Environment-Driven Modulation and Coding Schemes for Cognitive Multicarrier Communication Systems

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Abstract. With the deterioration of the electromagnetic environment, it is difficult for a single wireless communication system to satisfy the quality of communication service requirements in congested frequency bands. An effective solution is to establish a unified communication platform, which can accordingly change its systematic parameters, such as modulation, coding, available spectrum resource, etc. In this paper, an environment-driven communication system is devised to realize intelligent communication with variant data transmission requirements and quality of services. Different modulation coding schemes (MCS) are integrated in the environment-driven communication system to deal with the time-varying spectrum constraint. Besides, based on information of channel condition, the environment-driven system can select a suitable MCS to achieve preferable systematic performance. Simulation results indicate that the devised environment-driven communication system has good performance in different conditions.

Keywords: Environment-driven · Modulation and coding scheme · Multicarrier systems · Cognitive radio · Spectrally modulated and spectrally encoded signals

1 Introduction

Spectrum crowding will grow continuously due to wireless applications and spectral limitations. Although spectrum is seriously scarce, it is more important to access it [1]. In order to use the unused spectrum more effectively in the dynamic environment, cognitive radio (CR) arises. CR accommodates to fast-changing environmental conditions and provides controlled intervention for existing users in the meantime [2]. Nevertheless, most of the research is limited to consider only a specific waveform, which is not applicable to a wide range of users [3]. So we provide an emerging adaptive communication transmission method based on intelligent decision-making.

In this paper, we consider the general analysis structure for spectrally modulated and spectrally encoded (SMSE) signals [4–6]. Some parameters (i.e., spectrum utility sequence, channel coding, data modulation, spread spectrum code) are utilized to

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construct the framework. By changing these parameters, different communication systems can switch flexibly to achieve the purpose of matching user needs and reducing interference.

The communication technologies in SMSE framework include non-continuous orthogonal frequency division multiplexing (NC-OFDM), non-continuous multi-carrier code division multiple access (NC-MC-CDMA) and transform domain communication system (TDCS). Their brief description is as follows.

- OFDM is a multicarrier modulation technology, which can efficiently eliminate inter-symbol interference by inserting cyclic prefix (CP) among symbols. By transmitting data in parallel on subcarriers, OFDM can achieve a higher data rate. However, in order to prevent mutual interference among subcarriers, it is required that the subcarriers are orthogonal to each other. Unfortunately, the orthogonality of OFDM subcarriers is easily destroyed by Doppler shift [7]. Therefore, OFDM is suitable for scenarios with low speed and high signal-to-noise ratio.
- MC-CDMA splits the original data stream into parallel data by modulating the signal on spread sequences. This modulation technique can effectively resist the codes interference (ISI) induced by multipath effect and possesses unique advantages in frequency diversity [8]. In this paper, Hadamard matrix is used to generate the spread spectrum sequence of MC-CDMA.
- As a typical spectrum sharing communication system, TDCS can actively avoid the spectrum interference or the occupied frequency band by sensing the spatial electromagnetic environment information in a certain frequency band. By dynamically changing the transmission frequency band according to the perception results, TDCS can well avoid the interference frequency band [9]. Due to its active anti-interference ability, TDCS supports low-data-rate communication in harsh environments [10].

Different combinations of parameters can form different modulation coding schemes. How to intelligently choose the modulation coding scheme in different scenarios is the key problem. In the process of formulating the adaptive modulation coding scheme, a corresponding table of channel conditions and modulation coding scheme is obtained through simulation [11–14]. In practical application, we not only need to select the optimal range of modulation coding schemes based on the estimation of channel transfer quality, but also consider the needs of users, such as communication rate, so a fuzzy decision is added to make the final decision.

The rest of this article is made up of the following organizations. Section 2 depicts the analysis structure of the adaptive transmission system and summarizes the channel models used in the simulation. In Sect. 3, the method of adaptive modulation is described in detail, and the frame diagram of the system is given. The simulation results and conclusions are addressed in Sect. 4 and the last part respectively.

2 Environment-Driven Communication System

The vectors are shown in bold capital letters below. The model defines the waveform design for the user's Kth data symbol. Time indexes of the discrete and continuous expressions are n and t, while the frequency indexes are m and f separately.

A. Spectrum sensing

Spectrum sensing module samples the electromagnetic spectrum environment over the system's operating bandwidth and estimates the spectral content. A thresholding process is applied to the spectral estimate, producing a magnitude vector involving ones and zeros [15]. In other words, if the power spectrum amplitude of the subcarrier exceeds the threshold value, the subcarrier is considered to have been occupied and marked as 0. Otherwise, the subcarrier is considered unoccupied and marked as 1 (as shown in Fig. 1 and Fig. 2). Let the resulting spectrum utility sequence be $\mathbf{a} = [a_0, a_1, \ldots, a_n, \ldots, a_{N_F-1}]$.

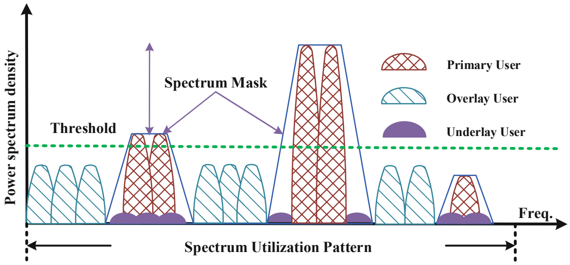

Fig. 1. Example of fully spectrum utilization pattern

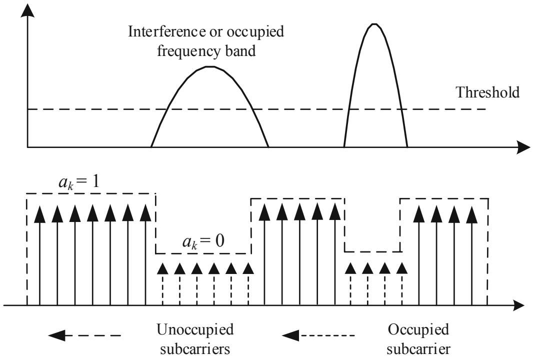

Fig. 2. Example of spectrum utilization vector

B. Modulation and coding schemes in SMSE

We choose the representation method of spectrum input and spectrum output framework (SMSE) in [1]. The spectrum is expressed as.

$$S_{SMSE} = \mathbf{A} \quad \mathbf{\Theta} \quad \mathbf{F} \tag{1}$$

where e represents Hadamard product, that is, array multiplication by element. **A**, **Θ** and **F** represent complex amplitude, phase, and frequency separately. In this paper, they are functions of four waveform design variables (data-in, encoding, frequency component availability and frequency component usage). Since we only discuss one-to-one transmission, $\mathbf{A}_k$, $\mathbf{\Theta}_k$ and $\mathbf{F}_k$ size $1 \times N_F$, every column for a different frequency component, a total of N_F frequency. The product of amplitude after spectrum operation is $A_{1m} \in \mathbf{A} = [A_{11}, A_{12}, .., A_{1N_F}]_{1\times N_F}$. The phase sum of spectrum operation is $\Theta_{1m} \in \mathbf{\Theta} = [\Theta_{11}, \Theta_{12}, .., \Theta_{1N_F}]_{1\times N_F}$. And the frequency on-off indicator is $F_{1m} \in \mathbf{F} = [F_{11}, F_{12}, .., F_{1N_F}]_{1\times N_F}$.

When the frequency interval is set to $\Delta f = 1/T_{sym}$, subcarriers are orthogonal to each other within a symbol time, that is, spectrum components of each subchannel are zero at frequencies of other subcarriers. Thus the inter-channel interference is eliminated. The SMSE waveform expression is developed by using spectrum utility sequence (**a**), channel code (**u**), complex data modulation (**d**) and spread spectrum code (**c**) design variables. The mth frequency component of the kth data modulator $s_k[m]$ is expressed as

$$s_k[m] = a_m u_{m,l} c_m d_{m,k} e^{j(\theta_{c_m}+\theta_{d_{m,k}})} \tag{2}$$

where $m \in \{0, 1, \ldots, N_F - 1\}$, a_m, $u_{m,l}$, c_m, $d_{m,k}$, θ_{c_m} and $\theta_{d_{m,k}}$ are magnitude and phase of the design variables. Then we put these design variables together and get

$$\begin{aligned} A_{m,k} &= u_{m,l} c_m d_{m,k} \\ \Theta_{m,k} &= e^{j(\theta_{c_m}+\theta_{d_{m,k}})} \\ F_m &= a_m \end{aligned} \tag{3}$$

The expression in (1) can be further modified to

$$s_k[m] = A_{m,k}\Theta_{m,k}F_m \tag{4}$$

The time-domain expression of SMSE symbols is produced by the application of IDFT operation to (4) and removing the imaginary part, written as

$$s_k[n]_{1\times 1} = \mathrm{Re}\{\frac{1}{N_F}\sum_{m=0}^{N_F-1} A_{m,k}\Theta_{m,k}F_m e^{j(2\pi f_m t_n)} \tag{5}$$

Since the spread spectrum code is not required, OFDM's expression can be obtained by removing the variable c_m:

$$s_k[m] = u_m d_{m,k} e^{j\theta_{d_{m,k}}} \tag{6}$$

For MC-CDMA and TDCS, although the spread spectrum code used is different, their expression forms are the same:

$$s_k[m] = a_m u_{m,l} c_m d_{m,k} e^{j(\theta_{c_m}+\theta_{d_{m,k}})} \tag{7}$$

where $d_{m,k}e^{j\theta_{d_{m,k}}}$ represents data modulation. We set $d_{m,k}e^{j\theta_{d_{m,k}}} = \alpha_{m,k} + j\beta_{m,k}$. When the modulation mode is QPSK, $\alpha_{m,k}, \beta_{m,k} \in \{\pm 1\}$. When the modulation mode is 16QAM, $\alpha_{m,k}, \beta_{m,k} \in \{\pm 1, \pm 3\}$.

C. Determine adaptive modulation parameters

A table of channel conditions and modulation coding scheme (mainly the corresponding table of SNR and BER or SNR and system throughput) is needed. It's obtained through simulation and test of large data volume for a long time. In practical applications, according to the user's rate requirements, reliability requirements and channel estimation results, the adaptive modulation parameters (e.g., **u**, **c**, **d**) are obtained by using intelligent decision-making to select the optimal modulation coding scheme.

D. Channel models

In this paper, the channel conditions are simply divided into three disparate channel models: the additive Gaussian white noise (AWGN) channel, Rice multipath fading channel and Rayleigh multipath fading channel.

AWGN channel model indicates that the only impact of the channel on the transmission signal is the Gaussian white noise process. AWGN is the most commonly used channel model for communication system simulation, so we won't go into details here.

Rayleigh is a particular channel fading without major line-of-sight (LOS) component. There are serious fade-in and fade-out events that can cause an unexpected interruption of the communication chain due to the RSS drop. Under the circumstances, phase, angle of arrival and the received signal strength (RSS) change. As the traffic moves around, it occasionally fades away over time, which is rapid decay. Although there is no ISI, rapid fading is still disruptive because the gain for deep fading is low. Expression (8) characterizes the probability density function of the Rayleigh model.

$$p(r) = \begin{cases} \frac{r}{\sigma^2} \exp(-\frac{r}{2\sigma^2}), & (r \geq 0) \\ 0, & (r < 0) \end{cases} \tag{8}$$

where σ^2 is the mean power of the time signal. The square amplitude r^2 determines SNR value. The threshold R that cannot be exceeded is given a definition in [5].

$$P(R) = P(r \leq R) = \int_0^R p(r)dr = 1 - \exp(\frac{r}{2\sigma^2}) \tag{9}$$

Table 1 gives simulation parameters of Rayleigh channel.

Table 1. Parameters of Rayleigh channel

Properties	Parameters
Path delays (s)	[20, 30, 70, 90, 110, 190, 410] * (10^{-9})
Average path gains (dB)	[0, −1, −2, −3, −8, −17.2, −20.8]
Sample rate (s)	1e−8

With the existent of LOS component, the fading form turns to be Rice, because LOS component obscures others. Under Rice fading, the steady main LOS signal overlays with the random multipath components. Rice factor is K, the proportion of main LOS component to dispersion constituent part:

$$K(dB) = 10\log(\frac{A^2}{2\sigma^2}) \tag{10}$$

Rician distribution is shown in (11), in which A is magnitude of main component. I_0 is the first kind of modified zeroth-order Bessel function. Along with the change of $A \to 0$ and $K \to -\infty$, Rician changes to Rayleigh.

$$p(r) = \begin{cases} \frac{r}{\sigma^2}\exp(-\frac{(r^2+A^2)}{2\sigma^2})I_0\frac{Ar}{\sigma^2}, & (r \geq 0) \\ 0, & (r < 0) \end{cases} \tag{11}$$

The simulation parameters of Rice channel are shown in Table 2.

Table 2. Parameters of Rice channel

Properties	Parameters
Path delays (s)	[0, 30, 70, 90, 110, 190, 410]*(10^{-9})
Average path gains (dB)	[−1, −2, −3, −8, −17.2, −20.8]
Sample rate (s)	1e−8

3 Adaptive Adjustment

A. Modulation of the transmitting signal

According to MCS, the corresponding bit allocation and modulation are performed on subcarriers. The detailed steps are described below (Fig. 3):

1) According to the adaptive modulation scheme, the corresponding convolutional code parameters are selected to encode binary data.
2) Data modulation, such as BPSK. Let the resulting digital information flow be $\mathbf{D} = [D_0, D_1, \ldots, D_n, \ldots, D_{N-1}]$.
3) Carry out corresponding sub-carrier data distribution.

   a) For NC-MC-CDMA, the frequency domain expression of the ith symbol is $\mathbf{S_i} = \lambda D_i \otimes \mathbf{P}_1$, among them, $\mathbf{P}_1 = [p_0, p_1, \ldots, p_n, \ldots, p_{N-1}]$ for the spread spectrum sequence, $\otimes$ for dot product, λ for the normalization factor. Data is placed on the subcarriers labeled 1 in turn, with the remaining subcarriers zeroed.
   b) For NC-OFDM, the frequency domain expression of data is $\mathbf{S} = \lambda\mathbf{D}$. The same as above, data is placed on the subcarriers labeled 1 in turn, with the remaining subcarriers zeroed.

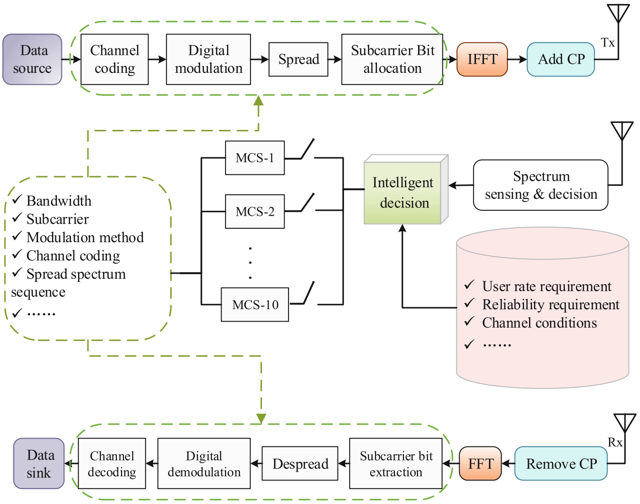

Fig. 3. Cognitive multicarrier communication system model

c) For TDCS, the detailed steps are as below: each user uses the pseudo-random sequence generator to generate the random bit sequence respectively, and then generates the corresponding pseudo-random sequence $\mathbf{P} = \{e^{jm_0}, e^{jm_1}, \ldots, e^{jm_n}, \ldots, e^{jm_{N-1}}\}$, according to the phase mapping diagram. m_n represents the phase of the nth element of the random phase sequence. The pseudo-random sequence for each user is separately multiplied by a utility sequence for each element to get the Fundamental Modulation Waveform (FMW). Its frequency domain expression is $\mathbf{B} = \lambda \mathbf{AP} = \lambda[A_0 e^{jm_0}, A_1 e^{jm_1}, \ldots, A_n e^{jm_n}, \ldots, A_{N-1} e^{jm_{N-1}}]$. In cyclic code shift keying (CCSK) module, $\log_2 N$ bits of data are taken every time to be converted into decimals, and the cyclic shift of $\mathbf{s}$ units of FMW is performed in time domain. For the ith symbol, the frequency-domain expression is $\mathbf{S_i} = [B_0 e^{\frac{j2\pi d\cdot 0}{N}}, B_1 e^{\frac{j2\pi d\cdot 1}{N}}, \ldots, B_k e^{\frac{j2\pi d\cdot k}{N}}, \ldots, B_{N-1} e^{\frac{j2\pi d\cdot (N-1)}{N}}]$.

4) Convert the above signal into a time-domain signal through IFFT module, and then add a cyclic prefix (CP) to each symbol.
5) Finally, send the signal through the transmission module.

B. Data processing at the receiving terminal

1) Receive the signal and complete the channel estimation, and remove the cyclic prefix of the acquired signal. Then obtain frequency-domain signal through the FFT module.
2) According to the electromagnetic characteristics of the external environment, spectrum characteristics of all regions are detected, and the spectrum perception results are compared with the pre-set threshold to generate the spectrum utility sequence.
3) Extract data of each corresponding position marked as 1 in spectrum utility sequence.

4) Perform adaptive demodulation. NC-MC-CDMA carries out related demodulation according to its spread spectrum code. NC-OFDM carries out digital demodulation directly. For TDCS, the specific steps are as follows: (i) Multiply the spectral utility sequence and the pseudo-random sequence of the user, and take the conjugate of the product. (ii) Multiply the data obtained in step 3. (iii) Carry out IFFT operation to extract the real part. (iv) Perform peak search, and output the peak position information as demodulation data.
5) Finally, the decimal demodulation data is converted into binary data, and the demodulation result is obtained.

4 Simulation Results

Considering transmission performance and anti-jamming capability, TDCS, NC-MC-CDMA, and NC-OFDM are chosen as the alternative data modulation systems. CCSK is selected as the digital modulation mode in TDCS. BPSK and 8PSK are selected as the digital modulation modes in NC-MC-CDMA and NC-OFDM. And the convolutional codes of 1/2 code rate and 2/3 code rate are selected as the channel encoding modes. Thus 10 fixed Modulation and Coding Schemes (MCS) are obtained, which are shown in Table 3.

Table 3. MCS parameters

Modulation and coding scheme	System	Modulation	Convolutional code
MCS-1	NC-MC-CDMA	BPSK	1/2
MCS-2	NC-MC-CDMA	BPSK	2/3
MCS-3	NC-MC-CDMA	8PSK	1/2
MCS-4	NC-MC-CDMA	8PSK	2/3
MCS-5	TDCS	CCSK	1/2
MCS-6	TDCS	CCSK	2/3
MCS-7	NC-OFDM	BPSK	1/2
MCS-8	NC-OFDM	BPSK	2/3
MCS-9	NC-OFDM	8PSK	1/2
MCS-10	NC-OFDM	8PSK	2/3

The simulation condition is 2048 subcarriers, in which the number of available subcarriers is 1024.

Adaptive modulation parameters are determined according to channel estimation and user requirements. Under different channel conditions, MCS performance will be different. Figure 4, Fig. 5, Fig. 6, Fig. 7, Fig. 8 and Fig. 9 show BER performance of each MCS under SNR and E_b/N_0 in AWGN channel, Rice fading channel and Rayleigh fading channel.

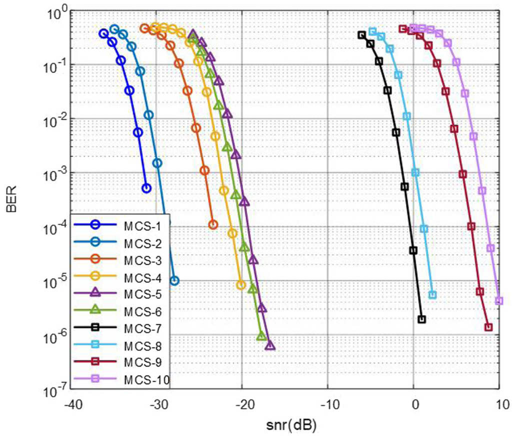

Fig. 4. BER performance under AWGN channel (SNR)

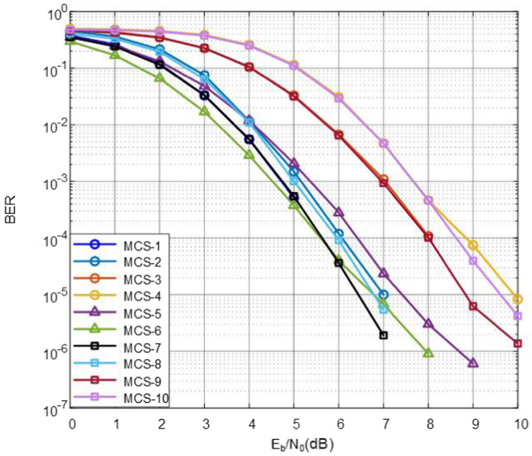

Fig. 5. BER performance under AWGN channel (E_b/N_0)

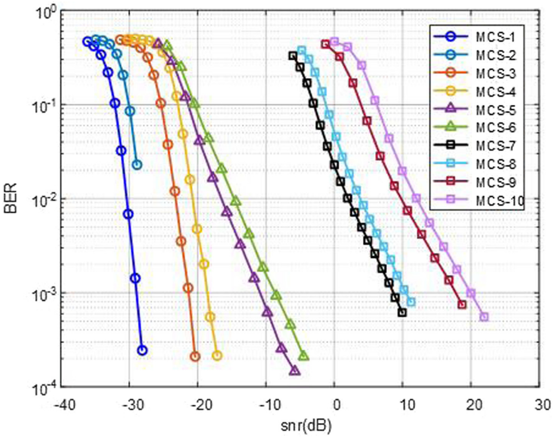

Fig. 6. BER performance under Rice channel (SNR)

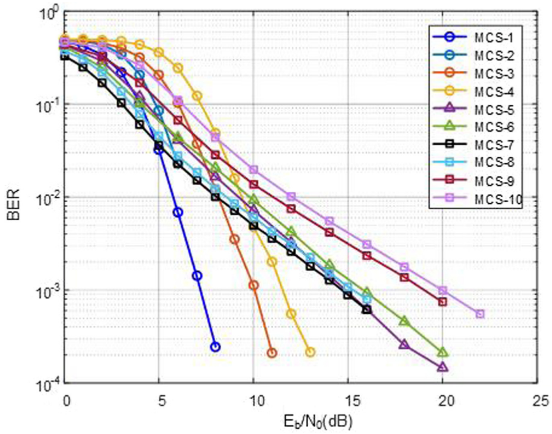

Fig. 7. BER performance under Rice channel (E_b/N_0)

Then, on the premise of achieving 10^{-3} BER, the minimum SNR or E_b/N_0 parameter model required for each MCS is obtained. AWGN channel is analyzed as a typical case. There are SNR and MCS mapping relation in Table 4 and E_b/N_0 and MCS mapping relation in Table 5.

Therefore, the MCS ladder diagram is obtained in Fig. 4 and Fig. 5.

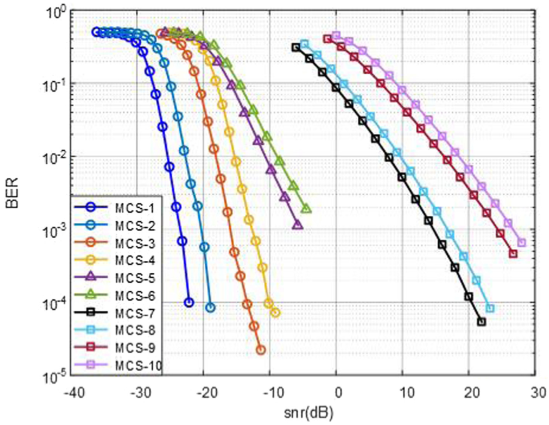

Fig. 8. BER performance under Rayleigh channel (SNR)

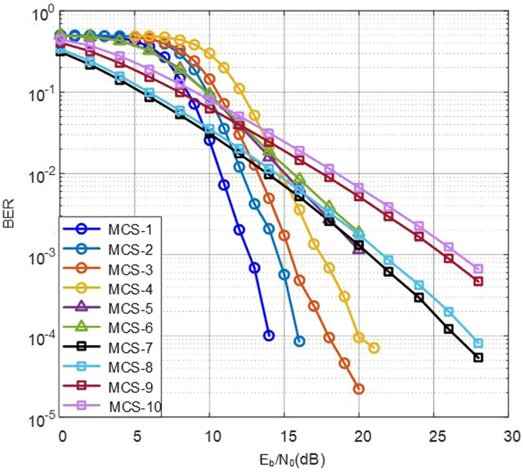

Fig. 9. BER performance under Rayleigh channel (E_b/N_0)

Table 4. SNR and MCS mapping relation

MCS type	SNR
1	[−31.4; −29.6] dB
2	[−29.6; −24.3] dB
3	[−24.3; −22.4] dB
4	[−22.4; −20.3] dB
5	[−20.3; −19.9] dB
6	[−19.9; −1.2] dB
7	[−1.2; 0.3] dB
8	[0.3; 5.8] dB
9	[5.8; 7.7] dB
10	[7.7; −] dB

Table 5. E_b/N_0 and MCS mapping relation

MCS type	E_b/N_0
5	[2.4; 2.8] dB
6	[2.8; 4.8] dB
1, 7	[4.8; 5.0] dB
2, 8	[5.0; 7.0] dB
3, 9	[7.0; 7.7] dB
4, 10	[7.7; −] dB

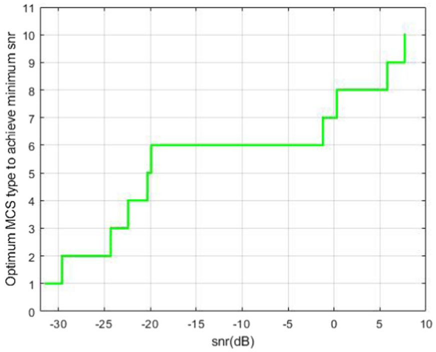

Fig. 10. Optimum MCS type to gain minimum SNR

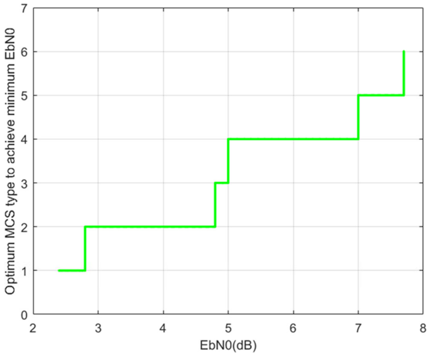

Fig. 11. Optimum MCS type to gain minimum E_b/N_0

In order to satisfy the requirement of BER and obtain a higher transmission rate, fuzzy factor can be used to further classify MCS. In Table 6, the greater the value of fuzzy factor is, the faster the data transfer rate is (Figs. 10 and 11).

Table 6. Fuzzy factor and MCS mapping relation

MCS type	Data transmission rate	Fuzzy factor
1, 2	Slow	1
3, 4, 5, 6	A bit slow	2
7, 8	Fast	3
9, 10	Very fast	4

Taking the above factors into consideration, the optimal MCS can be determined. The decision steps of other channels are the same as above.

5 Conclusion

For a complex and changing environment, the communication quality is unstable when adopting the traditional single communication system. The adaptive communication system proposed in this paper can flexibly respond to changes in environments, dynamically change MCS through channel estimation results, and achieve transmission rate maximization without sacrificing BER. The utilization of system resources can be improved and higher system throughput and capacity can be obtained.

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