Research on Doppler shift estimation algorithm for SC-FDE wireless communication system

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ABSTRACT

In order to solve the problem of Doppler shift caused by high speed movement of maglev train and high carrier frequency of train-ground wireless communication system, this paper studies the Doppler shift estimation algorithm of SC-FDE system, and proposes a two-stage estimation algorithm based on the excellent correlation characteristics of Gray sequence. Firstly, the coarse estimation and compensation of Doppler shift are carried out by using the gray sequence in the preamble training sequence. Then the fine estimation and compensation of Doppler shift are carried out by using the gray sequence inserted in the data block. Simulation analysis and experimental verification are carried out. The results show that the proposed algorithm can significantly improve the throughput performance of train-ground wireless communication system in high-speed mobile environment. The algorithm has high estimation accuracy and is easy to be implemented by hardware. It can be extended to SC-FDE systems in other large Doppler scenarios.

Keywords: train-ground wireless communication; Doppler shift; Gray sequence; single carrier frequency domain equalization; throughput

1. INTRODUCTION

With the rapid development of rail transit technology, the development of high-speed maglev train with a running speed of 600km/h has become a hot topic. The position, speed, status monitoring and other information of the maglev train during running need to be transmitted from the train to the ground control station through the train-ground wireless communication system. These information relate to the safety of train running, and should reach millisecond transmission delay and ensure extremely high transmission reliability [1], which poses a great challenge to the design of the train-ground wireless communication system. The design of train-ground wireless communication mainly faces two difficulties: one is to deal with the influence of complex channel environment such as multipath fading and Doppler shift, and the other is to solve the problem of frequent base station handover [2][3].

In digital wireless communication systems, in order to overcome the influence of multipath fading, OFDM (orthogonal frequency division multiplexing) or SC-FDE (single carrier frequency domain equalization) technology is usually used [4]. SC-FDE is currently the most widely used single carrier transmission scheme. Compared with OFDM multicarrier transmission scheme, SC-FDE has the same hardware implementation complexity, but has lower peak-to-average power ratio and carrier frequency offset sensitivity, which is more suitable for scenes with more severe Doppler shift. Therefore, SC-FDE is more suitable for high-speed maglev train-ground wireless communication system than OFDM. However, the spectrum efficiency of SC-FDE is lower, and the current spectrum resources in the low-frequency band are scarce, so it becomes a more reasonable choice to construct a high-speed maglev train-ground wireless communication network in the Millimeter wave band [5].

The Millimeter wave frequency band not only brings large bandwidth, but also brings larger Doppler shift. According to the channel model of single path High Speed Train (HST) proposed in 3GPP TS 38.101-4 specification [6], the Doppler shift is

$$f_d\left(\mathrm{t}\right)=f_c\frac{v}{c}\cos\theta\left(t\right). \tag{1}$$

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Where, f_c is the carrier frequency, v is the train moving speed, c is the speed of light, and $\theta(t)$ is the Angle between the train moving direction and the base station signal propagation direction.

Although SC-FDE system has lower carrier frequency offset sensitivity, its performance is still seriously affected in large Doppler shift scenarios. When SC-FDE technology is applied in train-ground wireless communication system, Doppler shift estimation and compensation must be performed.

In recent years, many scholars have done a lot of research on Doppler shift estimation and compensation algorithms, it can be divided into three categories: blind estimation, data-aided estimation and prior information-based estimation [7]. The Doppler shift estimation and compensation algorithms in OFDM system are very mature, such as the estimation algorithm based on cyclic prefix in time domain, the maximum likelihood estimation algorithm based on pilot in frequency domain, and the estimation algorithm based on training sequence, etc. [8-10]. The characteristics of SC-FDE system determine that the Doppler shift estimation should be performed in the time domain, so the time domain estimation algorithm based on OFDM system also has the potential to be applied to SC-FDE system. Jan-jaap van de Beek proposed a Doppler shift estimation algorithm based on cyclic prefix [8], according to the characteristics that the cyclic prefix of OFDM symbols and the tail data of symbols are the same, the correlation operation is carried out, and the Doppler shift is obtained by maximum likelihood estimation. This algorithm has low computational complexity and does not require additional data assistance, but cyclic prefixes are susceptible to multipath delay signals, and their performance is poor in high-speed mobile multipath fading channels. Timothy M.Schmidl and Donald C. Ox proposed a data-assisted algorithm, called SC algorithm [11], the core idea is to add cyclic prefix and two identical training sequences with half of the symbol length to the head of the data frame, and use the characteristic that two training sequences are identical to perform correlation operations to obtain Doppler shift estimation. The algorithm uses cyclic prefix to avoid the interference of multipath delay signals to the training sequence, but its repeated training sequence is easy to produce a long time peak platform after correlation operation, which has a great impact on timing synchronization accuracy. H. Minn improved the SC algorithm [12], the training sequence was changed to 4 sequences whose length was one quarter of the symbol length, effectively avoid the occurrence of the correlation peak platform, and the estimation range is doubled. However, the shorter training sequence also caused a decline in estimation accuracy, and in the scene of extremely fast motion such as high-speed maglev, the Doppler shift also changes rapidly, which has a great impact on the performance of the algorithm.

In order to solve the Doppler shift problem caused by the extremely fast moving speed and high carrier frequency of the high-speed maglev train-ground wireless communication system, this paper proposes a two-stage Doppler shift estimation algorithm based on Gray complementary sequence.

2. A TWO-STAGE DOPPLER SHIFT ESTIMATION ALGORITHM

2.1 Design of frame structure

Referring to the IEEE 802.11ad standard, the design of the system frame structure is shown in Figure 1. At the beginning of the frame structure is the preamble training sequence, filled with multiple identical gray sequences, followed by the channel estimation sequence, followed by the message header, including data length, CRC (cyclic redundancy check) and other information, followed by the transmitted data block.

PTS	CES	Header	Data block

Figure 1. Frame structure design

The training sequence uses Gray complementary sequence, Ga_{128} and Gb_{128} are a pair of complementary sequences. Gray sequence has the following characteristics: First, it has good autocorrelation and cross-correlation characteristics. The autocorrelation value of Gray complementary sequence is large, but the cross-correlation value is almost zero [13], which shows significant peak characteristics after autocorrelation operation. This algorithm uses the peak characteristic of correlation operation to estimate Doppler shift. Second, the sequence is generated by recursion, which satisfies the properties as follows [14]

$$Ra(i)+Rb(i)=\begin{cases}0 & i\neq 0\\ 2N & i=0\end{cases}$$
$$Ra(i)=\sum_{k=0}^{N}Ga_N(k)Ga_N(i+k), \tag{2}$$
$$Rb(i)=\sum_{k=0}^{N}Gb_N(k)Gb_N(i+k)$$

where *N* is the length of the sequence. Gray sequence generator and correlator based on multi-level iterative structure are easy to be implemented by hardware [15].

The Doppler shift correction is implemented in two steps. The first step is the coarse estimation and compensation based on the preamble training sequence to meet the requirements of a large estimation range. The second step is the fine estimation and compensation after frequency domain equalization to meet the requirements of high accuracy of estimation.

2.2 Doppler shift coarse estimation

Since several consecutive identical Ga_{128} sequences are sent in the preamble training sequence, the Ga_{128} can be used for coarse estimation of Doppler shift. After the matching filter is completed at the receiver, the sliding cross-correlation between the local Gray sequence $c(n)$ and the received signal $r(n)$ is carried out in the Gray correlator. Because the preamble training sequence of the received signal contains Gray sequence, when sliding to the position where the two gray sequences are aligned, an obvious correlation peak will appear. The training sequence in the received signal can be extracted by using this correlation peak, and symbol timing synchronization and carrier frequency synchronization can be carried out according to the obtained training sequence.

Assuming that the preamble training sequence sent by the transmitter generates the Doppler shift of ε after being transmitted through the wireless channel, then the signal after cross-correlation can be expressed as

$$\begin{aligned}y(n)&=r(n)c^*(n)\\&=c(n)e^{j(2\pi n\varepsilon/N+\varphi)}c^*(n)\\&=|c(n)|^2e^{j(2\pi n\varepsilon/N+\varphi)}\end{aligned}. \tag{3}$$

Since the value of Ga_{128} is $\{\pm1\}$, $|c(n)|^2=1$, and the phase information is obtained after the correlation operation between the preamble training sequence and the local sequence. The preamble training sequence is a repeated Gray sequence, and then the repeated part in the sequence $y(n)$ obtained after correlation is used for autocorrelation detection. Assuming that the length of correlation window is *N* and the correlation delay interval is *L*, the result after correlation operation can be expressed as

$$\begin{aligned}Z_\varepsilon&=\sum_{n=0}^{N-1}y(n+L)y^*(n)\\&=\sum_{n=0}^{N-1}|c(n+L)|^2e^{j(2\pi(n+L)\varepsilon/N+\varphi)}|c(n)|^2e^{-j(2\pi n\varepsilon/N+\varphi)}\\&=Ne^{j2\pi L\varepsilon/N}\end{aligned}. \tag{4}$$

Finally, the Doppler shift is estimated as

$$\hat{\varepsilon}_1=\frac{1}{2\pi L}\arg\left\{\sum_{n=0}^{N-1}r(\mathrm{n}+L)c^*(n+L)c(n)r^*(n)\right\}. \tag{5}$$

Since the value range of the $\arg\{\ \}$ is $(-\pi,\pi)$, the estimation range of this algorithm is

$$-\frac{1}{2L} < \hat{\varepsilon} < \frac{1}{2L}. \tag{6}$$

It can be seen from Equation (6) that the estimation range is related to the autocorrelation delay interval. Since the preamble training sequence is a repeated gray sequence, the correlation delay interval can be flexibly selected. When the Doppler shift of the system is large, a smaller correlation delay interval is recommended. For example, two adjacent Gray sequences are used for autocorrelation to obtain a larger estimation range of Doppler shift. When the Doppler shift is small, a larger correlation delay interval is recommended. For example, the first Gray sequence of the leader training sequence is used for autocorrelation with the last Gray sequence to improve the tracking accuracy of Doppler shift.

Two correlation operations are performed in the coarse estimation stage, which has the following advantages:

(1) Cross-correlation detection using local Gray sequence and received signals can reduce the impact of interference signals and improve the detection accuracy and SNR.

(2) The strong correlation between adjacent periodic signals can be used to reduce the interference of multipath signals and Doppler shift by the sliding autocorrelation operation of the signal after cross-correlation.

2.3 Doppler shift fine estimation

After coarse estimation and compensation, the residual Doppler shift is already small, and the received signal after frequency correction can be used for channel estimation, frequency domain equalization and decoding. However, in high-speed mobile scenarios, the residual Doppler shift may still have a certain impact on the system performance due to the variation of Doppler shift, hardware processing speed, algorithm accuracy and other reasons. In order to further reduce the bit error rate and improve the system performance, Doppler shift fine estimation and compensation are performed again after frequency domain equalization.

In the case of fast time-varying channels, block technology is usually used to improve the channel estimation accuracy [16], that is, a long data block is divided into several short data sub-blocks, and a UW (Unique Word) is inserted into each sub-block, as shown in Figure 2. Shortening the size of symbol blocks is equivalent to shortening the distance of channel estimation sampling points. UW inserted into each sub block also improves the tracking ability of channel changes Therefore, the performance degradation caused by the fast time-varying channel can be effectively suppressed.

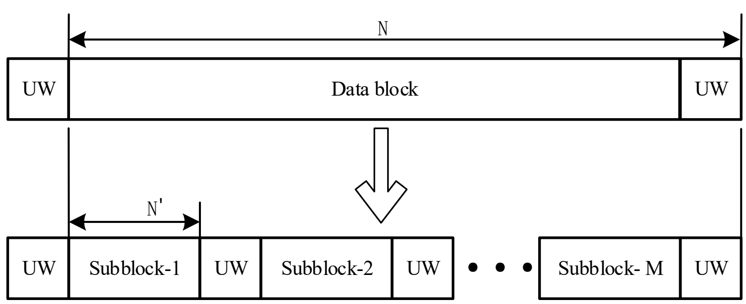


Figure 2. Diagram of dividing data blocks

The UW inserted in the sub-block can be used not only for channel estimation and interference avoidance between sub-blocks, but also for Doppler shift estimation and compensation.

The Doppler shift fine estimation is performed after the frequency domain equalization is completed. It is assumed that the UW inserted in each sub block is filled with the gray sequence Ga_{64}, and the UW signal $r(n)$ of the received signal is cross correlated with the local gray sequence $c(n)$ to obtain the cross-correlation peak. The correlated signal can be expressed as

$$y(n) = r(n)c^*(n). \tag{7}$$

The cross-correlation of UW signal without Doppler shift is the autocorrelation operation of local gray sequence. The correlated signal can be expressed as

$$z(n) = c(n)c^*(n). \tag{8}$$

The residual Doppler shift can be estimated by calculating the phase difference between the maximum cross-correlation peak of the UW signal with Doppler shift and the maximum cross-correlation peak of the UW signal without Doppler shift,

$$\frac{y(n)}{z(n)} = \frac{\max\{c(n)e^{j2\pi\varepsilon}c^*(n)\}}{\max\{c(n)c^*(n)\}} = e^{j2\pi\varepsilon}. \tag{9}$$

The Doppler shift is estimated as

$$\begin{aligned}\hat{\varepsilon}_2 &= \frac{1}{2\pi}\arg\left\{\frac{y(n)}{z(n)}\right\} \\ &= \frac{1}{2\pi}\arg\left\{\frac{\max\{r(n)c^*(n)\}}{\max\{c(n)c^*(n)\}}\right\}\end{aligned}. \tag{10}$$

Since the Doppler shift is finely estimated and compensated in each sub block, the influence of the residual Doppler shift can be limited to each sub block, and the gradual amplification over time can be avoided. In addition, the Doppler shift estimation of each sub-block uses the existing UW in the sub-block, which does not add additional training sequence overhead to the system.

3. SIMULATION ANALYSIS

In order to verify the performance of the Doppler shift estimation algorithm proposed in this paper, the link-level simulation model of SC-FDE system is established in this section to conduct simulation experiments and compare the system BER performance under three conditions: SC algorithm, Minn algorithm and the proposed algorithm. The simulation parameters are set as shown in Table 1. The result is shown in Figure 3.

Table 1. SC-FDE link-level simulation parameters.

Parameter	Value
Symbol rate [Msymbol/s]	500
Carrier center frequency [GHz]	38
Modulation mode	QPSK
Root raised cosine roll off coefficient	0.25
Root raised cosine filter order	24
Receiver moving speed [km/h]	0~600
Channel coding	None
Channel model	TDL-D
SNR	13

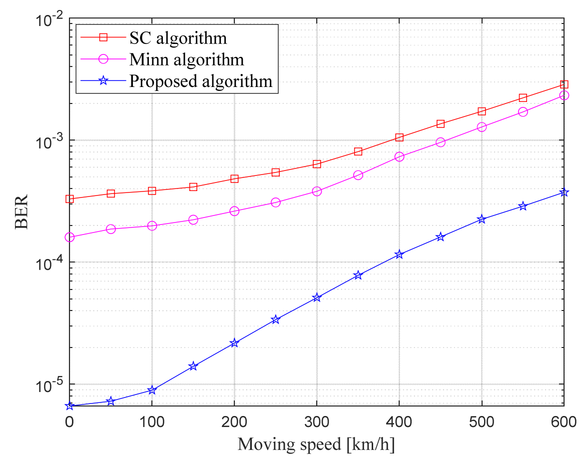


Figure 3. Comparison of BER under different technical conditions

As can be seen from Figure 3, the bit error rate of the three algorithms keeps rising with the increase of moving speed. At the same moving speed, the performance of the Minn algorithm is slightly better than that of the SC algorithm, and the performance of the proposed algorithm is significantly better than that of the Minn algorithm.

4. EXPERIMENTAL VERIFICATION

In order to verify the performance of this algorithm, a train-ground wireless communication test platform was built on the basis of the previous work in the laboratory. The schematic layout of the test platform scene is shown in Figure 4.

The whole track is 200 m long and the train runs on it During the test, the train firstly stops at the starting position, then accelerates to 288 km/h at a distance of 90 m. After running at a constant speed of 20 m, the train stops to 0 at a distance of 90 m.

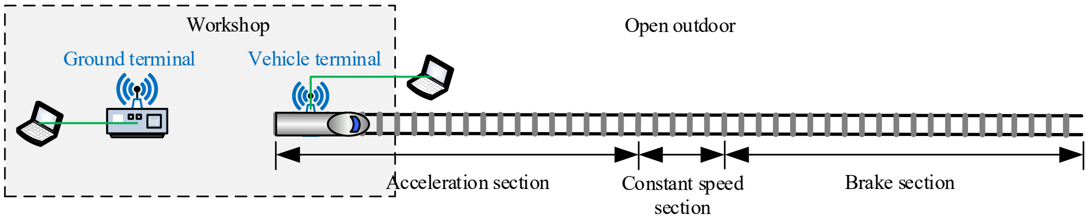
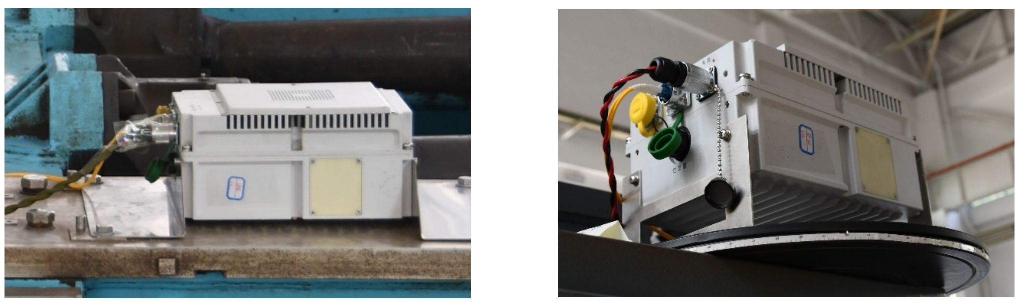


Figure 4. Layout of the test scene

The vehicular communication terminal is installed on the train, as shown in Figure 5(a), and the ground communication terminal is installed on the support on the ground 40 m away from the starting of the track, as shown in Figure 5(b). When the train runs along the track, the ground communication terminal and the vehicle communication terminal always keep the line-of-sight. The ground communication terminal is connected to test computer A, and the vehicle communication terminal is connected to test computer B.



(a) Vehicle communication terminal (b) Ground communication terminal

Figure 5. Test equipment

The main parameter configuration of ground communication terminal and vehicle communication terminal is shown in Table 2.

Table 2. Parameter configuration of SC-FDE terminal equipment.

Parameter	**Value**
Symbol rate [Msymbol/s]	500
Carrier center frequency [GHz]	38
Modulation mode	QPSK
Channel coding	LDPC

Because bit error rate is difficult to measure in practice, network throughput rate is mainly tested to evaluate the performance of train-ground wireless communication system. The network test software uses the open source Iperf3. The test computer A sends network packets to the test computer B, and the real-time throughput of the wireless network can be viewed through the interface of the Iperf3.

In order to compare and verify the actual effect of this algorithm, it is necessary to install the software of the train-ground wireless communication system into two states, SC algorithm (Ga_{128} is used for the training sequence) and the algorithm proposed in this paper, and test it in running state. The throughput test results are shown in Figure 6.

As can be seen from Figure 6, when SC algorithm is used, the peak throughput rate when the movement speed reaches 288km/h is significantly lower than that in the stationary state. When the proposed algorithm is used, the network throughput remains at about 460 Mbit/s when the moving speed reaches 288km/h, which is almost the same as that in the static state, and significantly higher than that of the SC algorithm. It is shown that the proposed algorithm can obviously improve the throughput performance of the system when moving at high speed.

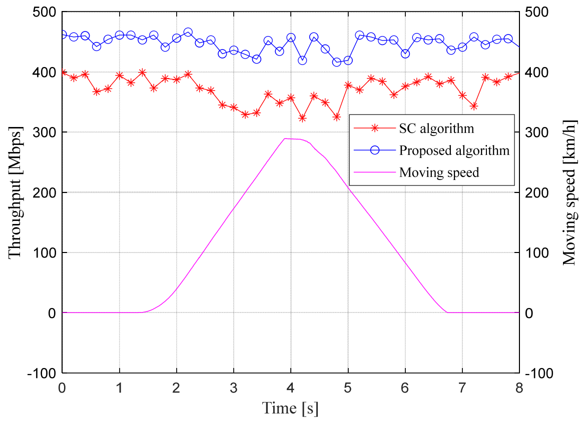


Figure 6. Test results of vehicle terminal throughput during movement

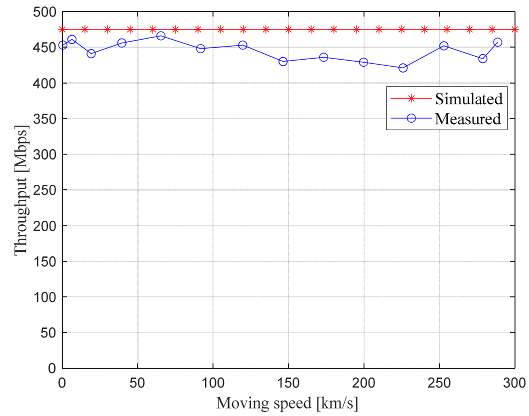


Figure 7. Comparison between simulation and measured data

Convert the measured throughput data into the "throughput / moving speed" coordinate curve according to the "moving speed/time" coordinate curve of the train, and then set the system simulation parameters to be consistent with the actual wireless communication terminal to simulate the throughput under the same conditions. The simulation results are compared with the experimental throughput, as shown in Figure 7.

It can be seen from Figure 7 that the throughput simulation results hardly change with the change of mobile speed, and the measured throughput fluctuates in a small range, this fluctuation does not reflect the correlation with the moving speed of the communication terminal, the reason for the fluctuation may be that it is affected by the change of the wireless channel when moving, and even if Iperf3 software is used for throughput testing in a static state, there will be some fluctuations. Therefore, it can be considered that the network throughput obtained in the experiment is not affected by the moving speed of the receiver, that is, the Doppler shift is well compensated.

5. CONCLUSION

In this paper, a two-stage Doppler shift estimation algorithm for SC-FDE system based on the excellent correlation characteristics of the Golay sequence is proposed. The algorithm uses the repeated preamble gray sequences in the received signal to cross correlate with the local gray sequences, and then uses the cross-correlation results to calculate the autocorrelation to obtain the coarse estimation. After the frequency domain equalization is completed, the gray sequence inserted in the sub block UW is used for cross-correlation calculation to obtain the fine estimation. Through twice Doppler shift estimation and compensation, both the requirements of large estimation range and high estimation accuracy are met. Although the computational complexity is increased, the increased hardware overhead of the algorithm in FPGA is affordable. The gray sequences used for Doppler shift estimation are all existing sequences in the system, which can simultaneously complete the functions of frame synchronization, channel estimation, guard interval, Doppler shift estimation, etc., without adding additional training sequences for Doppler shift estimation, and without reducing the spectral efficiency of the system. Simulation and experiment show that the algorithm proposed in this paper can significantly improve the performance of train-ground wireless communication system in high-speed mobile state, and has good practicability. In the next step, further experimental verification can be carried out when the experimental conditions of higher moving speed are available.

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