Design of adaptive rate FH-OFDM system based on 802.11g

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Abstract. In this paper, the wireless communication system based on 802.11g protocol is studied, and a set of FH-OFDM system supporting adaptive transmission rate is designed. The maximum transmission rate can reach 6.75Mbps, which is much higher than 2Mbps transmission rate of traditional FHSS system. A new joint receiver and transmitter detection algorithm is proposed to reduce the error rate of FH position detection by 8.8dB~11.68dB. The frequency hopping codebook is obtained by counting the bit error rate (BER) of each subcarrier. Selecting the subcarriers with lower bit error rate as frequency hopping points can further reduce the detection error rate by 4.27dB~6.17dB, the bit error rate by 8.0778dB~17.4121dB (in the case of 54 / 8Mbps), and 0.0533dB~21.6286dB (in the case of 6 / 8Mbps). And in this paper, we choose the most appropriate transmission rate under different mobile speed and different SNR. By adaptive rate, we can get high performance and efficient equalization of the system.

1. Introduction
With the rapid development of rail transit systems, subway transportation mainly uses wireless communication systems to realize the communication between trains and the ground. The wireless communication system is the core technology of the subway distributed management system. According to the wireless standard classification of train-to-ground communication, the current train control system in my country mainly includes the following categories: train control system based on GSM-R (railway dedicated global digital mobile communication system) communication, CBTC based on 802.11FHSS standard (communication-based Automatic train control system) system, and CBTC system based on 802.11g standard. At present, the train control system based on GSM-R communication is mainly used in national railway lines, and the CBTC system based on the 802.11FHSS standard is already very mature in the field of urban rail transit[1].

At present, scholars at home and abroad have conducted research on the design method and performance of CBTC based on IEEE802.11 series standards. Literature [2] designed a redundant CBTC vehicle-ground communication system structure based on the IEEE802.11g standard according to the actual environment of urban rail transit. Literature [1] verifies the availability of the vehicle-ground wireless communication network based on the wireless spread spectrum frequency hopping standard on high-speed trains running at 160km to 200km per hour through actual tests. In reference [3], the data communication subsystem of CBTC system is modeled, and the 802.11b standard is taken as an example for simulation. Under different wireless data transmission rates and train running speeds, the performance changes of WLAN are analyzed, and the train control system with redundant
equipment is proposed to ensure the reliable transmission of data communication. Literature [4-5] designed a set of message monitoring device to detect the Shanghai Metro Line 2 screen door linkage system based on 802.11g protocol.

On the one hand, the above research is mainly for the simulation and analysis of the link layer and the application layer, but the research on the communication transmission and reception design of the entire system is not deep enough, and the vehicle-to-ground communication system designed in accordance with the traditional 802.11g design uses conventional network cards. And packet capture software can obtain the message analysis vehicle-ground communication mechanism, and even crack it, so it is very necessary to add frequency hopping to improve security. On the other hand, the single-carrier modulation transmission rate of the traditional 802.11FHSS system is low, the highest is only 2Mbps. To this end, this article uses matlab to establish a subway car-ground communication system model based on 802.11g, and adds frequency hopping and adaptive rate improvements on this basis. The simulation results show that the improved system has good anti-interference ability and high speed. The transmission rate meets the needs of vehicle-ground communication.

2. System model

2.1 Transmitter model

The structure of the FH-OFDM transmitter based on 802.11g is as follows:

As shown in Figure 1, in the transmitter, the data is scrambled, encoded, and interleaved, which improves the reliability of wireless transmission. The encoding is a convolutional code, and the code rate is 1/2, 2/3, 3/4 [6].

Then the coded bits after the above processing will be modulated into two IQ signals. The specific modulation method used is selected according to different transmission data rate requirements. The modulation method selected in this article is consistent with 802.11g, including BPSK, QPSK, 16QAM, and 64QAM modulation method [7], other modulation methods can also be selected according to the actual situation, and different transmission rates correspond to their respective coding rates and modulation methods.

The OFDM complex equivalent baseband signal can be obtained by IDFT operation, which is expressed as follows:

$$S_i(k) = \sum_{i=0}^{N-1} d_{i,j} \exp\left( \frac{j 2 \pi k i}{N} \right) \quad 0 \leq k \leq N - 1$$  (1)

Wherein, $k$ represents the $k$ th subcarrier, $N$ represents the number of subcarriers, and $d_{i,j}$ ($i = 0, 1, \ldots, N - 1$) represents the data modulation symbol allocated to each subcarrier.

In actual scenarios, OFDM systems usually use faster IFFT/FFT[8] calculations for modulation and demodulation. The FFT length of 802.11g in 20MHz mode is 64, and there are 48 available data subcarriers. If all data sub-carriers transmit data, the transmission rate can reach up to 54 Mbps. The optional transmission rate of the FH-OFDM system designed in this article can follow the transmission
rate of 802.11g. Each OFDM symbol randomly selects 6 data sub-carriers for multi-carrier frequency hopping, so the transmission rate is divided by 8. This article selects \([6 12 18 24 36 48 54]/8\text{Mbps}\) These seven data transmission rates can reach up to 54/8 Mbps, or 6.75Mbps, which is much faster than the 2Mbps transmission rate of conventional 802.11FHSS.

The above process completes the baseband processing of digital communication, and the processed baseband signal also needs to be sent to the radio frequency processing terminal for high-frequency carrier modulation and amplification, and the signal is moved to a higher frequency for long-distance transmission through an antenna[9].

2.2 Receiver model

The structure of the FH-OFDM receiver based on 802.11g is shown in Figure 2:

![Figure 2. Structure of FH-OFDM receiver.](image)

The receiver basically realizes the reverse operation of the transmitter, so the modules used mainly include synchronization, channel estimation, OFDM demapping, frequency hopping position detection, demodulation, deinterleaving, and descrambling.

Assuming that both the sender and receiver are two antennas, there are:

\[
\begin{bmatrix}
Y_1 \\
Y_2
\end{bmatrix} = \begin{bmatrix}
h_{11} \\
h_{21}
\end{bmatrix} \begin{bmatrix}
X_1 \\
X_2
\end{bmatrix}
\]

(2)

Among them, the transmitted data is \(X_1\) and \(X_2\), and the received data is \(Y_1\) and \(Y_2\), \(\begin{bmatrix}
h_{11} \\
h_{21}
\end{bmatrix}\) is the MIMO channel.

At the receiving end, in order to restore the original data \(d_{r,j}\), DFT transformation can be performed on \(S_r(k)\):

\[
d_{r,j} = \sum_{k=0}^{N-1} S_r(k) \exp(-j \frac{2\pi kj}{N})
\]

(3)

Finally, the FFT signal undergoes corresponding demodulation and de-interleaving, and then sends it to the decoder to get the received bits.

Based on the above system model, 10,000 Monte Carlo simulations were performed for transmission and reception. The parameters of the 802.11g-based part of the simulation were set strictly in accordance with the protocol. In addition, the carrier frequency was 2.4GHz, the number of transmitting antennas was 2, and the number of receiving antennas was 2 MIMO channel considers
additive white Gaussian noise (AWGN), the system considers both large-scale fading and small-scale fading (multipath, delay, Doppler shift), FFT length 64, guard interval length 16, which can be the bit error rate (BER) of each transmission rate under the train speed of 30km/h is shown in Figure 3. It can be seen from the figure that the lowest transmission rate is 6/8Mbps, that is in the case of 0.75Mbps, the system also needs to achieve a BER of 0.1 when the signal-to-noise ratio (SNR) is greater than 25dB. The reason for the poor system performance is that every OFDM symbol Randomly select 6 sub-carriers. Due to the Doppler influence caused by the moving speed of the train, the delay caused by multipath and the influence of noise in the communication environment, errors are prone to occur when the receiving end detects the position of the sub-carrier.

![Figure 3. BER of 802.11g FH transceiver system.](image)

3. Improved FH-OFDM transceiver model

3.1 Design method for detecting frequency hopping position

In order to enable the receiver to more accurately detect the position of the frequency hopping subcarrier, this article uses the corresponding algorithm to optimize the system from the transmitter and receiver:

(1) Sending end:

$$\mathbf{S} = [S_{s,1}, S_{s,2}, \ldots, S_{s,M}]$$ is the number of OFDM symbols on the transmitter, where the $a$ OFDM symbol has 48 subcarriers, and $^T$ is the transposition operation. Divide these $M$ OFDM symbols into blocks in the time domain. If $M$ is divisible by $m$, they are equally divided into $m$ blocks. Each block has $L = M / m$ OFDM symbols. If $M$ is not divisible by $m$, each of the first $m-1$ blocks has $L = \text{floor} \left( M / m \right)$ OFDM symbols. The $m$th block has $L = M - \text{floor} \left( M / m \right) \cdot (m-1)$ OFDM symbols, and $\text{floor}(\cdot)$ is the round-down operation. The frequency hopping positions of several OFDM symbols in each block are the same.

(2) The receiving end:

Step 1: Initialize the number of blocks $\text{num\_block} = 1$.

Step 2: Take the $\text{num\_block}$ OFDM received symbol $[S_{r,1}, S_{r,2}, \ldots, S_{r,L}]$ for frequency hopping position detection. This $L$ OFDM symbol has been processed by frequency offset calibration and channel estimation. The $a$th OFDM received symbol $\mathbf{S}_{r,a} = [s_{a,1}, s_{a,2}, \ldots, s_{a,48}]^T$ has 48 subcarriers.

Step 3: Calculate the $L$ energy of OFDM received symbols $\mathbf{P}_r = [\mathbf{P}_1, \mathbf{P}_2, \ldots, \mathbf{P}_L]$, where the energy $\mathbf{P}_a = [P_{a,1}, P_{a,2}, \ldots, P_{a,48}]^T$ of the $a$th OFDM received symbol is corresponding to 48 subcarriers, and the energy of the $b$th sub-carrier of the $a$th OFDM received symbol is
\[ p_{a,b} = \left( \text{real}(s_{a,b}) \right)^2 + \left( \text{imag}(s_{a,b}) \right)^2 \], the real number operation is \( \text{real}(\cdot) \) and the imaginary number operation is \( \text{imag}(\cdot) \).

Step 4: Calculate the total energy \( \mathbf{P}_{\text{sum}} = \sum_{l=1}^{L} \mathbf{P}_l \) of \( L \) OFDM received symbols, and get

\[ \mathbf{P}_{\text{sum}} = \left[ P_{0,1}, P_{0,2}, \ldots, P_{0,48} \right]^T. \]

Step 5: Sort the energy \( \mathbf{P}_1 \) of the first OFDM received symbol, and select the 6 subcarrier indexes \( \text{ind}_1 = \left[ \text{ind}_{1,1}, \text{ind}_{1,2}, \ldots, \text{ind}_{1,6} \right]^T \) with the largest energy.

Step 6: Perform step 5 operation to \( \mathbf{P}_a \) \( (a = 2, 3, \ldots, L) \) and get \( \text{ind}_a = \left[ \text{ind}_{a,1}, \text{ind}_{a,2}, \ldots, \text{ind}_{a,6} \right]^T \), so there is \( \text{ind}_{\text{all}} = \left[ \text{ind}_1, \text{ind}_2, \ldots, \text{ind}_L \right] \).

Step 7: Count the number of times that each subcarrier index appears in \( \text{ind}_{\text{all}} \). The number of times that \( b \) th subcarrier appears is \( \text{cnt}_b \), and the number of times that 48 subcarrier indexes appear in \( \text{ind}_{\text{all}} \) is \( \text{C} = [\text{cnt}_1, \text{cnt}_2, \ldots, \text{cnt}_{48}] \). Select the 6 subcarrier indexes with the most occurrences as the detected frequency hopping positions \( \text{ind}_{\text{FH}}_1 = \left[ \text{ind}_{\text{FH},1}, \text{ind}_{\text{FH},2}, \ldots, \text{ind}_{\text{FH},6} \right]^T \). If there are subcarriers with the same occurrence times, select according to the total energy \( \mathbf{P}_{\text{sum}} \), and select the subcarrier index with the larger total energy as the detected frequency hopping position.

Step 8: \( \text{num \_ block} = \text{num \_ block} + 1 \), Repeat step 2-step 7 operations until \( \text{num \_ block} > m \), get the frequency hopping position of each block \( \left[ \text{ind}_{\text{FH},1}, \text{ind}_{\text{FH},2}, \ldots, \text{ind}_{\text{FH},m} \right] \).

3.2 Frequency hopping codebook generation

For subcarriers with too high bit error rate, it is not suitable to be used as a frequency hopping point to transmit data and affect system performance. Therefore, this article selects subcarriers with low bit error rate in advance for different transmission rates. The selection method is as follows:

Step 1: The number of data subcarriers is expressed as \( b_{\text{subcarrier}} \), \( b = 1 \) is the first subcarrier number. The transmission rate is expressed as \( \text{datarate}_a \), \( \alpha = 1 \) corresponds to the lowest transmission rate, and the number increases as the transmission rate increases.

Step 2: For the \( b \) th data subcarrier, set the SNR to 30dB, and perform transmission and reception processing for the train speed \( v_{n+1} = v_n + 10 \) respectively, where \( n = \{1, 2, \ldots, 7\} \), \( v_i = 0 \), perform \( mt \_ kl \) Monte Carlo calculations. Assuming that the bit error rate \( \left[ \text{BER}_{i,1}, \text{BER}_{i,2}, \ldots, \text{BER}_{i,7} \right] \) is obtained for the \( i \) th time, an average bit error rate \( \overline{\text{BER}}_b = \frac{1}{7 \times mt \_ kl} \sum_{i=1}^{mt \_ kl} \sum_{j=1}^{7} \text{BER}_{i,j} \) under different speeds of the \( b \) th data subcarrier can be finally obtained, in this article \( mt \_ kl = 10000 \).

Step 3: \( b = b + 1 \), repeat step 2 until \( b > 48 \), get the average bit error rate \( \overline{\text{BER}} = \left[ \text{BER}_{1}, \text{BER}_{2}, \ldots, \text{BER}_{48} \right] \) corresponding to 48 data sub-carriers.

Step 4: Choose a subcarrier with a bit error rate of 0.01 (this is the target BER of this article, which can be adjusted by yourself). Obtain the optimal set of subcarriers
\[ \text{IND}_\alpha = \left[ \text{IND}_{\alpha,1}, \text{IND}_{\alpha,2}, \cdots, \text{IND}_{\alpha,\beta} \right]^T \] at the data rate \( \alpha \) transmission rate, where \( 6 \leq \beta \leq 48 \), and \( \beta \) is an integer.

Step 5: \( \alpha = \alpha + 1 \). Repeat the operations of step 2-step4 until \( \alpha > 7 \), the number of subcarrier sets \( \{ \text{IND}_1, \text{IND}_2, \cdots, \text{IND}_7 \} \) corresponding to 7 transmission rates is obtained, which is the best subcarrier codebook, and then the frequency hopping position is selected in this set.

### 3.3 Improved system performance

The accuracy of the receiving end to detect the frequency hopping position can be used as one of the criteria for the design of the frequency hopping system, which can be expressed by the following formula:

\[
P_{\text{right}} = \frac{\sum_{i=1}^{mt} \sum_{kl} \text{len}(\text{index}_{i,t} \cap \text{index}_{i,r})}{\sum_{i=1}^{mt} \sum_{kl} \text{len}(\text{index}_{i,t})}
\]

\[
P_{\text{error}} = 1 - P_{\text{right}}
\]

Among them, \( \text{len}(\bullet) \) is the length of the vector, \( \text{index}_{i,t} \) is the carrier index of the transmitting terminal, \( \text{index}_{i,r} \) is the subcarrier index detected by the receiving terminal, \( \cap \) is the intersection, \( P_{\text{error}} \) is the detection error rate, \( mt \_ kl \) is the number of Monte Carlo, this paper carries out a total of 10000 Monte Carlo. The error rate of the original system model and the improved model is shown in Figure 4:

![Figure 4. System detection error rate before and after the improved algorithm.](image)

It can be seen from the figure that the detection error rate of the unimproved system, the improved detection algorithm system, the joint improved detection algorithm and subcarrier optimization system decreases with the increase of SNR, and the decreasing trend is roughly the same. The detection error rate of the improved system is lower than that of the original system. Even in the case of low SNR, the detection error rate of the improved system is lower than that of the original system in the case of high SNR. The detection error rate of the original system drops to below 0.1 when the SNR is 15dB. The improved system's detection error rate always remains below 0.1, and the detection error rate can be reduced to below 0.001 with the increase of SNR. The improved detection algorithm reduces the detection error rate by 8.8dB–11.68dB compared with no improvement, and the improved detection algorithm + subcarrier optimization reduces the detection error rate by 4.27dB–6.17dB than the improved detection algorithm. Obviously, the improved method designed in this paper is very effective.
Then bring the best subcarrier codebook into the 2.1 transceiver model, and select 6 of the best subcarrier codebook at the corresponding code rate for each frequency hopping position. When the train speed is 30km/h, the following can be obtained: Figure 5 Bit error rate of each transmission rate.

It can be seen from the figure that the improved system has reached a BER of less than 0.1 at a signal-to-noise ratio of 21dB even at the worst-performing bit rate of 6.75Mbps, and the BER of all code rates of the system when the signal-to-noise ratio is 30dB When it falls below 0.01, the bit error rate is reduced by 8.0778dB–17.4121dB (under 54/8Mbps). However, the original system can only achieve a BER of 0.1 when the SNR is greater than 25dB under the best performance of the 0.75Mbps code rate. For high-speed transmission rates, the error rate of the entire system does not decrease significantly as the SNR increases at 30dB. The BER is much higher than 0.1. Obviously, the improved system greatly improves the performance, ensuring the subsequent balanced design requirements of high bit rate and high performance.

4. Adaptive rate transceiver system
When the train moves at different speeds and SNRs, the required transmission rates are inconsistent. As shown in Figure 5, when the SNR is 5dB, choose 0.75Mbps to ensure that the bit error rate is below 0.1, and when the SNR is 30dB, choose any bit rate can ensure that the bit error rate is below 0.01. At this time, choosing 6.75Mbps can increase the transmission rate. Therefore, it is necessary to design and add an adaptive rate to obtain a high-performance and efficient balance of the system. The specific design ideas are as follows:

(1) Simultaneous interpreting codebook SNR with 7 different speeds ([0:10:60]km/h) and 7 transmission rates ([6 12 18 24 36 48 54]/8Mbps) are obtained.

step 1: The moving speed is expressed as $speed_v$, $v$ is speed number, $speed_1 = 0km/h$, $datarate_\alpha$ is transmission rate, initialize SNR $SNR_j = 0dB$, $j=1,v=1,\alpha=1$.

step 2: For the current mobile speed $speed_v$, the current transmission rate $datarate_\alpha$, the current SNR $SNR_j$, respectively send and receive processing, perform $mt_{kl}$ Monte Carlo operation, in this simulation $mt_{kl}=1000$, the bit error rate is $BER_{v,\alpha} = \sum_{i=1}^{mt_{kl}} \frac{BER_{v,\alpha,i}}{mt_{kl}}$.

step 3: $j = j + 1$, $SNR_j = SNR_{j-1} + \gamma$, where $\gamma$ is the increment of each SNR adjustment, which is 0.2db in this paper.

step 4: Repeat the operation of step 2-step 3 until $BER_{v,\alpha} < 0.01$ the signal-to-noise ratio $SNR_{v,\alpha}$ satisfying the current condition is recorded, and make $SNR_j = 0dB, j = 1$. 

![Figure 5. BER of improved 802.11g FH transceiver system.](image-url)
step 5: \( v = v + 1 \), Repeat the operation of step 2-step 4 on speed \( \nu \) until \( v > 7 \). When the transmission rate is \( datarate_\alpha \), make \( v = 1 \), the signal-to-noise ratio \( SNR_\alpha = [SNR_{1,\alpha}, SNR_{2,\alpha}, SNR_{7,\alpha}]^T \) satisfying the condition at different speeds is obtained.

step 6: \( \alpha = \alpha + 1 \), Repeat the operation of step 2-step 5 until \( \alpha > 7 \).

step 7: The SNR codebook \([SNR_1, SNR_2, \ldots, SNR_\alpha]\) of all transmission rate and all moving speed is obtained.

(2) Under different mobile speeds speed\(_r\), it is assumed that the SNR detected by the system \( SNR_{det} \) is the SNR detected by the receiver, and the number of the \( v \) line in the SNR codebook less than the \( SNR_{det} \) maximum value corresponds to the transmission rate selected by the adaptive system, which can not only ensure the system performance, but also improve the code rate.

Bring the frequency hopping codebook matrix generated in Chapter 3.2 and the SNR codebook generated in Chapter 4 into the transceiver model proposed in this article, and the comparison of the system's bit error rate performance and transmission rate under different moving speeds is shown in Figure 6.

![Figure 6. Comparison of system performance and transmission rate at different mobile speeds.](image)

It can be seen from the figure that the adaptive rate transceiver system designed in this article has a significantly higher transmission rate when the performance is close to the best transmission rate of 0.75Mbps, and as the train speed increases, adaptive bit rate transmission rate gradually decreases, but the bit error rate curve and the transmission rate curve change smoothly, and the performance stability of the entire system is very high. Due to the random selection of the average SNR in this article, the SNR will be particularly bad and will be particularly good. The bit error rate may be slightly worse than the ideal value, but within the allowable range, selecting a reasonable SNR can further improve this situation.

5. Summary

The transceiver model based on 802.11g designed in this paper is designed on the basis of the current train-to-ground communication in the subway environment. In order to overcome the shortcomings of traditional car-to-ground communication that channel congestion is greatly affected by noise in the 2.4G environment, frequency hopping communication is added. Under the background of wlan technology used in traditional CBTC communication, the system designed in this paper not only has the anti-interference ability of 802.11FHSS, but also inherits the high throughput rate of 802.11g, and is not susceptible to malicious monitoring and interference by third parties to ensure driving safety. At the same time, in order to achieve a balance between high performance and efficiency of the system, an adaptive rate design is added, which is well adapted to the situation of trains entering the platform.
to decelerate and leaving the platform to accelerate. For example, the platform screen door system of Shanghai line 2 mentioned above is very suitable for this design.

With the development of mobile communication, 4G communication and even 5G communication technology are gradually being applied to the subway car-ground communication system, but its cost is still relatively high, and the technology is not as mature as wlan, so it has not been popularized. The next step can be considered in the traditional. On the basis of the 802.11 protocol, 5G communication technology is added to obtain better performance, which can reduce the redundancy design reserved to ensure communication quality and reduce operating costs.

Acknowledgments
Research on test, maintenance and evaluation of DCS wireless system in Shanghai Shentong Metro Group Co., Ltd （JS-KY14R012）

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