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FREQUENCY ESTIMATION BY PILOT SET PARTITIONING FOR OFDM SYSTEMS WITH MULTIPLE TRANSMIT ANTENNAS

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Abstract—Cyclic delay diversity (CDD) is a simple approach to increase the frequency selectivity of the channel in an orthogonal frequency division multiplexing (OFDM) based transmission scheme. However, CDD can cause serious degradation in the performance of channel and frequency estimation in the frequency domain. This paper suggests a post-FFT frequency estimation scheme suitable for arbitrary cyclic delays in the CDD-OFDM system. By partitioning uncorrelated pilot subcarriers into subsets to be flat, and performing frequency estimation for each pilot subset, a robust integer frequency offset estimation scheme is derived.

1. INTRODUCTION

Recently, orthogonal frequency division multiplexing (OFDM) technique has received considerable attention for wireless networks due to their effective transmission capability when dealing with various types of channel impairment, and has been applied to high speed wireless local area network (WLAN) and ultra wideband (UWB) applications [1–8]. In addition, OFDM combined with multiple-input multiple-output (MIMO) signal processing has shown great promise of improved performance. Currently, 802.11n and 802.16e that include MIMO-OFDM modes are being standardized [9–11].

The use of multiple antennas and transmit diversity techniques has been proposed to improve error performance and capacity of wireless systems [12–14]. One of these concepts, cyclic delay diversity (CDD), is based on increasing the frequency selectivity by using several transmit antennas and sending modified replicas of the transmitted signal [15]. The CDD scheme has the effect of randomizing the channel frequency response by increasing the frequency-selectivity at the receiver, thus reduces the likelihood of deep fading [15–18]. In order to exploit the diversity of the frequency selective channel in the channel decoder, it was found that the cyclic delay should be as large as possible [18]. However, the increased frequency selectivity can be a problem for the channel and post-FFT frequency estimation [19, 20].

In this paper, estimation problems which occur with CDD-OFDM for the frequency estimation are addressed. To account for this issue, we suggest an improved integer frequency offset (IFO) estimation algorithm, which is designed for the purpose of weakening the effect of frequency-selective fading introduced by CDD. Because the cyclic delays are channel independent, thus utilization of this knowledge provides an improved IFO estimation scheme. To this end, the pilots are periodically assigned according to the periodicity of the channel, resulting in group-wise flat fading.

The paper is organized as follows: Next section outlines the signal model when OFDM systems adopts the CDD scheme. Section 3 highlights the principle of the pilot subset partitioning and its use for the IFO estimation in the CDD-OFDM system. In Section 4, we then present simulation results verifying the performance of the frequency estimator, and we conclude this paper with Section 5.

2. SIGNAL DESCRIPTION

We consider an equivalent baseband multiple-input single-output (MISO) channel with N_T transmit antennas and one receiver antenna. The output symbols of the IFFT at the t-th transmit antenna are denoted by $x_t(n)$, $n = 0, 1, \ldots, N-1$. At each transmit antenna, the same OFDM modulated signal is applied with delay Δ_t, $t = 0, 1, \ldots, N_T - 1$, then added a cyclic prefix (CP) with length N_g. So, the transmitted symbol from antenna t can be expressed as

$$x_t(n) = \frac{1}{\sqrt{N_T}} x(n - \Delta_t)_N,\ t = 0, 1, \ldots, N_T - 1 \tag{1}$$

with

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j2\pi kn/N} \tag{2}$$

where N_T is the number of transmit antenna, $X(k)$ represents the complex signals of the k-th subcarrier in the frequency domain, N is the number of FFT (IFFT) points, and $(\cdot)_N$ means the modulo-N operation. Without the loss of generality, there is no cyclic delay at 1st transmit antenna, i.e., $\Delta_0 = 0$.

After convolving with the channel impulse response, the received signal is in the form

$$y(n) = \frac{1}{\sqrt{N_T}} \sum_{t=0}^{N_T-1} \sum_{l=0}^{\tau_{\max}} h_t(n,\, l) x(n - l - \Delta_t)_N + w(n) \tag{3}$$

where $h_{l,\,t}(n)$ denotes the Rayleigh fading process of the propagation path with a delay of l samples observed from transmit antenna t, $\tau_{\max}$ is the maximum channel delay in samples, and $w(n)$ is the contribution of the AWGN.

As the carrier frequency offset (CFO) is generally greater than the subcarrier spacing, CFO ϵ is divided into $\epsilon = \epsilon_i + \epsilon_f$, where ϵ_i is the IFO and $\epsilon_f = [-1/2,\, 1/2)$ is the fractional frequency offset (FFO). To focus on the estimation of IFO, we assume perfect FFO recovery at the receiver. Then, this uncertainty yields

$$r(n) = y(n) e^{j2\pi\epsilon_i n/N} + \hat{w}(n) \tag{4}$$

where $\hat{w}(n)$ is statistically equivalent to $w(n)$. If the fading is constant for the duration of an OFDM symbol, $h_t(n,\, l) = h_t(l)$. So, $r(n)$ is transformed to the frequency domain by means of FFT yielding

$$R(k) = \frac{1}{\sqrt{N_T}} \sum_{t=0}^{N_T-1} H_t(k - \epsilon_i) X(k - \epsilon_i) e^{-j2\pi(k-\epsilon_i)\Delta_t/N} + \hat{W}(k) \tag{5}$$

where $\hat{W}(k)$ is the AWGN and $H_t(k)$ is the channel frequency response from the t-th transmit antenna given by

$$H_t(k) = \frac{1}{\sqrt{N}} \sum_{l=0}^{\tau_{\max}} h_t(l) e^{-j2\pi lk/N}. \tag{6}$$

In the frequency domain, therefore, the equivalent channel transfer function is written by

$$H(k) = \frac{1}{\sqrt{N_T}} \sum_{t=0}^{N_T-1} H_t(k) e^{-j2\pi k \Delta_t / N}. \tag{7}$$

As discussed in [8], a preferable choice of Δ_t is

$$\Delta_t = \frac{N}{N_T} + \Delta_{t-1},\ t = 0, 1, \ldots, N_T - 1 \tag{8}$$

which is the maximum possible cyclic delay, in the way that the mutual delay between all transmit antennas is maximized. Thus we have

$$H(k) = \frac{1}{\sqrt{N_T}} \sum_{t=0}^{N_T-1} H_t(k) e^{-j2\pi k t / N_T}. \tag{9}$$

If we assume that the channels $\{H_t(k)\}$ are frequency-flat and $\Delta_t = N/N_T + \Delta_{t-1}$ as in Eq. (8), it is effortlessly found that $H(k)$ is periodic with period $P_H = N/(\Delta_t - \Delta_{t-1}) = N_T$.

3. PROPOSED IFO ESTIMATION SCHEME

In this section, a description of pilot subset design and frequency estimation for OFDM systems using multiple transmit antennas is presented.

3.1. Pilot Subset Partitioning

The concept of the pilot allocation scheme is that the set having N_p pilot symbols is divided into several subsets so that the pilot symbols in each subset experience flat fading for given system parameters N, N_p, and Δ_t (or P_H). At the same time, all pilot symbols are designed to be allocated with approximately uniform distribution. To this end, the pilots are periodically assigned according to the periodicity of $H(k)$, resulting in group-wise flat fading. Since $N_p < N/P_H = \Delta_t - \Delta_{t-1}$ as seen in Eq. (8), the direct use of the above concept may make the distribution of pilots to be concentrated in a specific region of the OFDM spectrum. Specially, when Δ_t is chosen to meet Eq. (8), $N/P_H = N/N_T$. In this case, $N_p < N/N_T$ is practically unavoidable due to the limited number of transmit antennas.

To account for this problem, we define a spreading parameter Q given by

$$Q = \left\lceil \frac{\Delta_t - \Delta_{t-1}}{N_p} \right\rceil \tag{10}$$

where $\lceil x \rceil$ = first integer $> x$. Based on the parameter Q, the whole pilot symbols are grouped into N_s pilot subsets, thus the number of pilot subsets can be calculated as

$$N_s = \left\lceil \frac{QN_p}{\Delta_t - \Delta_{t-1}} \right\rceil . \tag{11}$$

With this provision, the minimum number of pilots in the i-th subset is given by

$$N_{p,\,l} = \left\lfloor \frac{N_p}{N_s} \right\rfloor ,\ l = 1,\, 2,\, \dots\, ,\, N_s \tag{12}$$

where $\lfloor x \rfloor$ = first integer $< x$. If N_p/N_s is not integer, $N_p - \sum_{l=1}^{N_s} N_{p,\,l}$ pilots are remained unassigned yet and they are assigned to one of N_s subsets.

The amount of cyclic delay Δ_t can be an arbitrary number [21]. In order to obtain the full diversity, moreover, the following condition should be met [18]

$$\Delta_t > \Delta_{t-1} + D \tag{13}$$

where D is the channel memory. So, if the delay amount has been chosen to be $N_p \geq \Delta_t - \Delta_{t-1}$ in contrast to the case in Eq. (8), the spreading factor should be $Q = 1$ as seen in Eq. (10) because the periodicity of $H(k)$ is increased.

Based on the above defined parameters, the overall procedure of the pilot subset assignment is summarized as follows

(i) To begin the procedure, set $l = 1$ and the first index of pilot subcarrier in the first subset $k_1 = 1$.

(ii) Calculate Q, N_s, and $N_{p,\,l}$ according to Eqs. (10), (11), and (12), respectively.

(iii) The first index of pilot subcarrier in the i-th subset is chosen to be $k_l = k_1 + (l-1)\lfloor QP_H/N_s \rfloor$.

(iv) The pilot indices are selected with the period of QP_H in $\mathcal{S}_l$ to have an equidistant subcarrier spacing QP_H starting from k_l, where $\mathcal{S}_l$ is the set of pilot indices in the l-th subset.

(v) If $l < N_s$, new pilot subset is chosen, $l = l + 1$, and go to the step (iii), otherwise go to the next step.

(vi) If $N_r = N_p - \sum_{l=1}^{N_s} N_{p,l} > 0$, i.e., there remains unassigned pilot symbols, they are assigned to one of N_r subsets by one, starting from $\mathcal{S}_1$ to $\mathcal{S}_{N_r}$.

(vii) Find $k_{\min} = \min\{\mathcal{S}\}$ and $k_{\max} = \max\{\mathcal{S}\}$. Based on $k_{\min}$ and $k_{\max}$, if necessary, $\mathcal{S}$ is shifted in subcarrier index, which places $\mathcal{S}$ in the middle of the OFDM spectrum.

As a result of the pilot allocation method, the channel responses of the pilot subcarriers in each subset are flat, resulting in $\mathcal{S} = \{\mathcal{S}_1 \cup \mathcal{S}_2 \cup \cdots \cup \mathcal{S}_{N_s}\}$. Fig. 1 shows a conceptual illustration of the pilot allocation procedure when $N_T = 2$.

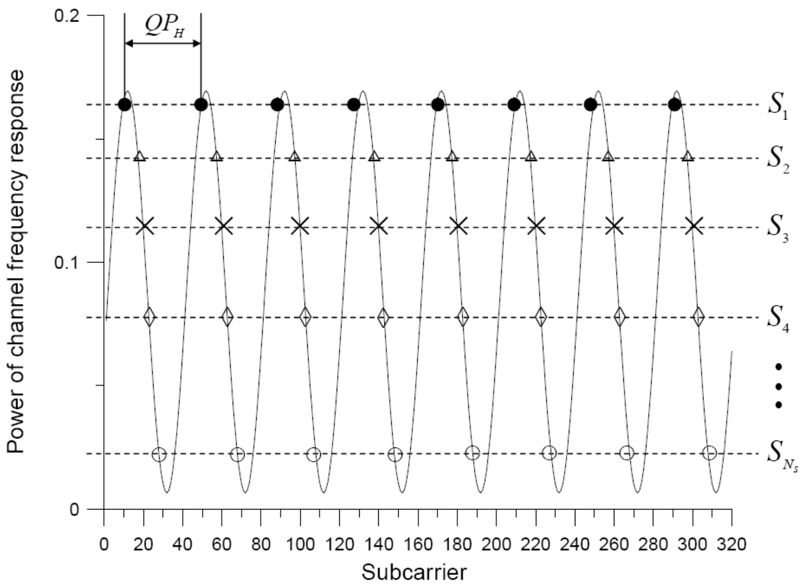

Figure 1. Example of the pilot subset allocation when $N_T = 2$.

3.2. Estimation Algorithm

In order to implement the robust IFO estimation scheme to the frequency selectivity introduced by adopting the CDD in OFDM systems, we use the pilot subsets designed as in the previous section.

As can be seen in Fig. 1, each pilot subset suffers from flat fading with the aid of the appropriate pilot subset allocation in spite of the frequency selectivity of the resulting channel transfer function.

Therefore, the correlation value is calculated individually within each grouped subset $\mathcal{S}_l$ and then summed as follows

$$\begin{aligned}\hat{\Delta}_i &= \arg\max_{|r|\leq M}\left\{\sum_{l=1}^{N_s}\left|\sum_{k\in\mathcal{S}_l} R(k+r)P^*(k)\right|\right\}\\ &= \arg\max_{|r|\leq M}\left\{\sum_{l=1}^{N_s}\left|\sum_{k\in\mathcal{S}_l} H(k-\epsilon_i+r)X(k-\epsilon_i+r)P^*(k)+\tilde{W}_l(k)\right|\right\}\end{aligned} \quad (14)$$

with

$$\tilde{W}_l(k) = \sum_{k\in\mathcal{S}_l} \hat{W}(k+r)P^*(k) \quad (15)$$

where a notation of r denotes a trial value of ϵ_i, $\{P(k), k \in \mathcal{S}\}$ are the pilot symbols known at the receiver, and M denotes the largest expected value of $|r|$ depending on the frequency stability of the transmitter and receiver oscillators.

Since $\{H(k),\, k \in \mathcal{S}_l\}$ are identical thanks to the pilot subset selection, IFO detector can be rearranged into

$$\hat{\epsilon}_i = \arg\max_{|r|\leq M}\left\{\sum_{l=1}^{N_s}\left|H(k_l-\epsilon_i+r)\sum_{k\in\mathcal{S}_l} X(k-\epsilon_i+r)P^*(k)+\tilde{W}_l(k)\right|\right\} \quad (16)$$

where the subcarrier index k_l represents $k \in \mathcal{S}_l$. Since $k - \epsilon_i + r \in \mathcal{S}_l$ says that $r = \epsilon_i$, it follows that

$$\begin{aligned}\sum_{k\in\mathcal{S}_l} X(k-\Delta_i+r)P^*(k) &= \sum_{k\in\mathcal{S}_l} |P(k)|^2\\ &= N_{p,l}.\end{aligned} \quad (17)$$

4. SIMULATION RESULTS AND DISCUSSION

To check the algorithm presented in the previous section, we simulate the conventional and proposed IFO estimators in the FM band. The channels are based on EIA channel model, which are widely used in analyses of FM performance [22]. More details of system and channel parameters are listed in Tables 1 and 2, respectively. We assume that the channel between each transmit antenna and the receive antenna is independent from each other, but shares the same power delay profile.

Table 1. Simulation parameters.

Parameter	Value
FFT size, N	320
Size of guard interval, N_g	32
Modulation	16QAM
System bandwidth	100 KHz
Carrier frequency	90 MHz
Number of pilot symbols, N_p	32
Number of transmit antennas, N_T	2
Amount of cyclic delay, Δ_1	$N/2$

Table 2. Channel models.

No	Channel model	Speed (km/h)	# of paths	Maximum delay (μs)
1	Urban (slow)	2	9	3
2	Urban (fast)	60	9	3
3	Rural	150	9	3
4	Terrain obstructed	60	9	16

For comparison purpose, we consider the conventional IFO estimation scheme developed in [23], which takes expression

$$\hat{\Delta}_i = \arg\max_{|r|\leq M} \left| \sum_{k\in\mathcal{S}} R(k+r)P^*(k) \right|. \tag{18}$$

Figure 1 shows the probability of failure, $Pr\{\hat{\epsilon}_i \neq \epsilon_i\}$, for channel model 1 (CM1) and CM2 when $M = 1$ is used. It is assumed that the FFO and timing error are perfectly corrected at the receiver. The performance curves of the conventional algorithm used in single-antenna case is also plotted for reference. As discussed, we find that the direct use of the conventional estimation scheme in CDD-OFDM systems leads to severe performance degradation due to high frequency selectivity, resulting in an error floor. On the other hand, the performance of the proposed IFO estimator combined with

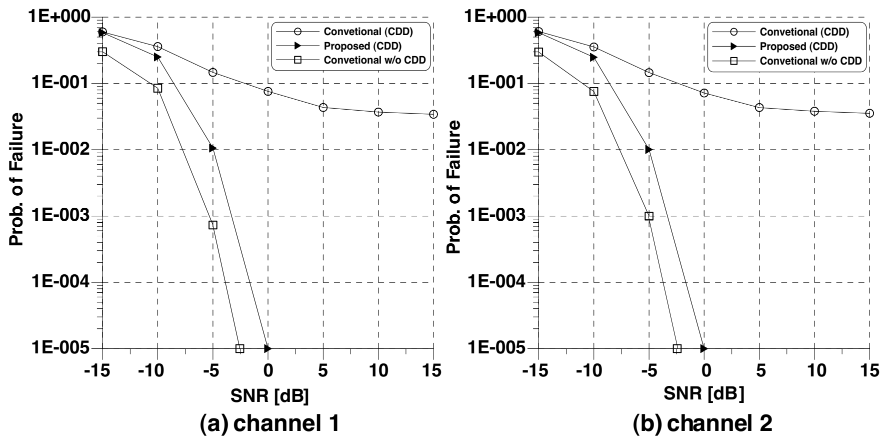

Figure 2. Estimation performance of the IFO estimators in channel models 1 and 2.

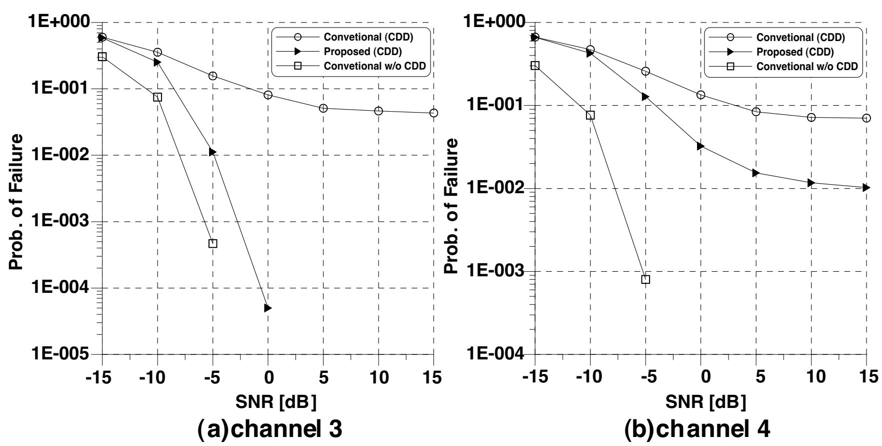

Figure 3. Estimation performance of the IFO estimators in channel models 3 and 4.

the pilot subset allocation method is shown to be close to that of the conventional scheme in OFDM systems without adopting CDD technique.

Similarly, Fig. 2 presents $\Pr\{\hat{\epsilon}_i \neq \epsilon_i\}$ for CM3 and CM4 when $M = 1$ is used. In CM4, which is more dispersive than other channels, the proposed IFO estimation scheme in CDD-OFDM systems fails to catch up with the conventional IFO scheme in single-antenna OFDM systems because of the increase of frequency selectivity of each channel, while still outperforming the conventional one applied to CDD-OFDM systems.

5. CONCLUSION

In order to improve the post-FFT based synchronization performance in the OFDM system using CDD scheme, we suggested an improved IFO estimation algorithm which is based on the pilot subset grouping. The performance of the proposed IFO estimator was compared with that of the conventional IFO estimator. It has been found by extensive simulations that the proposed estimation technique endowed with the properly chosen pilot subset has the advantage of being more robust against the frequency selective fading and outperforms the conventional estimation scheme.

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