Multiple Autocorrelation Function-based Maximum Doppler Frequency Estimation

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Abstract: In this paper, we introduce a maximum Doppler frequency estimation scheme based on autocorrelation function (ACF) and propose a modified ACF-based method for orthogonal frequency division multiplexing (OFDM) systems. The traditional ACF-based estimation scheme has a trade-off relationship between estimation range of the maximum Doppler frequency and the corresponding performances such as convergence time and steady-state jitter. Since this relationship depends on correlation interval between two OFDM symbols, it is important to design a flexible algorithm in known channel environment. In this paper, we analyze the characteristics of the ACF-based estimation scheme and propose an algorithm to guarantee stable performances such as estimation range and steady-state jitter regardless of correlation interval. Simulation results verify that the proposed method can improve the overall estimation performance in time-varying Rayleigh fading channel environment.

1. Introduction

Several maximum Doppler frequency estimation schemes have been suggested as an important part of channel coefficient estimation [1-5] and they can be categorized into three groups: based on level crossing rate, spectral estimation and ACF. For the wideband signal such as OFDM, however, the level crossing rate-based scheme is not realizable because the Doppler frequency spread is much smaller than the signal frequency bandwidth. Also, the spectral estimation-based scheme requires high computational complexity due to the necessity of multiple Fast Fourier Transforms (FFT) calculation and the threshold level dependence on noise variance. In contrast with the above two schemes, the ACF-based estimation scheme is simply applicable to practical OFDM systems and provides relatively good performance [5]. However, the conventional ACF-based scheme has a trade-off relationship between estimation range and the corresponding performances such as convergence time and steady-state jitter. Thus the performance varies with correlation interval and maximum Doppler frequency. For this reason, it is essential to design an algorithm to guarantee stable performance in time-varying Rayleigh fading channel. In this paper, we explain this point with various simulation results and propose a modified ACF-based method.

The organization of this paper is as follows. In section Ⅱ, we introduce a simple OFDM system model. In section Ⅲ, the ACF-based maximum Doppler frequency estimation scheme and the proposed method are described briefly. In section Ⅳ, simulation results are given and analyzed. Finally, some concluding remarks are provided in section Ⅴ.

2. Maximum Doppler Frequency Estimation

We consider an OFDM system employing N subcarriers for the transmission of N_u useful symbols where $N–N_u$ subcarriers at the edges of the spectrum are not used to avoid aliasing problem at the receiver. The useful symbols consist of data and pilot where the pilot allocation includes discontinuous pattern with the same subcarrier position. In this paper, we assume that the time-domain pilot interval is N_{PI} and does not vary shown in Figure 1.

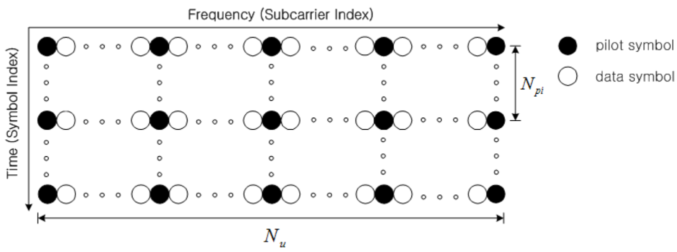

Figure 1. OFDM transmission scheme

In frequency domain, the k-th subcarrier signal of the m-th received OFDM symbol can be represented as

$$Y_m[k] = X_m[k]H_m[k] + W_m[k], \ \left(0 \le k < N\right) \quad (1)$$

where $X_m[k]$ is the transmitted symbol and $W_m[k]$ is zero-mean additive white Gaussian noise (AWGN) with variance σ_w^2. $H_m[k]$ is channel frequency response (CFR) which is discrete Fourier transform (DFT) of channel impulse response $h_m[l]$ with length L and can be expressed as

$$H_m[k] = \sum_{l=0}^{L-1} h_m[l]\exp\left(-j2\pi lk/N\right), \ \left(h_m[l] = \sum_{i=0}^{L-1}\alpha_i\delta\left[l-\tau_i\right]\right) \quad (2)$$

where α_i represents a different path complex gain and τ_i is the corresponding path delay normalized by the sampling spacing, which means there is no channel power loss caused by sampling time mismatch. Usually α_i is modeled as complex Gaussian processes with Jake's power spectrum, and all the delay paths are uncorrelated to each other. The maximum path delay L is assumed not to exceed the length of guard spacing N_{GI} ($L < N_{GI}$). To simplify analysis, we assume that synchronization is perfect at the receiver.

3. Maximum Doppler Frequency Estimation

3. 1 ACF-Based Doppler frequency estimation scheme

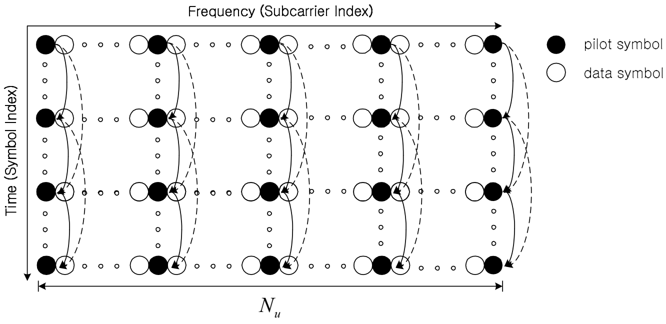

Figure 2. Concept of ACF-based Doppler frequency estimation scheme

Figure 2 shows an operational concept of the ACF-based maximum Doppler frequency estimation. The scheme basically utilizes CFR values which are estimated in the pilot subcarrier position as follows:

$$\widehat{H}_m[k] = \frac{Y_m[k]}{X_m[k]} = H_m[k] + W'_m[k], \quad \left(k \in \mathbf{S}_{pilot}\right) \tag{3}$$

where $\mathbf{S}_{pilot}$ is a set of pilot subcarrier positions and $W'_m[k]\left(= W_m[k]/X_m[k]\right)$. The estimation of the Doppler frequency is performed by correlation between two OFDM symbols with interval d and the correlation value $R_m[d]$ can be expressed as

$$R_m[d] = \frac{1}{N_p} \sum_{k \in \mathbf{S}_{cp}} \widehat{H}^*_{m-d}[k] \widehat{H}_m[k], \quad \left(k \in \mathbf{S}_{pilot}\right) \tag{4}$$

where N_p is the number of the used pilot symbols. Since the correlation value $R_m[d]$ varies with Doppler spread in time-varying Rayleigh fading channel, the direct estimation of the maximum Doppler frequency is impossible, so it requires a large number of OFDM symbols for the convergence. If M is the number of OFDM symbols including pilots, the average of correlation values can be represented as

$$\overline{R}_M[d] = \frac{1}{M-d} \sum_{m=d}^{M-1} R_m[d] \tag{5}$$

In general, if M is large enough, the average value converges to the zero-th order Bessel function as follows:

$$\lim_{M \to \infty} \overline{R}_M[d] = J_0(2\pi f_{d,\max} T_s d) \tag{6}$$

where $J_0(\cdot)$ is the zero-th Bessel function, $f_{d,\max}$ is the maximum Doppler frequency, and T_s is the OFDM symbol duration including cyclic prefix (CP). If ε denotes the normalized maximum Doppler frequency, it can be estimated by inversion of the zero-th order Bessel function as

$$\hat{\varepsilon} = \hat{f}_{d,\max} T_s = \frac{1}{d} J_0^{-1}\left(\overline{R}_M[d]\right) \tag{7}$$

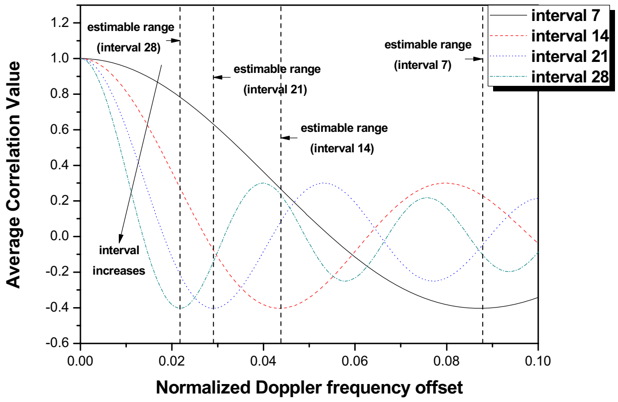

Figure 3. Zero-th order Bessel function

Figure 3 shows the zero-th order Bessel functions for the normalized maximum Doppler frequency ε and interval d. Note that the useful range is limited in the main-lobe because the zero-th order Bessel function is not a one-to-one map function. Thus the maximum value of normalized Doppler frequency within the estimable range is $\gamma/(2\pi d)$, $(\gamma \approx 3.83173)$ and it decreases as the correlation interval d is larger.

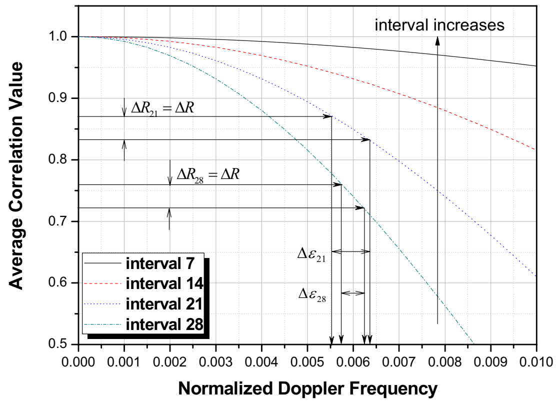

Figure 4. Nonlinearity of zero-th order Bessel function

Figure 4 shows non-linearity characteristic of the zero-th order Bessel function when the Doppler frequency is within the estimation range. For example, considering the correlation interval is 21 and 28, we can see that the variance of the estimated normalized Doppler frequency is smaller as the correlation spacing is larger ($\Delta\varepsilon_{28} < \Delta\varepsilon_{21}$) if the error range of the estimated average correlation value is same ($\Delta R_{21} = \Delta R_{28} = \Delta R$). For this reason, the steady-state jitter performance decreases in proportion to tangential gradient corresponding to the normalized Doppler frequency.

3. 2 Proposed Doppler frequency estimation

As shown in Figure 2, the considered OFDM transmission scheme enables multiple correlations among the pilots. Thus, the proposed algorithm performs consecutive multiple correlation with several intervals $[d_0, d_1, ..., d_i, ..., d_{I-2}, d_{I-1}]$ between two OFDM symbols with pilot where I is the number of the correlations to be considered. As mentioned above, however, a long correlation interval limits the estimation range of the ACF-based estimation scheme. In order to overcome the problem, we introduce a multiple inversion of the zero-th order Bessel function. Figure 5 shows an example of the proposed multiple inversion method.

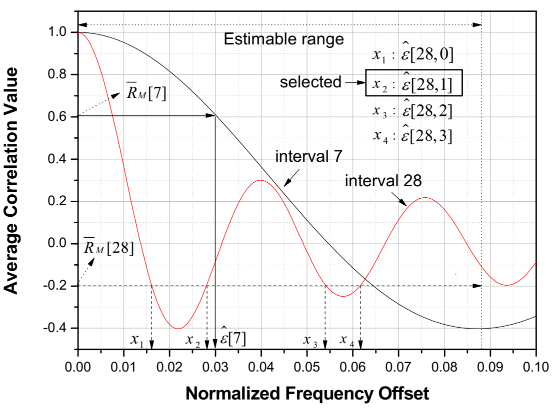

Figure 5. Concept of proposed method

Assuming that the estimated Doppler frequency on the basis of minimum correlation interval, $\hat{\varepsilon}[d_0]$, is reliable, we can find the closest value of the several possible estimated Doppler frequencies $\hat{\varepsilon}[d_i, l]$ for longer correlation interval d_i ($d_i > d_0$) as follows:

$$\bar{\varepsilon}[d_i] = \hat{\varepsilon}[d_i, l_{sel}] \\ where \left(l_{sel} = \min_{l} \left\{ \left| \hat{\varepsilon}[d_i, l] - \hat{\varepsilon}[d_0] \right| \right\} \right) \; for \;\; fixed \;\; d_i \tag{8}$$

Since the steady-state jitter performance improves in proportion to a tangential gradient of the zero-th order Bessel function as represented in Figure 4, we can consider a proper combination scheme of multiple correlation results using the gradient components. Also, we can calculate the gradient approximately because we assumed that the first estimation result by the minimum correlation interval is reliable. Thus, the proposed combination scheme can be expressed by

$$\bar{\varepsilon} = \sum_{i=0}^{I-1} w_{d_i} \cdot \bar{\varepsilon}[d_i], \; \left(w_{d_i} = G[d_i] \Big/ \sum_{i=0}^{I-1} G[d_i] \right) \tag{9}$$

where the gradient $G[d_i]$ is

$$G[d_i] = \left. \frac{\Delta J_0(2\pi\varepsilon d_i)}{\Delta\varepsilon} \right|_{\varepsilon=\bar{\varepsilon}[d_i]} \tag{10}$$

4. Simulation Results

In this section, we evaluate normalized mean square error (NMSE) performances of the ACF-based scheme and the proposed algorithm. The NMSE is defined as

$$NMSE \equiv \frac{MSE}{(f_{d,\max}T_s)^2} = \frac{E\left[\left| \hat{f}_{d,\max}T_s - f_{d,\max}T_s \right|^2 \right]}{(f_{d,\max}T_s)^2} \tag{11}$$

TABLE 1 summarizes the OFDM system parameters for performance evaluation. And multipath fading channel is generated by COST 207 Typical Urban model with delay profile as shown in TABLE 2.

TABLE 1
SIMULATION PARAMETERS

Parameters	Values
Center Frequency	2.6 [GHz]
Transmission Bandwidth	10 [MHz]
Sub-carrier Spacing	15 [kHz]
Sampling Frequency	15.36 [MHz]
FFT Size	1024
SNR	10[dB]
Channel Environment	COST 207 Typical Urban
Normalize Doppler frequency	0.03

TABLE 2
CHARACTERISTICS OF THE 'COST 207 TYPICAL URBAN' CHANNEL MODEL

Path	Power [dB]	Delay [μs]	Delay [sample]
1	-3	0	0
2	0	0.2	3
3	-2	0.6	7
4	-6	1.6	25
5	-8	2.4	37
6	-10	5.0	77

The evaluated correlation interval is d_0=7, d_1=14, d_2=21, and d_3=28 assuming that the pilot signal is transmitted every 7 OFDM symbol. The inversion of the zero-th order Bessel function is performed by one-to-one mapping table with resolution 0.0001 on the basis of normalized Doppler frequency.

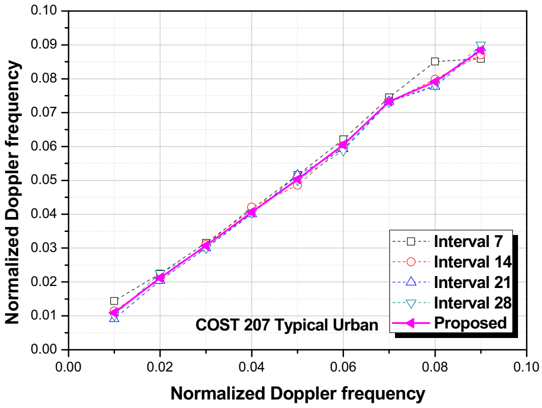

Figure 6. Mean performance

Figure 6 shows the mean performances of the original ACF-based scheme and proposed algorithm. As shown in this figure, the mean is close to the ideal value but some error components remain because of theoretically inevitable observation limit.

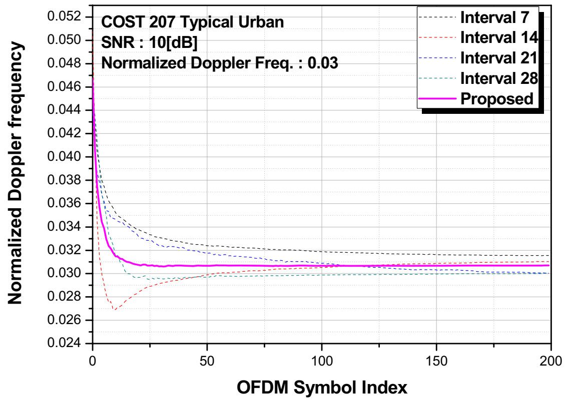

Figure 7. Tracking performance

Fig. 7 shows the tracking performances of the ACF-based estimation methods and the proposed algorithm. From this result, we can see that the convergence time of the proposed algorithm is the shortest among the considered methods.

Fig. 8 shows the NMSE performance. As shown in this figure, the proposed algorithm shows a stable estimation performance for overall Doppler frequency compared with the original ACF-based methods with different correlation interval.

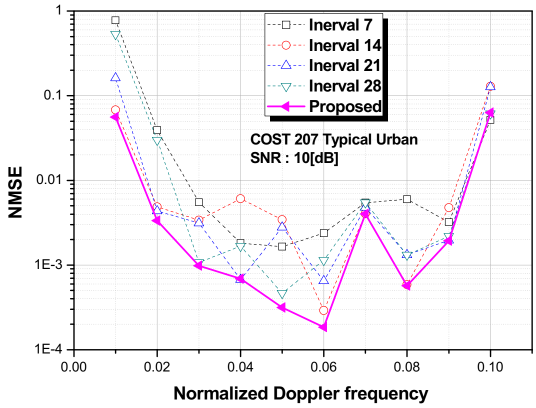

Figure 8. NMSE performance

5. Conclusion

In this paper, we have proposed an algorithm to estimate the maximum Doppler frequency based on ACF in OFDM systems. Simulation results have verified that the proposed algorithm can stably estimate the target values unrelated to the correlation interval and Doppler frequency. Therefore, the proposed algorithm is applicable to various OFDM systems.

References

[1] K. Baddour and N Beaulieu, “Robust Doppler spread estimation in nonisotropic fading channels,” *IEEE Trans. Wireless Commun.*, vol.4, pp.2677-2682 Nov. 2008

[2] Y. Ko. “Doppler spread estimation in mobile communication systems,” *IEICE Trans, Commun.*, vol.E88-B, no.2, pp.727-728, Feb. 2005

[3] O. Mauritz, “A hybrid method for Doppler spread estimation,” *IEEE VTC 2004*. Pp.962-965. May 2004.

[4] G. Park, D. Hong, and Ch. Kang, “A new Doppler spread estimation using FFT,” *IEICE Trans. Commun*, vol. E86-B, no.9, pp.2799-2803, Sept. 2003.

[5] A. Sampath and J. Holtzman, “Estimation of maximum Doppler frequency for handoff decision,” *IEEE VTC 93*, pp.859-862, May 1993.

[6] Richard van Nee, *OFDM for Wireless Multimedia Communications,* Artech House Publishers, Boston, 2000.

[7] Steven M. Kay, *Fundamentals of Statistical Signal Processing Vol. 1 Estimation Theory*, Prentice Hall PTR, New Jersey, 1993.

[8] Jueping Cai, Wentao Song, Zan Li, “Doppler spread estimation for mobile OFDM systems in Rayleigh fading channels,” *IEEE trans. Consumer Electronics*, Bol. 49, pp.973-977, Nov 2003.

[9] Yang-Seok Choi, Ozdural O.C, Huaping Liu, Alamouti S, “A maximum likelihood Doppler frequency estimator for OFDM systems,” *IEEE International Conf. on Commun.*, Vol. 10, pp.4572-4576, June 2006.