Position-Based Compressed Channel Estimation and Pilot Design for High-Mobility OFDM Systems

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Abstract:
Due to the development of High-Speed Trains (HSTs) in many countries, providing broadband wireless services in HSTs is crucial. Orthogonal Frequency-Division Multiplexing (OFDM) has been widely adopted for broadband wireless communications due to its high spectral efficiency. However, OFDM is sensitive to the time selectivity caused by high-mobility channels, which costs much spectrum or time resources to obtain the accurate Channel State Information (CSI). Here, a new position-based high-mobility channel model is proposed, in which the HST’s position information and Doppler shift are utilized to determine the positions of the dominant channel coefficients. Then, a joint pilot placement and pilot symbol design algorithm for compressed channel estimation is proposed. Simulation results demonstrate that the proposed method performs better than existing channel estimation methods over high-mobility channels.

Keywords: Channel estimation, Compressed Sensing (CS), high-mobility channels, Orthogonal Frequency Division Multiplexing (OFDM), position-based channel model.

I. INTRODUCTION:
Due to its high spectral efficiency Orthogonal Frequency Division Multiplexing (OFDM) has been widely adopted for broadband wireless communication systems. In OFDM systems, each subcarrier have a narrow band width ensures that the signal is strong against the frequency selectivity caused by the multipath delay spread. However, OFDM is sensitive to the time discrimination, which is induced by rapid time variations of mobile channels. In recent years, high-speed trains (HSTs) have been gradually developed in many countries, and OFDM has been adopted for high data rate services. Since an HST travels at a speed of around 500 km/h, the wireless channels suffer from a high Doppler shift. Wireless channels are both fast time varying and frequency in high mobility environments. As the quality of channel estimation has a major impact on the overall system performance, it is necessary to investigate reliable estimation methods in high-mobility environments. Various times varying channel models have been established and channels estimation for fast time varying channels has been extensively studied in the literature. Sung and Brady and Mostofi and Cox proposed several channel estimators by using a linear time-varying channel model. They assumed that the channel varies with time linearly in one or more OFDM symbols. The method in works well at low Doppler shifts since some channel matrix coefficients are ignored. Mostofi and Cox proposed two approaches to estimate time-varying channels: one using guard intervals and the other exploiting three consecutive symbols. However, the linear models can result in large modelling error and severely degrade the channel estimation performance in high-mobility environments, where the channel may change significantly even within one OFDM symbol.

II. SYSTEM MODEL:
HIGH SPEED TRAIN COMMUNICATIONS:
Consider well-recognized system architecture of broad-band wireless communication for HSTs as shown in Fig 1. The communication between Base Stations (BSs) and mobile users is conducted in a two-hop manner through a Relay Station (RS) deployed on the train. The RS has two antennas on the top of the train to communicate with the BS. On the other hand, multiple indoor antennas are distributed in the train carriages to communicate with mobile users by existing wireless communication technologies, e.g., Wireless Fidelity (Wi-Fi). The BSs are located 10–50 m Away from the railway at some intervals and connected with optical fibers. Here, we assume each BS is equipped with one antenna and has the same power allocation and coverage range. In this paper, we focus on the channel estimation between the BSs and the RS on the HST. When the HST camps in a single cell, the RS selects the antenna with better channel quality to communicate with the BS; when the HST moves across the cell edges, the front antenna executes handover, whereas the rear one remains connected to the serving BS. The HST is equipped with a GPS, which can estimate the HST’s instant position and speed information and send them to the BS [25]. Several factors may influence the performance of the GPS, such as signal arrival time measurement, atmospheric effects, terrains, and so on. In particular, when the HST runs in a tunnel, the GPS accuracy may be highly reduced. However, in this project we do not consider these factors and assume that the HST runs in a plain terrain. We also assume that the GPS estimates the HST’s speed and position information perfectly and sends the information to the BS with no time delay. Denote \( v \) as the speed of the HST and \( c \) as the light speed. The distance between BSs is denoted as \( D_0 \). Let \( D_{\text{max}} \) denote the maximum distance of the coverage of the BS to the railway, i.e., positions \( A \) and \( C \) to BS1. Let \( D_0 \) denote the minimum distance, i.e., the position \( B \) to BS1, and \( D_c \) denote the distance between \( A \) and \( B \). In each cell, we define the HST position \( \alpha \) as the distance between the serving antenna and the position \( A \), and \( \alpha = 0 \) at \( A \). Let \( \theta \) denote the angle between the signal transmitted from the BS to RS and the railway.
When the HST moves from A to C, \( \theta \) changes from \( \theta_{\text{max}} \) to \( \theta_{\text{max}} \). If \( D_{\text{max}} \ll D_0 \), then we have \( \theta_{\text{max}} \approx 0 \) and \( \theta_{\text{max}} \approx 180 \). Furthermore, HST suffers from the Doppler shift \( f_d \) at different positions, and \( f_d \) can be calculated by using the equation \( f_d = (v/c) f_c \cos \theta \), in which \( f_c \) is the carrier frequency. It is easy to find that \( f_d = 0 \) at \( \theta = 90^\circ \).

**OFDM SYSTEM:**

We consider an OFDM system with \( K \) subcarriers for the link between the BS and the RS in the HST communication system. The transmit signal at the \( k \)th subcarrier of the \( n \)th OFDM symbol is denoted as \( X(k) \), for \( n = 1, 2, \ldots, N \) and \( k = 1, 2, \ldots, K \). The transmitter performs the inverse Discrete Fourier transform (DFT), inserts the cyclic prefix (CP), and then transmits the signals to the channel. After removing the CP and passing the DFT operation at the receiver, the received signal in the frequency domain can be represented as \( Y = HX + W \), where \( Y = [Y(1), Y(2), \ldots, Y(K)]^T \) is the received signal vector over all subcarriers during the \( n \)th OFDM symbol, \( H \) is a \( K \times K \) channel matrix in the frequency domain, \( X = [X(1), X(2), \ldots, X(K)]^T \) is the transmitted signal vector over all subcarriers, and \( W = [W(1), W(2), \ldots, W(K)]^T \) denotes the noise vector, where \( W(K) \) is the additive white Gaussian noise (AWGN) with a zero mean and \( \sigma^2 \) variance. The entries of \( H \) are represented as

\[
H(k, d) = \frac{1}{K} \sum_{m=0}^{K-1} \sum_{l=0}^{l-1} h(l, m) e^{-j2\pi/d} e^{-j2\pi k(m-d-k)}
\]

1 \( \leq k, d \leq K 

Where \( h(l, m) \) is the \( l \)th channel tap in the \( m \)th sample time of the \( n \)th OFDM symbol, and \( I \) is the maximum number of channel taps. More detailed descriptions of \( H \) in high-mobility environments is given in the following. If the channel is time invariant, the off-diagonal term \( H(k, d) \), \( k \neq d \), is negligible, and the diagonal term \( H(k, d) \), \( k = d \), alone represents the channel in the frequency domain. Therefore, channel matrix \( H \) can be divided into two parts: the ICI-free channel matrix \( H_{\text{free}} \) and the ICI channel matrix \( H_{\text{ICl}} \). Then, signal frequency can be rewritten as

\[
Y = H_{\text{free}}^T X + H_{\text{ICl}}^T X + W
\]

**JOINT PILOT PLACEMENT AND PILOT SYMBOL DESIGN ALGORITHM**

**Input:** Initial pilot \( X_0 \) with the pilot placement \( p_0 \) and the pilot symbol \( x_0 \)

**Output:** Optimal pilot \( X_d^* \)

**Initialization:** Set \( X_0 = X_0 \); set \( M \), \( \mu \), \( \delta \), \( \kappa \), \( E \); set \( I([0]) = 0 \); set \( [0, 0] = 1 \); set \( k = 1 \)

for \( n = 0, 1, \ldots, M - 1 \) do

for \( k = 0, 1, \ldots, P - 1 \) do

Generate and update:

Generate a random power \( \mu \) with operator \( \gamma_{\mu}(\mu) \) if \( \mu \delta \{ X_m (p \pm m) \delta x \} < \{ X_m (p \pm m) \delta x \} \) then

Select pilot symbol power \( E_k \) to \( \min \mu_k \); update \( X_{m} \) and \( X_{m+1} \) with \( p_{m+1} \) and \( p_m \)

else

select pilot symbol power \( E_k \) to \( \min \mu_k \); update \( X_{m+1} \) and \( X_{m} \) with \( p_{m+1} \) and \( p_m \)

end if

If \( I([m + 1]) > I([m + 1]) \) then

\( X_{m+1} = X_{m+1} \) if \( k \)

end if

end for

end for

**PROBLEM FORMULATION:**

To get the better CS performance we are going to reduce \( \mu \delta \{ Xd(p) \delta x \} \) in our system. Because lower coherence leading to a better performance. The pilot symbol and the pilot
placement of the transmitted pilot matrix $X_{d(p)}$ are considered with the leading channel model dictionary $\Phi$ is defined in this paper. Let us start from the neutral of reducing $\mu_d(X_{d(p)}\Phi)$. This pilot design problem can be formulated as follows:

$$\min \mu_d(X_{d(p)}\Phi) \text{ Anywhere } p \text{ denotes the pilot placement set and } X_d \text{ denotes the pilot symbols in } X_{d(p)}.$$ According to average coherence definition the imperfect channel can be signified where $\rho(k_x, u)$ is the entry of $\Phi$ and $0 \leq u < v \leq L(2M+1) - 1$. Suppose that all the data and pilots are modulated symbols, and there are $T$ pilot power levels conforming to $T$ pilot placement subsets $\{S_t\}_{t=1}^T$. Then, we have $\sum_{t=1}^T S_t = P$, and we state the pilot power as $E_p = |X(k_{j_t})|^2$, $k_{j_t} \in S_t$. For $j_t \in \{1, 2, \ldots, P\}$ and $t = 1, 2, \ldots, T$. Moreover consider the proposed position based channel model, by taking pilot power into deliberation. When the HST changes to a definite position $\alpha$, the high-mobility channels can be exhibited by $b_x$ conforming to $f_0$. Therefore, we only need to study the property of the columns in $\Phi_x$. The columns in $\Phi_x$ can be represented as $\Phi(\cdot, u)$ and $u \in [L(M + x), L(M + x) + L - 1]$.

**PRACTICAL APPLICABILITY**

Here, we briefly discuss the applicability of the proposed scheme in a practical HST system. As aforementioned the BSs are connected with optical fibres and share the instant speed and position information of the HST, which are supported by the GPS. In a practical system, system parameters (such as $v_{\text{max}}$, $f_{\text{max}}$, etc.) can be collected in advance. Thus, the optimal pilots (including the pilot placement and pilot symbol) for different Doppler shifts $f_0$ (for HST positions $\alpha$) can be predesigned with Algorithm 1 by selecting corresponding $\Phi_x$ and then stored into a pilot codebook, which is an offline process. This pilot codebook is equipped at both the BS and the HST. When the HST runs, the BS obtains the instant speed and position information of the HST from the GPS and then calculates the instant $f_d$. At the beginning of each OFDM symbol, the BS selects the optimal pilot from the codebook according to $f_d$ and transmits it to estimate the channels. This transmitted pilot is also known at the HST for checking the same codebook. Note that we assume that $f_d$ is constant during one OFDM symbol. Thus, the selected pilot is optimal during each OFDM symbol. In this way, the proposed scheme can be well used in current HST systems without adding too much complexity. An example of the proposed pilot codebook is given in the simulation results.

<table>
<thead>
<tr>
<th>TABLE.III COMMUNICATION SYSTEM PARAMETERS</th>
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<tbody>
<tr>
<td>Parameters</td>
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<tr>
<td>BS power range</td>
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<tr>
<td>Distance between bs’s</td>
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<tr>
<td>Max distance of bs to railway</td>
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<tr>
<td>direct distance of bs to railway</td>
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<td>Carrier frequency $f_c$</td>
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<tr>
<td>Train speed</td>
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<tr>
<td>Light speed</td>
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</tbody>
</table>

**III. SOFTWARE REQUIREMENTS MATLAB**

The most important things to learn are how to enter matrices, how to use the: (colon) operator, and how to invoke functions.

**IV. CONCLUSION**

A new position-based compressed channel estimation method for high-mobility OFDM system is proposed. The estimation complexity is reduced by the proposed channel model by utilizing the position information. The pilot symbol and the pilot placement are jointly designed by the proposed algorithm to minimize the system average coherence. Simulation results demonstrate that the proposed method achieves better performances than existing channel estimation methods over high-mobility channels. Furthermore, with a predesigned pilot codebook, the proposed scheme is feasible for many current wireless OFDM communication systems.

**V. FUTURE SCOPE**

Hybrid compressed sensing algorithm as subspace orthogonal matching pursuit (SOMP) first identifies the channel sparsity and then iteratively refines the sparse recovery result which essentially combines the advantages of orthogonal matching pursuit (OMP) and subspace pursuit (SP), since SOMP belongs to greedy algorithms, its computational complexity is in the same order as OMP. This project can be improved further if we can implement the best pilot design techniques to estimate the channel properties exactly thus we can reduce the BER and MSE.

**VI. REFERENCES**


