

Image Transmission: A Case Study on Combined Scheme of LDPC-STBC in Asynchronous Cooperative MIMO Systems

Shan Ding, Lijia Zhang and Hongming Xu

Abstract—this paper presents a novel scheme which is capable of reducing the error rate and improves the transmission performance in the asynchronous cooperative MIMO systems. A case study of image transmission is applied to prove the efficient of scheme. The linear dispersion structure is employed to accommodate the cooperative wireless communication network in the dynamic topology of structure, as well as to achieve higher throughput than conventional space-time codes based on orthogonal designs. The LDPC encoder without girth-4 and the STBC encoder with guard intervals are respectively introduced. The experiment results show that the combined coder of LDPC-STBC with guard intervals can be the good error correcting coders and BER performance in the asynchronous cooperative communication. In the case study of image transmission, the results show that in the transmission process, the image quality which is obtained by applied combined scheme is much better than it which is not applied the scheme in the asynchronous cooperative MIMO systems.

Keywords—Cooperative MIMO, image transmission, linear dispersion codes, Low-Density Parity-Check (LDPC)

I. INTRODUCTION

THE radio communication techniques develop rapidly because of its convenience. But wireless channel is usually sensitive to the time-varying and multi-path fading, so it has a high bit error rate. Therefore, when the large scale of data is transmitted, the loss and distortion exist inevitably. The problems seem more important for image transmission through wireless channel. Traditionally, we use the error correcting code to lower the BER. However the conventional approach is too complex or it needs strict control information. In this paper, we use a new combined scheme of LDPC-STBC to enhance the image transmission performance. In a multiple-input-multiple-output (MIMO) system, spatial diversity obtains stronger anti-error ability. Theoretically, the error-resilience ability can increase as the increase of antenna number. However, it may not always be practical to accommodate multiple antennas at the mobile nodes in the network, because of the cost, size and other hardware limitations. In recent years, the concept of “cooperative diversity” has been proposed in the papers [1] [2], using the

antenna of other nodes with single ant in the network. The authors developed and analyzed cooperative diversity protocols that combat fading in wireless network, in [3] [4]. In their work, different nodes in the wireless network share their antennas and resource node to create a virtual array. It increases the capacity of system effectively. The space-time block coding (STBC) [5]-[7] techniques provide full spatial diversity in the context of collocated MIMO systems to ensure reliable wireless communications at high rates. But it doesn't have coding gain in communication over fading channels. LDPC code [8] can just to complement the problem. Therefore the concatenation scheme of STBC codes and LDPC codes (STBC-LDPC) was proposed to improve the error rate performance of the STBC in MIMO system [9]. On the basis of others' research, we use the combined coder of LDPC-STBC that achieved in the Rayleigh fading channel to get the good error rate performance in the asynchronous cooperative MIMO system. In practical, there is another problem about propagation delay. The signal from different ants is almost impossible to arrive at the destination node in the mean time. Due to the transmission delay, the inter-symbol interference (ISI) generated. Hence, we use the STBC added with guard intervals to efficiently eliminate the ISI and improve the transmission performance. Because of the increasing demands for wireless applications, the design of efficient communication system for progressive image transmission has recently attracted a lot of interests. The existing works for image delivery over MIMO mainly focus on the fixed MIMO structures, which lacked spatial diversity gain and might be inefficient in fierce fading channel. The combined scheme of LDPC-STBC can acquire not only the coding gain but also the diversity gain. Simulations present that the image encoded by the LDPC-STBC over cooperative MIMO system can be transferred much better. This paper is organized as follow: Section II introduces cooperative linear dispersion codes added the guard intervals in the asynchronous structure. The Section III describes the LDPC coding algorithm in the asynchronous Cooperative system. In the Section IV, the simulation results about the BER are shown. And the section V presents the case study of the scheme we proposed on image transmission. Finally, the section VI is the conclusion of the whole article.

II. COOPERATIVE LINEAR DISPERSION CODES (CLDC)

In general, cooperative schemes contain two phases of transmission, called the broadcast phase and the cooperation

Shan Ding is a associate professor with the Department of Information Science and Engineering, Northeastern University, Liaoning province, China (e-mail: dingshan@ise.neu.edu.cn).

Lijia Zhang is now with the Department of Information Science and Engineering, Northeastern University, Liaoning province, China (e-mail: zlj36524@163.com).

Hongming Xu is now with the Department of Information Science and Engineering, Northeastern University, Liaoning province, China (e-mail: xuhongming28@163.com).

phase. During the cooperative phase, cooperative nodes transmit the coded source information cooperatively, at the same time the space-time code-words are formed. The process as following:

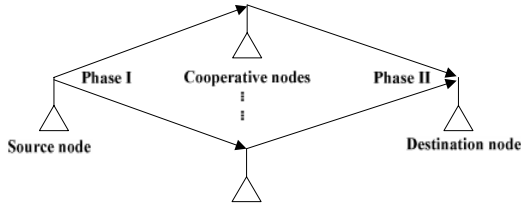


Fig. 1 Cooperative transmission of multiple cooperative nodes

We suppose each cooperative node to process the perfect source information vector $K = [s^1, \dots, s^Q]^T$ containing Q symbols obtained through the broadcast interval. The k th relay ($k=1, \dots, M$) disperses vector K by $S_k = A_k K$, the A_k is the dispersion matrix with dimension $T \times Q$ and the information is distributed among the T channel uses. The transmitted signal is S_k in the cooperative nodes. The space-time code-word C with dimension $M \times T$ as following:

$$C = \begin{pmatrix} S_1^T \\ \vdots \\ S_M^T \end{pmatrix} = \begin{pmatrix} (A_1 K)^T \\ \vdots \\ (A_M K)^T \end{pmatrix} \quad (1)$$

The overall power constraint of $E\{tr(CC^H)\} = T$, and then A_k satisfy $\sum_{k=1}^M tr(A_k A_k^H) = T$. If every cooperative node transmits with the small power, so A_k obeys: $tr(A_1 A_1^H) = \dots = tr(A_M A_M^H) = T/M$. At the destination node receiving the information from the cooperative nodes, the received signal matrix $Y = HC + V$, V is an additive white Gaussian noise process with zero mean and the variance is 1. Matrix H represents the Rayleigh fading channel functions through which Signal from the cooperative nodes to destination node pass. As a result of the different propagation delay from each cooperative node to destination node, the received signal from k th cooperative node is different. Usually pilot signals are used to detect for channel estimations of cooperative nodes in the cooperative system. From the arrival time of the pilot signals, the difference of the propagation delay can be calculated, so the receiver is synchronized to each cooperative node, but the ISI signals are generated for signals transmitted from the remaining nodes.

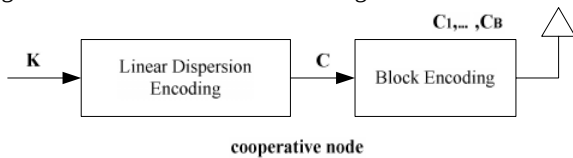


Fig. 2 Encoding in every cooperative node

Fig.2 describes the encoder employed at every cooperative node. The “Linear Dispersion Encoder,” as described on [10], generates codeword matrices C obeying (1). The “Block

Encoder” is introduced as following, more detailed describe, a block of information vectors is $[K_1, \dots, K_B]$, the CLDC [10] encoder generates the B number of code words $[C_1, \dots, C_B]$ based on (1). The “Block Encoder” changes the input B number of code words into T number as follows

$$F_i = [L_i(C_1), \dots, L_i(C_B), 0_D], (i = 1, \dots, T) \quad (2)$$

The $L_i()$ is defined the i^{th} column of a matrix, 0_D denotes a zero matrix with D number of columns serving as guard intervals. Based on the maximum delay difference, the length of guard intervals are equal or greater than the maximum propagation delay $\tau_{\max}$, $D \geq \tau_{\max}$. In the “Block Encoder”, guard intervals are inserted every B block of space-time code words, the effective symbol rate becomes $BQ/T(B+D)$, which approaches the maximum rate Q/T . The rearrangement of equation (2) is necessary, because intra-code-word interference is removed.

The channel response matrix is $H = P[h_1, \dots, h_M]$, P is the node power which is the constant, the received signal for i th transmission block becomes $y_i = HF_i + V_i (i=1, \dots, T)$. To the original code words $[C_1, \dots, C_B]$, the received signals are as following:

$$Y_j = [L_i(y_1), \dots, L_i(y_T)], (j = 1, \dots, B) \\ = HC_j + \sum_{k=2}^M h_k [P_1, P_2] G_k + V_j$$

The G_k is the ISI matrix of the k^{th} cooperative node, and it's caused by the propagation delay at the receiver. The first and second row of G_k is respectively the interference from code-word C_{j-1} and C_{j+1} . P_1 and P_2 are denoted the power of the interference separately.

Based on the matrix row operation, we get the equivalent system matrix:

$$\bar{Y}_j = \bar{H} \bar{\chi} \bar{K}_j + \sum_{k=2}^M \bar{H}_k \bar{\chi}_k \bar{K}_{isi} + \bar{V}_j$$

On the right side of the equation, the first item is the desirable signal, the second item is the ISI signals from the k th node, and the third item is the noise. The channel matrix $\bar{H}$ and dispersion matrix $\bar{\chi}$ are given as following: ($\otimes$ is the Kronecker product and the size of $\bar{\chi}$ is $MT \times MQ$.)

$$\bar{H} = H \otimes I \\ \bar{\chi} = \begin{pmatrix} A_1 & 0 & \dots & 0 \\ 0 & A_2 & \dots & 0 \\ \vdots & 0 & \ddots & \vdots \\ 0 & \dots & \dots & A_m \end{pmatrix}$$

The character of the dispersion matrix $\bar{\chi}$ determine the achievable performance, the challenge of achieving “cooperative diversity” is equivalent to designing the single $\bar{\chi}$ based on [3] [11]. To denote the matrix I is an identity matrix, the ISI matrix $\bar{H}_k$ for the k th node, the dispersion character matrix $\bar{\chi}_k$ and the vector $\bar{K}_{isi}$ denotes the

interference signal from the K_{j-1} and K_{j+1} . They are shown as following: ("0" is a zero matrix with a size of $T \times Q$)

$$\begin{aligned}\bar{H}_k &= \bar{h}_k [P_1, P_2] \otimes I \\ \bar{\chi}_k &= \begin{pmatrix} A_k & 0 \\ 0 & A_k \end{pmatrix} \\ \bar{K}_{isi} &= \begin{pmatrix} K_{j-1} \\ K_{j+1} \end{pmatrix}\end{aligned}$$

The receiver can carry out the linear maximum likelihood (ML) decoding as shown. In addition, the low-complexity sphere decoders designed for STBC can be achieved near ML performance with the lower decoder complexity [12] [13].

$$[K_1, \dots, K_B] = \arg \left\{ \min \left(\left\| \sum_{j=1}^B \left(\bar{Y}_j - \bar{H} \bar{\chi}_j \bar{K}_j - \sum_{k=2}^M \bar{H}_k \bar{\chi}_k \bar{K}_{isi} \right) \right\|^2 \right) \right\}$$

III. LOW-DENSITY PARITY-CHECK CODES

An LDPC code is a linear block code characterized by a sparse parity-check matrix H with low column weight and low row weight. Most methods for designing LDPC codes are based on the random construction that presents the disadvantages of storing and accessing a large parity-check matrix, encoding data, etc [14]. So the different construction of LDPC codes with large girth is used to design the LDPC code without cycles of length 4, in this paper. The design algorithm of the parity-check is as following: We assume that the parity-check matrix is H , column weight is 3 and row weight is v ($v > 3$). Then three sub-matrices D, E, F are designed and combined into matrix H_1 , $H_1 = [D, E, F]$ then transpose H_1 into H_2 , expand H_2 into desired parity-check matrix H using identity matrices and cyclic shift matrices of the identity matrix randomly.

A. Sub-matrix D

The design algorithm of D is as following:

1. Design a matrix D_0 with the dimension $v \times v^2$. Let the first element in every row is 1. So D_0 is as shown:

$$D_0 = \begin{bmatrix} 1 & 0 & 0 & \dots & 0 \\ 1 & \dots & \dots & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & \dots & \dots & 0 \end{bmatrix}_{v \times v^2} \quad (3)$$

2. If the D_0^k represents circularly shift D_0 for k right-shifting steps circularly, then

$$D_1 = D_0^1, D_2 = D_0^2, \dots, D_{v^2-1} = D_0^{v^2-1}$$

3. The matrix D and its dimension are $v^3 \times v^2$

$$D = [D_0, D_1, \dots, D_{v^2-1}]^T$$

B. Sub-matrix E

1. Define a matrix $E_0 = \{0\}_{v \times v^2}$, then $E_0(1,1) = E_0(2,2) = \dots = E_0(v,v) = 1$. For example is as following:

$$E_0 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & 0 & \vdots & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & 1 & 0 & \dots & 0 \end{bmatrix}_{v \times v^2} \quad (4)$$

2. Let $E_1 = [E_0, \dots, E_0]^T$, the number of E_0 included in E_1 is v .

3. The E_1^k represents the circularly right-shift of E_1 for k steps, then $E_2 = E_1^v, E_3 = E_1^{2v}, \dots, E_v = E_1^{(v-1)v}$.

4. Finally, we can get the sub-matrix $E = [E_1, \dots, E_v]$ with dimension $v^3 \times v^2$.

C. Sub-matrix F

The matrix F is as following:

1. Define a matrix F_0 with dimension $v \times v^2$ and every element of F_0 is zero, then $F_0(1,1) = F_0(2,v+1) = \dots = F_0(v, v^2 - v + 1) = 1$. For example is as following and $v=4$:

$$F_0 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}_{v \times v^2} \quad (5)$$

2. Let $F_1 = F_0^1, F_2 = F_0^2, \dots, F_{v-1} = F_0^{v-1}$, where F_0^k represents F_0 with circularly right-shifting k steps.

3. Let $F_v = [F_0, \dots, F_{v-1}]^T$.

4. Let $F = [F_v, \dots, F_v]^T$, there are v copies of F_v in F , so the dimension of F is $v^3 \times v^2$.

We use the sub-matrices D, E, F to define the H_1 , as following :

$$H_1 = \begin{bmatrix} D_0 & E_0 & F_0 \\ \vdots & \vdots & \vdots \\ D_{v-1} & E_0 & F_{v-1} \\ D_v & E_2 & F_0 \\ \vdots & \vdots & \vdots \\ D_{v^2-1} & E_v & F_{v-1} \end{bmatrix}_{v^3 \times 3v^2} \quad (6)$$

So $H_2 = H_1^T$, then the dimension of H_2 is $3v^2 \times v^3$.

D. The parity-check matrix H

1. Define the identity matrix I with dimension $p \times p$.

2. The I^k represents the identity matrix I with circularly right-shifting k steps. $I_1 = I^1, I_2 = I^2, I_{p-1} = I^{p-1}$, then $H_2 = \{I, I_1, I_{p-1}\}$.

3. Exchanging the one time in H_2 by the elements randomly and exchanging zero time by null matrices with the same dimension as I , then we get the parity-check matrix H , its dimension is $3pv^2 \times pv^3$. In the source node, the symbol information gets through the parity-check matrix H , then get the transmitter data with LDPC encoding in the source node as following:

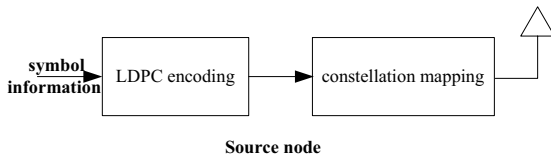


Fig. 3 LDPC coding system in the source node

IV. SIMULATION RESULTS

This section presents the simulation results for our scheme which is the combined code of LDPC-STBC. In the simulation, we use 2 cooperative nodes and one node with only one ant. The channel is the Rayleigh fading channel and the noise is the additive white Gaussian noise with zero mean and the variance is 1. The space-time decoder is ML decoder and the method of LDPC decoder us the sum-product algorithm [15] [16]. The parameters of the simulation are listed in table I.

TABLE I
SIMULATION PARAMETERS

Number of cooperative nodes	2
Number of antenna per-node	1
Period of the symbols	T_s
Propagation delay difference	τ
Modulation	BPSK
LDPC encoder	QC-LDPC without 4 girth
LDPC rate	1/2
Channel	Rayleigh fading channel
Max Doppler frequency	4 Hz
Noise	AWGN the mean is 0, the variance is 1
Detector	ML of Equation
LDPC decoder	The sum-product algorithm [15] [16]

The fig.4 shows the BER performance comparison. BER of the LDPC-STBC coder is better than the Alamouti STBC in the same antennas. So LDPC-STBC coder is proved to be effective in the MIMO systems. The needed parameters of simulation are shown in table I.

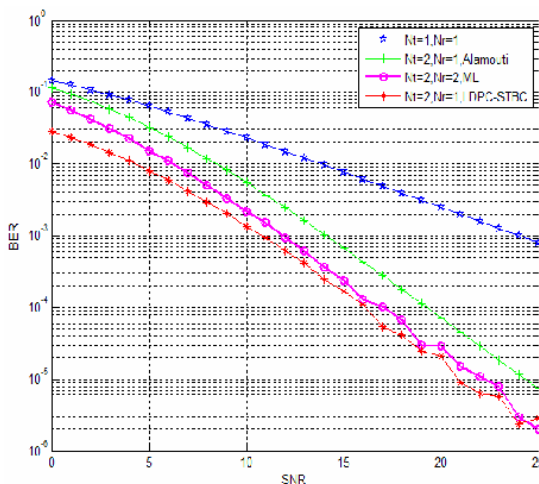


Fig. 4 BER performance comparison of LDPC-STBC and STBC coder without propagation delay in the Rayleigh fading channel

In Fig.5, BER performance of the non-coder shows the character of the asynchronous reception, where the propagation delays are different between two cooperative nodes. From the fig, we get that BER performance is getting worse with the increase of the propagation delay.

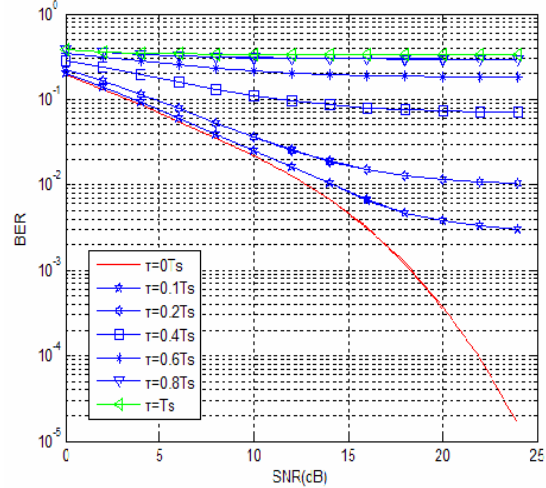


Fig. 5 BER performance comparison of non-coder with different propagation delay in the Rayleigh fading channel

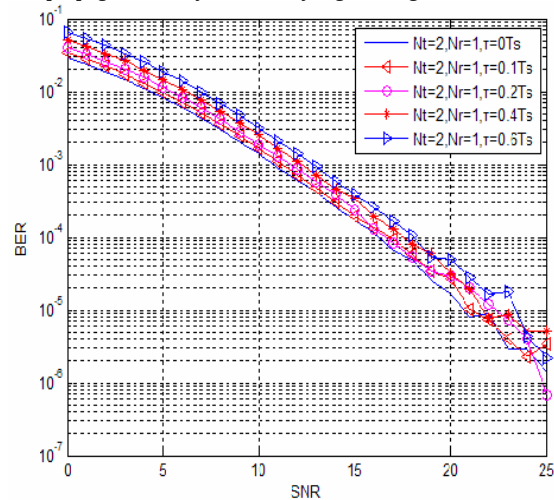


Fig. 6 BER performance comparison of LDPC-STBC with different propagation delay in the Rayleigh fading channel

Fig.6 characterizes the BER of LDPC-STBC with guard intervals are through Rayleigh fading channel in different propagation delay τ . Comparing fig.5, the fig.6 is shown to use guard intervals to combat the propagation delay, and BER is near to the non-propagation in the red line of fig.4.

V. CASE STUDY

In the future wireless communication, the wireless multi-media has been used for image transmission, picture transmission, video transmission and so on. According to the simulation results above, our scheme shows a good

transmission performance. In our case study, we use our scheme of the code to simulate the image transmission of the wireless communication system, then achieving better quality of reconstructed image

Based on the Fig.1, we use the wireless cooperative architecture. The source node gets the two-dimensional image and converts it to a 0-1 status and one-dimensional sequence that is ready to transmit. The TABLE I. shows the needed parameters of the wireless communication simulation.

The Fig.7 demonstrates the transmission process of the image of the simulation. During the processing, the converted into binary digital signal of the image data are BPSK modulate and encoding with our scheme. The middle of the Fig.7 is the transmitting image in the simulation. The whole simulation process uses the combined scheme of LDPC-STBC with guard intervals in asynchronous cooperative MIMO systems.

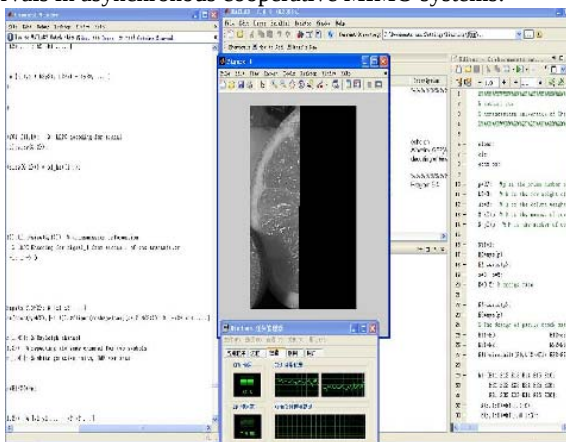


Fig. 7 The process of the image transmission

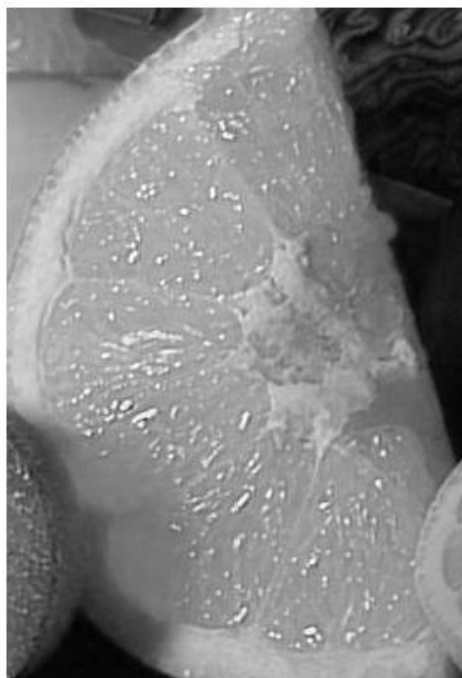


Fig. 8 The original image

In Fig.8, the picture is the original image without any modification.



Fig. 9 image transmission using traditional encoding scheme in the asynchronous structure and SNR=20dB, $\tau=0.1T_s$



Fig. 6 image transmission using the LDPC-STBC with guard intervals in the asynchronous structure SNR=20dB, $\tau=0.1T_s$

The Fig.10 is the image encoded with our combined scheme of the LDPC-STBC with guard intervals in asynchronous structure and the parameter of the communication environment listed in TABLE I. is same as Fig.9. In this

recording process, we make use of the LDPC without girth-4 which can detect the error bits and then correct them effectively. Meanwhile the STBC with guard intervals is employed, and it eliminates the ISI. Consequently, the BER is much lower and the performance is better. Comparing the images, it is easy to see that the second picture distort seriously. However the third picture encoded by the scheme we proposed is reconstructed perfectly. Obviously, our scheme is effective in image transmission.

VI. CONCLUSION

This paper proposes to use the combine of LDPC-STBC in the asynchronous cooperative communication, and applies the scheme to the image transmission. The simulation results separately compare the BER of the traditional coding method with the LDPC-STBC with the guard intervals. The figures show that the transmission performance is better and better. At last, we use the encoding scheme to simulate the image transmission, and compare the images using the different encoding scheme through the fading channel in the asynchronous structure. From the pictures it is easy to see that the image encoded by LDPC-STBC with guard interval gets the better transmission performance.

REFERENCES

- [1] K. C. Liang, X. D. Wang, and I. Berenguer, "Minimum error-rate linear dispersion codes for cooperative relays," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 2143–2157, Jul. 2007.
- [2] T. Cui, F. F. Gao, T. Ho, and A. Nallanathan, "Distributed space time coding for two-way wireless relay networks," *IEEE Trans. Signal Process.*, vol. 57, no. 2, pp. 658–671, Feb. 2009.
- [3] S. Q. Wei, D. L. Goeckel, and M. C. Valenti, "Asynchronous cooperative diversity," *IEEE Trans. Wireless Commun.*, vol. 5, no. 6, pp. 1547–1557, Jun. 2006.
- [4] J. Laneman and G. Wornell, "Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inform. Theory*, vol. 49, pp. 2415–2425, Oct. 2003.
- [5] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.
- [6] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inf. Theory*, vol. 45, no. 5, pp. 1456–1467, Jul. 1999.
- [7] B. Hassibi and B. M. Hochwald, "High-rate codes that are linear in space and time," *IEEE Trans. Inf. Theory*, vol. 48, no. 7, pp. 1804–1824, Jul. 2002.
- [8] R. G. Gallager, "Low density parity check codes," *IRE Trans. Inform. Theory*, vol. 8, no. 1, pp. 21–28, Jan. 1962.
- [9] H. Futaki and T. Ohtsuki, "LDPC-based space-time transmit diversity schemes with multiple transmit antennas," *IEEE Proc. VTC Spring 2003*, vol. 4, pp. 2589–2593, April 2003.
- [10] R. W. Heath, Jr. and A. Paulraj, "Linear dispersion codes for MIMO systems based on frame theory," *IEEE Trans. Signal Process.*, vol. 50, no. 10, pp. 2429–2441, Oct. 2002.
- [11] Y. Shang and X. G. Xia, "Limited-shift-full-rank matrices with applications in asynchronous cooperative communications," *IEEE Trans. Inf. Theory*, vol. 53, no. 11, pp. 4119–4126, Nov. 2007.
- [12] E. Viterbo and J. Boutros, "A universal lattice code decoder for fading channels," *IEEE Trans. Inf. Theory*, vol. 45, no. 5, pp. 1639–1642, Jul. 1999.
- [13] S. D. Howard, S. Sirianunpiboon, and A. R. Calderbank, "Low complexity essentially maximum likelihood decoding of perfect space-time block codes," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process.*, Taipei, Taiwan, Apr. 2009, pp. 2725–2728.
- [14] Fan J, Xiao Y, Kim K. Design LDPC codes without cycles of length 4 and 6[J]. *Research Letters in Communications*, Volume 2008(2008), Article ID 354137, doi:10.1155/2008/354137.
- [15] D. J. C. MacKay, "Good error-correcting codes based on very sparse matrices," *IEEE Transactions on Information Theory*, vol. 45, no. 2, pp. 399–431, 1999.
- [16] R. Lucas, M. P. C. Fossorier, Y. Kou, and S. Lin, "Iterative decoding of one-step majority logic decodable codes based on belief propagation," *IEEE Transactions on Communications*, vol. 48, no. 6, pp. 931–937, 2000.
- [17] J. Hou, P. H. Siegel, and L. B. Milstein, "Performance analysis and code optimization of low density parity-check codes on Rayleigh fading channels," *IEEE JSAC*, vol. 19, no. 5, pp. 924–934, May 2001.
- [18] N. Wu and H. Gharavi, "Asynchronous Cooperative MIMO Systems using A Linear Dispersion Structure," *IEEE Transactions on Vehicular Technology*, vol. 59, No. 2, pp. 779–787, February 2010.

Shan Ding received the B. E. degree in Department of Computer Science and Application in Northeastern University, Shenyang, China, in 1989, and the M. E. degree in Department of Electrical and Computer Engineering from Nagoya Institute of Technology of Japan, in 1999. He received his Ph.D. degree in computer science from Nagoya Institute of Technology in 2003. From Sept. 2004 to Aug. 2006, he was a visiting postdoctoral researcher in the Department of Information Engineering, the Graduate School of Information Science, Nagoya University, where he was financially supported by JSPS Postdoctoral Fellowship for Foreign Researchers. He is currently an Associate Professor in College of Information Science and Engineering, Northeastern University, P. R. China. His current research interests include algorithm design and analysis, real-time scheduling theory, and embedded system design. Email: dingshan@ise.neu.edu.cn