LETTER

Accurate Channel Identification with Time-Frequency Interferometry for OFDM

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SUMMARY In OFDM systems, the pilot signal averaging channel estimation is generally used to identify the channel state information (CSI). In this case, large pilot symbols are required for obtaining an accurate CSI. As a result, the total transmission rate is degraded due to large number of pilot symbols transmission. To reduce this problem, in this paper, we propose time-frequency interferometry (TFI) for OFDM to achieve an accurate CSI.

key words: *OFDM, time-frequency interferometry, CSI*

1. Introduction

Digital mobile multimedia applications as they are getting common lately create an ever increasing demand for broadband communication systems. To meet this demand, orthogonal frequency division multiplexing (OFDM) is attractive and widely studied in recent years [1], [2]. Since the signals are transmitted in parallel by using many subcarriers that are mutually orthogonal and the corresponding spectrum is shaped like rectangle, OFDM can achieve high frequency efficiency and high data rate. Moreover, OFDM has been chosen for several broadband WLAN standards like IEEE802.11a, IEEE802.11g and European HIPERLAN/2, and terrestrial digital audio broadcasting (DAB) and digital video broadcasting (DVB) was also proposed for broadband wireless multiple access systems such as IEEE802.16 wireless MAN standard and interactive DVB-T [3], [4].

In OFDM systems, the pilot signal averaging channel estimation is generally used to identify the channel state information (CSI) [5]. In this case, large pilot symbols are required to obtain an accurate CSI. As a result, the total transmission rate is degraded due to transmission of large pilot symbols. Recently, carrier interferometry (CI) has been proposed to identify the CSI of multiple-input multiple-output (MIMO). However, the CI used only one phase shifted pilot signal to distinguish all the CSI for the combination of transmitter and receiver antenna elements. In this case, without noise whitening, each detected channel impulse response is affected by the noise [6]. Therefore, the pilot signal averaging process is necessary for improving the accuracy of CSI [7]. To reduce this problem, in this paper, we propose time-frequency interferometry (TFI) for OFDM to achieve an accurate CSI. This paper is organized as follows. Configuration of the proposed TFI-OFDM system is described in Sect. 2. In Sect. 3, we show the computer simulation results. Finally, the conclusion is given in Sect. 4.

2. TFI-OFDM System

This section describes the proposed TFI-OFDM system, which employs time division multiplexing (TDM) transmission for multiple users. The proposed system is illustrated in Fig. 1.

2.1 Channel Model

We assume that a propagation channel consists of L discrete paths with different time delays. The impulse response $h(\tau, t)$ is represented as

$$h(\tau, t) = \sum_{l=0}^{L-1} h_l(t)\delta(\tau - \tau_l), \tag{1}$$

where h_l and τ_l are the complex channel gain and the time delay of the lth propagation path, respectively, and $\sum_{l=0}^{L-1} E|h_l^2| = 1$, where $E|\cdot|$ denotes the ensemble average operation. The channel transfer function $H(f, t)$ is the Fourier transform of $h(\tau, t)$ and is given by

$$\begin{aligned} H(f, t) &= \int_0^\infty h(\tau, t)\exp(-j2\pi f\tau)d\tau \\ &= \sum_{l=0}^{L-1} h_l(t)\exp(-j2\pi f\tau_l). \end{aligned} \tag{2}$$

In any radio transmission, the channel spectral response is not flat. When $L > 1$, $H(f, t)$ is no longer constant over the signal bandwidth. This channel is called the frequency-selective fading channel, and in this paper, we consider it for the purpose of evaluating TFI-OFDM system.

2.2 TFI-OFDM Transmitter

The transmitter block diagram of TFI-OFDM system is shown in Fig. 1(a). Firstly, the coded binary information data sequence is modulated, and N_p pilot symbols are appended at the beginning of the sequence. The TFI-OFDM transmit signal can be expressed in its equivalent baseband representation as

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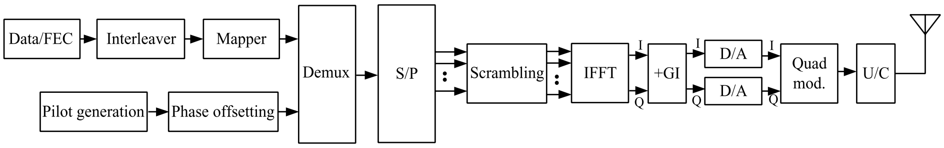
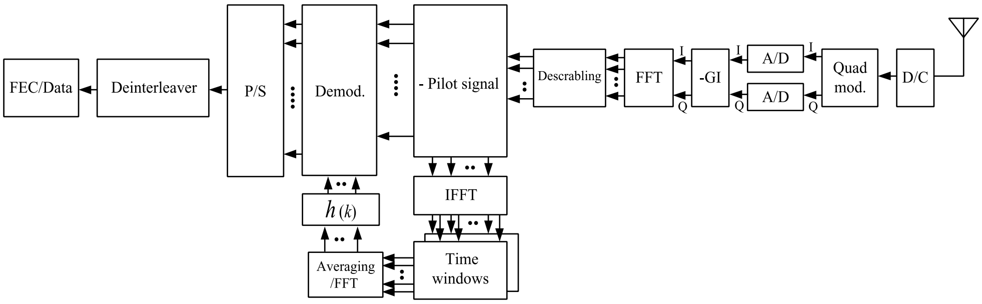


(a) Transmitter



(b) Receiver

Fig. 1 The proposed TFI-OFDM system.

$$s(t) = \sum_{i=0}^{N_p+N_d-1} g(t-iT)\cdot\left\{\sqrt{\frac{2S}{N_c}}\sum_{k=0}^{N_c-1} u(k,i) \cdot \exp\left[j2\pi(t-iT)k/T_s\right]\right\}, \tag{3}$$

where N_d and N_p are the number of data and pilot symbols, N_c is the number of carriers, T_s is the effective symbol length, S is the average transmitting power, T is the OFDM symbol length, respectively. The frequency separation between adjacent orthogonal subcarriers is $1/T_s$ and can be expressed, by using the kth subcarrier of the ith modulated symbol $d(k,i)$ with $|d(k,i)| = 1$ for $N_p \leq i \leq N_p + N_d - 1$, as

$$u(k,i) = c_{PN}(k)\cdot d(k,i), \tag{4}$$

where c_{PN} is a long pseudo-noise (PN) sequence as a scrambling code to reduce the peak average power ratio (PAPR). The guard interval T_g is inserted in order to eliminate the inter-symbol interference (ISI) due to the multi-path fading, and hence, we have

$$T = T_s + T_g. \tag{5}$$

In OFDM systems, T_g is generally considered as $T_s/4$ or $T_s/5$. Thus, we assume $T_g = T_s/4$ in this paper. In Eq. (3), $g(t)$ is the transmission pulse given by

$$g(t) = \begin{cases} 1 & \text{for } -T_g \leq t \leq T_s \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

For $0 \leq i \leq N_p - 1$, the transmitted pilot signal of kth subcarrier is given by

$$d(k,i) = \exp(-j2\pi k/T_s) + \exp(-j4\pi k T_g/T_s) \tag{7}$$

where N_p is the number of pilot symbols. In this case, pilot signal of TFI-OFDM can multiplex the same impulse responses in twice on the time domain without overlapping to each other as shown in Fig. 2(a). This pilot signal pattern is the originality of the TFI-OFDM. Moreover, due to the superposition of Eq. (7), the transmission power of pilot signals is $1/2$ for $0 \leq i \leq N_p - 1$.

2.3 Receiver Structure

The receiver structure is illustrated in Fig. 1(b). By applying the FFT operation, the received signal $r(t)$ is resolved into N_c subcarriers. The received signal $r(t)$ in the equivalent baseband representation can be expressed as

$$r(t) = \int_{-\infty}^{\infty} h(\tau,t)s(t-\tau)d\tau + n(t), \tag{8}$$

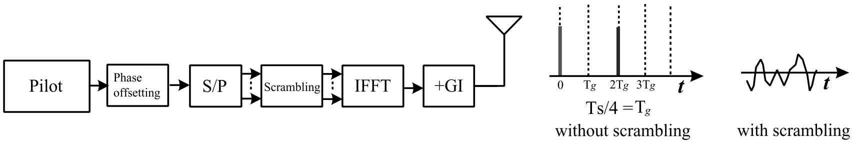
where $n(t)$ is additive white Gaussian noise (AWGN) with a single sided power spectral density of N_0. The kth subcarrier $\tilde{r}(k,i)$ is given by

$$\begin{aligned}\tilde{r}(k,i) &= \frac{1}{T_s}\int_{iT}^{iT+T_s} r(t)\exp\left[-j2\pi(t-iT)k/T_s\right]dt \\ &= \sqrt{\frac{2S}{N_c}}\sum_{e=0}^{N_c-1} u(e,i)\cdot\frac{1}{T_s}\int_0^{T_s}\exp[j2\pi \\ &\quad \cdot(e-k)t/T_s]\cdot\left\{\int_{-\infty}^{\infty} h(\tau,t+iT)g(t-\tau)\right. \\ &\quad \left.\cdot\exp(-2\pi e\tau/T_s)d\tau\right\}dt + \hat{n}(k,i),\end{aligned} \tag{9}$$

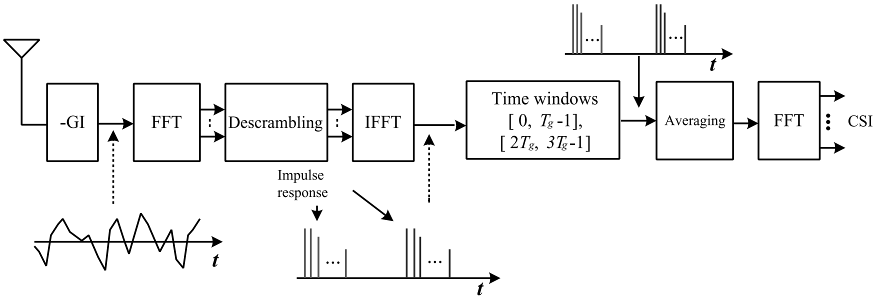
where $\hat{n}(k,i)$ is AWGN noise with zero-mean and a variance of $2N_0/T_s$. Assuming that the maximum τ_l is shorter than the guard interval T_g, the integral with respect to τ becomes, from Eq. (6),

$$\begin{aligned}&\int_{-\infty}^{\infty} h(\tau,t+iT)g(t-\tau)\exp(-j2\pi e\tau/T_s)d\tau \\ &\quad = \int_0^{T_s} h(\tau,t+iT)\exp(-j2\pi e\tau/T_s)d\tau \\ &\quad = H(e/T_s,t+iT).\end{aligned} \tag{10}$$

Assuming that $\epsilon_l(t)$ remains almost constant over the symbol



(a) Transmitter



(b) Receiver

Fig. 2 The concept of TFI-OFDM system.

length T,

$$\epsilon_i(t+iT) \approx \epsilon_i(iT) \quad \text{for } 0 \leq t \leq T, \tag{11}$$

and hence, we have

$$H(k/T_s, t+iT) \approx H(k/T_s, iT), \quad \text{for } 0 \leq t \leq T. \tag{12}$$

As a result, Eq. (9) can be rewritten as

$$\begin{aligned}\tilde{r}(k,i) \approx\ & \frac{1}{T_s}\sqrt{\frac{2S}{N_c}}\sum_{e=0}^{N_c-1} u(e,i)\cdot\int_0^{T_s}\exp[j2\pi \\ & \cdot(e-k)t/T_s]\cdot\left\{\int_{-\infty}^{\infty} h(\tau, t+iT)\right. \\ & \left.\cdot g(t-\tau)\exp(-2\pi e\tau/T_s)d\tau\right\}dt + \hat{n}(k,i) \\ =\ & \sqrt{\frac{2S}{N_c}}H(k/T_s, iT)u(k,i) + \hat{n}(k,i).\end{aligned} \tag{13}$$

After descrambling, the output signal $r(k,i)$ is given by

$$\begin{aligned}r(k,i) =\ & \frac{c_{PN}^*(k)}{|c_{PN}(k)|^2}\{\tilde{r}(k,i)\}, \\ =\ & \sqrt{\frac{2S}{N_c}}H(k/T_s, iT)d(k,i) + \hat{n}(k,i),\end{aligned} \tag{14}$$

where $\frac{c_{PN}^*(k)}{|c_{PN}(k)|^2}$ is the descrambling operation.

2.4 Proposed Channel Estimation Scheme

Since $T_g = T_s/4$, TFI-OFDM can multiplex the same impulse responses in twice on the time domain. After the pilot signal separation, the pilot signal is converted to the time domain signal $\hat{r}(t)$ again as

$$\begin{aligned}\hat{r}(t) =\ & \sum_{i=0}^{N_p-1}\sqrt{\frac{2P}{N_c}}\sum_{k=0}^{N_c-1} r(k,i)\exp[j2\pi(t-iT)k/T_s] \\ =\ & \sum_{i=0}^{N_p-1}\sqrt{\frac{2P}{N_c}}h(\tau, t+iT)\sum_{k=0}^{N_c-1} d(k,i) \\ & \cdot\exp[j2\pi(t-iT)k/T_s] + \tilde{n}(t) \\ =\ & \sum_{i=0}^{N_p-1}\sqrt{\frac{2P}{N_c}}\sum_{l=0}^{L-1} h_l(t+iT) \\ & \cdot\frac{1}{\sqrt{2}}\{\delta(\tau-\tau_l) + \delta(\tau-\tau_l-2T_g)\} \\ & + \tilde{n}(t),\end{aligned} \tag{15}$$

where P is the power of pilot signals. The converted time domain signal $\hat{r}(t)$ is shown in Fig. 2(b). From Eq. (7), $\sum_{k=0}^{N_c-1} d(k,i)\exp[j2\pi(t-iT)k/T_s]$ shows two impulses with time shift as $\delta(\tau - 2T_g)$, and the output signals are equivalent to time domain multiplexed impulse responses. By averaging of these impulse responses, we can reduce the noise power. Therefore, the impulse response of kth subcarrier $\tilde{H}(k)$ is obtained by

$$\begin{aligned}\tilde{H}(k) =\ & \frac{1}{\sqrt{P/N_c}}\sum_{e=0}^{N_c-1}\frac{1}{T_s}\int_0^{T_s}\left\{\sum_{l=0}^{L-1} h_l(t+iT)\right. \\ & \Big\{\delta(\tau-\tau_l) + \delta(\tau-\tau_l-2T_g)\Big\} \\ & \left.\cdot\exp(-2\pi e\tau/T_s)d\tau\right\}dt + \eta(k),\end{aligned} \tag{16}$$

where $\eta(k)$ is AWGN component with $E[|\eta(k)|]^2 = E[|\frac{\hat{n}(k,i)}{2}|]^2 = \frac{\sigma^2}{2}$. Observing Eq. (16), we can see that the estimated CSI of TFI-OFDM can be obtained an improved accuracy compared with the conventional OFDM.

3. Computer Simulated Results

In this section, the performance of the proposed TFI-OFDM is compared with the conventional pilot signal averaging based OFDM. Figure 1 shows a simulation model of the proposed TFI-OFDM. On the transmitter, the pilot signals are assigned for each transmitter using Eq. (7). In this case, TFI-OFDM can multiplex the same impulse responses in the receive antenna in twice on the time domain without overlapping to each other as shown in Fig. 2(a). The data stream is encoded. Here, convolutional codes (rate R = 1/2, constraint length $\mathcal{K} = 7$) with bit interleaving are used. These have been found to be efficient for transmission of an OFDM signal over a frequency selective fading channel. The coded bits are QPSK modulated, and then the pilot signal and data signal are multiplexed with scrambling using PN code to reduce the PAPR. The OFDM time signals are generated by an IFFT and transmitted to the frequency selective and time variant radio channel after cyclic extensions have been inserted. The transmitted signals are subject to broadband channel propagation. In the simulation, we assume that OFDM symbol period is $10\,\mu$s, guard interval is $2\,\mu$s, and $L = 15$ path Rayleigh fadings have exponential shapes and a path separation $T_{path} = 125\,n$sec. The maximum Doppler frequencies are assumed to be 10 Hz and 300 Hz. In the receiver, the received signals are erased the guard interval and S/P converted. The parallel sequences are passed to an FFT operator, which converts the signal back to the frequency domain. After descrambling and IFFT, each impulse response can be estimated by extracting and averaging twice impulse responses using the time windows with Eq. (16) as shown in Fig. 2(b). The frequency domain data signal is detected and demodulated using the estimated channel impulse response. After detection, bits are detected by the Viterbi soft decoding algorithm. The packet consists of $N_p = 1$ pilot symbol and $N_d = 20$ data symbols. Table 1 shows the simulation parameters.

Figure 3 shows the BER of the conventional pilot signal averaging based OFDM with $N_p = 1$ and $N_p = 2$, the conventional CI-OFDM with $N_p = 1$, and TFI-OFDM at Doppler frequencies of 10 Hz and 300 Hz. The proposed scheme can estimate the accurate CSI compared with the conventional pilot signal averaging based OFDM with $N_p = 1$ and CI-OFDM with $N_p = 1$ by averaging the same impulse responses in twice on the time domain without overlapping to each other as $\sum_{k=0}^{N_c-1} d(k,i) \exp\left[j2\pi(t - iT)k/T_s\right]$. From the simulation results, it is shown that our proposed scheme achieves 2.8 dB and 0.5 dB gains compared with the conventional pilot signal averaging based OFDM with $N_p = 1$ and $N_p = 2$ at Doppler frequencies of 10 Hz and 300 Hz, respectively. Moreover, CI used only one phase shifted pilot signal to distinguish all the CSI for the combination of transmitter and receiver antenna elements. Therefore, the performance of the CI is the same as the conventional pilot signal averaging based OFDM with $N_p = 1$.

Table 1 Simulation parameters.

Data Modulation	QPSK
Data detection	Coherent
Symbol duration	$10\,\mu$s
Frame size	21 symbols ($N_p = 1$, $N_d = 20$)
FFT size	64
Number of carriers	64
Guard interval	16 sample times
Fading	15 path Rayleigh fading
Doppler frequency	10, 300 Hz
FEC	Convolutional code (R=1/2, $\mathcal{K}$=7)

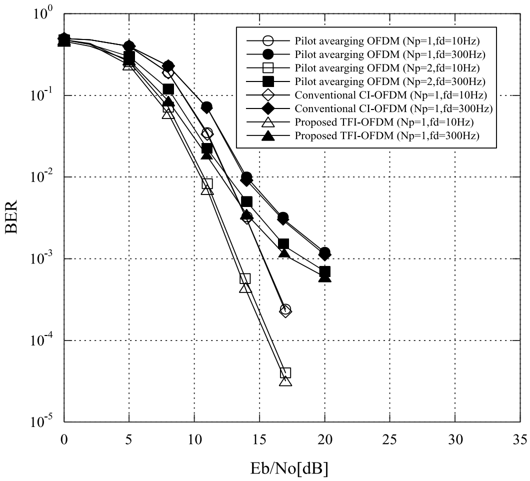


Fig. 3 BER of the conventional pilot signal averaging based OFDM with $N_p = 1$ and $N_p = 2$, the conventional CI-OFDM with $N_p = 1$, and TFI-OFDM at Doppler frequencies of 10 Hz and 300 Hz.

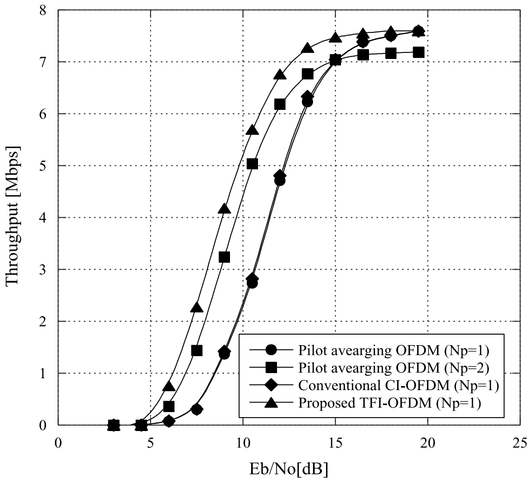


Fig. 4 Throughput of the conventional pilot signal averaging based OFDM with $N_p = 1$ and $N_p = 2$, the conventional CI-OFDM with $N_p = 1$, and TFI-OFDM at Doppler frequency of 10 Hz.

Figure 4 shows the throughput of the conventional pilot signal averaging based OFDM with $N_p = 1$ and $N_p = 2$, the conventional CI-OFDM with $N_p = 1$, and TFI-OFDM at Doppler frequency of 10 Hz. Since the proposed scheme uses the reduced number of pilot symbols compared with the conventional pilot signal averaging based OFDM with $N_p = 2$, the total transmission rate is increased. As a result, the proposed scheme achieves about 5% improvement to compare with the conventional pilot signal averaging based

OFDM with $N_p = 2$ in high E_b/N_0.

4. Conclusion

In this paper, we have proposed TFI-OFDM systems to achieve the accurate CSI without increasing the number of pilot symbols. TFI-OFDM can multiplex the same impulse responses in twice on the time domain without overlapping to each other. By averaging of these impulse responses, we can obtain the accurate channel impulse response. From the simulation results, it is shown that our proposed scheme achieves 2.8 dB and 0.5 dB gains compared with the conventional pilot signal averaging based OFDM with $N_p = 1$ and $N_p = 2$ at Doppler frequency of 10 Hz.

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