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Resource Block Embedding: Towards High Throughput Broadband Multimedia Wireless Networks

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***Abstract*—For orthogonal frequency-division multiplexing (OFDM) based wireless systems, a resource block (RB) in a two-dimensional time-frequency plane is defined as a data block spanned by a number of consecutive OFDM symbols over a number of consecutive subcarriers. Traditionally, RBs contain modulation symbols for data transmission and pilot symbols for channel estimation.**

In this paper, we present a novel approach to RB designs for OFDM systems with multiple antennas at the transmitter and the receiver (i.e., MIMO-OFDM). The proposed approach, termed resource block embedding, does not require explicit pilot symbols to estimate the channel at the receiver, and hence reduces the channel estimation overhead significantly. We describe, in detail, the encoding and decoding algorithms for our proposed embedded resource blocks (ERB) for single-user single-antenna transmission, two transmitter antenna Alamouti code, four transmitter antenna stacked Alamouti code, and multi-stream spatial multiplexing. We also outline construction of ERBs for multi-user MIMO systems.

I. Introduction

Next generation wireless systems are embracing the orthogonal frequency division multiplexing (OFDM) and multiple-input and multiple-output (MIMO) technologies [1], [2], [3]. OFDM waveform provides robustness against frequency-selective channel fading over wider transmission bandwidths, and allows us exploit the multi-user diversity gains in a wireless network [4]. On the other hand, it is well established that, without requiring additional bandwidth, MIMO techniques provide enormous increase in the data rates needed to support exploding data demands [5]. Furthermore, the combination of MIMO and OFDM provides high data rates over wider transmission bandwidths with improved reliability against time- and frequency-selective channel fading, and interference robustness [6].

To estimate the MIMO-OFDM wireless channel in spatial, temporal and frequency domains, it is a common practice to transmit known symbols (also referred to as pilots). However, pilot insertion leads to inefficiencies in the use of transmission power, time and bandwidth. More importantly, a fixed pilot overhead might not be sufficient to estimate a rapidly varying channel, whereas it might be wasteful to estimate a channel that does not vary appreciably. In emerging systems such as IEEE 802.11n [1], IEEE 802.16m [2] and 3GPP LTE [3], which are based on MIMO-OFDM technologies, pilots and data symbols appear on distinct time and/or frequency resources. That is, the pilots and data do not overlap. Since many different configurations are possible in placing pilots and data symbols within a resource block (RB), the consequence is that design and implementation of traditional RBs is less flexible. For example, in MIMO-OFDM systems, the RB design with spatial-multiplexing is different from the one with space-frequency or space-time coding.

In this paper, we present novel approaches to RB designs with MIMO-OFDM technologies. In our proposal, referred to as embedded resource blocks (ERBs), the pilot symbols are embedded in the unknown modulated data symbols. As a result, there is no need for separate allocation of valuable resources such as transmission time and bandwidth to carry these pilot symbols. This leads to significant resource savings, thereby improving the overall spectral efficiency. Since all the modulation symbols in our ERB design contain a portion of pilots, our approach enables improved channel estimation accuracy and reliability performance over channels with high variability, and efficient resource utilization over channels with little variability. We present ERB designs for the following scenarios:

1) Single-user single-input and multiple-output (SIMO) OFDM systems
2) Single-user MIMO-OFDM systems with spatial multiplexing, two-transmitter-antenna Alamouti coding [9], and four-transmitter-antenna stacked-Alamouti coding [10], [11]
3) Multi-user MIMO-OFDM systems with base-station cooperation

The rest of this paper is organized as follows. In Section II we introduce the concept of resource block embedding. In Section III we present the embedded resource block designs for single-user SIMO systems. Encoding and decoding of ERBs for single-user MIMO systems, namely spatial-multiplexing, space-time/frequency coding, are detailed in Section IV, whereas extensions of ERB designs for multi-user MIMO systems is briefly discussed in Section V. We conclude this paper in Section VI.

II. Resource Block Embedding

A resource block in two-dimensional time-frequency plane is defined as a region spanned by N_T consecutive OFDM symbols over N_F consecutive frequency tones (or subcarriers/subchannels). Each one of the $N_T N_F$ symbols within an RB is referred to as a resource unit (RU). Traditionally, an RB contains N_D data modulation symbols and N_P pilot symbols for channel estimation, leading to a spectral efficiency per RB of $N_D/(N_T N_F)$.

For OFDM systems operating over time-varying and frequency-selective fading channels, the channel coherence

TABLE I
NORMALIZED CHANNEL COHERENCE BANDWIDTH, $N_{C,F}$, FOR VARIOUS CHANNEL MODELS.

Channel Name	Power-Delay Profile	σ_{RMS} (nsec)	$N_{C,F}$
ITU-Ped-A	Power (dB) = [0, −9.7, −19.2, −22.8] Delay (nsec) = [0, 110, 190, 410]	46.0	400
ITU-Ped-B	Power (dB) = [0, −0.9, −4.9, −8.0, −7.8, −23.9] Delay (nsec) = [0, 200, 800, 1200, 2300, 3700]	633.4	30
ITU-Veh-A	Power (dB) = [0, −1.0, −9.0, −10.0, −15.0, −20.0] Delay (nsec) = [0, 310, 710, 1090, 1730, 2510]	370.4	50
ITU-Veh-B	Power (dB) = [−2.5, 0, −12.8, −10, −25.2, −16] Delay (nsec) = [0, 300, 8900, 12900, 17100, 20000]	4001.4	10
SUI-1	Power (dB) = [0.0, −15.0, −20.0] Delay (nsec) = [0.0, 400, 900]	110.5	170
SUI-2	Power (dB) = [0.0, −12.0, −15.0] Delay (nsec) = [0.0, 400, 1100]	202.9	100
SUI-3	Power (dB) = [0.0, −5.0, −10.0] Delay (nsec) = [0.0, 400, 900]	263.7	70

time, $N_{C,T}$, is defined as the number of consecutive OFDM symbols during which the channel remains constant, whereas the channel coherence bandwidth, $N_{C,F}$, is defined as the number of consecutive subcarriers over which the channel remains constant. From [7], approximate values of $N_{C,T}$ and $N_{C,F}$ are given by

$$N_{C,T} \approx \left\lfloor \frac{1}{f_D T_S}\sqrt{\frac{9}{16\pi}} \right\rceil \tag{1}$$

$$\text{and} \quad N_{C,F} \approx \left\lfloor \frac{1}{5\sigma_{\mathsf{RMS}}\Delta_f} \right\rceil, \tag{2}$$

where $\lfloor x \rceil$ is an integer that is close to x, f_D is the maximum Doppler frequency, T_S is the OFDM symbol duration, σ_{RMS} is the root-mean-square delay spread and Δ_f is the sub-carrier bandwidth.

As an example, for the IEEE 802.16e WiMax wireless system operating over 2 GHz carrier frequency with 10 MHz system bandwidth, we have $\Delta_f = 10.94$ KHz, and, with a cyclic-prefix length of 11.428575 μsec, $T_S = 102.85$ μsec. Using these parameters, Table I presents values of $N_{C,F}$ for various practical channel models whereas Table II presents values of $N_{C,T}$ for various terminal speeds. When N_F is chosen to be less than $N_{C,F}$, and N_T is chosen to be less than $N_{C,T}$, the wireless channel is approximated to remain constant over the RB of size $N_T \times N_F$ RUs. An ERB is defined as the RB in which there are no explicit RUs allocated for channel estimation.

TABLE II
NORMALIZED CHANNEL COHERENCE TIME, $N_{C,T}$, AS A FUNCTION OF MOBILITY AT A CARRIER FREQUENCY OF 2.0 GHZ.

Speed (km/h)	f_D (Hz)	$N_{C,T}$
3	5.55	740
30	55.55	74
60	111.11	37
120	222.22	19
200	370.37	11

III. ERBs: Single-User SIMO Systems

We denote by $D(n)$, $n = 1, \ldots, N-1$, where $N = N_T \times N_F$, the modulation symbols at the input of the ERB mapping unit. The output of ERB is denoted by $X(n)$, $n = 1, \ldots, N$, where $X(n)$ is transmitted over the nth RU. The mapping rule is described as

$$X(n) = \alpha_1 (D(n) - m) + \beta \quad n = 1, \ldots, N-1 \tag{3}$$

$$X(N) = \alpha_2 m \tag{4}$$

where

$$m = \frac{1}{N-1}\sum_{j=1}^{N-1} D(j) \tag{5}$$

is the sample mean of the input modulation symbols. In (3) and (4), α_1, α_2 and β are positive constants that are chosen in such a way that a certain power constraint is satisfied. As an example, if each $X(n)$ is required to have an average energy of E_S, then we have

$$\alpha_1^2\left(1 - \frac{1}{N-1}\right) + \beta^2 = E_S \tag{6}$$

$$\text{and} \quad \alpha_2 = \sqrt{(N-1)\,E_S}. \tag{7}$$

Since N channel uses are consumed to transmit $N-1$ modulation symbols, the effective transmission rate of SIMO-ERB is $(N-1)/N$ symbols per channel use.

1) Channel Estimation and Data Detection: Since the channel is assumed to be constant over the RB of size N symbols, the vector-valued signal received over L receiver antennas is

$$\mathbf{y}(n) = \mathbf{h}X(n) + \mathbf{w}(n), \quad n = 1, \ldots, N, \tag{8}$$

where $\mathbf{y}(n) = [y_1(n), \ldots, y_L(n)]^T$, $\mathbf{h} = [h_1, \ldots, h_L]^T$ is the SIMO channel, and $\mathbf{w}(n) = [w_1(n), \ldots, w_L(n)]^T$ is the zero-mean additive white Gaussian noise with covariance matrix $\mathrm{E}\left[\mathbf{w}(n)\mathbf{w}^H(n)\right] = \sigma_w^2\mathbf{I}_L$. Here, $\mathbf{I}_L$ is the L-by-L identity matrix.

An estimate of the channel $\mathbf{h}$ is given by

$$\begin{aligned}\widehat{\mathbf{h}} &= \frac{1}{\beta(N-1)}\sum_{n=1}^{N-1}\mathbf{y}(n) \\ &= \frac{1}{\beta(N-1)}\sum_{n=1}^{N-1}\left(\mathbf{h}\left[\alpha_1 (D(n) - m) + \beta\right] + \mathbf{w}(n)\right) \\ &= \mathbf{h} + \frac{1}{\beta(N-1)}\sum_{n=1}^{N-1}\mathbf{w}(n).\end{aligned} \tag{9}$$

The mean-square error per receiver antenna is

$$\begin{aligned}
\sigma_e^2 &= \frac{1}{L}\text{trace}\left(\mathrm{E}\left[\left(\widehat{\mathbf{h}}-\mathbf{h}\right)\left(\widehat{\mathbf{h}}-\mathbf{h}\right)^H\right]\right)\\
&= \frac{\text{trace}\left(\mathrm{E}\left[\left(\frac{\sum_{n=1}^{N-1}\mathbf{w}(n)}{\beta(N-1)}\right)\left(\frac{\sum_{n=1}^{N-1}\mathbf{w}(n)}{\beta(N-1)}\right)^H\right]\right)}{L}\\
&= \frac{\sum_{n=1}^{N-1}\text{trace}\left(\mathrm{E}\left[\mathbf{w}(n)\mathbf{w}^H(n)\right]\right)}{L\beta^2\left(N-1\right)^2}\\
&= \frac{\sigma_w^2}{\beta^2\left(N-1\right)}. \qquad (10)
\end{aligned}$$

Using the channel estimate $\widehat{\mathbf{h}}$ from (9), soft estimates of $D(n)$, $n=1,\ldots,N-1$, are obtained as

$$\widehat{D}(n) = \frac{\widehat{X}(n)-\beta}{\alpha_1}+\widehat{m}, \qquad (11)$$

$$\text{where} \quad \widehat{X}(n) = \frac{\widehat{\mathbf{h}}^H\mathbf{y}(n)}{\widehat{\mathbf{h}}^H\widehat{\mathbf{h}}}. \qquad (12)$$

$$\text{and} \quad \widehat{m} = \frac{1}{\alpha_2}\times\frac{\widehat{\mathbf{h}}^H\mathbf{y}(N)}{\widehat{\mathbf{h}}^H\widehat{\mathbf{h}}}. \qquad (13)$$

IV. ERBs: Single-User MIMO Systems

A. Spatial Multiplexing

In this section, we present ERB mapping rule for MIMO-OFDM systems with K transmitter antennas. For simplicity, we assume that the number of streams is equal to the number of transmitter antennas.

1) ERB Mapping Rule: The desired number of modulation symbols is divided into K streams each with N modulation symbols. For a given choice of N_T, we choose N_F as $N_F = \frac{N+K}{N_T}$. We also assume that N is divisible by K. The modulation symbol on nth channel use on transmitter antenna k is denoted by $D_k(n)$. With this, the ERB mapping rule for MIMO-OFDM with spatial-multiplexing is described as follows.

We first define the partial sample mean of data symbols as

$$m_{t,l} = \frac{K}{N}\sum_{j=(l-1)\frac{N}{K}+1}^{l\frac{N}{K}} D_t(j) \qquad t,l=1,\ldots,K. \qquad (14)$$

The encoded symbols, using the ERB parameters α_1, α_2, β, and δ, and the variables $m_{t,l}$, are given by (15), as shown at the top of next page. Note that α_1,α_2,β and δ are positive constants that are chosen in such a way that a certain power constraint is satisfied.

Since $N+K$ channel uses are consumed to transmit NK modulation symbols, the effective transmission rate of SM-ERB is $NK/(N+K)$ symbols per channel use.

2) Channel Estimation and Data Detection: Since the channel is assumed to be constant over $N_TN_F = N+K$ uses, the received signal can be written as

$$\mathbf{y}(n) = \sum_{t=1}^{K}\mathbf{h}_tX_t(n)+\mathbf{w}(n), \quad n=1,\ldots,N+K, \qquad (16)$$

where $\mathbf{h}_t$ is the channel from tth transmitter antenna.

Using the proposed ERB mapping rule in (14) and (15), an estimate of $\mathbf{h}_l$ is obtained as

$$\begin{aligned}
\widehat{\mathbf{h}}_l &= \frac{K}{N\beta}\sum_{n=(l-1)\frac{N}{K}+1}^{l\frac{N}{K}}\mathbf{y}(n)\\
&= \frac{K}{N\beta}\sum_{n=(l-1)\frac{N}{K}+1}^{l\frac{N}{K}}\left(\sum_{t=1}^{K}\mathbf{h}_tX_t(n)+\mathbf{w}(n)\right)\\
&= \frac{K}{N\beta}\sum_{n=(l-1)\frac{N}{K}+1}^{l\frac{N}{K}}\Bigg(\mathbf{h}_l\left[\alpha_1\left(D_l(n)-m_{l,l}\right)+\beta\right]+\\
&\qquad \sum_{t=1,t\neq l}^{K}\mathbf{h}_t\alpha_2\left(D_t(n)-m_{t,l}\right)+\mathbf{w}(n)\Bigg)\\
&= \mathbf{h}_l+\frac{K}{N\beta}\sum_{n=(l-1)\frac{N}{K}+1}^{l\frac{N}{K}}\mathbf{w}(n), \quad l=1,\ldots,K. \qquad (17)
\end{aligned}$$

Since $X_t(N+n) = \delta m_{t,n}$, $t=1,\ldots,K$, $n=1,\ldots,K$, the received signal at channel use $N+n$, $n=1,\ldots,K$, is

$$\begin{aligned}
\mathbf{y}(N+n) &= \sum_{t=1}^{K}\mathbf{h}_t\delta m_{t,n}+\mathbf{w}(N+n)\\
&= \begin{bmatrix}\mathbf{h}_1 & \cdots & \mathbf{h}_K\end{bmatrix}\begin{bmatrix}\delta m_{1,n}\\ \vdots\\ \delta m_{K,n}\end{bmatrix}+\mathbf{w}(N+n). \qquad (18)
\end{aligned}$$

Upon defining an L-by-K matrix $\mathbf{G}$ and a K-by-K matrix $\mathbf{D}$ as

$$\mathbf{G} = \begin{bmatrix}\widehat{\mathbf{h}}_1 & \cdots & \widehat{\mathbf{h}}_K\end{bmatrix} \qquad (19)$$

$$\text{and} \quad \mathbf{D} = \text{diag}\left(\underbrace{\frac{1}{\delta},\cdots,\frac{1}{\delta}}_{K \text{ times}}\right), \qquad (20)$$

each of the K^2 sample mean variables $m_{t,n}$, $t=1,\ldots,K$, $n=1,\ldots,K$, can be estimated as

$$\begin{bmatrix}\widehat{m}_{1,n}\\ \vdots\\ \widehat{m}_{K,n}\end{bmatrix} = \mathbf{D}\left(\mathbf{G}^H\mathbf{G}+\widehat{\sigma}^2\mathbf{I}_K\right)^{-1}\mathbf{G}^H\mathbf{y}(N+n), \qquad (21)$$

where $\widehat{\sigma}^2$ is the estimated noise variance per complex dimension.

Using the channel estimates, estimates of transmitted symbols can be obtained, for example, using the linear minimum mean-square error (LMMSE) receiver [8], as

$$\begin{bmatrix}\widehat{X}_1(n)\\ \vdots\\ \widehat{X}_K(n)\end{bmatrix} = \left(\mathbf{G}^H\mathbf{G}+\widehat{\sigma}^2\mathbf{I}_K\right)^{-1}\mathbf{G}^H\mathbf{y}(n) \quad n=1,\ldots,N. \qquad (22)$$

Using $\widehat{X}_t(n)$, and the partial sample mean estimates $\widehat{m}_{t,l}$, $n=1,\ldots,N$ and $t,l=1,\ldots,K$, estimates of the data symbols are obtained as in (23), as shown on the next page.

$$X_t(n) = \begin{cases} \alpha_1\left(D_t(n) - m_{t,l}\right) + \beta & t=1,\ldots,K, \quad l=1,\ldots,K, \quad n=(l-1)\frac{N}{K}+1,\ldots,l\frac{N}{K}, \quad t=l \\ \alpha_2\left(D_t(n) - m_{t,l}\right) & t=1,\ldots,K, \quad l=1,\ldots,K, \quad n=(l-1)\frac{N}{K}+1,\ldots,l\frac{N}{K}, \quad t\neq l \\ \delta m_{t,l} & t=1,\ldots,K, \quad l=1,\ldots,K, \quad n=N+l \end{cases} \tag{15}$$

$$\widehat{D}_t(n) = \begin{cases} \frac{\widehat{X}_t(n)-\beta}{\alpha_1} + \widehat{m}_{t,l} & t=1,\ldots,K, \quad l=1,\ldots,K, \quad n=(l-1)\frac{N}{K}+1,\ldots,l\frac{N}{K}, \quad t=l \\ \frac{\widehat{X}_t(n)}{\alpha_2} + \widehat{m}_{t,l} & t=1,\ldots,K, \quad l=1,\ldots,K, \quad n=(l-1)\frac{N}{K}+1,\ldots,l\frac{N}{K}, \quad t\neq l \end{cases} \tag{23}$$

B. Two-Transmitter-Antenna Alamouti Code

The Alamouti code with two transmitter antennas, and operating over two channel uses, $2n-1$ and $2n$, is described as [9]

$$\begin{bmatrix} X_1(n) & -X_2^*(n) \\ X_2(n) & X_1^*(n) \end{bmatrix}, \tag{24}$$

where the row corresponds to the transmitter antenna index and the column corresponds to the channel use index. Here, $*$ denotes the complex-conjugate operation. Since two distinct modulation symbols are transmitted over two channel uses, the rate of this code is 1 symbol per channel use.

1) ERB Mapping Rule: With $2N$ modulation symbols, $D_k(n)$, $k=1,2$ and $n=1,\ldots,N$, the ERB mapping rule with two transmitter antennas and two modulation streams using the Alamouti scheme is described as

$$X_1(n) = \begin{cases} \alpha_1\left(D_1(n) - m_1\right) & n=1,\ldots,N \\ \delta m_1 & n=N+1 \end{cases} \tag{25}$$

$$X_2(n) = \begin{cases} \alpha_2\left(D_2(n) - m_2\right) + \beta & n=1,\ldots,N \\ \delta m_2 & n=N+1 \end{cases} \tag{26}$$

where $\alpha_1, \alpha_2, \beta$ and δ are the ERB parameters, and m_1 and m_2 are the sample mean values of the two data streams:

$$m_1 = \frac{1}{N}\sum_{n=1}^{N} D_1(n) \tag{27}$$

$$\text{and} \quad m_2 = \frac{1}{N}\sum_{n=1}^{N} D_2(n). \tag{28}$$

Since we have consumed $N+1$ channel uses to transmit $2N$ modulation symbols, the effective transmission rate of Alamouti-ERB is $2N/(N+1)$ symbols per channel use.

2) Channel Estimation and Data Detection: Since the channel is assumed to be constant over $N+1$ uses, the received signal can be written as

$$\mathbf{y}(2n-1) = \mathbf{h}_1 X_1(n) + \mathbf{h}_2 X_2(n) + \mathbf{w}(2n-1) \tag{29}$$

$$\mathbf{y}(2n) = -\mathbf{h}_1 X_2^*(n) + \mathbf{h}_2 X_1^*(n) + \mathbf{w}(2n) \tag{30}$$

$$\mathbf{y}(2N+1) = \mathbf{h}_1 \delta m_1 + \mathbf{h}_2 \delta m_2 + \mathbf{w}(2N+1) \tag{31}$$

$$\mathbf{y}(2N+2) = -\mathbf{h}_1 \delta m_2^* + \mathbf{h}_2 \delta m_1^* + \mathbf{w}(2N+2), \tag{32}$$

where $n=1,\ldots,N$.

Using (25)-(30), the channel from the first transmitter antenna is estimated as

$$\begin{aligned} \widehat{\mathbf{h}}_1 &= -\frac{1}{N\beta}\sum_{n=1}^{N}\mathbf{y}(2n) \\ &= \mathbf{h}_1 \frac{1}{N\beta}\sum_{n=1}^{N}\left[\alpha_2\left(D_2(n)-m_2\right)^* + \beta\right] - \\ &\quad \mathbf{h}_2 \frac{1}{N\beta}\sum_{n=1}^{N}\alpha_1\left(D_1(n)-m_1\right)^* - \\ &\quad \frac{1}{N\beta}\sum_{n=1}^{N}\mathbf{w}(2n) \\ &= \mathbf{h}_1 - \frac{1}{N\beta}\sum_{n=1}^{N}\mathbf{w}(2n). \end{aligned} \tag{33}$$

In a similar manner, the channel from the second transmitter antenna is estimated as

$$\begin{aligned} \widehat{\mathbf{h}}_2 &= \frac{1}{N\beta}\sum_{n=1}^{N}\mathbf{y}(2n-1) \\ &= \mathbf{h}_1 \frac{1}{N\beta}\sum_{n=1}^{N}\alpha_1\left(D_1(n)-m_1\right) + \\ &\quad \mathbf{h}_2 \frac{1}{N\beta}\left[\alpha_2\left(D_2(n)-m_2\right) + \beta\right] + \\ &\quad \frac{1}{N\beta}\sum_{n=1}^{N}\mathbf{w}(2n-1) \\ &= \mathbf{h}_2 + \frac{1}{N\beta}\sum_{n=1}^{N}\mathbf{w}(2n-1). \end{aligned} \tag{34}$$

Since the Alamouti code transmitted over channel uses $2N+1$ and $2N+2$ is also orthogonal, we can estimate m_1 and m_2 by linear processing $\mathbf{y}(2N+1)$ and $\mathbf{y}(2N+2)$, from (31) and (32), as

$$\widehat{m}_1 = \frac{1}{\delta} \times \frac{\widehat{\mathbf{h}}_1^H \mathbf{y}(2N+1) + \widehat{\mathbf{h}}_2^T \mathbf{y}^*(2N+2)}{\widehat{\mathbf{h}}_1^H \widehat{\mathbf{h}}_1 + \widehat{\mathbf{h}}_2^H \widehat{\mathbf{h}}_2} \tag{35}$$

$$\text{and} \quad \widehat{m}_2 = \frac{1}{\delta} \times \frac{\widehat{\mathbf{h}}_2^H \mathbf{y}(2N+1) - \widehat{\mathbf{h}}_1^T \mathbf{y}^*(2N+2)}{\widehat{\mathbf{h}}_1^H \widehat{\mathbf{h}}_1 + \widehat{\mathbf{h}}_2^H \widehat{\mathbf{h}}_2}. \tag{36}$$

Using the estimated channels $\widehat{\mathbf{h}}_1$ and $\widehat{\mathbf{h}}_2$, and the estimated sample means $\widehat{m}_1$ and $\widehat{m}_2$, soft estimates of the modulation symbols $\{D_1(n), D_2(n)\}$, for $n=1,\ldots,N$, are given by

$$\widehat{D}_1(n) = \frac{\widehat{X}_1(n)}{\alpha_1} + \widehat{m}_1 \tag{37}$$

$$\text{and} \quad \widehat{D}_2(n) = \frac{\widehat{X}_2(n)-\beta}{\alpha_2} + \widehat{m}_2, \tag{38}$$

where, for $n = 1, \ldots, N$,

$$\widehat{X}_1(n) = \frac{\widehat{\mathbf{h}}_1^H \mathbf{y}(2n-1) + \widehat{\mathbf{h}}_2^T \mathbf{y}^*(2n)}{\widehat{\mathbf{h}}_1^H \widehat{\mathbf{h}}_1 + \widehat{\mathbf{h}}_2^H \widehat{\mathbf{h}}_2} \tag{39}$$

$$\widehat{X}_2(n) = \frac{\widehat{\mathbf{h}}_2^H \mathbf{y}(2n-1) - \widehat{\mathbf{h}}_1^T \mathbf{y}^*(2n)}{\widehat{\mathbf{h}}_1^H \widehat{\mathbf{h}}_1 + \widehat{\mathbf{h}}_2^H \widehat{\mathbf{h}}_2}. \tag{40}$$

C. Four-Transmitter-Antenna Stacked-Alamouti Code

The stacked-Alamouti code with four transmitter antennas, operating over channel uses $2n-1$ and $2n$, is described as [10], [11]

$$\begin{bmatrix} X_1(n) & -X_2^*(n) \\ X_2(n) & X_1^*(n) \\ X_3(n) & -X_4^*(n) \\ X_4(n) & X_3^*(n) \end{bmatrix}, \tag{41}$$

where, as before, the row corresponds to the transmitter antenna index and the column corresponds to the channel use index. Since four distinct modulation symbols are transmitted over two channel uses, the rate of this code is 2 symbols per channel use.

1) ERB Mapping Rule: We choose N_T and N_F such that $N_T N_F = 2N + 4$. We also assume that N is divisible by 2. With $4N$ modulation symbols, $D_k(n)$, $k = 1, \ldots, 4$ and $n = 1, \ldots, N$, the ERB mapping rule is described as follows.

We first define the partial sample mean of data symbols as

$$m_{t,l} = \frac{2}{N} \sum_{j=(l-1)\frac{N}{2}+1}^{l\frac{N}{2}} D_t(j) \quad l = 1, 2, \quad t = 1, \ldots, 4. \tag{42}$$

The encoded symbols, using the ERB parameters α_1, α_2, β, and δ, and the variables $m_{t,l}$, are given by

$$X_1(n) = \begin{cases} \alpha_1 \left(D_1(n) - m_{1,1}\right) + \beta & n = 1, \ldots, \frac{N}{2} \\ \alpha_2 \left(D_1(n) - m_{1,2}\right) & n = \frac{N}{2} + 1, \ldots, N \\ \delta m_{1,1} & n = N + 1 \\ \delta m_{1,2} & n = N + 2 \end{cases} \tag{43}$$

$$X_2(n) = \begin{cases} \alpha_2 \left(D_2(n) - m_{2,1}\right) & n = 1, \ldots, \frac{N}{2} \\ \alpha_2 \left(D_2(n) - m_{2,2}\right) & n = \frac{N}{2} + 1, \ldots, N \\ \delta m_{2,1} & n = N + 1 \\ \delta m_{2,2} & n = N + 2 \end{cases} \tag{44}$$

$$X_3(n) = \begin{cases} \alpha_2 \left(D_3(n) - m_{3,1}\right) & n = 1, \ldots, \frac{N}{2} \\ \alpha_1 \left(D_3(n) - m_{3,2}\right) + \beta & n = \frac{N}{2} + 1, \ldots, N \\ \delta m_{3,1} & n = N + 1 \\ \delta m_{3,2} & n = N + 2 \end{cases} \tag{45}$$

and

$$X_4(n) = \begin{cases} \alpha_2 \left(D_4(n) - m_{4,1}\right) & n = 1, \ldots, \frac{N}{2} \\ \alpha_2 \left(D_4(n) - m_{4,2}\right) & n = \frac{N}{2} + 1, \ldots, N \\ \delta m_{4,1} & n = N + 1 \\ \delta m_{4,2} & n = N + 2 \end{cases} \tag{46}$$

Since we have used $2N + 4$ channel uses to transmit $4N$ modulation symbols, the effective transmission rate of stacked-Alamouti ERB is $2N/(N + 2)$ symbols per channel use.

2) Channel Estimation and Data Detection: Since the channel is assumed to be constant over $2N + 4$ uses, the received signal can be written as

$$\begin{aligned} \mathbf{y}(2n-1) &= \mathbf{h}_1 X_1(n) + \mathbf{h}_2 X_2(n) + \mathbf{h}_3 X_3(n) \\ &\quad + \mathbf{h}_4 X_4(n) + \mathbf{w}(2n-1), \end{aligned} \tag{47}$$

$$\begin{aligned} \text{and} \quad \mathbf{y}(2n) &= -\mathbf{h}_1 X_2^*(n) + \mathbf{h}_2 X_1^*(n) - \mathbf{h}_3 X_4^*(n) \\ &\quad + \mathbf{h}_4 X_3^*(n) + \mathbf{w}(2n), \end{aligned} \tag{48}$$

where $n = 1, \ldots, N + 2$.

The channel from each of the four transmitter antennas is estimated as

$$\begin{aligned} \widehat{\mathbf{h}}_1 &= \frac{2}{N\beta} \sum_{n=1}^{\frac{N}{2}} \mathbf{y}(2n-1) \\ &= \mathbf{h}_1 + \frac{2}{N\beta} \sum_{n=1}^{\frac{N}{2}} \mathbf{w}(2n-1), \end{aligned} \tag{49}$$

$$\begin{aligned} \widehat{\mathbf{h}}_2 &= \frac{2}{N\beta} \sum_{n=1}^{\frac{N}{2}} \mathbf{y}(2n) \\ &= \mathbf{h}_2 + \frac{2}{N\beta} \sum_{n=1}^{\frac{N}{2}} \mathbf{w}(2n), \end{aligned} \tag{50}$$

$$\begin{aligned} \widehat{\mathbf{h}}_3 &= \frac{2}{N\beta} \sum_{n=1}^{\frac{N}{2}} \mathbf{y}(N+2n-1) \\ &= \mathbf{h}_3 + \frac{2}{N\beta} \sum_{n=1}^{\frac{N}{2}} \mathbf{w}(N+2n-1), \end{aligned} \tag{51}$$

$$\begin{aligned} \text{and} \quad \widehat{\mathbf{h}}_4 &= \frac{2}{N\beta} \sum_{n=1}^{\frac{N}{2}} \mathbf{y}(N+2n) \\ &= \mathbf{h}_4 + \frac{2}{N\beta} \sum_{n=1}^{\frac{N}{2}} \mathbf{w}(N+2n). \end{aligned} \tag{52}$$

Upon stacking $\mathbf{y}(2N+2n-1)$ and $\mathbf{y}^*(2N+2n)$, for $n = 1, 2$, in one column, we write

$$\begin{aligned} \begin{bmatrix} \mathbf{y}(2N+2n-1) \\ \mathbf{y}^*(2N+2n) \end{bmatrix} &= \begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 & \mathbf{h}_3 & \mathbf{h}_4 \\ -\mathbf{h}_2^* & \mathbf{h}_1^* & -\mathbf{h}_4^* & \mathbf{h}_3^* \end{bmatrix} \begin{bmatrix} \delta m_{1,n} \\ \delta m_{2,n} \\ \delta m_{3,n} \\ \delta m_{4,n} \end{bmatrix} \\ &\quad + \begin{bmatrix} \mathbf{w}(2N+2n-1) \\ \mathbf{w}^*(2N+2n) \end{bmatrix}. \end{aligned} \tag{53}$$

Upon defining a $2L$-by-4 matrix $\mathbf{H}$ and a 4-by-4 matrix $\mathbf{U}$ as

$$\mathbf{H} = \begin{bmatrix} \widehat{\mathbf{h}}_1 & \widehat{\mathbf{h}}_2 & \widehat{\mathbf{h}}_3 & \widehat{\mathbf{h}}_4 \\ -\widehat{\mathbf{h}}_2^* & \widehat{\mathbf{h}}_1^* & -\widehat{\mathbf{h}}_4^* & \widehat{\mathbf{h}}_3^* \end{bmatrix}, \tag{54}$$

$$\text{and} \quad \mathbf{U} = \operatorname{diag}\left(\frac{1}{\delta}, \frac{1}{\delta}, \frac{1}{\delta}, \frac{1}{\delta}\right), \tag{55}$$

each of the 8 sample mean variables $m_{t,n}$, $t = 1, \ldots, 4$, $n = 1, 2$, can be estimated as

$$\begin{bmatrix} \widehat{m}_{1,n} \\ \widehat{m}_{2,n} \\ \widehat{m}_{3,n} \\ \widehat{m}_{4,n} \end{bmatrix} = \mathbf{U}\left(\mathbf{H}^H \mathbf{H} + \widehat{\sigma}^2 \mathbf{I}_4\right)^{-1} \mathbf{H}^H \begin{bmatrix} \mathbf{y}(2N+2n-1) \\ \mathbf{y}^*(2N+2n) \end{bmatrix}. \tag{56}$$

Having access to the channel estimates, estimates of transmitted symbols can be obtained, for example, using the LMMSE receiver, as

$$\begin{bmatrix}\widehat{X}_1(n)\\ \widehat{X}_2(n)\\ \widehat{X}_3(n)\\ \widehat{X}_4(n)\end{bmatrix} = \left(\mathbf{H}^H\mathbf{H} + \widehat{\sigma}^2\mathbf{I}_4\right)^{-1}\mathbf{H}^H\begin{bmatrix}\mathbf{y}(2n-1)\\ \mathbf{y}^*(2n)\end{bmatrix}, \qquad (57)$$

where $n = 1, \ldots, N$.

Using $\widehat{X}_t(n)$, and the partial sample mean estimates $\widehat{m}_{t,l}$, for $t = 1, \ldots, 4$, $n = 1, \ldots, N$, and $l = 1, 2$, estimates of the data symbols are obtained as

$$\widehat{D}_1(n) = \begin{cases}\frac{\widehat{X}_1(n)-\beta}{\alpha_1} + \widehat{m}_{1,1} & n = 1, \ldots, \frac{N}{2}\\ \frac{\widehat{X}_1(n)}{\alpha_2} + \widehat{m}_{1,2} & n = \frac{N}{2}+1, \ldots, N\end{cases} \qquad (58)$$

$$\widehat{D}_2(n) = \begin{cases}\frac{\widehat{X}_2(n)}{\alpha_2} + \widehat{m}_{2,1} & n = 1, \ldots, \frac{N}{2}\\ \frac{\widehat{X}_2(n)}{\alpha_2} + \widehat{m}_{2,2} & n = \frac{N}{2}+1, \ldots, N\end{cases} \qquad (59)$$

$$\widehat{D}_3(n) = \begin{cases}\frac{\widehat{X}_3(n)}{\alpha_2} + \widehat{m}_{3,1} & n = 1, \ldots, \frac{N}{2}\\ \frac{\widehat{X}_3(n)-\beta}{\alpha_1} + \widehat{m}_{3,2} & n = \frac{N}{2}+1, \ldots, N\end{cases} \qquad (60)$$

$$\widehat{D}_4(n) = \begin{cases}\frac{\widehat{X}_4(n)}{\alpha_2} + \widehat{m}_{4,1} & n = 1, \ldots, \frac{N}{2}\\ \frac{\widehat{X}_4(n)}{\alpha_2} + \widehat{m}_{4,2} & n = \frac{N}{2}+1, \ldots, N\end{cases} \qquad (61)$$

V. ERBs: Multi-User MIMO Systems

So far, we have considered ERB designs for single-user MIMO-OFDM systems. Extensions of ERB designs to multi-user systems is straightforward. As an example, we describe below a construction of ERBs for wireless networks with base-station cooperation.

A. ERBs for Base-Station Cooperation

We consider a scenario in which two base stations cooperate for downlink transmission to serve two cell-edge mobile stations for cell-edge throughput improvement. We assume that each BS has M_T transmitter antennas to transmit K streams, and each MS has L antennas at the receiver. The M_T-by-K precoder matrix at BS k is denoted by $\mathbf{T}_k$, $k = 1, 2$, whereas the L-by-M_T channel matrix between BS k and MS j is denoted by $\mathbf{H}_{j,k}$. The channel and the precoder matrices are assumed to be constant over N channel uses.

Denote by $\mathbf{x}_k(n)$ the K-by-1 data vector at BS k for the nth channel use. With this, the received signal at MS j is

$$\begin{aligned}\mathbf{y}_j(n) &= \mathbf{H}_{j,1}\mathbf{T}_1\mathbf{x}_1(n) + \mathbf{H}_{j,2}\mathbf{T}_2\mathbf{x}_2(n) + \mathbf{w}_j(n)\\ &= \begin{bmatrix}\mathbf{H}_{j,1}\mathbf{T}_1 & \mathbf{H}_{j,2}\mathbf{T}_2\end{bmatrix}\begin{bmatrix}\mathbf{x}_1(n)\\ \mathbf{x}_2(n)\end{bmatrix} + \mathbf{w}_j(n)\\ &= \begin{bmatrix}\mathbf{H}_{j,1} & \mathbf{H}_{j,2}\end{bmatrix}\begin{bmatrix}\mathbf{u}_1(n)\\ \mathbf{u}_2(n)\end{bmatrix} + \mathbf{w}_j(n), \end{aligned} \qquad (62)$$

where $\mathbf{u}_j(n) = \mathbf{T}_j\mathbf{x}_j(n)$ is the precoded data by BS j.

We denote by $\mathbf{H}_{j,\mathsf{pre}} = \begin{bmatrix}\mathbf{H}_{j,1}\mathbf{T}_1 & \mathbf{H}_{j,2}\mathbf{T}_2\end{bmatrix}$ the L-by-$2K$ composite precoded MIMO channel, whereas by $\mathbf{H}_{j,\mathsf{raw}} = \begin{bmatrix}\mathbf{H}_{j,1} & \mathbf{H}_{j,2}\end{bmatrix}$ the L-by-$2M_T$ composite raw MIMO channel. With these, it is easy to recognize that the BSC signal model is very similar to the single-user MIMO spatial multiplexing system described in Section IV-A.

It follows from Section IV-A that if the receivers need to estimate the precoded channel $\mathbf{H}_{j,\mathsf{pre}}$ with N modulation symbols per RB, then we need the channel to remain constant over at least $N + 2K$ channel uses. That is, $N_T N_F > N + 2K$. Since we need to estimate the channel from $2K$ effective transmit antennas, we need to ensure that N is also divisible by $2K$. In a similar manner, if the receivers desire an estimate of the raw-channel $\mathbf{H}_{j,\mathsf{raw}}$, then we need $N_T N_F > N + 2M_T$, and N should be divisible by $2M_T$. Since $K \leq M_T$, we notice that estimation of the precoded channel is simpler compared with estimation of the raw channel. In either case, signal encoding, channel estimation, and data detection for BSC follow directly from the approach presented in Section IV-A for single BS spatial multiplexing systems.

VI. Concluding Remarks

In this paper, we have introduced the idea of embedded resource blocks. Unlike the conventional RB designs, ERBs are shown to be very flexible to design, and have superior spectral efficiency performance. We have presented detailed encoding and decoding algorithms for ERBs with single-stream SISO, multi-stream MIMO, two-transmitter-antenna Alamouti, and four-transmitter-antenna stacked Alamouti transmission formats. We have also presented extensions of ERB constructions for a multi-user MIMO system with base-station cooperation.

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