Improving Performance and Detection Schemes of MIMO-OFDM Systems in the Presence of Phase Noise and Doubly-Selective Fading Where Channel is Both Time and Frequency Selective

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ABSTRACT

MIMO-OFDM technology is a combination of multiple-input multiple-output (MIMO) wireless technology with orthogonal frequency division multiplexing (OFDM) that has been recognized as one of the most promising techniques to support high data rate and high performance in different channel conditions. In this paper we analyze the impacts of phase noise to multiple-input multiple-output (MIMO) orthogonal frequency division multiplexing (OFDM) systems over doubly selective Rayleigh fading. Where channel is both time and frequency selective. Similar to single-antenna OFDM, Orthogonal frequency division multiplexing (OFDM) techniques have been investigated extensively to combat the effect of multipath delay. MIMO-OFDM suffers from significant performance degradation due to phase noise and time-selective fading, which causes intercarrier interference (ICI). We derive the expressions of carrier to interference and signal to interference plus noise ratios. After characterizing the common phase error (CPE) caused by phase noise and ICI caused by phase noise, as well as time-selective fading, using a minimum mean-squared error-based scheme to mitigate the effect of both phase noise and time-selective fading. Equally we evaluated and compared various detection schemes and their performances combined with the proposed CPE mitigation scheme. With numerical results, we examined the relative performances and the potential error floors of these detection schemes which show a total reduction of noise to 5%.

Keywords: ICI, MIMO-OFDM, ZF, MMSE, phase noise, time-selective fading

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing is considered a promising transmission technique for wideband wireless communications. One of the disadvantages of Orthogonal Frequency Division Multiplexing is its sensitivity to phase noise, which is a random process caused by the fluctuation of the transmitter and receiver oscillators [Pollet, 1995]. It is widely accepted that phase noise in Orthogonal Frequency Division Multiplexing has two major effects [Tomba, 1998], [Armada, 2001] Common Phase error (CPE), a constant rotation to the signal constellation, and intercarrier interference (ICI) due to the loss of orthogonality among subcarriers caused by the fast changes of the oscillator phase.

The Common Phase error (CPE) term is the same for all subcarriers within one Orthogonal Frequency Division Multiplexing symbol interval and changes slowly from one symbol to another. If phase noise level is low, Common Phase error (CPE) approximately equals the mean of the phase deviation of an oscillator within one Orthogonal Frequency Division Multiplexing symbol. The Intercarrier Interference (ICI) term is a random process. Schemes which compensate phase noise in Orthogonal Frequency Division Multiplexing systems have been proposed [S. Wu, 2002]. The signal-to-interference–plus–noise ratio (SINR) expression for single-antenna Orthogonal Frequency Division Multiplexing systems with various phase noise levels and different number of subcarriers was derived [Zheng, 2004].

Multi-Input Multi-output (MIMO) antennas have been combined with Orthogonal Frequency Division Multiplexing (OFDM) to improve spectral efficiency through spatial multiplexing [Stuber, 2004]. Similar to single-antenna OFDM, MIMO-OFDM is also highly sensitive to phase noise. Common Phase error (CPE) estimation schemes for MIMO-OFDM systems were derived in [Schnek, 2004] a decision-directed approach for compensation of phase noise in MIMO-OFDM

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systems was studied [Nikitopoulos, 2004]. Besides phase noise- time-selective fading also destroys the orthogonality among different subcarriers within one Orthogonal Frequency Division Multiplexing (OFDM) symbol and causes Intercarrier interference (ICI) [Russell, 1995]. Similar to single-antenna Orthogonal Frequency Division Multiplexing (OFDM), MIMO-OFDM is also vulnerable to channel time selectivity. Error performance of MIMO-OFDM systems in the presence of time-selective fading without considering phase noise was analysed [Stamoulis, 2002].

Although the issue caused by phase noise and time-selective fading in MIMO-OFDM has been recognized, the exact quantitative effect of the combination of the two has not been well addressed. Phase noise mitigation for MIMO-OFDM in fast time-varying fading environments has not been well studied either. In this chapter, It was analyzed, via mainly an analytical approach, the impact of phase noise to the performance of MIMO-OFDM systems over doubly-selective Rayleigh fading channels. After characterizing Common Phase error (CPE) caused by phase noise and Intercarrier Interference (ICI) caused by phase noise and time-selective fading, an MMSE-based mitigation scheme to effectively minimize the impact of phase noise was derived. The author also compare four detection schemes, Zero forcing, ZF, MMSE, decorrelating division feedback (DF) and MMSE-DF schemes, and evaluate their SER performance.

II. METHODS AND MATERIAL

A. System Model

Consider a MIMO-OFDM system with $N_t$ transmit antennas, $N_r$ receive antennas, and $N_s$ subcarriers in a doubly-selective Rayleigh fading environment. Input data are assumed to be independent variables with zero mean and unit variance. The time domain data sequence is obtained by taking the inverse discrete Fourier transform (IDFT) of the data block for each transmit antenna. A cyclic prefix (CP) with a length longer than the channel length is inserted at the beginning of each of the data sequences. The data sequences with a cyclic prefix (CP) are then transmitted through $N_t$ independent antennas. At each receive antenna, the cyclic prefix (CP) is removed and a discrete fourier Transform (DFT) unit sequence is applied. Let $x_k = [x_{k1}, ... , x_{kN_s}]^T$ and $y_k = [y_{k1}, ... , y_{kN_s}]^T$ denote, respectively, the transmitted and received data for all antennas on subcarrier $k$, where $0 \leq k \leq N_s - 1$. The general form of the received signal in MIMO-OFDM over slowly fading channels (the channel is time-invariant over several Orthogonal Frequency Division Multiplexing (OFDM) symbol periods) (OFDM) signal are time and frequency synchronised to each other, allowing the interference between subcarriers to be carefully controlled. These multiple subcarriers overlap in the frequency domain but do not cause inter-carrier interference (ICI) due to the orthogonal nature of the modulation.

B. Space-Time Coded Orthogonal frequency division multiplexing (OFDM) Transmitter

Consider a Multi-Input Multi-Output- Orthogonal frequency division multiplexing (OFDM) system with $N_t$ transmit antennas, $N_r$ receive antennas, and $N_s$ subcarriers. The channel is frequency-selective Rayleigh fading and is modeled as quasi-static, allowing it to be constant over an orthogonal frequency division multiplexing (OFDM) block and change independently from one block to another.

Input symbol sequence $\{a(0), a(1), ..., a(N_sN_r - 1)\}$ is serial-to-parallel converted into $N_t$ sequences, each of length $N_s$, as $a_p(k) = a(k + (p - 1)N_s)$; $k = 0, ..., N_s - 1$, $p = 1, ..., N_t$. Each of the $N_t$ sequences $\{a_1(k), a_2(k), ..., a_{N_t}(k)\}$, $k = 0, ..., N_s - 1$, is mapped to a matrix $\Psi_k$ of size $N_s \times N$ ( $N$ is the number of time burst defined in STC) by using the orthogonal space- time block coding scheme given in [Tarokh,1999]

$$\{a_1(k), a_2(k), ..., a_{N_t}(k)\} \Rightarrow \Psi_k, \quad k = 0, ..., N_s - 1$$

(3.1)
For instance, if we apply the Alamouti code for a system with two transmit antennas, \( \Psi_k \) is obtained as
\[
\Psi_k = \begin{bmatrix}
a(k) \cdot a^*(k) \\
a(k) \cdot a^*_j(k)
\end{bmatrix}
\]  
(3.2)

Then we take the inverse discrete Fourier transform (DFT) of \( \{ \Psi_k, \Psi_{k+N-1} \} \) as

\[
S_m = \frac{1}{\sqrt{N_t}} \sum_{k=0}^{N_t-1} \Psi_k \cdot e^{j2\pi mk/N_t}
\]  
(3.3)

Where \( S_m \) is given by
\[
S_m = \begin{bmatrix}
S_0 \ldots S_{N_t-1}
\end{bmatrix}
\]

(3.4)

It is easy to recognize that \( \{ S_{p,n}(m) \}, \ p = 1, \ldots, N_t, \ n = 0, \ldots, N_t - 1, \ m = 0, \ldots, N_t - 1, \) are transmitted in parallel using the \( N_t \) subcarriers and \( N_t \) antennas over \( N_t \) time intervals. Thus, each transmitted symbol is coded onto the space, time, and frequency dimensions through the ST-OFDM process.

### C. Multi-Input Multi-Output Wireless Channel

In a frequency-selective fading channel with \( L \) resolvable paths, there exists mutual interference between adjacent Orthogonal frequency division multiplexing (OFDM) blocks. This interblock interference (IBI) could be cancelled by adding a cyclic prefix (CP) of length \( C_P \) to each transmitted block. At the receiver, the Cyclic Prefix is discarded, leaving InterBlock Interference-free information-bearing signals. The channel matrix \( H \) is block-circulant with \( N_t \) blocks expressed as

\[
H = \begin{bmatrix}
H(0) & \cdots & H(-1) & \cdots & H(1) \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
0 & \cdots & H(0) & \cdots & H(0)
\end{bmatrix}
\]

(4.1)

where \( 0 \) is a zero matrix of size \( N_t \times N_t \). Each nonzero block of \( H \) represents the MIMO spatial channel matrix of size \( N_t \) for a particular path \( l \) and is expressed as

\[
H(l) = \begin{bmatrix}
h_{ij}(l) & \cdots & h_{ij}(l) \\
h_{ji}(l) & \cdots & h_{ji}(l)
\end{bmatrix}
\]

(4.2)

where \( h_{ij}(l), \ 1 \leq i \leq N_t, \ 1 \leq j \leq N_t, \) is zero-mean complex Gaussian with unit variance. In a practical scenario, insufficient spacing among antennas will cause spatial correlation.

#### a) The Impact of Intercarrier Interference ICI Caused by Phase Noise and Time-Varying Fading

In the presence of phase noise and time-selective fading, the effective \( N_s N_r \times N_s N_t \) spatiotemporal channel matrix \( H_t \) during the \( t \)th (OFDM) Orthogonal Frequency Division Multiplexing symbol period with the effects of phase noise taken into consideration is expressed in APPENDIX C.

#### b) Phase Noise Suppression and Data Detection

As mentioned in Section 4.5, do not hold for MIMO-OFDM systems in the presence of phase noise and time-selective fading. The term \( P_{kk} \) carries data symbols, but the distortion \( P_{kk} \) is a function of the phase noise process, which is costly to estimate. Additionally, when \( N_t \) is large, this term is very small due to the scaling factor \( 1/N_t \). Therefore, the term \( P_{kk} \) will be treated as noise for the derivation of minimum mean-squared error, MMSE-based phase noise mitigation and the third term on the right-hand side in the APPENDIX B, the intercarrier interference ICI term caused by both phase noise and time-selective fading.

For Orthogonal frequency division multiplexing (OFDM) systems over fast fading channels, channel estimates are generally obtained by transmitting pilot symbols at certain positions of the frequency-time grid [Simeone, 2004]. When significant phase noise is also present, a joint scheme to simultaneously estimate Common phase error (CPE) and channel state information (CSI) is needed. Such a joint estimation appears to be very challenging because of the mutual coupling effects of phase noise and channel fading processes is out of the scope of this chapter. The author thus assumes perfect channel state information (CSI) at the receiver.
III. RESULTS AND DISCUSSION

Numerical Results

Simulations are carried out based on the “SUI-5” channel model [Falconer, 2002], which is one of six channel models adopted by IEEE 802.16a for evaluating broadband wireless systems in the 2-11GHz band. The author considered a system with two transmits antennas and three receive antennas which employs QPSK modulation.

The doubly-selective Rayleigh fading channel is assumed to have three resolvable multipath components. These paths are modelled as independent complex Gaussian random variables and have relative delays of 0μs, 5μs, and 10μs. The rms delay spread of the channel is 3.05μs and the maximum Doppler shift of the channel is calculated based on a carrier frequency of \( f_c = 2\text{GHz} \).

### Table 1: Parameter Values Used in the System Simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Geometry</td>
<td>Horizontal Antenna on side R=1000m</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>( f = 2\text{GHz} )</td>
</tr>
<tr>
<td>System Bandwidth</td>
<td>( W = 5\text{MHz} )</td>
</tr>
<tr>
<td>Path Loss Exponent</td>
<td>( r = 0.7 )</td>
</tr>
<tr>
<td>Shadow Fading</td>
<td>Lognormal with Standard Deviation = 0 dB</td>
</tr>
<tr>
<td>Multipath Fading</td>
<td>Rayleigh (( \alpha = 0 ))</td>
</tr>
<tr>
<td>Antennas Pattern</td>
<td>Omnidirectional or Uniform over 120°</td>
</tr>
<tr>
<td>Thermal Noise Density</td>
<td>( N_0 = -174 \text{ dBm/Hz} )</td>
</tr>
<tr>
<td>Mobile Station's Noise Figure</td>
<td>( N_{0} = 0 \text{ dB} )</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>PT = 5 W for ( f = 2\text{GHz} ) PT = 37 W for ( f = 5\text{GHz} )</td>
</tr>
<tr>
<td>Medium Cell-Scale SNR</td>
<td>( p = 20 \text{dB} )</td>
</tr>
<tr>
<td>Transmit Antenna Array (BS) Length</td>
<td>BS = 8 m</td>
</tr>
<tr>
<td>Receive Antenna Array (MS) Length</td>
<td>MS = 0.1 m</td>
</tr>
<tr>
<td>AoA Statistics (at the Base Station)</td>
<td>Laplacian Power Angular Spectrum with Angular Spread = 15°, ( \beta = 1 )</td>
</tr>
<tr>
<td>AoA Statistics (at the Mobile Station)</td>
<td>Laplacian Power Angular Spectrum with Angular Spread = 45°, ( \beta = 111^\circ )</td>
</tr>
</tbody>
</table>

### Table 2: Parameter Values Used in the System Simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Speed VS</td>
<td>30km, 60km, 100km, 200km, 400km</td>
</tr>
<tr>
<td>Number of Subcarriers, N</td>
<td>12, 64, 128, 256, 512</td>
</tr>
<tr>
<td>Data Symbol Size</td>
<td>5 = 5b/10, 7, 10b, 10s, 10-4, 10-5</td>
</tr>
<tr>
<td>Phase Noise (dB)</td>
<td>( \mu_{\text{phase}, 0} = 0 \text{ dB} ) ( \mu_{\text{phase}, 10} = 5 \text{ dB} )</td>
</tr>
<tr>
<td>Frequency</td>
<td>( f_c = 2\text{GHz} )</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Different Modulation</th>
<th>For AWGN Channel</th>
<th>For Rayleigh Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>64-QAM</td>
<td>2.3 dB</td>
<td>2.3 dB</td>
</tr>
<tr>
<td>256-QAM</td>
<td>3.6 dB</td>
<td>3.6 dB</td>
</tr>
<tr>
<td>1024-QAM</td>
<td>3.25 dB</td>
<td>2.5 dB</td>
</tr>
</tbody>
</table>

MIMO-OFDM system more vulnerable to phase noise or time variations of the channel coefficients. The author has assumed perfect channel state information CSI for all numerical results so far. In practical systems, however, there exist channel estimation errors. It is beyond the scope of this chapter to discuss channel estimation schemes for time-selective fading channels.

To access its impact, channel estimation error is emulated by introducing an error with a normalized average MSE defined as \( \text{MSE} = \frac{E [||H - \hat{H}||^2_F] / E [||H||^2_F]}{,} \) where \( \hat{H} \) has the same form, except that phase noise terms and OFDM symbol index are neglected. The performance results of MIMO-OFDM systems with various MSE values are shown in Fig. 1, where all parameters, except \( \beta = 10\text{Hz} \), are the same as those applied in Fig. 2. The proposed MMSE-based phase noise suppression scheme and the MMSE detection scheme are employed in this simulation. It is observed that the Performance degradation is negligible only when the MSE value of channel estimation errors is small (e.g., \( 10^{-3} \)).
The strongest signal refers to the signal with the highest signal-to-noise ratio (SNR), and the weakest signal refers to the signal with the lowest SNR. As the number of subcarriers increases, however, system performance deteriorates rapidly.

**Discussion**

Fig. 2 shows the CIR values as a function of data symbol period $T_s$, the 3-dB phase noise linewidth $\beta$, and the number of subcarriers $N_s$ within one OFDM symbol. These curves are obtained by using the analytical expression given in Eq. (4.1) and simulations based on the maximum Doppler shift under a vehicle speed of $v_s = 100\text{Km/h}$. Simulation results match well with the theoretical results. CIR is found to be inversely proportional to $T_s$, $N_s$, and $\beta$; thus, increasing $\beta$ or $T_s$ makes the MIMO-OFDM system more vulnerable to phase noise or time variations of the channel coefficients.

**Figure 2:** CIR comparisons with different number of subcarriers and phase noise linewidth ($v_s = 100\text{Km/h}$).

In Fig. 3, SINR versus $E_s/N_0$ curves under different values of $\beta T_s$ and $v_s$ are obtained by using computer simulations. The OFDM symbol is assumed to have $N_s = 256$ subcarriers, and data symbol period is $T_s = 10^{-6}$ seconds. It is observed that SINR is inversely proportional to $\beta T_s$. With a fixed but large value of $\beta T_s$ (e.g., $10^{-3}$), however, the difference between SINR curves corresponding to different vehicle speeds diminishes. This is because when $\beta T_s$ is large, ICI is dominated by phase noise. On the other hand, with a smaller $\beta T_s$ value such as $\beta T_s = 10^{-4}$, increasing the Doppler shift (or vehicle speed) clearly lowers the SINR value.

**Figure 3:** SINR versus $E_s/N_0$ for MIMO-OFDM with different vehicle speed and phase noise variance ($N_s = 256, T_s = 10^{-6}$s).

**Figure 4:** CIR comparisons with different number of subcarriers and phase noise linewidth ($v_s = 100\text{Km/h}$).

Fig. 4. shows the SER performance of the proposed MMSE-based phase noise suppression scheme together with those of a phase-noise-free system and a system without phase noise correction when the MMSE detection scheme is considered. System parameters chosen are: $N_s = 128$, $T_s = 10^{-7}$s, $\beta = 10\text{Hz}$, and $v_s = 30\text{Km/h}$. It is observed that without phase noise correction, even a very mild amount of phase noise ($\beta T_s = 10^{-6}$) causes a high error floor. On the other hand, the proposed scheme significantly reduces the effect of phase noise. Note that performance of the proposed scheme does not approach that of the phase-noise-free system because this scheme mitigates only CPE, and it does not eliminate ICI, which is caused by both phase noise and time-selective fading.

**Figure 4:** CIR comparisons with different number of subcarriers and phase noise linewidth ($v_s = 100\text{Km/h}$).

Shown in Fig. 4 are the simulated SER performances of the system when the proposed MMSE-based phase noise suppression scheme and the MMSE detection scheme described are employed. Other parameters chosen are: $N_s = 64$, $T_s = 10^{-7}$s, and $v_s = 100\text{Km/h}$. Performances with different values of the 3-dB phase noise variance ($\beta T_s = 10^{-7}$, $10^{-6}$, $3 \times 10^{-6}$, and $10^{-5}$) are compared. The performance curve of a phase-noise-free MIMO-OFDM system is used as the baseline performance. It appears
that the scheme works effectively only when $\beta T_s$ is small.

In Fig. 6.., we compare the performances of four different detection methods: the ZF, MMSE, decorrelating DF, and MMSE-DF schemes when the MMSE–based phase noise suppression scheme applied. Other than that $\beta = 30\text{Hz}$, all other parameters are the same as those applied for Fig. 4.. Performance of the ML scheme is used as the benchmark for other detection schemes. Since these schemes are not specifically optimized for MIMO-OFDM systems with phase noise over fast time-varying fading channels for which ICI should be dealt with, error floors are observed for all cases. Note that from Eqs. (4.1) and (4.2), the energy of ICI due to the phase noise and time-selective fading is found to spread over all subcarriers, which is different from the assumption that most of ICI on each subcarrier comes from several neighbouring subcarriers. Consequently, ICI suppression for the scenario studied in this chapter becomes more challenging than the case dealt with earlier.

We have assumed perfect CSI for all numerical results so far. In practical sys-tems, however, there exist channel estimation errors. It is beyond the scope of this chapter to discuss channel estimation schemes for time-selective fading channels. To access its impact, channel estimation error is emulated by introducing an error with a normalized average MSE defined as $MSE = E \left[ ||H - \hat{H}||^2_F \right] / E \left[ ||H||^2_F \right]$, where $H$ has the same form as Eq. (4.1), except that phase noise terms and OFDM symbol index are neglected. The performance results of MIMO-OFDM systems with various MSE values are shown in Fig. 4.2., where all parameters, except $\beta = 10\text{Hz}$, are the same as those applied in Fig. 8.. The proposed MMSE-based phase noise suppression scheme and the MMSE detection scheme are employed in this simulation. It is observed that the performance degradation is negligible only when the MSE value of channel estimation errors is small (e.g., $10^{-5}$).

IV. CONCLUSION

We have analyzed the impact of phase noise and channel time selectivity on the performance of MIMO-OFDM systems. Specifically, we have quantified ICI caused by phase noise and channel time variations. A phase noise suppression scheme based on the MMSE criterion is proposed, which is shown to effectively reduce the effect of phase noise. Performances of five detection schemes are compared, and it

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