Comprehensive Study on Coded Modulation Schemes for Future Communication

Longzhou Liu
School of Information and Communication Engineering. Beijing University of Posts and Telecommunications Beijing, China 100876
longzhou@tju.edu.cn

Abstract. In the future communication technology standards, wireless communication in high mobility scenes is extremely important, but the fast fading of the channel and the Doppler frequency shift caused by high-speed mobile will seriously affect the overall performance of the system. The communication performance indicators such as bit error rate (BER), computational complexity and transmission capacity will degrade. This paper introduces several coded modulation schemes of joint coding modulation diversity (JCMD), orthogonal time-frequency space (OTFS) modulation and space-frequency block code (SFBC), and uses bit interleaved coded modulation (BICM) as a reference for comparison. The simulation results show that the JCMD scheme has the best block error rate (BLER) performance under different moving speed and code rate conditions. And JCMD has strong robustness, can achieve large performance gains even under the conditions of high speed and high code rate.

1. Introduction (Heading 1)
With the development of high speed railway (HSR) systems, driverless cars, and Internet of Vehicles, and further requirements are also imposed on wireless communication technologies in high-speed mobile scenes. In the 5th generation (5G) mobile communication system, there are three typical application scenarios: enhanced Mobile BroadBand (eMBB), massive Machine Type Communications (mMTC), and Ultra-Reliable and Low Latency Communications (URLLC) [1]. The maximum moving speed of 5G system under nominal quality of service (QoS) conditions can reach 500km/h [2]. Therefore, high mobility will be one of the important goals of future mobile communication systems. In Orthogonal Frequency Division Multiplexing (OFDM) system, the fast fading of the channel caused by high-speed will greatly reduce the accuracy of channel estimation, and the accompanying Doppler frequency shift caused will cause Inter-Carrier Interference (ICI), which seriously affects the overall performance of the communication system [2]. So, designing a robust coded modulation scheme suitable for high-speed communication scenarios is particularly important for future requirements.

In recent years, a lot of research work shows that high mobility communication faces challenges such as high penetration loss, fast switching, and Doppler Effect [3]. The Bit-Interleaved Coded Modulation (BICM) techniques introduced in [4] has become a mature coded modulation technology widely used in communication standards, which can increases the time-diversity in fading channels. Based on the principle of space-time block code (STBC), the literature [6] applies the idea of Alamouti coding to the frequency domain, encodes the subcarriers in each OFDM symbol, and obtains
the space-frequency block code (SFBC), which can overcome the frequency selectivity fading and achieve good performance in a fast fading channel environment. The Orthogonal Time Frequency and Space (OTFS) modulation scheme proposed in [8] introduces a kind of modulation technique in delay-Doppler domain, which can effectively eliminate the influence of fast fading caused by high-speed mobile. The OTFS system can maintain high reliability and throughput under high speed. The joint coding and modulation (JCMD) scheme proposed in [11], can optimize with channel coding, modulation, and interleaving. Compared to BICM, JCMD can obtain great time diversity, frequency diversity, and modulation diversity, which can achieve greater performance gains. Meanwhile, JCMD has strong robustness in high-speed mobile scenarios.

This paper mainly discusses the performance of several coding modulation schemes described above in high mobility scenarios. Based on link-level simulation results under different code rates and moving speeds, block error rate (BLER) is used as a performance indicator to evaluate system performance.

The remainder of this paper describes the technical principles and simulation results of several coded modulation schemes. In Section II, the system model and principle of BICM, JCMD, OTFS and SFBC will be introduced. The Section III will show the simulation results and performance comparison of various coded modulation schemes under different velocity and code rate conditions. The Section IV will summarize evaluation conclusions for these coded modulation schemes.

Notations: Throughout the paper, the matrix and the vector will be denoted by boldface uppercase and boldface lowercase, respectively. The superscripts $^*$, $^H$ and $^{-1}$ denotes conjugate operation, conjugate transposition and inverse of matrix, respectively.

2. System model
In this section, algorithm principles and key features of four coded modulation schemes will be discussed and compared comprehensively.

2.1. Bit-Interleaved Coded Modulation
As a mainstream coded modulation technology, Bit-Interleaved Coded Modulation (BICM) has been widely used in Long Term Evolution (LTE) systems. BICM applies interleaving technology to binary codes, which can achieve larger Hamming distances and effectively resist channel fading.

As the system structure shown in Fig. 1, the transmitting end performs bit interleaving after FEC encoding, and then modulates binary codes into QAM modulated symbols. The QAM modulated symbols are mapped to time-frequency resources and then transmitted after undergoing OFDM modulation. In the receiver, the soft bit information is de-interleaved after QAM demodulation and then decoded by the FEC decoder. According to simulation results in [8], BICM schemes perform very well and can obtain advantages in fast fading channels.

2.2. Space-Frequency Block Code
The essence of the space-time block code (STBC) scheme described in [6] is that the same information is orthogonally encoded and transmitted from two antennas. The receiver can distinguish the two independent signals and obtain the diversity gain only by linear combination. Based on this idea, space-frequency block code (SFBC) can be implemented between different sub-carriers of the same OFDM
symbol according to the principle of Alamouti coding. After that, the frequency diversity and spatial
diversity can be obtained at the same time, and the channel fast fading can be well restrained.

![Fig. 2 SFBC of OFDM system block diagram](image)

As shown in Fig. 2, considering a 2×2 Multiple-Input Multiple-Output (MIMO) system, at the
transmitting end, the QAM modulated symbols are allocated to the time-frequency resource grid, and
the sequence in the nth OFDM symbol block is defined as:

$$x(n) = [x_0(n), x_1(n), \ldots, x_{N_c-2}(n), x_{N_c-1}(n)]^T$$  \hspace{1cm} (1)

Where $N_c$ is the length of modulation symbols in the nth OFDM symbol block. According to
Alamouti coding scheme, the transmission sequence of the two transmission antennas can be
expressed as:

$$\begin{align*}
x_1(n) &= [x_0(n), -x_1(n), \ldots, x_{N_c-2}(n), -x_{N_c-1}(n)]^T \\
x_2(n) &= [x_1(n), x_0(n), \ldots, x_{N_c-1}(n), x_{N_c-2}(n)]^T
\end{align*}$$  \hspace{1cm} (2)

For convenience of processing, define $x_e(n)$ and $x_o(n)$ as even and odd components of $x(n)$, respectively.

$$\begin{align*}
x_e(n) &= [x_0(n), x_2(n), \ldots, x_{N_c-2}(n)]^T \\
x_o(n) &= [x_1(n), x_1(n), \ldots, x_{N_c-1}(n)]^T
\end{align*}$$  \hspace{1cm} (3)

Further, the space frequency coding matrix can be expressed as:

$$G(n) = \begin{bmatrix} x_e(n) & x_o(n) \\ -x_o(n) & x_e(n) \end{bmatrix}$$  \hspace{1cm} (4)

After the receiver removes CP and achieves FFT transformation, the even and odd components of
the jth receiving antenna's received signal $y_j(n)$ in the frequency domain can be expressed as:

$$\begin{align*}
y_{j,e}(n) &= h_{j,e}(n)x_e(n) + h_{j,o}(n)x_o(n) + z_e(n) \\
y_{j,o}(n) &= -h_{j,e}(n)x_o(n) + h_{j,o}(n)x_e(n) + z_o(n)
\end{align*}$$  \hspace{1cm} (5)

Where $h_{j,e}(n)$ and $h_{j,o}(n)$ respectively represent even and odd components of the frequency
response of the ith transmitting antenna to the jth antenna channel. $z_e(n)$ and $z_o(n)$ represent even
and odd components of additive white Gaussian noise (AWGN) vector $z(n)$ with zero mean and
variance $\sigma^2$, respectively.
If ideal channel estimate can be obtained, the combined successive time signals can be obtained as follows:

\[ \hat{x}_{j,o}(n) = h_{j,i,o}(n)y_{j,i,o}(n) + h_{j,i,e}(n)y_{j,i,e}(n) \]
\[ \hat{x}_{j,e}(n) = h_{j,i,e}(n)y_{j,i,o}(n) - h_{j,i,o}(n)y_{j,i,e}(n) \]  

(6)

\[ \hat{x}_{j,o}(n) \text{ and } \hat{x}_{j,e}(n) \] represent the odd and even components of the combined signal, respectively. Then, the combined results can be used for demodulation and decoding.

2.3. Orthogonal Time Frequency and Space modulation

OTFS modulation is a two-dimensional (2D) modulation scheme of time-frequency Doppler domain, which can make full use of the diversity of time-frequency domain. OTFS modulation establishes the relationship between time-frequency domain and delay-Doppler domain by Symplectic Finite Fourier Transform (SFFT) or Inverse Symplectic Finite Fourier Transform (ISFFT). The time-varying multipath channel in the time-frequency domain can be transformed into a time-invariant 2D convolution channel in the delay-Doppler domain, which can effectively resist the Doppler effects caused by high mobility.

Fig. 3 OTFS mod/demod block diagram

Fig. 3 shows the structure of the OTFS modulation system. At the transmitting end, consider a set of \( N \times M \) Quadrature Amplitude Modulation (QAM) modulated symbols \( x[k,l] \), \( k = 0, \ldots, N-1 \), \( l = 0, \ldots, M-1 \), which are assigned to the 2D resource grid in delay-Doppler domain. The ISFFT of \( x[k,l] \) is as [3]:

\[ X[n,m] = \frac{1}{MN} \sum_{k=0}^{N-1} \sum_{l=0}^{M-1} x[k,l] b_{n,m} \]  

(7)

Where \( b_{n,m} = e^{-j2\pi \frac{mn}{MN}} \) denote 2D basic function, which can modulate QAM symbols into time-frequency domain symbols \( X[n,m] \). Then \( X[n,m] \) is converted into time domain signal by Heisenberg transform as follows:

\[ s(t) = \sum_{n=-M/2}^{M/2} \sum_{m=-N/2}^{N/2} X[n,m] g_n(t-nT) e^{j2\pi \frac{nm}{M}(t-nT)} \]  

(8)

Where \( g_n(t) \) indicates the transmit pulse function. The Heisenberg transform is a generalized representation of the inverse fast Fourier transform (IFFT) transform in OFDM, whose inverse transform is called Wigner transform.
In the receiver, the receiving signal \( Y[n,m] \) in the time-frequency domain can be obtained by Wigner transform as follows:

\[
Y[n,m] = \int g_n(t-nT)r(t)e^{-j2\pi nf(t-nT)}dt
\]  

(9)

Where \( g_n(t) \) indicates the receiving pulse function and \( r(t) \) denotes the receiving signal in time domain. Next, \( Y[n,m] \) will convert into receiving signal \( y[k,l] \) of the delay-Doppler domain as follows:

\[
y[k,l] = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} Y(n,m)h_{k,l}^*(n,m)
\]  

(10)

According to (7)-(10), the matrix form of system transport model can be expressed as:

\[
Y = H(\tau, \nu) \otimes X + V
\]  

(11)

The operator \( \otimes \) denotes 2D circular convolution and \( H(\tau, \nu) \) represents the delay-Doppler domain channel impulse response matrix. \( X, Y \) and \( V \) denotes the data matrix, receiving signal matrix and noise matrix, respectively.

Further, the matrix product of (11) can be expressed as:

\[
vec(Y) = H(\tau, \nu)_{mn}vec(X) + vec(V)
\]  

(12)

Where the operator \( vec(\cdot) \) can convert matrix into vector and \( H(\tau, \nu)_{mn} \) denotes a \( MN \times MN \) circulant matrix. Obviously, the (12) can be seen as a linear system, and minimum mean square error (MMSE) equalizers can be used for linear detection. The detection matrix can be expressed as:

\[
W^H = \left( H(\tau, \nu)^H H(\tau, \nu) + \sigma^2 I_{MN} \right)^{-1} H(\tau, \nu)^H
\]  

(13)

Where \( I_{MN} \) denotes identity matrix and represents the noise variance.

2.4. Joint Coding and Modulation

Multi-dimensional rotational modulation distributes transmitted symbols to different components. When different components are fading through independent channels, the system can obtain signal space diversity. Taking 2D rotational modulation as an example, consider a QAM modulated symbol \( u_j = A + Bj \), and the rotational modulated symbol is represented as \( x_j = X + Y j \). The rotational modulation can be expressed as:

\[
\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix}
\]  

(14)

Where \( \theta \) denotes the rotation angle. If rotation angle is optimal, the system can obtain the maximum modulation diversity. The joint coding and modulation diversity-single input single output (JCMD-SISO) system can be expressed as Fig.4:
In Fig. 4, the QAM modulated symbols are modulated with a certain rotation angle after the bit interleaving. Then these symbols are divided into I (in-phase)-components and Q (quadrature)-components. Let the Q-components pass through time-frequency Q-component interleaving. These new complex constellation points, consisting of the original I-components and interleaved Q-components, is the transmission signal. At the receiving end, the Q-components of the complex sequence are de-interleaved firstly. And then the I-components and the new Q-components are combined into a new complex sequence of received constellation points. In this way, I-components and Q-components of the complex sequence can

Fad through different channels, which can achieve frequency diversity gain for communication system. Considering the previous rotational modulation, the JCMD system can simultaneously acquire frequency diversity and modulation diversity.

In addition to system reliability, a MIMO system can be considered for further improvement of system capacity. The structure of joint coding and modulation diversity-single input single output (JCMD-MIMO) system is shown in Fig. 5. In the JCMD-MIMO system, the transmitted symbols of each antenna are spatially interleaved and spatial Q-components interleaved. Compared to the JCMD-SISO system, the JCMD-MIMO system can fully obtain time diversity, frequency diversity, and space diversity.

Spatial interleaving is a spiral layered coding method, which is to rearrange the A-road signal at a specific moment, and its interweaving rules are as follows:

$$x_{k}^{t} = x_{k'}^{t}, k' = [(k + t - 2) \mod N_{r}] + 1$$ (15)

In (15), $t \in [1, ..., N_{c}]$, $k, k' \in [1, ..., N_{r}]$, $N_{c}$ and $N_{r}$ are number of symbols and antennas, respectively. $x_{k}^{t}$ is the uninterleaved symbol on the $k$th antenna at time $t$, and $x_{k'}^{t}$ is the interleaved symbol on the $k'$th antenna at time $t$.

The spatial Q-component interleaving is to rearrange the Q-component data blocks of $N_{r}$ antennas. Next, the I-components and Q-components of new data block on each antenna are interleaved in the
block. There are two kinds of interleaving rule: cyclic interleaving and reverse interleaving. Consider that the signal vector of the kth antenna is \([i_k, q_k]\), and the rearranged signal vector is \([i_{k'}, q_{k'}]\), where \(i_k\) and \(q_k\) represent I-components and Q-components of data block on the kth antenna, respectively.

The rules for circular interleaving are as follows:

\[
i_{k'} = i_k, k' = k + 1 \\
q_{k'} = q_k, k' = (k + 1)N_i
\]  

(16)

The rules for reverse interleaving are as follows:

\[
i_{k'} = i_k, k' = k \\
q_{k'} = q_k, k' = N_i - k - 1
\]  

(17)

In addition, in order to further eliminate the interference between the antennas, the precoder in Fig.5 can be singular value decomposition (SVD) precoding, so that the I and Q components of the transmitted symbol experience different channel fading.

3. Simulation Results

In order to comprehensively analyze the performance of the coded modulation schemes mentioned in section II, this paper separately simulates SISO system and MIMO system under different moving speeds and different code rate conditions. And BLER is used as performance indicator to compare the performance gain of these coded modulation schemes.

3.1. Single Input Single Output system simulation

The SISO system simulation compares the performance of OTFS, JCMD, and BICM schemes at low speed (30km/h) and high speed (300km/h). Table I lists the simulation parameter settings of the SISO system. Where the length of information bits \(K=288\) corresponds to low code rate \(R=1/2\), New Radio-Low-density Parity-check (NR-LDPC) codes and New Radio-Polar (NR-Polar) codes simultaneously serve as channel coding schemes under this conditions. Where the length of information bits \(K=1200\) corresponds to high code rate \(R=5/6\), NR-LDPC is used as the channel coding scheme at this time. All schemes have the same spectral efficiency and ideal channel estimation.

| Tab. 1 SISO System simulation parameters |
|----------------------------------------|
| Parameters                             | Value                   |
| Carrier frequency                      | 4GHz                    |
| System bandwidth                       | 10MHz                   |
| Carrier spacing                        | 15KHz                   |
| FFT length                             | 1024                    |
| User velocity                          | 3km/h; 300km/h          |
| Modulation type                        | QPSK                    |
| Channel coding                         | NR-Polar; NR-LDPC       |
| Length of information bits \(K\)       | 288bits; 1200bits       |
| Code rate \(R\)                        | 1/2; 5/6                |
| Modulation type                        | QPSK                    |
| Channel type                           | TDL-C-300ns             |
In Fig. 6, the dotted lines and solid lines represent NR-Polar codes and NR-LDPC codes, respectively. For NR-LDPC codes, when the user velocity is 3 km/h, JCMD can achieve 0.35 dB and 0.2 dB SNR gain at target BLER = 0.01 compared with OTFS and BICM, respectively; when the user velocity is 300 km/h, JCMD can achieve 0.7 dB and 0.4 dB SNR gain at target BLER = 0.01 compared with OTFS and BICM, respectively. Therefore, under the conditions of short code length and low code rate, the JCMD scheme has the better performance than other coded modulation schemes. And the performance gain of JCMD increases with the increase of speed compared to BICM. Similarly, when the channel coding scheme is NR-Polar, an approximate conclusion can be drawn. And the curve shows that all schemes have better performance in NR-Polar code encoding under the conditions of short code length. The comparison results show that JCMD can be applied to different moving speeds and coding schemes, and has strong robustness.

As shown in Fig. 7, the dotted lines and solid lines indicate that the user velocities are 30 km/h and 300 km/h, respectively. When the velocity is 30 km/h, JCMD can obtain 2.1 dB and 0.5 dB SNR gain compared with OTFS and BICM respectively. And JCMD can obtain 0.3 dB and 3.1 dB SNR gain compared with OTFS and BICM respectively, at a speed of 300 km/h. Therefore, the JCMD scheme can maintains good performance gain compared with other schemes, and has good robustness in long code length, high code rate, and high speed environment. Combined with previous conclusions drawn from Fig. 6, the results show that the JCMD scheme has better performance and robustness than other coded modulation schemes in the SISO system.
3.2. Multiple-Input Multiple-Output system simulation

The MIMO system simulation compares the performance of OTFS, JCMD, SFBC, BICM schemes under low speed (3km/h) and high speed (300km/h) conditions. Table II lists the simulation parameter settings for the MIMO system. All schemes use NR-LDPC as the channel coding scheme and use ideal channel estimation. The antenna configuration scheme is that two transmitting antennas correspond to two receiving antennas (2T2R) or one transmitting antenna corresponds to two receiving antennas (1T2R). And all schemes have the same spectral efficiency comparison by adjusting the modulation order.

**Tab. 2 MIMO System simulation parameters**

| Parameters                  | Value       |
|-----------------------------|-------------|
| Carrier frequency           | 4GHz        |
| System bandwidth            | 10MHz       |
| Carrier spacing             | 15KHz       |
| FFT length                  | 1024        |
| User velocity               | 30km/h; 300km/h |
| Modulation type             | QPSK        |
| Channel coding              | NR-LDPC     |
| Length of information bits K| 1200bits    |
| Code rate R                 | 5/6         |
| Modulation type             | QPSK        |
| Antenna configuration       | 1T2R; 2T2R  |
| Channel type                | TDL-A-30ns  |

According to the BLER performance of MIMO system shown in Fig.8 (a) and Fig.8 (b), the JCMD 2T2R scheme always outperforms other coded schemes. For user velocity 30km/h, JCMD 2T2R can achieve about 2.6dB and 5.1dB SNR gain at BLER=0.01 compared with SFBC 2T2R and BICM 1T2R, respectively. When the user velocity is 300km/h, JCMD 2T2R can achieve about 2.6dB and 6.4dB SNR gain at BLER=0.01 compared with SFBC 2T2R, BICM 1T2R, respectively. This shows that the JCMD scheme can fully obtain the diversity advantage, maximize the performance gain, and have strong robustness compared with other schemes.

4. Conclusion

Based on the analysis of the simulation results in the previous section, the OTFS can outperform than BICM in SISO system with high code rate and low order modulation. And SFBC performs better than BICM in MIMO system. But compared to other schemes, the JCMD scheme always has best BLER.
performance and stronger robustness under any code rate, channel coding schemes and velocity. Especially in MIMO system, JCMD can achieve great performance gain while improving transmission capacity. Therefore, JCMD is more suitable as a candidate for future coded modulation scheme.

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