pilot sequence to be transmitted to the destination.

The destination receives the pilot signals from the relay during the second slot and performs the estimation of the relay-destination channel as

$$\widehat{H}_{rd}^{2}(n) = R_d^{2}(n)/P(n). \tag{13}$$

The noise power estimation is done as

$$\sigma_{rd}^{2} = \frac{1}{N_c}\sum_{n=0}^{N_c-1}\left|\widehat{N}_{rd}^{2}(n)\right|^2 \tag{14}$$

where

$$\widehat{N}_{rd}^{2}(n) = R_d^{2}(n) - \widehat{H}_{rd}^{2}(n)P(n). \tag{15}$$

SIMULATION RESULTS AND DISCUSSIONS

Computer simulation parameters are summarized in Table 1. In this computer simulation, we assume an OFDM or SC block size of $N_c = 256$ data symbols with the GI length of $N_g = 16$ FFT samples. Rate-1/2 convolutional coding with the generator vectors $g_1 = [111]$ and $g_2 = [101]$ and a block interleaver of size 32x16 are used. The hard decision Viterbi is used for decoding. The non coded/encoded data is QPSK modulated. The propagation channel is and L-path block Rayleigh fast fading channel having uniform power delay profile, where the path gains remain constant over one OFDM/SC block and vary frame-by-frame. The path gains are zero mean independent complex variables with $E[|h_l|^2] = 1/L$. We assume $\tau_0 = 0 < \tau_1 < \cdots < \tau_{L-1}$ and that the l-th path time delay is $\tau_l = l\Delta$, where $\Delta \geq 1$ denotes the time delay between adjacent paths. The maximum time delay of the channel is less than the GI length. Chu sequence $p(t) = cos(\pi t^2/N_c) + jsin(\pi t^2/N_c)$ for $t = 0 \sim N_c - 1$ is used as pilot.

C. BER Performance

We discuss the OFDM and SC-FDE BER performances with and without channel coding and pilot-assisted CE as a function of the average signal energy per bit to AWGN power spectrum density ratio ($E_b/N_0 = 0.5 \times E_s/N_0 \times (1 + N_g/N_c)(1 + 1/N_b)$. We note that the maximum diversity order achievable at the destination may only be equal to two, since only two different paths (direct and relay deviated path) exist in this three nodes cooperative relay network. To exploit the channel frequency and time diversity, we use channel coding.

Table 1. Simulation parameters.

Transmitter	Channel coding	½ convolution codes size 3 encoder
	Modulation	QPSK
	No. of IFFT points	N_c=256
	Transmission technique	SC or OFDM
	Bit rate	100 Mbps
Channel	Carrier frequency	5 GHz
	Channel model	L path block frequency selective Rayleigh fading
	Doppler spread	40 Hz
Receiver	No. of FFT points	N_c=256
	FDE	MMSEC for SC MRC for OFDM
	Channel estimation	Pilot assisted

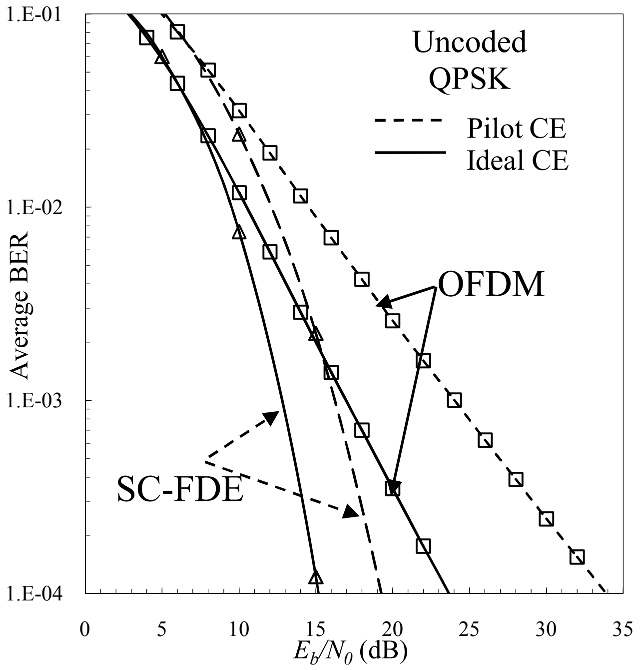
Fig. 4 illustrates the average BER performance with pilot assisted CE in two cases: *(a)* non coded performance and *(b)* encoded performance. The channel estimation introduces an error due to the pilot assisted CE and also to noise estimation.

Fig. 4(a) shows the better performance of SC-FDE in comparison with OFDM when no coding is applied. For BER=10^{-3}, the required E_b/N_0 degradation from the ideal CE case is about 5dB for SC-FDE while 8dB for OFDM. Fig. 4(b) plots the encoded BER performance. Due to the hard decision decoding with block interleaving used in this paper, the performance of OFDM is slightly worse than that of SC-FDE.

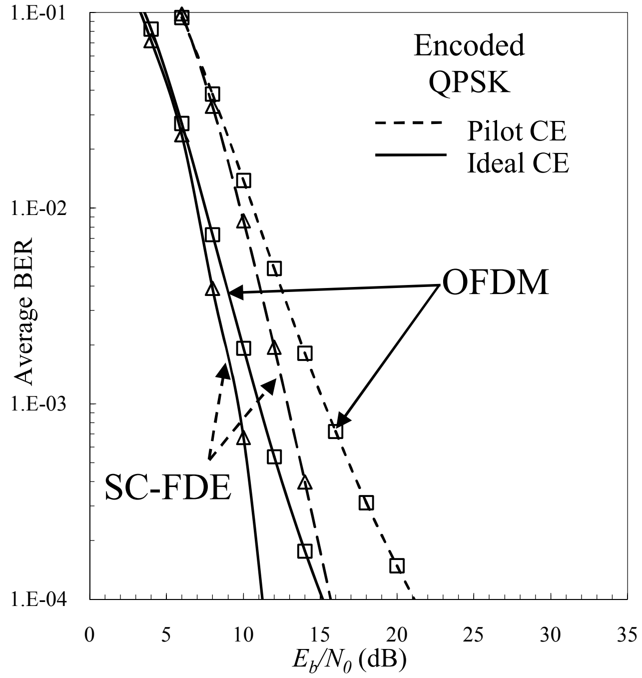
D. Impact of channel frequency-selectivity

The performance of coded OFDM and coded SC-FDE is largely influenced by the channel itself due to channel frequency-selectivity. The channel frequency-selectivity is a function of the number of paths L, as well as of the time delay between these paths; as L decreases the channel becomes less frequency-selective and when L=1 it becomes a frequency-nonselective channel (i.e., single-path channel).

Fig. 5 illustrates the BER performance as a function of the number of channel paths L for coded SC-FDE and OFDM with pilot-assisted CE. The average BER performance in OFDM case improves as L increases. For BER $= 10^{-3}$, OFDM obtains a 10 dB gain as L increases from 1 to 16. SC-FDE provides better BER performance irrespective of the degree of frequency selectivity of the channel.



(a) Uncoded



(b) Encoded

Fig. 4. BER Performance.

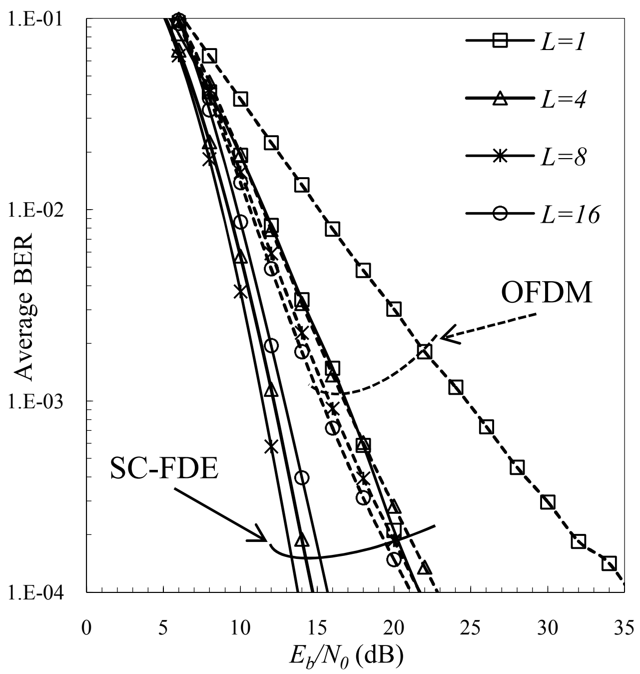


Fig. 5. Encoded pilot assisted BER Performance.

CONCLUSIONS

In this paper, a performance comparison of cooperative OFDM and SC-FDE relay networks with pilot assisted channel estimation in a frequency-selective channel was presented. At the destination terminal, joint diversity combining and FDE are performed to improve the BER performance. It was shown that in the uncoded case, SC-FDE achieves better performance than OFDM due to frequency diversity gain obtained through MMSE-FDE. In the coded case, OFDM performance can considerably improve; however SC-FDE still provides better BER performance. The possible reason for this may be that the hard decision decoding with block interleaving of one block size is used and therefore, achievable coding gain is relatively small. Cooperative relay network using powerful coding and decoding is an interesting future study topic.

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