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Multi-User Chaos MIMO-OFDM Scheme for Secure Mobile Communications

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Abstract– For the achievement of smart community which comprehensively controls social infrastructures, it is expected that wireless multihop networks are utilized. In the wireless multihop transmission, personal data are forwarded by the third person so that the wireless security is indispensable. In current wireless systems, the security is ensured by encryption at the upper layers. However, it tends to need a complex protocol or processing which is not suitable for the multihop protocol with a simple manner. To solve it, we have proposed a chaos multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) scheme having physical-layer encryption and channel-coding abilities. However, the multiuser transmission which is essential for efficient multihop network has not been considered yet. Therefore, in this paper, we propose a multiuser (MU) chaos MIMO-OFDM scheme which achieves the physical-layer security and channel-coding gain in MU-MIMO transmission. The improved performances are shown through computer simulations.

1. Introduction

In wireless communications, frequency is a limited resource whose spectral efficiency is always required to be improved, and it is not practical to attempt to expand the frequency band per one user for higher-capacity transmissions. A multiple-input multiple-output (MIMO) technique in which multiple antennas in both transmitter and receiver simultaneously communicate using a same frequency band can increase a channel capacity without expanding the frequency band, and is drawing much attentions. The transmission rate can be increased in proportion to the minimum numbers of transmit and receive antennas. However, in the mobile terminals such as smart phone, the number of antennas and the signal processing ability are limited by the restriction of package and battery sizes, and the capacity enhancement of MIMO is restricted by the mobile terminal limitation even if the base station can prepare a lot of antennas. To address this problem, a multiuser MIMO (MU-MIMO), a kind of advanced MIMO techniques, has been proposed in which a spatial multiple access can be achieved and the system capacity is increased even with a single antenna of mobile terminals, and many improved MU-MIMO systems are studied [1-4]. In MU-MIMO, a beamforming is conducted at the transmitter to avoid making the signals for multiple receivers interfered each other. In particular, the transmitter adjust the transmit weights multiplied to each transmit symbol of MIMO according to the channel matrix between the transmitter and all receivers so as to make the each user's signal orthogonal. By this orthogonal beamforming, the interference-free simultaneous transmission is achieved.

On the other hand, along with the development of wireless technologies, a smart community system has been developed with the use of wireless multihop transmission, e.g., smart meters. In those wireless multihop transmissions, personal data are transmitted via third person's terminal, and thus, ensuring the security is indispensable. Usually the encryption is conducted with the upper-layer protocols. However, complicated processes with an increased complexity are needed when the complicated secure protocol is installed in implementation. To solve this problem, we have proposed a MIMO multiplexing transmission with a physical-layer security called chaos MIMO (C-MIMO) in [5]. By ensuring the physical-layer security the upper-layer secure protocols can be omitted and the complexity increase can be restricted. In C-MIMO, the modulated signals are generated utilizing deterministic and irregular characteristics of chaos, introduced by the principle of chaos communication. In addition, a rate-one channel coding is conducted by using chaos signals correlated with transmit bits. Hence, the physical-layer security and channel coding gain are obtained in tradeoff with the decoding search increase. As stated above, the security has to also be ensured in wireless multiple access network and MU-MIMO with the physical-layer security is effective in terms of multiple-access scheme, spectral efficiency, and secure protocol. However, the application of C-MIMO into MU-MIMO has not been considered yet. Therefore, in this paper, we propose a multiuser chaos MIMO-orthogonal frequency division multiplexing (OFDM) scheme enabling multiuser transmission with the physical-layer security and channel coding gain by applying C-MIMO into MU-MIMO environments.

In the following, the chaos-MIMO-OFDM transmission scheme and the proposed MU-C-MIMO-OFDM scheme are introduced in Section 2 and 3. The numerical results in which the security are ensured and the coding gain is improved according to the number of users are shown in Section 4 and the conclusions are drawn in Section 5.

2. Chaos-MIMO-OFDM System

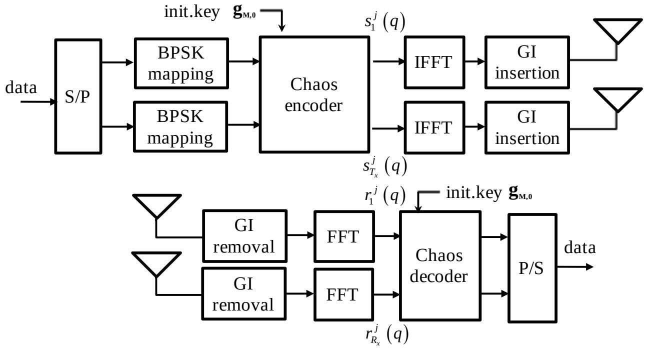

Fig. 1 System block diagram of chaos MIMO-OFDM.

Fig. 1 shows the baseband system model of C-MIMO-OFDM [6] where T_x and R_x are the numbers of transmit and receive antennas, respectively. The chaos encoder and decoder are inserted into the conventional MIMO-OFDM. The variables in the figure are introduced in the following subsections.

2. 1 Transmit and Receive Symbols

In the C-MIMO-OFDM, the transmit data in one OFDM frame is denoted by the complex vector as

$$\mathbf{d} = \{d_0, \cdots, d_{TxN-1}\} \quad (1)$$

where N is number of subcarriers. The block transmission is adopted to obtain the channel coding gain. When B is defined as the number of chaos block length, j-th data block is given from (1) as

$$\mathbf{d}^j = \{d_0^j, \cdots, d_t^j, \cdots, d_{TxB-1}^j\} \quad (2)$$

where $0 \le j \le N/B-1$. Then, the complex chaos vector corresponding to the data block is prepared as

$$\mathbf{c} = \{c_0, \cdots, c_t, \cdots, c_{TxB-1}\} \quad (3)$$

and the multiplied vector at each element

$$\begin{aligned}\mathbf{s}^j &= \mathbf{c} * \mathbf{d}^j = \{c_0 d_0^j, \cdots, c_t d_t^j, \cdots, c_{T_xB-1} d_{T_xB-1}^j\} \\ &= \{s_0^j, \cdots, s_t^j, \cdots, s_{T_xB-1}^j\}\end{aligned} \quad (4)$$

is the transmit symbol at j-th block where each element is allocated to different subcarrier of OFDM and the generation method of $\mathbf{c}$ is described in subsection 2.3. The transmit sequence of j-th block from l-th MIMO transmit antenna is defined as

$$\begin{aligned}\mathbf{s}_l^j &= \{s_{B(l-1)}^j, \cdots, s_{Bl-1}^j\} \\ &= \{s_l^j(0), \cdots, s_l^j(q), \cdots, s_l^j(B-1)\}\end{aligned} \quad (5)$$

where $1 \le l \le T_x$, then l-th antenna transmits the sequence of

$$\mathbf{s}_\mathbf{l} = \{\mathbf{s}_l^0, \cdots, \mathbf{s}_l^j, \cdots, \mathbf{s}_l^{N/B\text{-}1}\} \quad (6)$$

Similarly to (5), the receive sequence is defined by

$$\mathbf{r}_m^j = \{r_m^j(0), \cdots, r_m^j(q), \cdots, r_m^j(B-1)\} \quad (7)$$

where m is the number of receive antenna and $1 \le m \le R_x$.

2.2 Maximum Likelihood Sequence Estimation in Decorder

Let's consider the transmit and receive vectors of q-th symbol $(0 \le q \le B-1)$ in j-th block as

$$\mathbf{s}^{j,q} = \left[s_1^j(q) \cdots s_{T_x}^j(q)\right]^{\mathrm{T}}$$

$$\mathbf{r}^{j,q} = \left[r_1^j(q) \cdots r_{R_x}^j(q)\right]^{\mathrm{T}}$$

where T is the matrix transpose. When the channel matrix between the transmitter and the receiver at q-th symbol (subcarrier) at j-th block is given by

$$\mathbf{H}^{j,q} = \begin{bmatrix} H_{11}^j & \cdots & H_{1T_x}^j \\ \vdots & \ddots & \vdots \\ H_{R_x1}^j & \cdots & H_{R_xT_x}^j \end{bmatrix} \quad (8)$$

Then, the decoded sequence $\hat{\mathbf{s}}^j$ at j-th block can be obtained by the maximum likelihood sequence estimation (MLSE) as

$$\hat{\mathbf{s}}^j = \arg\min_{\mathbf{s}^j} \sum_{q=0}^{B-1} \left\| \mathbf{r}^{j,q} - \mathbf{H}^{j,q}\mathbf{s}^{j,q} \right\| \quad (9)$$

Thus, the joint block decoding in term of chaos decoding and MIMO detection is conducted.

2. 3 Generation of Chaos Symbols

The generation method of chaos symbols in (3) is described. To obtain the channel coding gain the chaos symbols are generated with correlated to the data vector of (2). t-th chaos symbol c_t of (3) is generated by

$$c_t = \exp\left\{ j2\pi \tan^{-1}\left(\mathrm{Im}[s_t] / \mathrm{Re}[s_t]\right)\right\}$$

Here, $0 \le t \le T_xB-1$ and s_t is a pseudo random Gaussian symbol given by

$$s_t = \frac{1}{M}\sum_{i=0}^{M-1}\left\{\left(\mathrm{Re}[g_{ti}] + \mathrm{Im}[g_{ti}]\right)\exp\left(j8\pi\left[\mathrm{Re}[g_{ti}] - \mathrm{Im}[g_{ti}]\right]\right)\right\}$$

where g_{ti} is i-th of M chaos element symbols at index t. M is the number of chaos element symbols to make s_t Gaussian symbols by central limit theorem. Because c_t is a unit vector having random phase, the encryption of $\mathbf{d}^j$ in (4) is executed by the phase shift operation and the signal power of $\mathbf{s}^j$ is not changed by $\mathbf{c}$. Here, let M chaos element symbols denoted as

$$\mathbf{g}_{M,t} = \left(g_{t0}, \cdots, g_{t(M-1)}\right), \quad 0 < \mathrm{Re}[g_{ti}], \mathrm{Im}[g_{ti}] < 1 \quad (10)$$

and its initial vector is denoted by

$$\mathbf{g}_{M,0} = \left(g_{00}, \cdots, g_{0(M-1)}\right)$$

This $\mathbf{g}_{M,0}$ becomes the key vector shared by the transmitter and the receiver. Thus, the proposed C-MIMO scheme is a type of common key encryption. The chaos element symbols of (10) are iteratively calculated by the following equations of (11) - (14).

$$x_0 = \begin{cases} \mathrm{Re}\left[g_{(t-1)i}\right] & (b_m = 0) \\ 1-\mathrm{Re}\left[g_{(t-1)i}\right] & \left(b_m = 1, \mathrm{Re}\left[g_{(t-1)i}\right] > 1/2\right) \\ \mathrm{Re}\left[g_{(t-1)i}\right] + 1/2 & \left(b_m = 1, \mathrm{Re}\left[g_{(t-1)i}\right] \le 1/2\right) \end{cases} \quad (11)$$

$$y_0 = \mathrm{Im}\left[g_{(t-1)i}\right] \quad (12)$$

$$x_{l+1} = 2x_l \bmod 1, \quad y_{l+1} = 2y_l \bmod 1 \quad (13)$$

$$\mathrm{Re}\left[g_{ti}\right] = x_{BO+b_m}, \quad \mathrm{Im}\left[g_{ti}\right] = y_{BO+b_m} \quad (14)$$

Here, BO is a positive constant, $m = \left(t + T_x B - 1\right) \bmod T_x B$, and b_m is the transmit bit corresponding m-th data symbol d_m^j at j-th block. Thus, the chaos symbols are correlated with the transmit bits in the same block and the convolutional channel coding effect is obtained. Eq. (13) is the Bernoulli shift map and it makes g_{ti} chaotic.

3. Proposed MU-C-MIMO-OFDM System

Fig. 2 shows the system block diagram of the proposed MU-C-MIMO-OFDM. Based on C-MIMO-OFDM described in Section 2, MU-MIMO architecture is added and the multiuser transmission is achieved. Each user has the different key $\mathbf{g}_{M,0}$ from each other but shares it only with the transmitter, and then, the secure transmission with channel coding gain for each user is obtained.

3. 1 Transmitter and Receiver Design

Consider the downlink MU-C-MIMO-OFDM. Let U as the number of users $\left(1 \le k' \le U\right)$, R'_x as the number of receive antennas per one user, and $T_x = UR'_x$ as the number of transmit antennas. Then, the transmit sequence $\mathbf{S}^{j,n}$ in j-th block at n-th subcarrier is defined by

$$\mathbf{S}^{j,n} = \left[S_{1,1} \cdots S_{1,R'_x} \cdots S_{k',1} \cdots S_{k',R'_x} \cdots S_{U,1} \cdots S_{U,R'_x}\right]^{\mathrm{T}}$$
$$= \left[\left(\mathbf{S}_1^{j,n}\right)^{\mathrm{T}} \cdots \left(\mathbf{S}_{k'}^{j,n}\right)^{\mathrm{T}} \cdots \left(\mathbf{S}_U^{j,n}\right)^{\mathrm{T}}\right]^{\mathrm{T}}$$

where $S_{k',1}$ is the transmit symbol to k'-th user's first receive antenna and the vector $\mathbf{S}_{k'}^{j,n}$ is the transmit sequence to user k' as

$$\mathbf{S}_{k'}^{j,n} = \left[S_{k',1} \cdots S_{k',R'_x}\right]^{\mathrm{T}}$$

The receive sequence of k'-th user is defined by

$$\mathbf{R}_{k'}^{j,n} = \left[R_{k',1} \cdots R_{k',R'_x}\right]^{\mathrm{T}}$$

and the sequence of all users $\mathbf{R}_{k'}^{j,n}$ is given by

$$\mathbf{R}^{j,n} = \left[\left(\mathbf{R}_1^{j,n}\right)^{\mathrm{T}} \cdots \left(\mathbf{R}_{k'}^{j,n}\right)^{\mathrm{T}} \cdots \left(\mathbf{R}_U^{j,n}\right)^{\mathrm{T}}\right]^{\mathrm{T}}$$
$$= \left[R_{1,1} \cdots R_{1,R'_x} \cdots R_{k',1} \cdots R_{k',R'_x} \cdots R_{U,1} \cdots R_{U,R'_x}\right]^{\mathrm{T}}$$

Then, this $\mathbf{R}^{j,n}$ is obtained by

$$\mathbf{R}^{j,n} = \mathbf{H}^{j,n}\mathbf{V}^{j,n}\mathbf{S}^{j,n} = \tilde{\mathbf{H}}^{j,n}\mathbf{S}^{j,n} \quad (15)$$

where $\mathbf{V}^{j,n}$ is precoding matrix in j-th block at n-th subcarrier and $\tilde{\mathbf{H}}^{j,n}$ is block diagonal matrix. By multiplying the precoding matrix $\mathbf{V}^{j,n}$ to the transmit vector $\mathbf{S}^{j,n}$, the inter-user interference is eliminated. The derivation of $\mathbf{V}^{j,n}$ is described in the next subsection. Eq. (15) can be denoted by the matrix form as

$$\begin{bmatrix} \mathbf{R}_1^{j,n} \\ \vdots \\ \mathbf{R}_{k'}^{j,n} \\ \vdots \\ \mathbf{R}_U^{j,n} \end{bmatrix} = \begin{bmatrix} \tilde{\mathbf{H}}_1^{j,n} & & & & \mathbf{0} \\ & \ddots & & & \\ & & \tilde{\mathbf{H}}_{k'}^{j,n} & & \\ & & & \ddots & \\ \mathbf{0} & & & & \tilde{\mathbf{H}}_U^{j,n} \end{bmatrix} \begin{bmatrix} \mathbf{S}_1^{j,n} \\ \vdots \\ \mathbf{S}_{k'}^{j,n} \\ \vdots \\ \mathbf{S}_U^{j,n} \end{bmatrix} \quad (16)$$

$$\mathbf{R}_{k'}^{j,n} = \tilde{\mathbf{H}}_{k'}^{j,n}\mathbf{S}_{k'}^{j,n}$$

where $\tilde{\mathbf{H}}_{k'}^{j,n}$ is $R'_x \times R'_x$ equivalent channel matrix for user k'.

3. 2 Derivation of Precoding Matrix

First, $T_x \times R'_x$ precoding matrix $\hat{\mathbf{V}}_{k'}^{j,n}$ for k'-th user in j-th block at n-th subcarrier is derived [7, 8]. When $\mathbf{H}_k^{j,n}$ is $R'_x \times T_x$ channel matrix between the transmitter and k-th user, $\hat{\mathbf{V}}_{k'}^{j,n}$ has to satisfy

$$\mathbf{H}_k^{j,n}\hat{\mathbf{V}}_{k'}^{j,n} = \mathbf{0}, \quad \left(k' \ne k\right)$$

Next, $\left(U-1\right)R'_x \times T_x$ subchannel matrix of all users except k'-th user is defined by

$$\hat{\mathbf{H}}_{k'}^{j,n} = \left[\left(\mathbf{H}_1^{j,n}\right)^{\mathrm{T}} \cdots \left(\mathbf{H}_{k'-1}^{j,n}\right)^{\mathrm{T}} \left(\mathbf{H}_{k'+1}^{j,n}\right)^{\mathrm{T}} \cdots \left(\mathbf{H}_U^{j,n}\right)^{\mathrm{T}}\right]^{\mathrm{T}}$$

Then, when $\hat{\mathbf{H}}_{k'}^{j,n}$ is decomposed to singular value, we obtain

$$\hat{\mathbf{H}}_{k'}^{j,n} = \hat{\mathbf{U}}_{k'}^{j,n}\hat{\mathbf{D}}_{k'}^{j,n}\left(\hat{\mathbf{V}}_{k'}^{j,n}\right)^{\mathrm{H}} \quad (17)$$

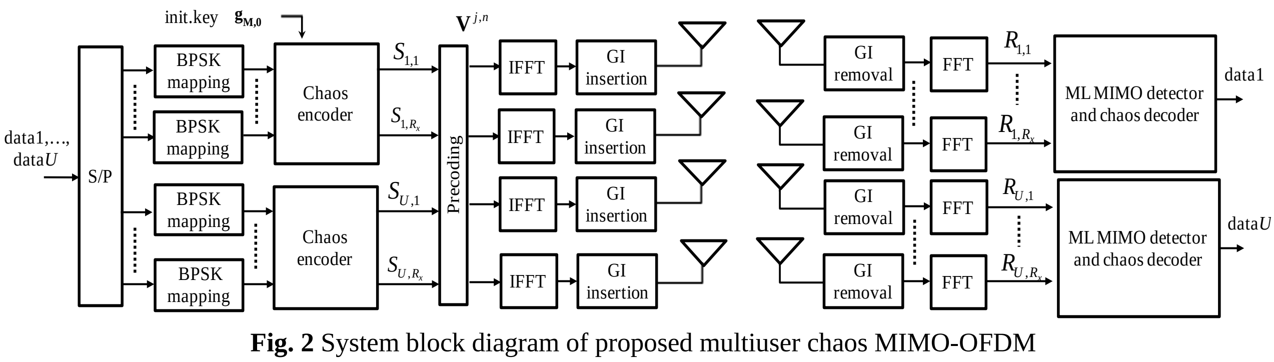

Fig. 2 System block diagram of proposed multiuser chaos MIMO-OFDM

where $\hat{\mathbf{U}}_{k'}^{j,n}$ and $\hat{\mathbf{V}}_{k'}^{j,n}$ are $(U-1)R'_x \times (U-1)R'_x$ and $T_x \times T_x$ unitary matrices, respectively, and $\hat{\mathbf{D}}_{k'}^{j,n}$ is the $(U-1)R'_x \times T_x$ diagonal matrix whose diagonal and non-diagonal elements are the square root of eigenvalue of $\left(\hat{\mathbf{H}}_{k'}^{j,n}\right)^{\mathrm{H}} \hat{\mathbf{H}}_{k'}^{j,n}$ and zero, respectively. Here, H means the Hermite transpose and the column vectors of $\hat{\mathbf{D}}_{k'}^{j,n}$ from $(U-1)R'_x+1$ to T_x become zero vectors. From (17) it satisfies

$$\hat{\mathbf{H}}_{k'}^{j,n}\hat{\mathbf{V}}_{k'}^{j,n} = \hat{\mathbf{U}}_{k'}^{j,n}\hat{\mathbf{D}}_{k'}^{j,n} \tag{18}$$

and when the column vectors from $(U-1)R'_x+1$ to T_x of the left term in (18) are extracted , we obtain

$$\begin{pmatrix} \mathbf{H}_1^{j,n}\hat{\mathbf{v}}_{k'}^{j,n}\left((U-1)R'_x+1\right) & \cdots & \mathbf{H}_1^{j,n}\hat{\mathbf{v}}_{k'}^{j,n}(T_x) \\ & \ddots & \\ \mathbf{H}_{k'-1}^{j,n}\hat{\mathbf{v}}_{k'}^{j,n}\left((U-1)R'_x+1\right) & \cdots & \mathbf{H}_{k'-1}^{j,n}\hat{\mathbf{v}}_{k'}^{j,n}(T_x) \\ \mathbf{H}_{k'+1}^{j,n}\hat{\mathbf{v}}_{k'}^{j,n}\left((U-1)R'_x+1\right) & \cdots & \mathbf{H}_{k'+1}^{j,n}\hat{\mathbf{v}}_{k'}^{j,n}(T_x) \\ & \ddots & \\ \mathbf{H}_U^{j,n}\hat{\mathbf{v}}_{k'}^{j,n}\left((U-1)R'_x+1\right) & \cdots & \mathbf{H}_U^{j,n}\hat{\mathbf{v}}_{k'}^{j,n}(T_x) \end{pmatrix} = \mathbf{0} \tag{19}$$

where $\hat{\mathbf{v}}_{k'}^{j,n}(i)$ is i-th column vector of $\hat{\mathbf{V}}_{k'}^{j,n}$. It is confirmed from (19) that the column vectors from $(U-1)R'_x+1$ to T_x of $\hat{\mathbf{V}}_{k'}^{j,n}$ form null for all users other than user k. Therefore, k' -th user's precoding matrix $\hat{\mathbf{V}}_{k'}^{j,n}$ of $T_x \times R'_x$ is given by

$$\hat{\mathbf{V}}_{k'}^{j,n} = \left(\hat{\mathbf{v}}_{k'}^{j,n}\left((U-1)R'_x+1\right)\ \hat{\mathbf{v}}_{k'}^{j,n}\left((U-1)R'_x+2\right)\cdots\hat{\mathbf{v}}_{k'}^{j,n}(T_x)\right)$$

and finally comprehensive precoding matrix $\mathbf{V}^{j,n}$ for all users is composed as follows:

$$\mathbf{V}^{j,n} = \left(\hat{\mathbf{V}}_1^{j,n}\ \hat{\mathbf{V}}_2^{j,n}\cdots\hat{\mathbf{V}}_U^{j,n}\right)$$

3. 3 Decoding of MU-C-MIMO-OFDM

The decoding algorithm of MU-C-MIMO-OFDM is almost the same as (9) expect the channel matrix in making the symbol replica. k' -th user conducts the MLSE decoding by

$$\hat{\mathbf{S}}_{k'}^{j} = \arg\min_{\mathbf{S}_{k'}^{j}} \sum_{n=0}^{B-1}\left\|\mathbf{R}_{k'}^{j,n} - \tilde{\mathbf{H}}_{k'}^{j,n}\mathbf{S}_{k'}^{j,n}\right\| \tag{20}$$

Here, $\mathbf{S}_{k'}^{j}$ is the transmit block of k' -th user in j-th block and $\hat{\mathbf{S}}_{k'}^{j}$ is the decoded block.

4. Numerical Results

The performances of the proposed scheme are evaluated by computer simulations under the conditions of Table 1. It is assumed that the channels are assumed as an i.i.d 1-dB decaying 9-path quasi-static Rayleigh fading in terms of each antenna and MIMO-OFDM block, and that the channels are perfectly known to all receivers. The block length is four and the numbers of users are 1, 2, 4 and 8. Each user has different chaos initial key which is shared only with the transmitter. In addition, to obtain the average performance the initial keys are randomly changed at each block. Fig. 3 shows the bit error rate (BER) performances decoded by MLSE of (20) at each block. It is shown that the BER of the proposed scheme is improved for the conventional unencrypted MIMO with maximum likelihood decoding (MLD) over 5 dB of average E_b/N_0 regardless of the number of users. However, it is noted that the decoding complexity is increased in the proposed scheme due to the block decoding. It is also found that the BER becomes 0.5 when the initial key is not identical, that is, the physical-layer security is ensured for every user.

Fig. 4 shows the BER performance versus the number of users at average E_b/N_0 = 15 dB. From Figs. 3 and 4 it is shown that BER is slightly improved according to the increase of the number of users. In MIMO-OFDM, if the channel coding is used in the frequency direction, BER is improved because of the frequency diversity effect. When the number of delay paths and delay spread is increased, the frequency diversity effect is enlarged and the performance is improved more. In the proposed scheme this effect happens according to the increase of users. Because the frequency diversity is obtained by the channel coding function of C-MIMO, the BER is improv-

Table 1 Simulation conditions.

Channel	1dB decaying 9-path quasi-static Rayleigh fading			
Modulation	BPSK			
Num. of 1OFDM symbols	64			
Num. of transmit antenna T_x	2	4	8	16
Num. of receive antenna per user R'_x	2			
Num. of users U	1	2	4	8
Chaos	Bernoulli shift map			
Num. of MIMO symbols on 1 block B	4			
Num. of chaos signals M	10			
Num. of chaos iteration BO	19			
Receive channel state inf.	Perfect			
Decoding algorithm	MLSE			

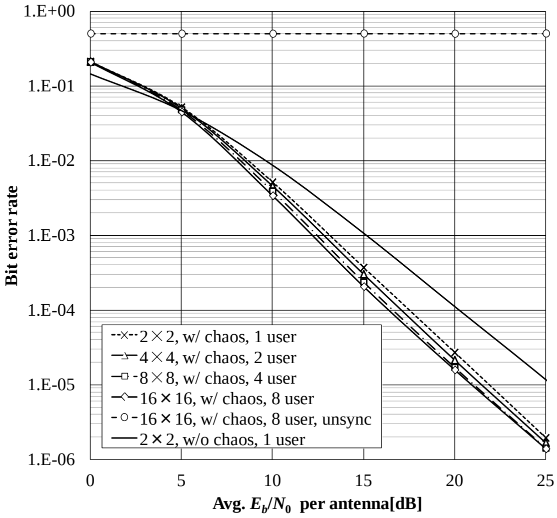

Fig. 3 BER performance comparison of single-user and multiuser MIMO in downlink.

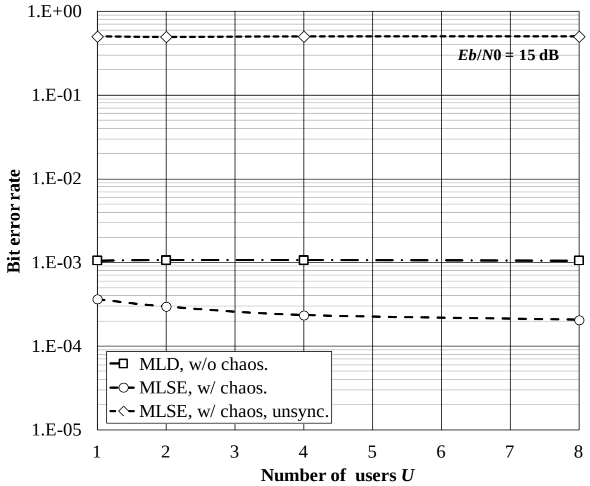

Fig. 4 BER performance versus number of users at E_b/N_0 =15 dB.

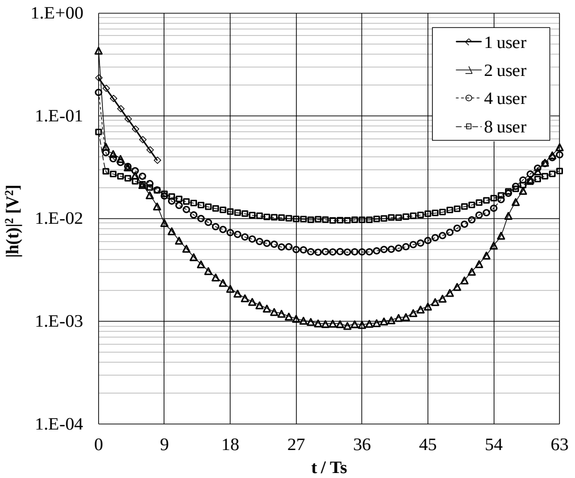

Fig. 5 Average squared impulse response of $\tilde{\mathbf{H}}_{k'}^{j,n}$ in time domain.

ed compared to MIMO-MLD regardless of *U*. Furthermore, as shown in Fig. 5, the equivalent channel ($\tilde{\mathbf{H}}_{k'}^{j,n}$ of (16)) is changed according to the number of users. Fig. 5 is calculated from the ensemble average of squared impulse response transformed from one subcarrier channel of OFDM channel matrix $\tilde{\mathbf{H}}_{k'}^{j,n}$ in the frequency domain. We can see that the delay spread effect is enlarged according to the increase of users. Thus, as a result strong frequency diversity effect is obtained and the BER is improved in proportion to the number of users. When the number of antenna is increased, antenna diversity is usually obtained. This is the same as the effect of Fig. 5.

5. Conclusions

In this paper, we extended chaos MIMO-OFDM scheme to multiuser MIMO technique and proposed a multiuser chaos MIMO-OFDM having physical-layer security for every user and channel coding gain. According to the increase of users the frequency diversity effect was enlarged and the BER performance of the proposed scheme was improved.

For future studies, the application of multilevel modulation and the reduction of decoding complexity will be considered.

Acknowledgments

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