Distance Estimation between Base Station and User Terminal Using Multi-Carrier Signal

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Distance Estimation between Base Station and User Terminal Using Multi-Carrier Signal

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Abstract — We discuss the distance estimation between the base station and user terminal in wireless communications using multi-carrier signal. In this paper, we propose a method to reduce the influence of frequency difference due to the signal regeneration and relay. It is based on the group delay method which is a simple distance estimation algorithm. The distance estimation accuracy of the method is evaluated by computer simulation.

Index Terms — distance estimation, user terminal, multi-carrier signal, group delay, frequency difference.

1. Introduction

In the wireless communications, it is important to know the number of user terminals in a certain area for controlling user terminals [1]. We discuss the methods of estimating the distance between the base station and the user terminal [2].

They basically utilize multi-carrier signal and are regarded as a kind of time-of-flight measurement. However, in the system where the terminal regenerates and relays the signal from base station, slight frequency difference may occur between the transmitted signal and the received signal after round trip. This yields the distance estimation error. In this paper, we consider the methods including countermeasures against the frequency difference in the distance estimation system using multi-carrier signal transmission.

2. Multi-carrier Signal Transmission and Reception Model

We consider the transmission and reception model of the multi-carrier signal as shown in Fig. 1. M equal amplitude sinusoidal signals of equispaced frequencies \( f_1, \cdots, f_M \) are mixed and transmitted from the base station to the terminal. This multi-carrier signal after round trip is received at the base station in the multipath environment of \( L \) delayed waves. Sampling the received signal with the sampling frequency \( F_s \), we obtain \( N_p \times N_s \) sample data. Here, it is assumed that the signal has a frequency difference \( f_{\text{dif}} \) due to signal regeneration and relay at the terminal. In this case, the received signal \( C(t) \) is expressed as

\[
C(t) = \sum_{l=1}^{L} c_l(t) + z(t)
\]

where \( s_{cl} \) and \( \tau_l \) are the complex amplitude and propagation delay time of the \( l \)-th multipath wave (delayed wave), and \( z(t) \) is the internal noise. In this system, we calculate correlation between the received signal and the source signal at each carrier frequency to extract terminal distance information, which is given by

\[
x_m(n) = \frac{1}{N_p} \sum_{r=N_p(n-1)+1}^{N_p n} C(t) \exp\left(-2\pi f_m \frac{t}{F_s}\right)
\]

\[
(m = 1, \cdots, M; n = 1, \cdots, N_p)
\]

where \( N_p \) samples are used for a correlation calculation and thus we can have \( N_s \) correlation outputs for each carrier. \( N_p \) is called block size in this paper.

3. Estimation of Terminal Distance Using Group Delay

(1) Group Delay Method

We utilize group delay of the received multi-carrier signal to estimate the terminal distance (propagation distance). In the method with group delay, on the condition that the first arriving wave is dominant, the propagation distance \( d \) of the wave is estimated from the difference in phase between adjacent frequencies as follows:

\[
X_m = \frac{1}{N_p} \sum_{n=1}^{N_p} x_{m+1}(n) x_m^*(n)
\]

\[
d = \frac{1}{M-1} \sum_{m=1}^{M-1} c \frac{X_m}{2\pi(f_{m+1} - f_m)}
\]

where \( c \) is the propagation speed.

(2) Group Delay with Multiple Block Sizes

As above-mentioned, when there is a frequency difference \( f_{\text{dif}} \), the phase cannot be correctly extracted and thus the estimation accuracy deteriorates. Among the correlations obtained from (3), there occurs the phase rotation \( \varphi \) due to the frequency difference, which is expressed as

\[
\varphi = 2\pi f_{\text{dif}} \frac{N_p}{F_s}
\]

When \( \varphi \) is equal to an integral multiple of one cycle of sampling frequency, that is \( f_{\text{dif}} \times N_p \) is an integer multiple of \( F_s \), the estimation accuracy deteriorates seriously. This is because the component having such phase rotation disappears as a result of correlation calculation. One can see that the effect of \( f_{\text{dif}} \) depends on the value of \( N_p \). Therefore, we execute the correlation calculations for some values of \( N_p \), and derive the propagation distance from the group delay for each value of \( N_p \). By taking the median for the multiple distance values obtained, it is possible to remove the values contaminated by the influence of the frequency difference.
4. Performance Analysis by Computer Simulation

Computer simulation of terminal distance estimation is carried out in the situation where the frequency difference exists. The compared algorithms are shown in the Table I, and the parameters of the simulation are described in the Table II. Root-MUSIC [1],[3] using the correlation snapshots of $N_s = 100$ ($N_p = 600$) is included for a reference. For examining the basic performance, we assume here that the number of waves is equal to 1 ($L = 1$).

The Root Mean Squared Error (RMSE) is used for the performance evaluation when the frequency difference $f_{dif}$ is increased from 1kHz to 50kHz with 1kHz step. The characteristics of RMSE in the methods versus frequency difference are shown in Fig. 2. Also, in the figure, the estimated theoretical lower limit (Cramer-Rao Bound [4]) is shown as Approximate CRB. From Fig. 2, Group Delay 1 significantly degrades the estimation accuracy due to the influence of the frequency difference. Group Delay 2 reduces the influence of the frequency difference by using block processing in correlation calculation, so resulting in improved estimation accuracy. However, even in the Group Delay 2, the estimation accuracy deteriorates seriously at specific values of frequency difference. It can be seen that Root-MUSIC with the same block size has similar characteristics to Group Delay 2, although it is called high-resolution algorithm. In contrast, Group Delay 3 which uses multiple block sizes demonstrates that it maintains high estimation accuracy for frequency difference up to 50 kHz. It is due to the median filtering effect of multiple correlation blocks.

5. Conclusion

The terminal distance estimation accuracy of methods based on group delay of multi-carrier signal has been evaluated under the influence of frequency difference. As a result of simulation, it is demonstrated that the influence of the frequency difference can be reduced by using multiple block sizes and median filtering in correlation calculation.

References


TABLE I

<table>
<thead>
<tr>
<th>Compared methods</th>
<th>Notation</th>
<th>$N_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group Delay with no block processing</td>
<td>Group Delay 1</td>
<td>60,000</td>
</tr>
<tr>
<td>Group Delay with a fixed block size</td>
<td>Group Delay 2</td>
<td>600</td>
</tr>
<tr>
<td>Group Delay with multiple block sizes</td>
<td>Group Delay 3</td>
<td>600, 500, 375</td>
</tr>
<tr>
<td>Root-MUSIC with a fixed block size</td>
<td>Root-MUSIC</td>
<td>600</td>
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</tbody>
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TABLE II

<table>
<thead>
<tr>
<th>Simulation Conditions</th>
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<tbody>
<tr>
<td>Center frequency</td>
</tr>
<tr>
<td>Frequency bandwidth</td>
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<tr>
<td>Number of carriers $M$</td>
</tr>
<tr>
<td>Sampling frequency $f_s$</td>
</tr>
<tr>
<td>Number of data samples $(N_s \times N_p)$</td>
</tr>
<tr>
<td>Frequency difference $f_{dif}$</td>
</tr>
<tr>
<td>Number of incident waves $L$</td>
</tr>
<tr>
<td>User terminal distance</td>
</tr>
<tr>
<td>Input SNR</td>
</tr>
<tr>
<td>Power</td>
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<tr>
<td>Number of trials</td>
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</table>

Fig. 1. Multi-carrier signal transmission and reception model.

Fig. 2. RMSE of distance estimates vs. frequency difference.