Adaptive Technologies of Hybrid Carrier Based on WFRFT Facing Coverage and Spectral Efficiency Balance

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Abstract. Adaptive Modulation and Coding (AMC) and power control are adopted to balance spectral efficiency and coverage facing the problem of spectrum shortage in recent years. Considering the Orthogonal Frequency Division Multiplexing (OFDM) scheme with high spectral efficiency and the Single Carrier-Frequency Domain Equalization (SC-FDE) scheme with wide coverage, this paper combines the switching of carrier schemes with AMC and power control to maximize system throughput. The proposal of hybrid carrier communication system based on Weighted-type Fractional Fourier Transform makes the integration of OFDM and SC-FDE possible, which solves the problem of smooth transition between the two schemes. This paper analyzes the relationships between coverage and spectral efficiency in the flat fading channel and gives suggestions to the user equipment of different carrier schemes. Then we have proposed the calculation strategy of power control parameters and the switching strategy of the carrier schemes and modulation and coding schemes under power control in the frequency-selective fading channel.

Keywords: Weighted-type Fractional Fourier Transform · Adaptive Modulation and Coding (AMC) · Power control · Coverage · Spectral efficiency

1 Introduction

In the early development stage of communication technology, the system can only design strategies according to the worst channel condition to ensure the quality of communication because of the time-varying fading characteristics of the wireless channels. However, if the system still uses the conservative strategies as the channel condition improves, extend resources such as spectrum, power and channel capacity will be wasted. Link-adaptive transmission technology, which includes power control, Adaptive Modulation and Coding (AMC), etc., has been proposed to solve this problem.

J. Hayes proposed the power control technology in 1968 [1]. This technology avoids the impact on other users and ensures the communication quality at the same time. The core idea of AMC technology is to dynamically change the Modulation and Coding Schemes (MCSs) at the transmitter according to the time-varying channel conditions. To maximize the spectral efficiency on the basis of the reliability of the

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wireless transmission system, the low-order MCSs will be considered under poor channel conditions and high-order MCSs will be considered under excellent channel conditions [2, 3].

High-speed communication can be achieved easily using Multi Carrier (MC) scheme such as Orthogonal Frequency Division Multiplexing (OFDM) because of its high throughput. Nevertheless, OFDM signals have the problem of high Peak-to-Average Power Ratio (PAPR). If PAPR is high, the efficiency of Power Amplifier (PA) will be reduced because of the back-off. Thus, it is difficult for OFDM scheme to realize long-distance transmission. On the other hand, the Single Carrier (SC) signals have low PAPR and wide coverage can be realized easily.

Considering the characteristics of OFDM and SC schemes, if the two carrier schemes can be integrated under one system framework, it is possible to achieve both wide coverage and high spectral efficiency. A hybrid SC/MC system has been proposed by the research team at Tohoku University [4–7]. It is verified that the system can improve the throughput performance and extend the transmission distance.

The proposal of Hybrid Carrier (HC) communication system based on Weighted-type Fractional Fourier Transform (WFRFT) can also make the integration of the two schemes possible [8]. The system can transform the carrier scheme from SC to OFDM smoothly through parameters adjustment, which is different from the system above. The problem of incompatibility between the SC and MC schemes is solved through weighted integration of the two carrier schemes, providing the technical basis for further enhancing the flexibility and adaptive capabilities of the communication system.

Technologies such as AMC and power control are the main methods to reflect the system adaptive capabilities. In the existing research, SC or MC carrier scheme is usually combined with the technologies above, and the balance between the transmission rate and coverage is achieved through the switching of the MCSs. Based on the existing research, this paper introduces HC system based on WFRFT, utilizes the diverse characteristics provided by HC signals, and combines existing AMC and power control technologies to maximize the throughput of the system.

This paper is divided into five sections. The Sect. 2 introduces the HC system based on WFRFT. The Sect. 3 analyzes the relationships between coverage and spectral efficiency in the flat fading channel. The Sect. 4 introduces the switching strategy of the carrier schemes and MCSs under power control. In Sect. 5, the conclusions are presented.

2 HC System Based on WFRFT

2.1 HC Communication System

The system diagram of Single Carrier-Frequency Domain Equalization (SC-FDE) and OFDM is shown in Fig. 1. It can be seen that SC-FDE moves the Inverse Fast Fourier Transform (IFFT) module at the transmitter of OFDM to the receiver, so the SC system can also perform Frequency Domain Equalization (FDE).

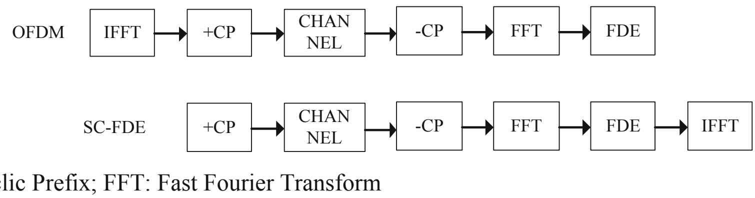


Fig. 1. System diagram of OFDM and SC-FDE

The proposal of WFRFT introduced the concept of HC. The HC is composed of SC and MC components, and the coefficient α determines the proportion of SC and MC in the HC system. The expression of α-order WFRFT is as follows

$$F_{4W}^{\alpha}[x(n)] = w_0(\alpha)x(n) + w_1(\alpha)X(n) + w_2(\alpha)x(-n) + w_3(\alpha)X(-n) \tag{1}$$

Where $x(n)$ is the data information to be processed and $X(n)$ is the Discrete Fourier Transform of $x(n)$. The expression of α in the Eq. (1) is as follows

$$w_l(\alpha) = \cos\left[\frac{(\alpha - l)\pi}{4}\right]\cos\left[\frac{2(\alpha - l)\pi}{4}\right]\exp\left[\pm i\frac{3(\alpha - l)\pi}{4}\right] \tag{2}$$

The matrix expression form of α-order WFRFT is shown below

$$\boldsymbol{W}_{\alpha} = w_0(\alpha)\boldsymbol{I} + w_1(\alpha)\boldsymbol{F} + w_2(\alpha)\boldsymbol{\Gamma} + w_3(\alpha)\Gamma\boldsymbol{F} \tag{3}$$

The matrix $\boldsymbol{I}$ is the identity matrix, and the matrix $\boldsymbol{F}$ is the matrix form of FFT, $[F]_{m,n} = \frac{1}{\sqrt{N}}\exp[-j2\pi mn/N]$, where m and n range from 1 to $N\ -1$. Matric $\boldsymbol{\Gamma}$ is

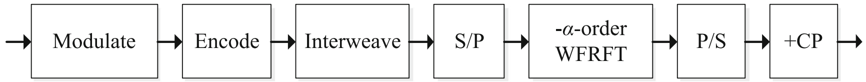
$$\boldsymbol{\Gamma} = \begin{pmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 1 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \end{pmatrix}_{N\times N} \tag{4}$$

This paper is based on the HC system. The carrier scheme is changed by adjusting the coefficient α. That is, the system mentioned above is MC transmission when $\alpha = 1$ and SC transmission when $\alpha = 0$. When α is between 0 and 1, it is HC transmission.

In [9–11], the PAPR characteristic of the HC signals is studied and the conclusion showed that the PAPR has a smooth transition between SC and MC as α changes. The BER performance in the frequency-selective channel also transforms smoothly between the two schemes [12].

2.2 The Structure Diagrams of Transmitter and Receiver

The transmitter and receiver structure diagrams in the flat fading channel are given in Fig. 2 and Fig. 3. There need to be FDE operation at the receiver in the frequency-selective fading channel. The data processing process in the transmitter and receiver is described in detail below.



S/P: Serial/Parallel Convert; P/S: Parallel/Serial Convert

Fig. 2. Structure diagram of transmitter

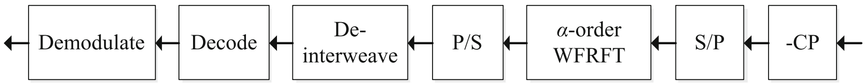


Fig. 3. Structure diagram of receiver

At the transmitter, the data need to be modulated, encoded, interweaved, S/P converted, and then sent to the -α-order WFRFT module. After the P/S conversion, CP is added and the data are transmitted over the multipath channel.

After receiving data, the receiver removes CP first, then performs S/P conversion, α-order WFRFT, and P/S conversion. Finally, the data need to be de-interweaved, decoded, and demodulated respectively.

3 The Relationships Between Coverage and Spectral Efficiency in the Flat Fading Channel

In the flat fading channel, the Block Error Rate (BLER) performance of each carrier scheme is the same, and the coverage is only determined by the Maximum Average Output Power (MATP). On the other hand, the PAPR performances of different carrier schemes are different, so the MATP values are also different. We simulated the relationships between coverage and spectral efficiency of three typical carrier schemes supposing that the signals are transmitted with MATP and gave suggestions to the User Equipment (UE) of different carrier schemes.

3.1 PAPR and MATP

In the traditional SC and OFDM carrier schemes, both the number of subcarriers and the constellation mapping methods affect the PAPR characteristics of the signals. The HC system based on WFRFT can control the PAPR of the signals through another dimension: the transformation order α. The PAPR curves of SC, HC and OFDM signals are obtained by simulating the HC system with α from 0 to 1 in steps of 0.1.

Figure 4, Fig. 5 and Fig. 6 show the Complementary Cumulative Distribution Function (CCDF) curves of PAPR for HC signals with different modulation schemes. The abscissa is the threshold of $PAPR_0$, and the ordinate is the probability that the PAPR value exceeds $PAPR_0$. The number of subcarriers is 512, and the oversampling factor is 8 [13]. Table 1 represents the PAPR of these three typical carrier schemes. When α changes from 1 to 0, the PAPR characteristic of the HC signals transforms smoothly from that of OFDM to SC.

At the transmitter, if the PA works near the saturation region, it can achieve higher power efficiency. However, when the signals have a high PAPR value, the PA can only process it by Input Back-Off (IBO) to ensure that it does not enter the nonlinear region. Among them, the IBO factor is defined as follows

$$IBO = 10\log_{10}(\frac{P_{sat}}{P_{av}}) = P_{sat}[\mathrm{dB}] - P_{av}[\mathrm{dB}] \tag{5}$$

where $P_{sat}[\mathrm{dB}]$ and $P_{av}[\mathrm{dB}]$ are the saturation and average power of signals sent to PA, respectively. In order to ensure the probability that the output signals occur non-linear distortion less than a certain threshold, the IBO cannot be lower than the corresponding $PAPR_0$.

After the power back-off, the average transmission power can be expressed as

$$P_t = P_{max} - IBO \tag{6}$$

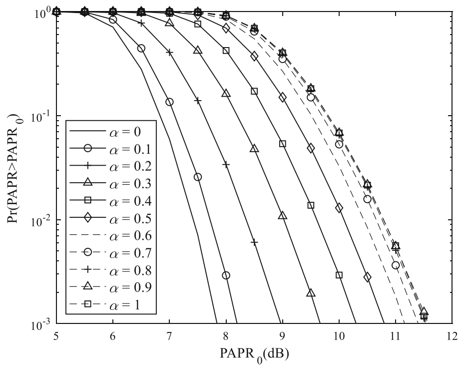


Fig. 4. CCDF of PAPR for HC signals with 4-QAM

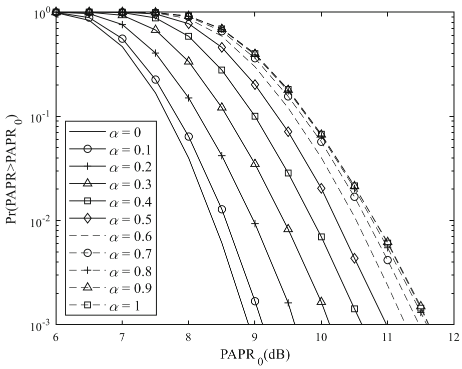


Fig. 5. CCDF of PAPR for HC signals with 16-QAM

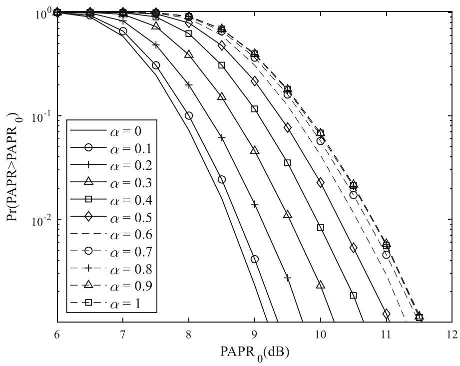


Fig. 6. CCDF of PAPR for HC signals with 64-QAM

Table 1. PAPR of different carrier schemes with different modulation schemes

Modulation scheme	SC(α = 0)	HC(α = 0.5)	MC(α = 1)
4QAM	7.86	10.80	11.57
16QAM	8.88	10.98	11.62
64QAM	9.20	11.05	11.56

where P_{max} is the maximum output power of PA without regard of IBO. This paper assumes P_{max} = 35 dBm. MATP refers to the transmission power under the condition of IBO = $PAPR_0$. For example, when the SC scheme adopts 4QAM, its $PAPR_0$ and MATP are 7.86 dB and 27.14 dBm, respectively.

Then we need to calculate the received power P_r and Signal-to-Noise Ratio (SNR) to select the optimal MCS for UE at each distance. P_r is defined as follows

$$P_r = P_t + 20\log_{10}(\frac{\lambda}{4\pi d_0}) - 10\log_{10}(\frac{d}{d_0})^{3.8} \tag{7}$$

In Eq. (7), the second term was free space electromagnetic loss and third term was propagation loss. At 2 GHz, λ and d_0 were 0.15 m and 100 m [14].

The received SNR is calculated by the received power P_r, single sideband noise power spectral density N_0 of −174 dBm/Hz and system bandwidth B

$$SNR = P_r - N_0 B \tag{8}$$

3.2 The Relationships Between Coverage and Spectral Efficiency

The MCSs selected in this paper are shown in Table 2. The coding scheme is convolutional code and the constrained length is 7 for rate 1/2 and 8 for rate 1/3.

Figure 7 shows the BLER performances of different MCSs in the flat fading channel. We can find that the BLER performances reduce gradually from MCS1 to MCS6 and the abscissa in Fig. 7 is E_b/N_0.

Table 2. Modulation and coding schemes selected

MCS index	Modulation scheme	Coding rate
MCS1	4QAM	1/3
MCS2	4QAM	1/2
MCS3	16QAM	1/3
MCS4	16QAM	1/2
MCS5	64QAM	1/3
MCS6	64QAM	1/2

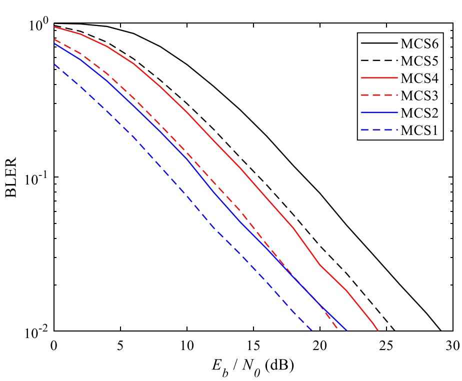


Fig. 7. Simulation of BLER performances in the flat fading channel

However, the SNR calculated from the received power is E_s/N_0, and the conversion method of E_s/N_0 [dB] and E_b/N_0 [dB] is shown in Eq. (9)

$$E_s/N_0[\mathrm{dB}] = E_b/N_0[\mathrm{dB}] + 10\lg R_\mathrm{b} \tag{9}$$

In Eq. (9), the spectral efficiency R_b(bit/s/Hz) is defined as

$$R_b = \frac{N \cdot log_2 J \cdot \eta_{coding}}{(N+M) \cdot T_S \times 1/T_S} = \frac{N \cdot log_2 J \cdot \eta_{coding}}{N+M} \tag{10}$$

where T_S is the sample period, N is the symbol length, M is the CP length, η_{coding} refers to the coding rate, and $log_2 J$ refers to modulation order of J-QAM. When J = 4, 16, 64, the modulation orders are 2, 4, 6, respectively.

This paper uses BLER = 10% as the standard to delimit the switching thresholds of the MCSs [15]. The results are shown in Table 3.

Then the relationships between the spectral efficiency and coverage of the SC (α = 0), HC (α = 0.5), and MC (α = 1) carrier schemes in the flat fading channel are analyzed. Suppose that the three carrier schemes are all transmitted with their MATP, and the MATP values of different carrier schemes with different modulation schemes are shown in Table 4.

Table 3. Switching thresholds of different MCSs in the flat fading channel

MCS index	E_b/N_0[dB]	E_s/N_0[dB]
MCS1	8.72	6.96
MCS2	11.1	11.1
MCS3	11.67	12.91
MCS4	14.61	17.62
MCS5	15.43	18.44
MCS6	18.82	23.59

Table 4. MATP [dBm] of different carrier schemes with different modulation schemes

Modulation scheme	SC(α = 0)	HC(α = 0.5)	MC(α = 1)
4QAM	27.14	24.20	23.43
16QAM	26.12	24.02	23.38
64QAM	25.80	23.95	23.44

Table 5. Received SNR [dB] of different modulation schemes and MCS selected at each distance under SC scheme

Distance/m	4QAM	16QAM	64QAM	MCS index
100	42.68	41.64	41.34	MCS6
150	35.99	34.97	34.65	MCS6
200	31.24	30.22	29.90	MCS6
250	27.56	26.54	26.22	MCS6
300	24.55	23.53	23.21	MCS4
350	22.01	20.99	20.67	MCS4
400	19.80	18.78	18.46	MCS4
450	17.96	16.84	16.52	MCS3
500	16.12	15.10	14.78	MCS3
550	14.56	13.53	13.21	MCS3
600	13.11	12.09	11.77	MCS2
650	11.79	10.77	10.45	MCS2
700	10.57	9.55	9.23	MCS1
750	9.43	8.41	8.09	MCS1
800	8.36	7.34	7.02	MCS1
850	7.36	6.34	6.02	MCS1
900	6.42	5.40	5.08	None

Taking the SC scheme as an example, the received SNR under different modulation schemes and the selected MCS are shown in Table 5. At 400 m, the MCS5 also meets the SNR requirements, but the MCS4 with the same spectral efficiency is used because of its better BLER performance. In actual systems, if the SNR conditions permit, high coding rates such as 3/4 and 5/6 can be selected to achieve higher spectral efficiency.

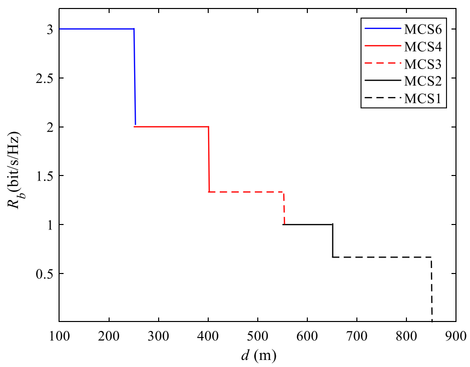


Fig. 8. Simulation of spectral efficiency and coverage under SC scheme

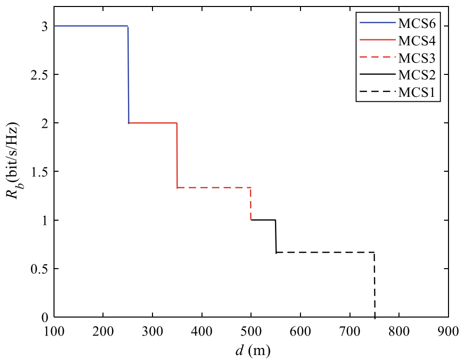


Fig. 9. Simulation of spectral efficiency and coverage under HC scheme

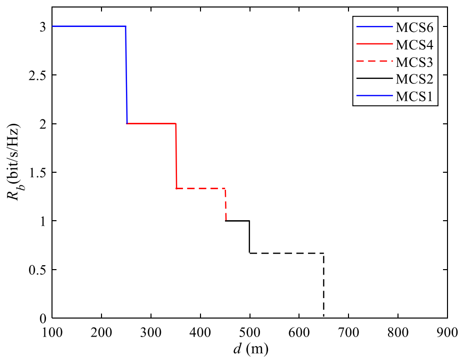


Fig. 10. Simulation of spectral efficiency and coverage under MC scheme

According to the same processing method, the received SNR and the selected MCS at each distance under the HC and MC schemes can be calculated. According to the results, the relationships between the spectral efficiency and coverage of the three carrier schemes are shown in Fig. 8, Fig. 9 and Fig. 10. The abscissa is the distance from UE to the base station, and the ordinate is the spectral efficiency.

It can be seen from Fig. 8, Fig. 9 and Fig. 10 that the balance between the spectral efficiency and coverage can be obtained through the switching of the MCSs for any given carrier scheme in the flat fading channel. It can also be seen that the SC scheme has the largest coverage area of 850 m; the MC scheme has the smallest coverage area of 650 m; and the HC scheme has a coverage area of 750 m, which is between that of SC and MC.

Through the above analysis, the conclusion can be reached: the UE can maximize system throughput through the switching of the MCSs for a given carrier scheme. In the flat fading channel, if the UE adopts the SC scheme, there is no need to change the carrier scheme, and the SC scheme transmission can obtain the best performance; if the OFDM scheme is adopted, the PAPR performance can be improved through WFRFT precoding to obtain the same coverage as the SC scheme.

4 Switching Strategy of Carrier Schemes and MCSs Under Power Control in the Frequency-Selective Fading Channel

In the frequency-selective fading channel, different carrier schemes have different BER performances. Compared with the flat fading channel, the frequency-selective fading channel can also achieve gain through the switching of the carrier schemes. We propose a new uplink selection strategy of the carrier scheme and MCS under power control in the frequency-selective channel. This strategy considers the PAPR, BLER performances of the signals, and the power control parameters.

4.1 Power Control

The power control in this paper aims at the reliability of the receiver, and the power control parameters are calculated based on the SNR switching thresholds of different MCSs in the flat fading channel. Thus, the UE can transmit signals with the lowest power on the basis of ensuring the BLER performance of the receiver. The calculation process is shown in Fig. 11 and the specific steps are as follows.

1. Starting from 100 m, select the SNR switching threshold of the MCS with the highest spectral efficiency, that is, 23.59 dB of the MCS6.
2. The transmission power is calculated by Eq. (11), which is derived from Eq. (7) and Eq. (8)

$$P_t = SNR + N_0 B - \left(20\log_{10}(\frac{\lambda}{4\pi d_0}) - 10\log_{10}(\frac{d}{d_0})^{3.8} \right) \qquad (11)$$

3. Judge whether the P_t is greater than the MATP of the MC scheme under this modulation scheme. If less, P_t is the power control parameter at this distance, and continue to use the SNR at the next distance until the calculated power is greater than the MATP of MC scheme under this modulation scheme. Otherwise, the SNR switching threshold of the MCS with the highest spectral efficiency in the remaining MCSs is selected at this distance.
4. After switching to a new MCS, continue to perform steps 2 and 3 until there is no MCS with lower spectral efficiency. Use P_t as the power control parameter at this distance, continue to use the SNR at the next distance and calculate P_t.
5. Judge whether P_t is greater than the MATP of the SC scheme under this modulation scheme. If less, P_t is the power control parameter at this distance, and the SNR will continue to be used at the next distance until the calculated power is greater than the MATP of SC scheme under this modulation scheme. Then end the process.

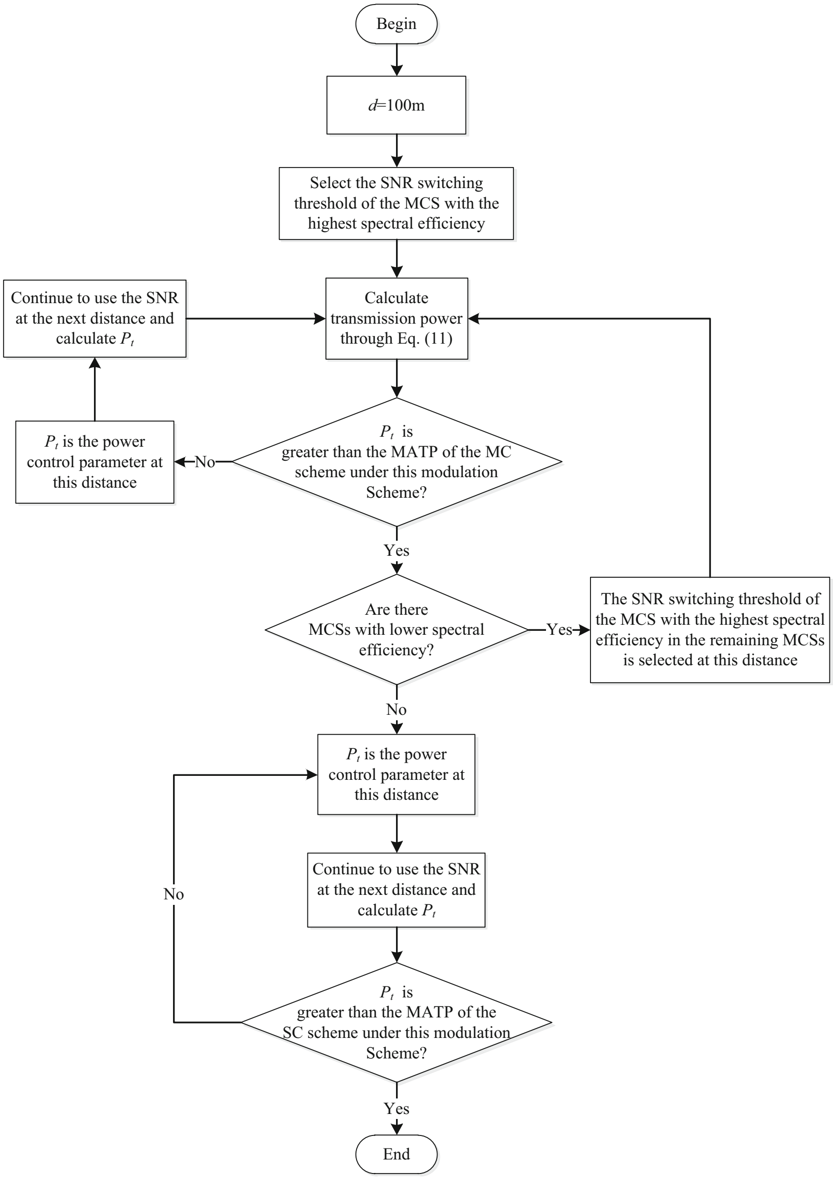


Fig. 11. Calculation process of power control parameters

Finally, the calculated power control parameters are shown in the second column of Table 6. In order to meet the requirements of the actual system better, the parameters in the second column of Table 6 are rounded as the integer multiple of 0.5, and the rounded results are shown in the third column of Table 6.

It can be seen from Table 6 that the power control parameters drop at 250–300 m, 350–400 m, 450–500 m and 500–550 m because of the switching of the MCSs.

Table 6. Power control parameters rounded or not at each distance

Distance/m	Unrounded power control parameters/dBm	Rounded power control parameters/dBm
100	8.05	8.5
150	14.74	15.0
200	19.49	19.5
250	23.17	23.5
300	20.21	20.5
350	22.75	23.0
400	20.25	20.5
450	22.19	22.5
500	22.12	22.5
550	19.55	20.0
600	20.99	21.0
650	22.31	22.5
700	23.53	24.0
750	24.67	25.0
800	25.74	26.0
850	26.74	27.0

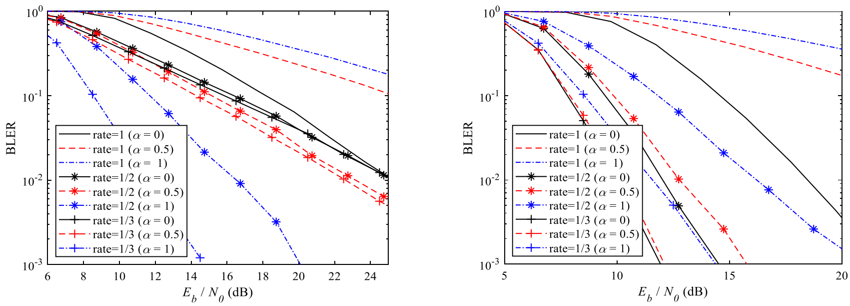
4.2 BLER Performances of Different Carrier Schemes and MCSs

Table 7 shows the simulation conditions in the frequency-selective fading channel. Figure 12 shows the BLER performances of 4QAM under Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) equalization. The simulation also takes the uncoded signals into consideration for comparison. The BLER performances of 16QAM and 64QAM are also simulated with the same parameters shown in Table 7. Then the SNR switching thresholds of all MCSs can be obtained.

In Fig. 12, we can find that the BLER performances of the MC signals under ZF and MMSE equalization are almost the same and that of the SC signals are different. The BLER performances of the HC signals are always between that of SC and MC.

Table 7. Simulation parameters of HC system in the frequency-selective fading channel

Parameter name	Value
Transmission Scheme	SC, HC(α = 0.5), MC
Decision Mode	Hard
Carrier Frequency	2 GHz
Channel Bandwidth	100 MHz
Number of Subcarriers	512
Symbol Period	10 ns
MCS Index	MCS1–MCS6
FDE Algorithms	FD-ZF, FD-MMSE
Multipath Delay	[0 100 200 300 500 700] ns
Average Path Gain	[0 − 3.6 − 7.2 − 10.8 − 25.2] dB
CP Length	80 symbols' length
Doppler Frequency Offset	0



a) ZF equalization b) MMSE equalization

Fig. 12. BLER performances of 4QAM under different equalization algorithms

4.3 Switching Strategy of Carrier Schemes and MCSs Under Power Control

We propose a new uplink selection strategy of the carrier scheme and MCS based on the previous work. This strategy considers the PAPR, BLER performances of the signals, and the power control parameters. There are 18 schemes totally through all combination of the three carrier schemes and six MCSs. This strategy prefers to select the scheme with the highest spectral efficiency among the schemes that meet the requirements of the received SNR and MATP. If there is more than one scheme with the highest spectral efficiency, the scheme with the lowest SNR switching threshold will be selected, so that the system can have strong robustness. Among them, meeting the SNR requirement means that the switching SNR of the MCS needs to be less than the received SNR at this distance and meeting the MATP requirement means that the MATP of the scheme needs to be greater than the power control parameter.

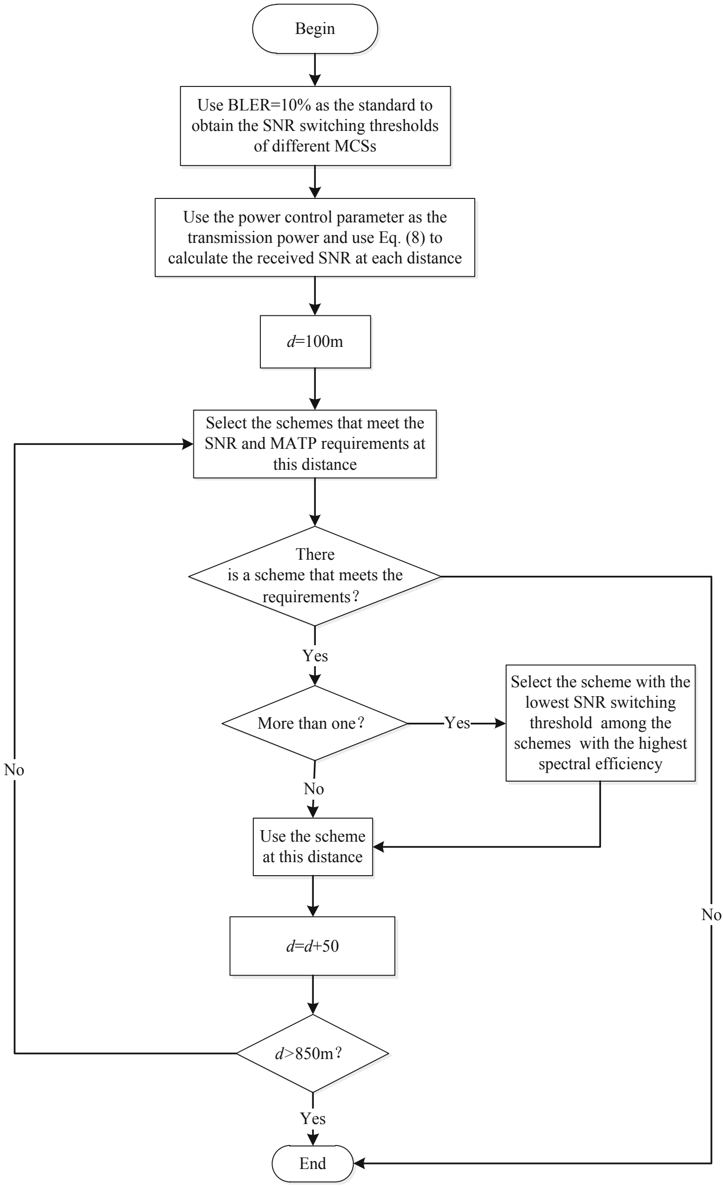


Fig. 13. The flowchart of carrier scheme and MCS selection strategy

The strategy flowchart is shown in Fig. 13, and the specific steps are as follows.

1. Use BLER = 10% as the standard to obtain the SNR switching thresholds of different MCSs under different carrier schemes; use the power control parameter as the transmission power, and use Eq. (8) to calculate the received SNR at each distance.

2. Starting from 100 m, select the schemes that meet the SNR and MATP requirements at this distance.
3. Judge whether there is a scheme that meets the requirements, if not, end the process of this strategy; if so, judge whether there is more than one that meets the requirements. If only one, use the scheme at this distance. Otherwise, the scheme with the lowest SNR switching threshold is selected among the schemes with the highest spectral efficiency.
4. Follow steps 2 and 3 at the next distance until the schemes at all distances are selected or no scheme meets the requirements at a certain distance.

We obtain the SNR switching thresholds of different carrier schemes under ZF and MMSE equalization through the BLER simulation, as shown in Table 8 and Table 9.

Table 8. SNR [dB] switching thresholds of different MCSs under ZF equalization

MCS index	SC	HC	MC
MCS1	13.42	11.75	6.16
MCS2	15.6	14.44	10.9
MCS3	19.45	17.94	12.3
MCS4	22.15	20.9	17.62
MCS5	24.75	23.3	17.5
MCS6	27.9	26.75	23.1

Table 9. SNR [dB] switching thresholds of different MCSs under MMSE equalization

MCS index	SC	HC	MC
MCS1	5.3	5.4	6.16
MCS2	8.73	9.1	11.1
MCS3	14.4	14	12.7
MCS4	18.2	18	18
MCS5	21.3	20.4	17.62
MCS6	25.9	24.9	23.2

The received SNR calculated from the power control parameters is shown in Table 10, where the second column is calculated according to the unrounded power control parameters in Table 6, and the third column is calculated according to the rounded power control parameters. Taking the SNR calculated according to the unrounded parameters as an example, the received SNR is 23.59 dB and the transmission power is 8.05 dBm at 100 m. There are 15 schemes which meet the requirements of SNR and MATP and only one scheme with the highest spectral efficiency, that is, the MC scheme with MCS6.

Table 10. Received SNR [dB] calculated by rounded power or not at each distance

Distance/m	Received SNR calculated by unrounded power	Received SNR calculated by rounded power
100	23.59	24.04
150	23.59	23.85
200	23.59	23.60
250	23.59	23.92
300	17.62	17.91
350	17.62	17.87
400	12.91	13.16
450	12.91	13.22
500	11.1	11.48
550	6.96	7.41
600	6.96	6.97
650	6.96	7.15
700	6.96	7.43
750	6.96	7.29
800	6.96	7.22
850	6.96	7.22

Finally, the switching results under ZF and MMSE equalization are shown in Table 11 and Table 12, where the second and third columns are calculated according to the second column of Table 10 and the fourth and fifth columns are calculated according to the third column.

From Table 11, the UE adopts the MC scheme at all distances under ZF equalization. As the distance increases, the spectral efficiency gradually decreases. The SC and HC schemes have not been adopted due to the high SNR switching thresholds. At the same time, a new MCS is switched at 250 m because the transmission power is rounded from 23.17 dBm to 23.5 dBm, which is greater than the MATP of the MC scheme at 64QAM.

It can be seen from Table 12 that the UE adopts the MC scheme with high-order MCSs at near distances and the SC scheme with low-order MCSs at far distances under MMSE equalization. The switching of the carrier schemes and MCSs is achieved, so that the HC system can reach a better balance between the coverage and spectral efficiency through the parameter adjustment.

From Table 11 and Table 12, it can be found that a new MCS is switched at 250 m under MMSE equalization, which is the same as ZF equalization. The difference between the two is that the UE adopts the MC scheme at all distances under ZF equalization, while the UE adopts the MC scheme with high-order MCSs at near distances and the SC scheme with low-order MCSs at far distances under MMSE equalization. The reason is that the SNR gain brought by the low PAPR performances of the SC signals is not as large as that brought by the BLER performances of the MC signals for low-order MCSs under ZF equalization. The SC scheme outperforms the MC scheme under low-order MCSs and its MATP is higher when MMSE equalization

Table 11. Carrier scheme and MCS selected at each distance under ZF equalization

Distance/m	Carrier scheme	MCS index	Carrier scheme	MCS index
100	MC	MCS6	MC	MCS6
150	MC	MCS6	MC	MCS6
200	MC	MCS6	MC	MCS6
250	MC	MCS6	MC	MCS5
300	MC	MCS5	MC	MCS5
350	MC	MCS5	MC	MCS5
400	MC	MCS3	MC	MCS3
450	MC	MCS3	MC	MCS3
500	MC	MCS2	MC	MCS2
550	MC	MCS1	MC	MCS1
600	MC	MCS1	MC	MCS1
650	MC	MCS1	MC	MCS1

Table 12. Carrier scheme and MCS selected at each distance under MMSE equalization

Distance/m	Carrier scheme	MCS index	Carrier scheme	MCS index
100	MC	MCS6	MC	MCS6
150	MC	MCS6	MC	MCS6
200	MC	MCS6	MC	MCS6
250	MC	MCS6	MC	MCS5
300	MC	MCS5	MC	MCS5
350	MC	MCS5	MC	MCS5
400	MC	MCS3	MC	MCS3
450	MC	MCS3	MC	MCS3
500	SC	MCS2	SC	MCS2
550	SC	MCS1	SC	MCS1
600	SC	MCS1	SC	MCS1
650	SC	MCS1	SC	MCS1
700	SC	MCS1	SC	MCS1
750	SC	MCS1	SC	MCS1
800	SC	MCS1	SC	MCS1
850	SC	MCS1	SC	MCS1

is adopted. Thus, it is used at long distances. The HC scheme has not been adopted under ZF and MMSE equalization, which shows that the HC scheme cannot achieve the optimal performance of the spectral efficiency and coverage in this scenario, and the system can only switch schemes between SC and MC.

5 Conclusion

We propose the adaptive technologies of HC based on WFRFT facing the balance of coverage and spectral efficiency. The relationships between the spectral efficiency and coverage of different carrier schemes in the flat fading channel are analyzed. We can find that the coverage is gradually reduced when the carrier scheme transforms from SC to MC. Therefore, if the UE adopts the SC scheme, there is no need to change the carrier scheme. If the OFDM scheme is adopted, the PAPR performance of the OFDM signals can be improved by WFRFT precoding, so that it can obtain the same coverage as the SC scheme. In the frequency-selective channel, this paper takes power control into consideration. The UE adopts the MC scheme at all distances under ZF equalization, because the SNR gain brought by the low PAPR performances of the SC signals is not as large as that brought by the BLER performances of the MC signals for the low-order MCSs. The UE adopts the MC scheme with high-order MCSs at near distances and the SC scheme with low-order MCSs at far distances under MMSE equalization, which maximizes the overall spectral efficiency of the system, and the incompatibility of SC and MC can be solved easily through HC system based on WFRFT.

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