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Channel prediction of wideband OFDM systems in a millimeter-wave band based on multipath delay estimation

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Abstract: Multi-user MIMO systems enable high capacity transmission. A base station, however, needs accurate channel state information (CSI). In time-varying environments, the CSI may be outdated at the actual transmission time. One of the solutions to this issue is channel prediction. The authors have proposed the prediction method using FISTA, a compressive sensing technique, for OFDM systems in a millimeter-wave band. Unfortunately, in realistic multipath environments, the prediction performance of the proposed technique degrades. In this letter, we examine the prediction performance in wider OFDM systems. It will be shown that FISTA reveals excellent performance in a sufficiently wide band case.

Keywords: channel prediction, multipath, delay estimation, compressive sensing, OFDM, IDFT

Classification: Wireless Communication Technologies

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1 Introduction

A base station (BS) needs downlink channel state information (CSI) for multi-user MIMO transmission that enables high capacity communication. Radio propagation, however, usually varies due to the motion of user equipment (UE) and/or scatters. In such time-varying multipath environments, the CSI estimated with pilot symbols may be outdated at the actual transmission time, and the precoding performance may degrade. If we predict CSI from observed past one, we can reduce the degradation. Among prediction techniques, the sum-of-sinusoids method [1] predicts channels by resolving an arrival signal into individual multipath components and summing the predicted ones. This corresponds to predicting a future delay profile. If the complex amplitude of each multipath component is estimated accurately, we can predict reliable channels for a long prediction range. At millimeter-wave frequencies, channel responses are sparse [2], and we can apply a compressive sensing technique such as the fast iterative shrinkage-thresholding algorithm (FISTA) [3] to obtain the complex amplitudes of multipath components. The authors have proposed the CSI prediction method in which FISTA resolves the arrival signal in a wideband OFDM system into multipath components in the delay domain, and recently reported the prediction performance [4]. Unfortunately, in realistic multipath environments [5], the prediction performance of the proposed technique degrades and is almost the same as that of the method using the conventional inverse discrete Fourier transform (IDFT). In this letter, we will show the prediction performance in wider OFDM systems.

2 Formulation of the CSI prediction

The goal of this letter is to examine the CSI prediction using delay profile estimation in wideband OFDM systems, and we deal with SISO-OFDM for the sake of simplicity. Extending to MIMO systems is a future work. The prediction technique can be applied to both of FDD and TDD.

We express the downlink channel state at subcarrier frequency f_s at time t as $H(f_s; t)$ ($s = 1, 2, \dots, S_c$), where S_c denotes the number of subcarriers in OFDM. We assume that the BS has the CSI at time t_0 and t_1 , i.e., $H(f_s; t_0)$ and $H(f_s; t_1)$ ($t_0 < t_1$) with pilot symbols. Representing the pilot symbol transmission interval as T_{int} , we have $t_1 = t_0 + T_{\text{int}}$. Note that T_{int} is the channel measurement interval. We predict the channel state at time t_2 , $H(f_s; t_2)$, from $H(f_s; t_0)$ and $H(f_s; t_1)$ ($t_1 < t_2$).

We assume that all the multipath components arrive in the delay range from τ_{min} to τ_{max} . We discretize the delay range into P sampling points. The i th delay sampling point is given by $\tau'_i = \tau_{\text{min}} + (i - 1)\Delta\tau$, where $\Delta\tau = (\tau_{\text{max}} - \tau_{\text{min}})/(P - 1)$

and $i = 1, 2, \dots, P$. Expressing the complex amplitude of multipath component at delay τ'_i at time t as $A'_i(t)$, we approximately have

$$\sum_{i=1}^P A'_i(t) \exp(-j2\pi f_s \tau'_i) = H(f_s; t) \quad (s = 1, 2, \dots, S_c). \quad (1)$$

At time t_0 and t_1 , the right-hand side is $H(f_s; t_0)$ and $H(f_s; t_1)$, respectively. As stated previously, they have been obtained with pilot symbols. At each time, we have S_c linear equations, and the P complex amplitudes $A'_i(t)$ are unknowns.

- (a) When $P = S_c$, (1) is an even-determined case, and should theoretically be solved. However, because the subcarrier frequency interval Δf_s and/or delay sampling point interval $\Delta \tau$ are/is small, the equations are usually ill-conditioned, and we cannot solve them.
- (b) When $P < S_c$, (1) is an over-determined case, and the least squares method with the pseudo-inverse matrix should be used. Unfortunately, the method usually does not work because of the ill condition also in this case.
- (c) When $P > S_c$, (1) is an under-determined case. The solution is not determined uniquely, and we should use the pseudo-inverse matrix. Due to the ill-conditioned situation, the matrix inversion cannot be done in most cases.

To overcome the above ill condition, we tried the Tikhonov regularization and the rank reduction technique. Unfortunately, they did not work well in our cases. On the other hand, in millimeter-wave bands, channels are sparse, and most of $A'_i(t)$ are 0. We can expect that $A'_i(t)$ are obtained by the ℓ_1 - ℓ_2 optimization [6], which minimizes the squared error with the ℓ_1 -norm regularization term. This is a compressive sensing technique. In this study, we use FISTA [3] for the ℓ_1 - ℓ_2 optimization. The detail procedure for obtaining $A'_i(t_0)$ and $A'_i(t_1)$ using FISTA, and prediction of $A'_i(t_2)$ are stated in [4]. From $A'_i(t_2)$, we can predict the future channels $H(f_s; t_2)$ by the following equation:

$$\hat{H}(f_s; t_2) = \sum_{i=1}^P A'_i(t_2) \exp(-j2\pi f_s \tau'_i). \quad (2)$$

3 Simulations

In this section, we show simulation results of the channel prediction method with FISTA. In addition to them, we also consider the performance using the conventional IDFT for multipath detection in the delay domain. As for the channel model, we used the 28-GHz non-line-of-sight model proposed in [5].

Table I shows the simulation parameters. Refer to [4, 5] for symbols and terms that are not defined in this letter. Strictly speaking, since $\Delta f_s = 120$ kHz, the bandwidth B is 199.92 MHz for $S_c = 1666$. In this letter as shown in Table I, we write $B = 200$ MHz for the sake of simplicity. This is the same also for $B = 400$ MHz, 800 MHz. In a frame configuration in the 5G system employing TDD for 28 GHz, the downlink duration is 0.25 ms, and the channel measurement interval T_{int} was set 0.25 ms as shown in Table I. Furthermore, in the simulations, we ignored noise, that is, we assumed that $H(f_s; t_0)$ and $H(f_s; t_1)$ were obtained accurately.

Table I. Simulation parameters

Lowest subcarrier frequency f_1	28 GHz		
Subcarrier frequency interval Δf_s	120 kHz		
Bandwidth B	200 MHz	400 MHz	800 MHz
Number of subcarriers S_c	1666	3333	6666
Number of unknowns for multipath components P	313	626	1251
Delay sampling point interval for FISTA $\Delta\tau$	0.8 ns	0.4 ns	0.2 ns
Delay sampling point interval for IDFT $1/B$	5 ns	2.5 ns	1.25 ns
δ for FISTA	2.08×10^4	4.17×10^4	8.33×10^4
Distance between BS and UE	60.2 m		
Minimum delay point τ_{\min}	150 ns		
Maximum delay point τ_{\max}	400 ns		
UE velocity	20 m/s		
Channel measurement interval T_{int}	0.25 ms		
Channel measurement time t_0, t_1	$t_0 = 0$ s $t_1 = t_0 + T_{\text{int}} = 0.25$ ms		
Channel prediction time t_2	$t_2 = t_1 + T$ $T = 0.025, 0.050, 0.075, \dots, 0.250$ ms		
μ for FISTA	1.0		
ε for FISTA	1×10^{-6}		
Number of clusters	3		
Number of subpaths for each cluster	10		
Cluster excess delay interval	25 ns		
Subpath delay interval	2.5 ns		
Shadowing	Disregarded		
Number of trials K	100		

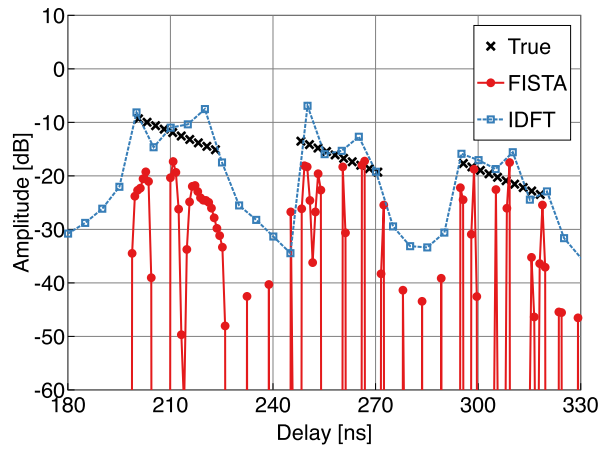
We determined the subpath phases, mean azimuth and elevation angles of arrival from the lobes, and angle spreads by random numbers [5]. Changing the random numbers, we conducted $K = 100$ trials, and evaluated the channel prediction performance using the normalized mean square error (MSE) defined by

$$\text{Normalized MSE [dB]} = 10 \log_{10} \left(\frac{1}{K} \sum_{k=1}^K \frac{E\{|\Delta H^{(k)}(f_s; t_2)|^2\}}{E\{|H^{(k)}(f_s; t_2)|^2\}} \right), \quad (3)$$

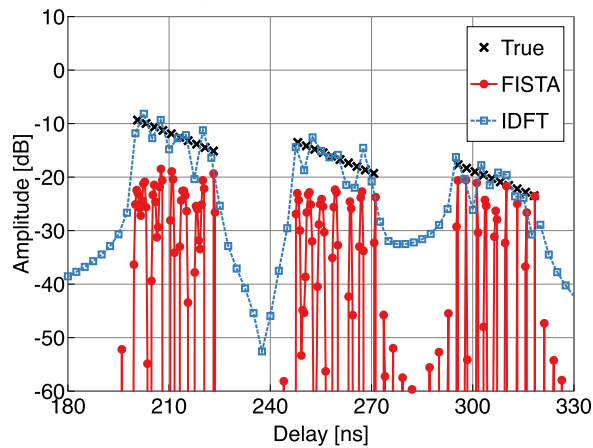
where $E\{\}$ is the mean for all the subcarrier frequencies f_s , and $\Delta H^{(k)}(f_s; t_2)$ is the channel prediction error at the s th subcarrier for the k th trial.

Fig. 1 shows examples of multipath component estimation results in the delay domain at t_0 for different frequency bandwidths. Note that Fig. 1 shows only the delay range where all the multipath components arrive. We see that three clusters exist and each cluster has ten subpaths expressed by \times marks. IDFT cannot resolve the subpaths for any bandwidth. FISTA cannot detect them correctly for $B = 200$ MHz, 400 MHz either. However, when $B = 800$ MHz, it is seen that FISTA can resolve all the subpaths. Estimated amplitudes look rather low, but we see several estimated responses in the neighborhood of each subpath. Combining them, the estimated amplitude will have a higher value.

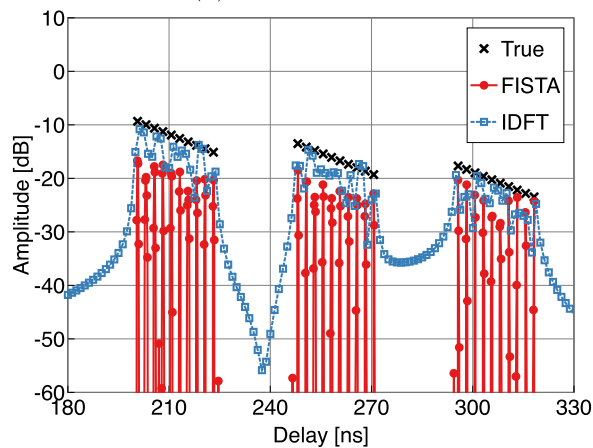
Fig. 2 shows the channel prediction performance, Normalized MSE versus T . As stated in Section 2, $t_2 = t_1 + T$ holds, that is, we predict the channel at T from the



(a) $B = 200$ MHz



(b) $B = 400$ MHz



(c) $B = 800$ MHz

Fig. 1. Examples of multipath component estimation results at t_0 .

estimation time t_1 . The maximum prediction range $T = 0.25$ ms is the same as the downlink duration in the 5G system employing TDD for 28 GHz as stated previously. The performance of FISTA using 200 MHz or 400 MHz bandwidth data is almost the same as that of IDFT. Considering that we ignored noise, the performance is poor. When the bandwidth is 800 MHz, however, the CSI prediction performance

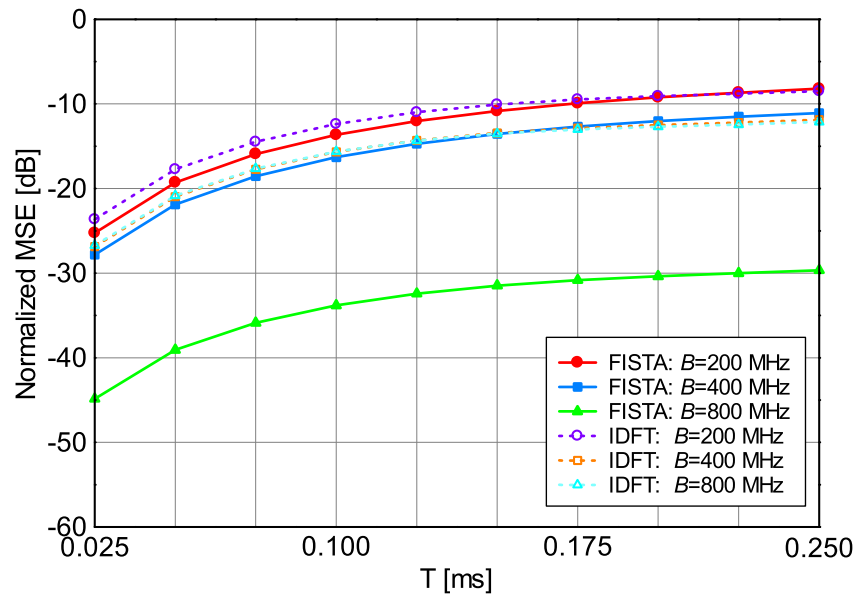


Fig. 2. Channel prediction performance.

of FISTA is improved greatly and is much better than that of IDFT. This is because each multipath component is resolved by the wider bandwidth data as shown in Fig. 1(c). It is seen that even though we use a compressive sensing technique, wider bandwidth data are required to predict CSI accurately.

4 Conclusions

In this letter, we have examined the CSI prediction of OFDM systems based on delay profile estimation. We used FISTA to resolve multipath components in the delay domain, and compared the CSI prediction performance with that of IDFT. It has been shown that in realistic millimeter-wave propagation environments, if the bandwidth of OFDM is sufficiently wide, FISTA reveals excellent performance, which is much better than that of IDFT.