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Paper

Partial Layered Division Multiplexing with STBC for ISDB-T and Next Generation DTTB Systems

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Abstract In order to realize next generation digital terrestrial television broadcasting (DTTB) systems, the currently deployed Integrated Services Digital Broadcasting Terrestrial (ISDB-T) is still essential due to the spectrum-scarcity. This paper proposes a layered division multiplexing (LDM) scheme to simultaneously transmit ISDB-T stream and a secondary data stream over a common frequency band. The next generation DTTB system can be obtained by combining the ISDB-T and the secondary data streams. In the proposed scheme, we deploy the primary layer for transmission of ISDB-T signal and the secondary layer for transmission of secondary data stream both employed space time block coding. In addition, we only adopt partial LDM to reduce the interference between two systems, since the transmission capacity of the secondary layer exceeded the minimum requirement due to reuse of primary layer.

Key words: ISDB-T, DTTB, partial layered division multiplexing, single frequency network, STBC

1. Introduction

The current Integrated Services Digital Broadcasting - Terrestrial (ISDB-T) transmits high definition TV (HDTV) broadcasting in Japan[1]. Recently, next generation digital terrestrial television broadcasting (DTTB) systems for higher resolution TV, e.g., 4K-resolution and 8K-resolution, have been investigated. The field experiment operated by Nippon Hoso Kyokai (NHK) successfully transmitted a 8K signal using space time block coding (STBC) over a single frequency network (SFN) system[2]. The experiment of the 8K DTTB system was conducted in a rural area so that TV subscribers will not be affected by co-channel interference. However, an issue needs to be considered is how to implement the next generation DTTB system without requiring new frequency resources. Currently, the UHF band from 470 MHz to 710 MHz are assigned for the ISDB-T[1]. One of the promising way is to transmit the next generation DTTB signal with the current ISDB-T signal over common frequency band simultaneously. The ISDB-T receiver only requires simple STBC decoder in order to demodulate properly the ISDB-T stream.

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In this paper, we accomplish this task by exploiting the non-orthogonal multiplexing capability of Layered Division Multiplexing (LDM) technique[3]. LDM became popular for next generation DTTB because of its efficient frequency utilization and robust performance. In fact, the LDM was employed in Advanced Television Systems Committee (ATSC) 3.0 as a new technology for next generation DTTB system[4]. LDM is composed of two layers namely primary layer signal for high power signal transmission, and the secondary layer signal designed for high capacity transmission. The signal power assigned at secondary layer is sufficiently low compared to the primary layer.

Although LDM has a similarity to hierarchical modulation, LDM is more flexible compared to hierarchical modulation. LDM has more freedom on how much transmission rate will be implemented for primary and secondary layer. It is because LDM uses two independent constellations with different transmission power overlapping with each other. While hierarchical modulation uses only single constellation for two different information (e.g. combination of 4-PSK for primary layer and 16QAM in the secondary layer results to a 64QAM)[5]. For 4-PSK in 64QAM hierarchical modulation, the number of bits per symbol in each subcarrier is 6, because 2 bits are modulated by using QPSK for primary layer, and additional of 4 bits are modulated for secondary layer. Another example is the QPSK/16QAM hierarchical modulation, where 4 bits per symbol are used[6]. In QPSK/16QAM hierarchical modulation, 2 bits are used for primary layer, while additional of 2 bits for the secondary data stream can be implemented. In summary, the conceptual difference between LDM and hierarchical modulation are: 1.) LDM is configured by use of spectrum overlap technology while the hierarchical modulation mainly focuses on backward compatibility and it does not based on spectrum overlapping. 2.) LDM receiver basically equips signal cancellation to retrieve the secondary layer signal, while the hierarchical receivers does not have such signal cancellation.

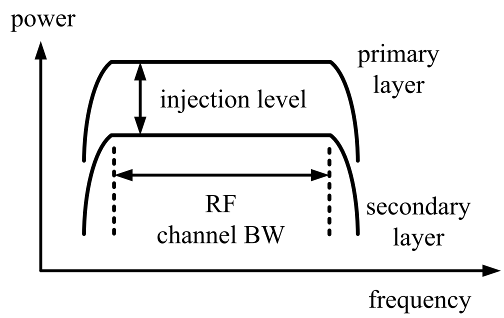

Fig. 1 LDM for ISDB-T and secondary data stream

This paper proposes a dual transmission scheme for ISDB-T and secondary data stream using LDM as illustrated in fig. 1. In fig. 1, the primary layer is assigned for ISDB-T, and the secondary layer is assigned for secondary data stream. However, LDM is prone to interference due to superposition between the primary and secondary layer. And also, the primary layer symbol is wasted because it is only use for cancellation to obtain the secondary layer. In order to solve these issues, the proposed receiver reuses the primary layer to reconstruct higher data rate streams in combination with the secondary data stream. A related work is the augmented data transmission (ADT)-based ultrahigh definition (UHD) television transmission system using an existing ATSC terrestrial DTV system[7]. The ADT combines the Moving Picture Experts Group-2 (MPEG-2) based DTV signal, High Efficiency Video Coding (HEVC)-based DTV signal, and HEVC-based ADT signal to form a 4K UHD video.

With the reuse of the ISDB-T data for next generation DTTB system, we can reduce the transmission capacity requirement for secondary data stream resulting to less implementation of LDM. With partial LDM implementation, we can reduce the interference between upper and lower layer. Hence, the secondary layer data stream does not lay down over the whole symbols, but partial secondary layer symbols are employed to transmit additional data. At the receiver, the estimated ISDB-T symbol is not only used for cancellation itself, but also the demodulated ISDB-T data can be treated as supplemental data of next generation DTTB system. The contribution of this research is threefold:

(1) The proposed system will reuse the current ISDB-T frequency spectrum resulting in a very efficient utilization of the spectrum resources.
(2) The primary layer of LDM is both used as an interference cancellation of secondary layer signal, and part of the transmitted data of the next generation DTTB system. In this way, the primary layer signal will not be wasted since it will be combine with the secondary layer data.
(3) The interference between two layers of LDM will be reduced since not all but part of the transmitted signal are LDM implemented. In this way, the overall error rate of the received data will be reduced.

The rest of the paper is organized as follows. Section 2 describes the system configuration of the proposal. Section 3 explains about LDM for ISDB-T receiver and the proposed next generation DTTB receiver. Section 4 will explain the channel estimation. Section 5 shows the channel capacity of LDM. Performance evaluation is given in Section 6 and conclusions are drawn in the last section.

2. System configuration

Figure 2 shows the system block diagram of the two transmitters and the next generation DTTB receiver in SFN. The next generation DTTB system adopts multiple transmitters that operates in an identical frequency band[8]. Each of the transmitters composes of two antennas with different polarities making the system equivalent to a multiple input multiple output (MIMO) system. The dual polarized antennas transmit simultaneously using horizontal and vertical polarized waves for different data streams resulting to an increase of transmission capacity[2]. Meanwhile, MIMO with STBC for single stream enhances reliability because of diversity gain.

The SFN requires the transmitters to be synchronized with each other to avoid intersymbol interference. One of the techniques for synchronization of the transmitters is longer duration cyclic prefix (CP) of OFDM systems. Longer duration CP makes the transmit delay

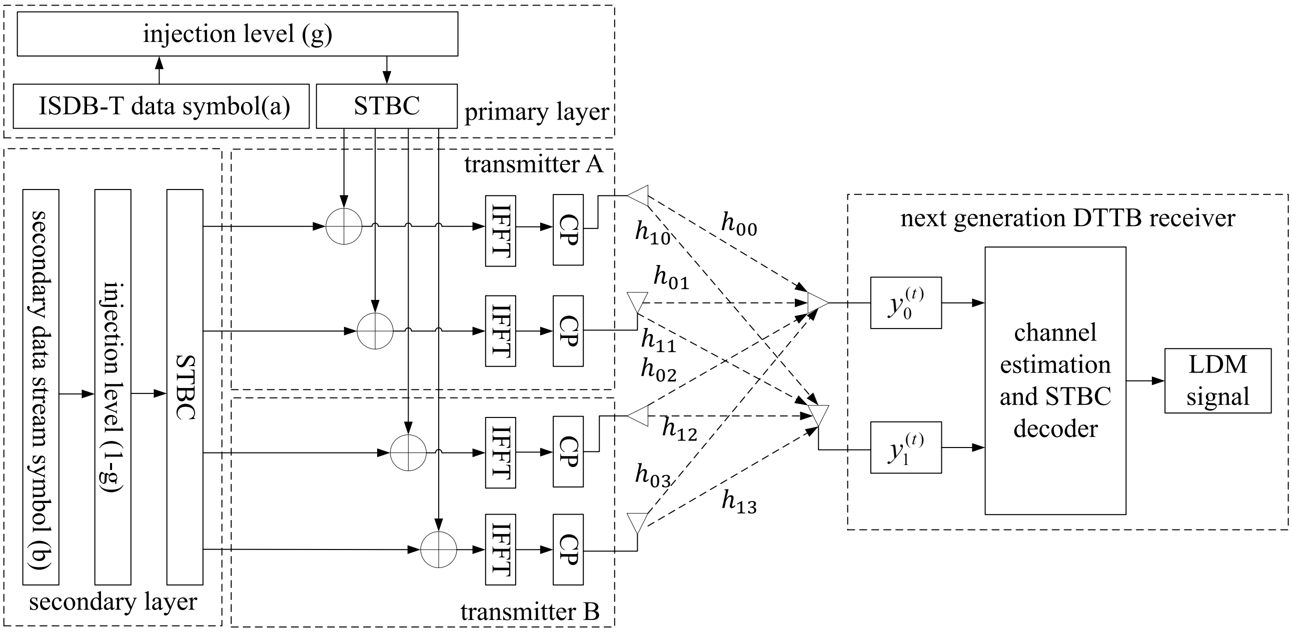

Fig. 2 system block diagram

among different transmitters fall within the duration of CP. Another promising technique is the STBC application[10]. The STBC uses Alamouti code to increase the diversity effect of MIMO.

The proposed system employs LDM where the primary layer is ISDB-T system while the secondary layer is for transmitting a part of high data rate stream that can be combined with ISDB-T. The ISDB-T data and secondary data stream are combined in frequency domain before inverse fast Fourier transform (IFFT). Since the secondary data stream signal is placed in the secondary layer, it is necessary that the signal power will be adjusted using the injection level g before combination with ISDB-T signal.

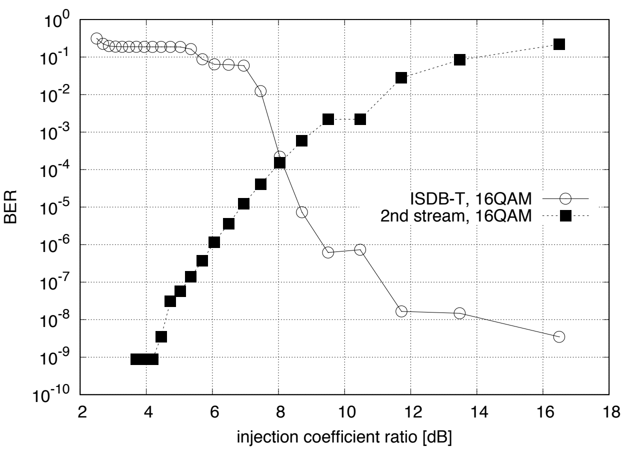

Fig. 3 BER performance for different values of injection coefficient ratio

The way the value of g was chosen is by simulating different values of g as shown in fig. 3. The simulation in fig. 3 shows the bit error rate (BER) performance for the ISDB-T and secondary data stream given the different values of injection coefficient ratio in the Eb/No=25dB region. The injection coefficient ratio can be calculated by $10 \cdot \log(g/(1-g))$. Here we can observe that the optimum value of injection coefficient ratio is around 8dB where the BER for the primary and secondary layer are almost the same.

The system model can be described as a 4×2 MIMO system with a channel defined as $h_{i,j}$ from j-th antenna of the transmitter to i-th antenna of the receiver. The received signal with noise $\mathbf{n}$ can be modeled as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \quad (1)$$

where $\mathbf{y}$ is a vector defined as

$$\mathbf{y} = \begin{bmatrix} y_0^{(t)} \\ y_1^{(t)} \\ \vdots \\ y_0^{(t+3)} \\ y_1^{(t+3)} \\ y_0^{*(t+4)} \\ y_1^{*(t+4)} \\ \vdots \\ y_0^{*(t+7)} \\ y_1^{*(t+7)} \end{bmatrix}. \quad (2)$$

Each entries of $\mathbf{y}$ is a received signal of each antenna. The $y_0^{(t)}$ and $y_1^{(t)}$ are received signals at time t in horizontal and vertical polarization, respectively. The notation $(\cdot)^*$ denotes the complex conjugate.

The channel matrix $\mathbf{H}$ is the equivalent channel matrix for STBC process for primary and secondary layer as shown in fig. 2. The channel matrix $\mathbf{H}$ can be defined as

$$\mathbf{H} = \begin{bmatrix} \mathbf{J} \\ \mathbf{J}^* \end{bmatrix}, \tag{3}$$

where $\mathbf{J}$ is,

$$\mathbf{J} = \begin{bmatrix} h_{00} & h_{01} & h_{02} & h_{03} \\ h_{10} & h_{11} & h_{12} & h_{13} \\ h_{01} & -h_{00} & h_{03} & -h_{02} \\ h_{11} & -h_{10} & h_{13} & -h_{12} \\ h_{02} & -h_{03} & -h_{00} & h_{01} \\ h_{12} & -h_{13} & -h_{10} & h_{11} \\ h_{03} & h_{02} & -h_{01} & -h_{00} \\ h_{13} & h_{12} & -h_{11} & -h_{10} \end{bmatrix}. \tag{4}$$

This type of channel matrix for STBC will have an equivalent STBC rate of 1/2 which is 4 transmitted symbols per 8 time instances. The transmitted signal $\mathbf{x}$ is a composite symbol of primary and secondary layer. It can be represented by

$$\mathbf{x} = \begin{bmatrix} g \cdot a_0 + (1-g) \cdot b_0 \\ g \cdot a_1 + (1-g) \cdot b_1 \\ g \cdot a_2 + (1-g) \cdot b_2 \\ g \cdot a_3 + (1-g) \cdot b_3 \end{bmatrix}, \tag{5}$$

where a_i and b_i corresponds to transmitting symbols for primary and secondary layer in the i-th symbol, respectively. Here we can observed that both ISDB-T signal and secondary data stream signal are both multiplied to the channel matrix $\mathbf{H}$ for STBC. This implies that the ISDB-T signal also undergoes STBC process as shown in fig. 2.

In this paper, we want to propose a partial LDM assuming that the achievable capacity of the secondary layer exceeds the minimum requirements due to the reuse of the ISDB-T data. The proof is provided in section 5. In that way, we need not to implement LDM for all the transmitted signal from ISDB-T transmission and next generation DTTB transmission. With partial LDM, the Eq.(5) can be simplified into

$$\mathbf{x}_{(50)} = \begin{bmatrix} g \cdot a_0 + (1-g) \cdot b_0 \\ g \cdot a_1 + (1-g) \cdot b_1 \\ a_2 \\ a_3 \end{bmatrix}, \tag{6}$$

for 50% partial LDM where 2 out of 4 transmitted signals only use LDM, while

$$\mathbf{x}_{(75)} = \begin{bmatrix} g \cdot a_0 + (1-g) \cdot b_0 \\ g \cdot a_1 + (1-g) \cdot b_1 \\ g \cdot a_2 + (1-g) \cdot b_2 \\ a_3 \end{bmatrix}, \tag{7}$$

is for the case of 75% partial LDM where 3 out of 4 transmitted signals are LDM implemented.

To avoid pilot interference between ISDB-T system and secondary data stream system, the pilot for ISDB-T is shared with the secondary data stream system. The scattered pilots (SP) are transmitted using

$$\begin{bmatrix} \mathrm{SP}_k \\ \mathrm{SP}_k \\ 0 \\ 0 \end{bmatrix}, \tag{8}$$

in the k-th subcarrier of transmitted signal $\mathbf{x}$. The subcarrier position of the SP is the same all throughout the transmitted signals. The section 4 about channel estimation will explain the details on how the received pilots where combined to avoid interference with each other.

3. Proposed LDM decoder

3.1 Primary layer LDM decoder

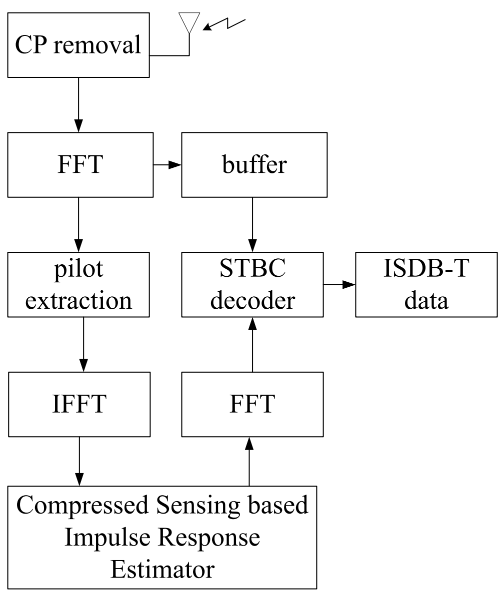

Fig. 4 ISDB-T receiver with STBC decoder

Figure 4 shows the block diagram of the ISDB-T receiver. Since the ISDB-T receiver has only single antenna, the received signal in Eq.(2) and the channel matrix in Eq.(3) are different for the case of ISDB-T.

The received signal for ISDB-T $\mathbf{y}_{(up)}$ in the primary layer LDM is defined to be

$$\mathbf{y}_{(up)} = g\mathbf{H}_{(up)}\mathbf{a} + (1-g)\mathbf{H}_{(up)}\mathbf{b} + \mathbf{n}_{(up)}, \qquad (9)$$

where $\mathbf{a}^T = \begin{bmatrix} a_0 & a_1 & a_2 & a_3 \end{bmatrix}^T$ and $\mathbf{b}^T = \begin{bmatrix} b_0 & b_1 & b_2 & b_3 \end{bmatrix}^T$ are the transmitted ISDB-T data symbols and secondary data stream symbols, respectively. The entries of $\mathbf{y}_{(up)}$ are defined as,

$$\mathbf{y}_{(up)} = \begin{bmatrix} y_1^{(t)} \\ \vdots \\ y_1^{(t+3)} \\ y_1^{*(t+4)} \\ \vdots \\ y_1^{*(t+7)} \end{bmatrix}, \qquad (10)$$

which are composed of symbols from received single antenna. And also, the channel matrix for ISDB-T $\mathbf{H}_{(up)}$ can be defined as

$$\mathbf{H}_{(up)} = \begin{bmatrix} h_{10} & h_{11} & h_{12} & h_{13} \\ h_{11} & -h_{10} & h_{13} & -h_{12} \\ h_{12} & -h_{13} & -h_{10} & h_{11} \\ h_{13} & h_{12} & -h_{11} & -h_{10} \\ h_{10}^* & h_{11}^* & h_{12}^* & h_{13}^* \\ h_{11}^* & -h_{10}^* & h_{13}^* & -h_{12}^* \\ h_{12}^* & -h_{13}^* & -h_{10}^* & h_{11}^* \\ h_{13}^* & h_{12}^* & -h_{11}^* & -h_{10}^* \end{bmatrix}. \qquad (11)$$

The term $(1-g)\mathbf{H}_{(up)}\mathbf{b}$ in Eq.(9) will add an interference to the ISDB-T received signal. To lessen the interference to the ISDB-T signal, the proposed system uses only partial LDM where only part of the total transmitted signal uses LDM[11]. In this way, we can minimize the value of $\mathbf{b}$ which results to a less interference to the received ISDB-T signal. In addition, the injection coefficient g is properly controlled to lessen the signal power of the secondary data stream for further reduction of interference.

Using the received pilot signals, the estimated channel for ISDB-T $\hat{\mathbf{H}}_{(up)}$ can be obtain using compressed sensing in time domain[12]. The channel estimation is explain in section 4 where each entries of $\hat{\mathbf{H}}_{(up)}$ was obtained using compressed sensing based impulse response estimator. And then, the estimated channel for ISDB-T $\hat{\mathbf{H}}_{(up)}$ will be use to decode the ISDB-T symbols a_1, a_2, a_3, and a_4 using STBC[10] with the following equation

$$\hat{\mathbf{a}} = \frac{\hat{\mathbf{H}}_{(up)}^H}{\|\hat{\mathbf{H}}_{(up)}\|}\mathbf{y}_{(up)}, \qquad (12)$$

where $\hat{\mathbf{a}}^T = \begin{bmatrix} \hat{a}_0 & \hat{a}_1 & \hat{a}_2 & \hat{a}_3 \end{bmatrix}^T$ is the estimated signals for ISDB-T. The notation $\|\cdot\|$ and $(\cdot)^H$ denote norm and Hermitian transpose, respectively. The Eq.(12) also describes the STBC block in fig. 4 where the $\mathbf{y}_{(up)}$ is the received signal from the buffer.

3.2 Detection for secondary layer data stream

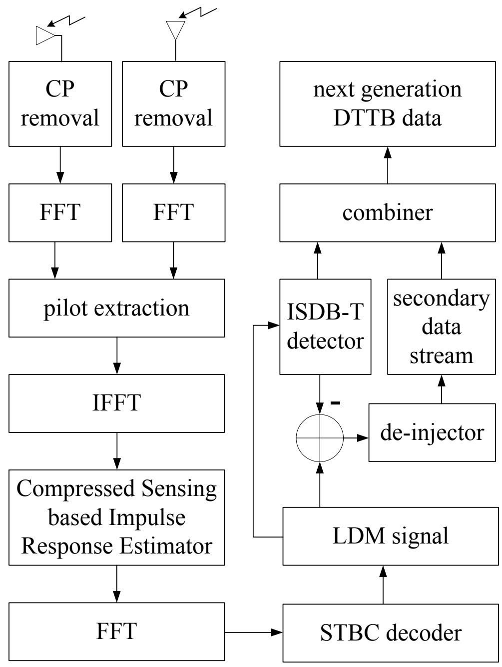

Fig. 5 receiver configuration

For initialization, the proposed receiver will estimate the ISDB-T signal in the primary layer LDM which is basically the same procedure in the Section 3.1. The channel estimation is also using compressed sensing based impulse response estimator as of section 3.1. The details about channel estimation is describe in section 4. And then, the secondary data stream in the secondary layer will be estimated before combining the two data streams to form a data for next generation DTTB system.

Figure 5 shows the block diagram of the proposed next generation DTTB receiver. Here we can see that the receiver is composed of two antennas with different polarities. The equivalent low pass received signal and channel response are denoted by $\mathbf{y}$ and $\mathbf{H}$, of equations (2) and (3), respectively.

At first, using the received pilots, the channel can be estimated using compressed sensing[12]. And then, diversity combined signal using STBC decoding can be represented by,

$$\hat{\mathbf{x}} = \frac{\hat{\mathbf{H}}^H}{\|\hat{\mathbf{H}}\|}\mathbf{y}, \qquad (13)$$

where $\hat{\mathbf{x}}^T = \begin{bmatrix} \hat{x}_0 & \hat{x}_1 & \hat{x}_2 & \hat{x}_3 \end{bmatrix}^T$. Estimated symbol of secondary layer $\hat{\mathbf{b}}$ can be obtained as,

$$\hat{\mathbf{b}} = \frac{1}{1-g}(\hat{\mathbf{x}} - g \cdot \hat{\mathbf{a}}). \quad (14)$$

Finally, using the combiner, we can exploit the ISDB-T data $\hat{\mathbf{a}}$ and the secondary data stream $\hat{\mathbf{b}}$ to acquire the whole transmitting data.

4. Channel estimation using compressed sensing

This section will discuss the channel estimation for both ISDB-T receiver and next generation DTTB receiver using compressed sensing (CS). Although other channel estimation methods are also applicable in this system, CS was chosen because the channel is considered as sparse. CS is a popular technique for estimating a sparse information using only few measurements[13)]. A sparse can be defined as a vector where most entries are zero and only few are non-zero. The sparse information that we are going to estimate is the channel impulse response (CIR)[12)]. The CS equation can be defined as

$$\delta = \mathbf{\Phi}\hat{\delta} + \mathbf{n}, \quad (15)$$

where δ, $\mathbf{\Phi}$, and $\hat{\delta}$ is the observed CIR vector, measurement matrix, and estimated CIR vector, respectively. We can estimate the CIR in Eq.(15) using the algorithm of CS called Orthogonal Matching Pursuit (OMP)[14)].

In order to avoid pilot interference from different antenna, the demodulator needs four different received signals in different time instant for each receiving antenna. The observed CIR $\delta_{i,j}$ for each channel $h_{i,j}$ can be obtain using pilot extraction defined as

$$\delta_{00} = \frac{1}{4}\mathbf{F}^{-1}\mathbf{E}\Big(\mathbf{y}_0^{(t)} - \mathbf{y}_0^{(t+1)} + \mathbf{y}_0^{(t+4)} - \mathbf{y}_0^{(t+5)}\Big), \quad (16)$$

$$\delta_{01} = \frac{1}{4}\mathbf{F}^{-1}\mathbf{E}\Big(\mathbf{y}_0^{(t)} + \mathbf{y}_0^{(t+1)} + \mathbf{y}_0^{(t+4)} + \mathbf{y}_0^{(t+5)}\Big), \quad (17)$$

$$\delta_{02} = \frac{1}{4}\mathbf{F}^{-1}\mathbf{E}\Big(\mathbf{y}_0^{(t+2)} + \mathbf{y}_0^{(t+3)} + \mathbf{y}_0^{(t+6)} + \mathbf{y}_0^{(t+7)}\Big), \quad (18)$$

$$\delta_{03} = \frac{1}{4}\mathbf{F}^{-1}\mathbf{E}\Big(-\mathbf{y}_0^{(t+2)} + \mathbf{y}_0^{(t+3)} - \mathbf{y}_0^{(t+6)} + \mathbf{y}_0^{(t+7)}\Big), \quad (19)$$

$$\delta_{10} = \frac{1}{4}\mathbf{F}^{-1}\mathbf{E}\Big(\mathbf{y}_1^{(t)} - \mathbf{y}_1^{(t+1)} + \mathbf{y}_1^{(t+4)} - \mathbf{y}_1^{(t+5)}\Big), \quad (20)$$

$$\delta_{11} = \frac{1}{4}\mathbf{F}^{-1}\mathbf{E}\Big(\mathbf{y}_1^{(t)} + \mathbf{y}_1^{(t+1)} + \mathbf{y}_1^{(t+4)} + \mathbf{y}_1^{(t+5)}\Big), \quad (21)$$

$$\delta_{12} = \frac{1}{4}\mathbf{F}^{-1}\mathbf{E}\Big(\mathbf{y}_1^{(t+2)} + \mathbf{y}_1^{(t+3)} + \mathbf{y}_1^{(t+6)} + \mathbf{y}_1^{(t+7)}\Big), \quad (22)$$

$$\delta_{13} = \frac{1}{4}\mathbf{F}^{-1}\mathbf{E}\Big(-\mathbf{y}_1^{(t+2)} + \mathbf{y}_1^{(t+3)} - \mathbf{y}_1^{(t+6)} + \mathbf{y}_1^{(t+7)}\Big), \quad (23)$$

where $\mathbf{F}$ and $\mathbf{E}$ are the N-size FFT matrix and pilot arrangement matrix, respectively. The vector $\mathbf{y}_i$ is the OFDM received signal for all subcarriers of the i-th antenna in vector form with size N. The FFT matrix can be described as

$$\mathbf{F} = \frac{1}{\sqrt{N}}\left[\exp\left(-j\frac{2\pi kn}{N}\right)\right]_{\substack{0 \leqq k < (N-1) \\ 0 \leqq n < (N-1)}}, \quad (24)$$

while pilot arrangement matrix $\mathbf{E}$ is a diagonal matrix where the diagonal part contains $\mathbf{e} = \begin{bmatrix} e_0 & e_1 & \cdots & e_{N-1} \end{bmatrix}^T$. Each entries of $\mathbf{e}$ is defined as,

$$e_{Cm+i} = \begin{cases} \dfrac{1}{\mathrm{SP}_m} & (i=0) \\ 0 & (0 < i < C) \end{cases}, \quad (25)$$

where $m \in \{0, ..., (M-1)\}$ and $C = N/M$. The SP_m is the m-th pilot symbol out of M total of pilots placed in OFDM subcarriers.

For the case of measurement matrix $\mathbf{\Phi}$, the measurement matrix is given by,

$$\mathbf{\Phi} = \mathbf{F}^{-1}\mathbf{Q}\mathbf{F}, \quad (26)$$

where $\mathbf{Q} = \mathrm{diag}(\mathbf{q}), \mathbf{q} = \begin{bmatrix} q_0 & q_1 & \cdots & q_{N-1} \end{bmatrix}^T$ that indicates the position of the pilots in the subcarriers. Each entries of $\mathbf{q}$ is defined as,

$$q_{Cm+i} = \begin{cases} 1 & (i=0) \\ 0 & (0 < i < C) \end{cases}. \quad (27)$$

Finally, we can now estimate the CIR $\hat{\delta}$ of Eq.(15) using OMP algorithm. The OMP is a greedy method that aims stagewise minimization of the approximation error to the observed CIR[14)].

The algorithm 1 shows the details about the OMP. For the initialization of OMP, the algorithm needs only the observed CIR δ and the number of iteration η. After obtaining the estimated CIR $\hat{\delta}$, the estimated channel $\hat{\mathbf{h}}$ can now be acquire by $\hat{\mathbf{h}} = \mathbf{F}^{-1}\hat{\delta}$.

Algorithm 1 Orthogonal Matching Pursuit (OMP)

Require: δ ▷ observed vector
Ensure: $\hat{\delta}$ ▷ estimated sparse vector
$\mathbf{r}_i \leftarrow \delta$
$\mathbf{\Phi} = \begin{bmatrix}\phi_0 & \phi_1 & \cdots & \phi_N\end{bmatrix}$
$\mathbf{\Lambda}_i \leftarrow [\,]$
$\mathbf{Y}_i \leftarrow [\,]$
$i \leftarrow 1$
while $i \leqq \eta$ **do**
$\lambda_i = \arg\max_k |\mathbf{r}_{i-1}^H \phi_k|$
$\mathbf{\Lambda}_i = \mathbf{\Lambda}_{i-1} \cup \{\lambda_i\}$
$\mathbf{Y}_i = [\mathbf{Y}_{i-1}, \phi_{\lambda_i}]$
$\mathbf{w}_i = \arg\min_w ||\mathbf{Y}_i \mathbf{w} - \delta||_2^2$
$\mathbf{r}_i = \delta - \mathbf{Y}_i \mathbf{w}_i$
$i = i + 1$
end while
return $\hat{\delta} = \mathbf{w}_\eta$

5. Achievable channel capacity

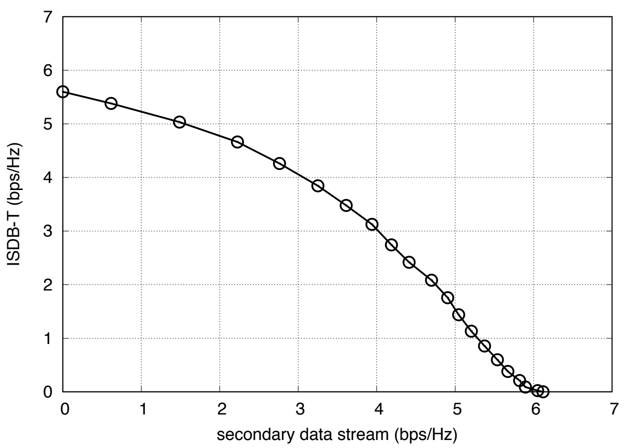

Fig. 6 ISDB-T and secondary data stream capacity trade-off for LDM

Figure 6 shows the achievable channel capacity trade-off between ISDB-T and secondary data stream using LDM. The channel capacity for the primary layer can be obtained using

$$R_u = R \cdot E\left[\log\left(1 + \sum_{n_m=0}^{7} \frac{g^2 \frac{\mathrm{SNR}_u}{T_\mathrm{x}} ||[\mathbf{H}_{(up)}]_{n_m}||^2}{1 + (1-g)^2 \frac{\mathrm{SNR}_u}{T_\mathrm{x}} ||[\mathbf{H}_{(up)}]_{n_m}||^2}\right)\right], \quad (28)$$

while the channel capacity for the secondary layer is

$$R_l = R \cdot E\left[\log\left(1 + (1-g)^2 \frac{\mathrm{SNR}_l}{T_\mathrm{x}} ||[\mathbf{H}]||^2\right)\right]. \quad (29)$$

A derivation of the eq.(28) is provided in the appendix section A for further explanation. The R and T_x are the STBC maximal rate and number of transmitter antennas, respectively[9]. While the SNR_u and SNR_l refers to the SNR threshold for primary and secondary layer, respectively. We assume that the $\mathrm{SNR}_u = 20$dB, and $\mathrm{SNR}_l = 25$dB which is a reasonable value for fixed receiver with roof-top antennas[3].

For the DTTB system using ADT, the capacity will only require 12Mbps for MPEG-2 signal and 12.5Mbps for HEVC signal to form a 4K (30 frames) UHDTV[7]. Assuming that the ISDB-T only requires 3 bps/Hz for a 6 MHz bandwidth, the achievable spectral efficiency for secondary data stream will be around 24Mbps based on the fig. 6. A 24Mbps channel capacity is assumed to have an ideal channel coding, and a perfect channel estimation wherein pilots are unnecessary. We also assumed that the receiver side uses a maximum ratio combiner for the received signals. A 24Mbps for secondary data stream is too high since the requirement is only around 12.5Mbps. With the reuse of the ISDB-T data for next generation DTTB system, we can reduce the capacity load for the secondary data stream. In this way, we proposed a partial LDM to reduce the achievable capacity of the secondary data stream while reducing the error rate due to interference between primary and secondary layer of LDM.

6. Numerical analysis

Table 1 simulation parameters

LDM layer	primary	secondary
data	ISDB-T	secondary data stream
modulation	QPSK, 16QAM	QPSK, 16QAM, 64QAM, 256QAM
channel estimation (CE)	OMP	OMP with perfect ISDB-T detector
OMP iteration (η)	6	6
injection coefficient ratio $10 \cdot \log(g/(1-g))$	QPSK in fig.7→ 12dB QPSK in fig.8,10 → 6dB 16QAM in fig.9,11,12 → 8dB 64QAM in fig.12 → 7.5dB 256QAM in fig.12 → 6.9dB	
FFT size (N)	8192	
number of pilot (M)	1024	
pilot type	scattered	
guard interval	$N/16$	
OFDM frame	10,000	
channel model	TU6	
noise type	AWGN	

Table 2 TU6 delay profile

delay (μs)	power (dB)
0	-3
0.2	0
0.5	-2
1.6	-6
2.3	-8
5.0	-10

Table 3 bit rate

modulation type	full LDM	75% LDM	50% LDM
QPSK	7.11Mbps	5.33Mbps	3.56Mbps
16QAM	14.22Mbps	10.67Mbps	7.11Mbps
64QAM	21.33Mbps	16.00Mbps	10.67Mbps
256QAM	28.44Mbps	21.33Mbps	14.22Mbps
1024QAM	35.56Mbps	26.67Mbps	17.78Mbps

The computer simulation was performed using C++ library for signal processing and communication[16]. Table 1 shows the simulation parameters of the experiment for both primary and secondary layers of LDM. For simplicity purposes, a forward error correction for primary layer is assumed to be ideal e.g. perfect ISDB-T detector. Table 2 shows the delay profile of the TU6 channel model used in the simulation[17]. In this simulation, the performance of the ISDB-T system for primary layer, and the secondary layer are investigated separately. The Eb/No that was used in this experiment is the Eb/No of the secondary layer. Table 3 shows the bit rate for different modulation type vs. LDM type if the channel characteristic is ignore. The bit rate is calculated using

$$\frac{(\text{STBC rate}) \cdot (N - M) \cdot \log_2(\text{modulation type})}{\text{duration of effective OFDM symbol}}$$

where the STBC rate are 1/2, 3/8, and 1/4 for full LDM, 75% LDM, and 50% LDM, respectively. The OFDM effective symbol period is $1008\mu s$[1]. The bit rate shown in the table is both applicable for primary and secondary layer since both layer exhibit STBC transmission.

At first, we will evaluate the performance of the system using the conventional ISDB-T receiver without STBC decoder.The conventional ISDB-T receiver can demodulate without any problem using

$$\begin{bmatrix} g \cdot a + (1-g) \cdot b_0 \\ g \cdot a + (1-g) \cdot b_1 \\ (1-g) \cdot b_2 \\ (1-g) \cdot b_3 \end{bmatrix}, \qquad (30)$$

as a transmitted signal for Eq.(5). For simplicity, we use the same ISDB-T symbol a for all time instances t to $t+7$. The conventional ISDB-T detection is described in appendix section B. Figure 7 shows the bit error rate (BER) performance for the conventional ISDB-T, and the secondary data stream for next generation DTTB receiver. The BER performance for ISDB-T is within acceptable error rate in the Eb/No=25dB region using QPSK for both layers. However, the performance for the secondary data stream is only limited to the low order modulation such as QPSK. In the next simulations, a STBC decoder will be added to the ISDB-T receiver to lessen the error rate, and to allow higher order modulation for secondary data stream.

For the ISDB-T with STBC decoder, the simulation compares the BER in cases of two transmitters and single transmitter. And then, we will evaluate the performance of the proposed partial LDM in comparison with full LDM. The performance for higher modulation will be discuss in the last part of the simulation. The pairs in the simulations (e.g. pair A, pair B, and pair C) indicate the pair of primary and secondary layers of LDM. For example in fig. 8, pair A describes the ISDB-T as a primary layer, and 2nd stream as a secondary layer wherein the system has 2 transmitters. On the other hand, the pair B indicates that the primary layer is the ISDB-T, and the secondary layer is the 2nd stream where the system only uses 1 transmitter.

From all the results of the shown figures, we always observed that the ISDB-T receiver has low error rate compared to that of secondary data stream because primary layer has higher power compared to the secondary layer.

Figure 8 shows the BER performance of the ISDB-T receiver and secondary data stream using QPSK. In fig. 8, we compare the performance with two transmitters versus single transmitter using full LDM. In order to realize single transmitter, the values of $h_{02}, h_{12}, h_{03}, h_{13}$ of $\mathbf{J}$ and $\mathbf{H}_{(up)}$ will be set to zero. The $h_{02}, h_{12}, h_{03}, h_{13}$ are the channels for transmitter B in fig. 2. While for the case of two transmitter, the values of $h_{02}, h_{12}, h_{03}, h_{13}$ of $\mathbf{J}$ and $\mathbf{H}_{(up)}$ will be nonzero. In fig. 8, the error rate for 2 transmitters is less compared to single transmitter. It is found that the diversity improves the performance when the number of transmitter increases. In the Eb/No region of 25dB, we can improve up to 10dB for ISDB-T, while 5dB for secondary data stream.

Similarly, the BER performance of 16QAM is shown in fig. 9. In this figure, the performance for 2 transmitters has less error rate compared with single transmitter. In Eb/No region of 25dB, the diversity improves the performance of both layers by around 5dB.

Figure 10 shows the BER performance of partial LDM. In this figure, we compare partial LDM of 50% and 75%, with the full LDM. The transmitted signal for partial LDM of 50% and 75% can be described in Eq.(6) and Eq.(7), respectively. Here we observed that the performance of the secondary data stream is the same in spite of partial use in LDM. The partial LDM slightly changes the BER performance of the ISDB-T. In fig. 10, we observed a higher error rate in case of ISDB-T full LDM compared to ISDB-T partial LDM. The difference of the ISDB-T full LDM and ISDB-T partial LDM is of 1dB because the modulation that was implemented is only QPSK.

However, for the case of 16QAM as shown in fig. 11, we observed that the error rate for the ISDB-T partial LDM of 50% and 75% is around 2dB and 1dB lower compared to full LDM in the Eb/No region of 25dB. Theoretically, partial LDM realizes lower interference compared to full LDM because the value of the term $g\mathbf{H}_{(up)}\mathbf{b}$ in Eq. (9) is lesser which represents the secondary layer signal.

To fully qualify for 4K transmission, the primary layer should have at least 12Mbps, while the secondary layer should be at least 12.5Mbps[7]. Based on table 3, the primary layer and secondary layer can use 16QAM or higher order using full LDM. In fig. 11, the full LDM for both layers using 16QAM qualifies to transmit a 4K transmission. Other option is to use a 16QAM for primary layer, and 64QAM in the secondary layer. However, the transmission capacity using 64QAM full LDM is around 21.33Mbps which is high enough in comparison to a minimum requirement of 12.5Mbps. In that way, a 75% partial LDM can be applied to reduce the transmission capacity to 16Mbps and lessen the bit error rate in the primary layer. Figure 12 shows the BER performance of the primary layer set to 16QAM, together with various modulation type in the secondary layer. All the parameters in fig. 12 is capable of 4K transmission. In this figure, the Eb/No is set to 25dB. Here we can observe that we can gradually reduce the error for the primary layer using partial LDM.

In summary, the BER performance for ISDB-T without STBC decoder is within acceptable level. However, the modulation type for secondary layer is only limited to low order type, e.g. QPSK. With the ISDB-T receiver with STBC decoder, it can lessen the error rate which opens an opportunity for the secondary layer to implement higher order modulation. Increasing the number of transmitters can also lessen the error rate for both primary and secondary layer due to STBC diversity. In addition, implementing a partial LDM can lessen further the error rate due to less interference between primary and secondary layer.

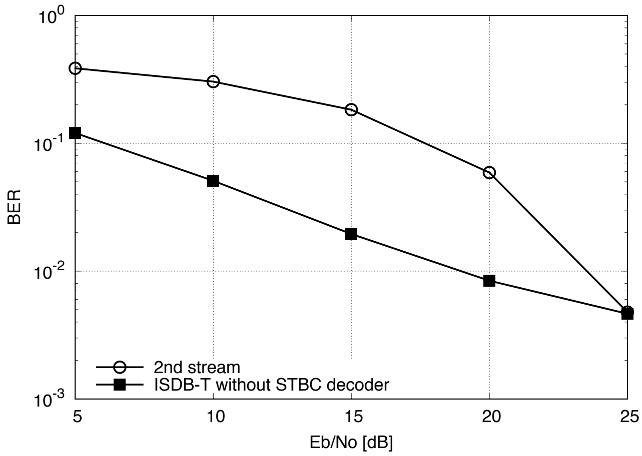

Fig. 7 BER performance using conventional ISDB-T receiver without STBC decoder, and the secondary data stream

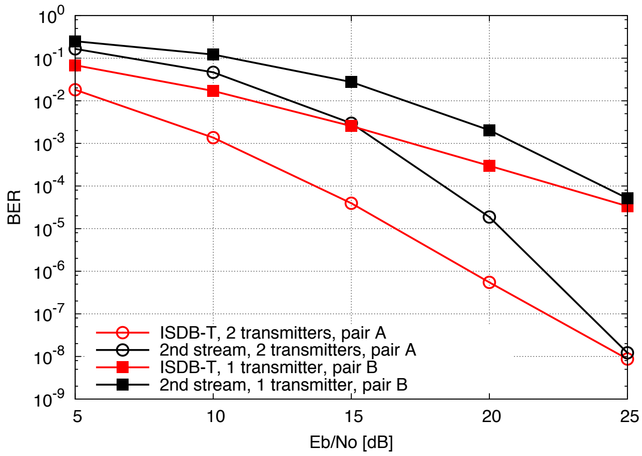

Fig. 8 BER performance for 2 transmitters vs. 1 transmitter using QPSK full LDM

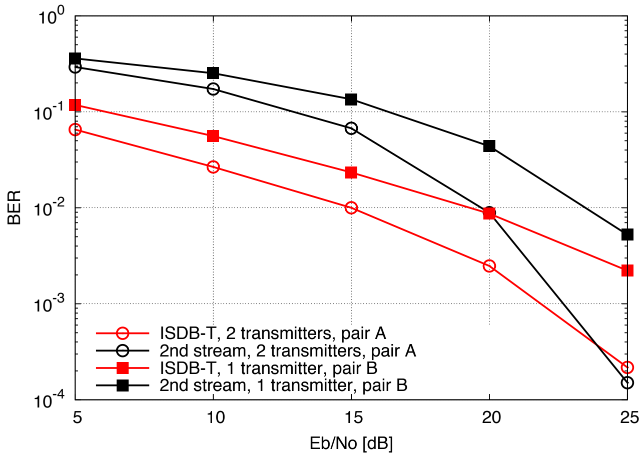

Fig. 9 BER performance for 2 transmitter vs. 1 transmitter using 16QAM full LDM

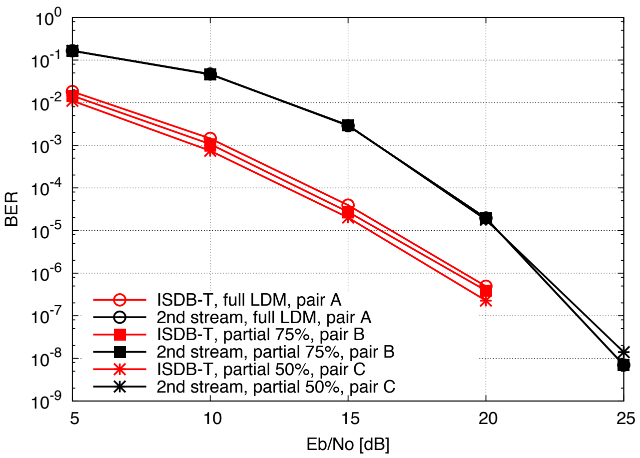

Fig. 10 BER performance for full LDM vs. partial LDM using QPSK

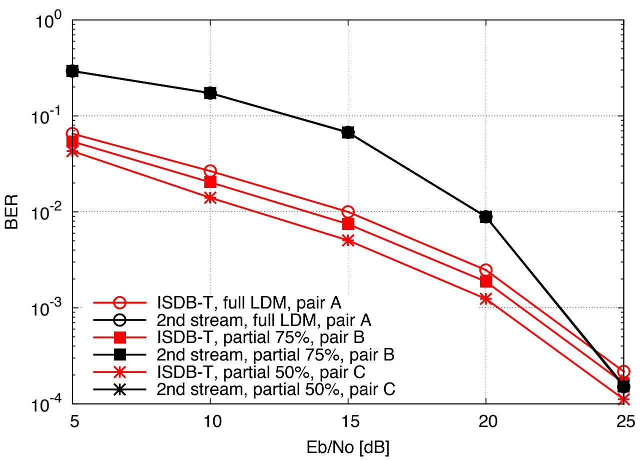

Fig. 11 BER performance for full LDM vs. partial LDM using 16QAM

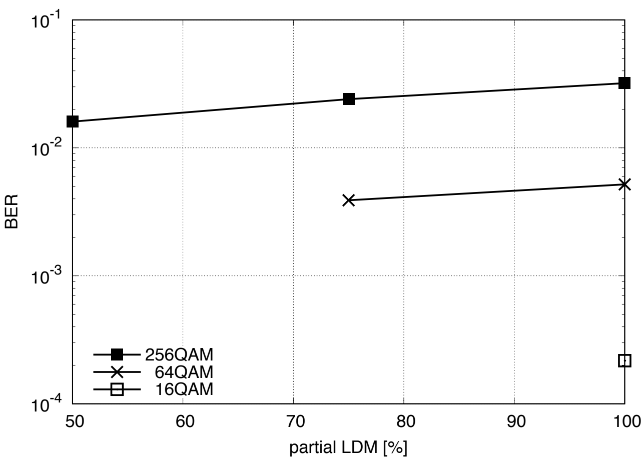

Fig. 12 BER performance for primary layer using various modulation type in secondary layer; Eb/No=25dB, 16QAM for primary layer

7. Conclusions

This paper proposed an efficient broadcast transmission system for the ISDB-T system and next generation terrestrial DTTB system. For efficient frequency spectrum utilization, we implemented LDM to transmit the ISDB-T in the primary layer and a secondary data stream in the secondary layer of LDM. The proposed system is carried out using space time block coding in a single frequency network to increase the diversity gain.

In order not to waste the primary layer of LDM, the next generation DTTB system reuses the primary layer by combining the ISDB-T data and the secondary data stream. In this way, we can lessen the interference between two layers of LDM by implementing partial LDM where only few transmitted signal uses LDM. Partial LDM can be applied since the achievable capacity for the secondary layer exceeds the required capacity due to reuse of primary layer.

The simulation of the conventional ISDB-T without STBC decoder shows an acceptable error rate of 10^{-3} to 10^{-2} in the Eb/No=25dB region. However, the modulation type for the secondary layer is only limited to QPSK, which suggest an implementation of STBC decoder for ISDB-T. The simulation for LDM-STBC with multiple transmitters shows that error rate for both layers can be lessen compared to the system with only single transmitter. In addition, the BER performance of primary layer was further improved by introducing partial LDM. To fully qualify for 4K transmission, both layers should be at least 16QAM, or a partial LDM can be applied in the secondary layer when using modulation type higher than 16QAM.

Appendix

A. Derivation of Eq.(28)

Let us first define a ergodic spectral efficiency of STBC as[9)]

$$R \cdot E\Big[\log(1+\mathrm{SNR})\Big],$$

where the STBC maximal rate R

$$R = \frac{T_x/2+1}{T_x},$$

for T_x even, and

$$R = \frac{(T_x+1)/2+1}{T_x+1},$$

for T_x odd.

For simplicity, let us assumed that $T_x = 2$. The

Alamouti scheme operates across two successive channels i.e. subcarriers $j = 1, 2$. The received signal for the primary layer can be described as

$$\mathbf{y}_{(up)}[j] = g\sqrt{\mathrm{SNR}_u}\mathbf{H}_{(up)}\mathbf{a}[j] + (1-g)\sqrt{\mathrm{SNR}_u}\mathbf{H}_{(up)}\mathbf{b}[j] + \mathbf{n}[j].$$

The $\mathbf{b}[j]$ can be treated as Gaussian noise with zero mean, covariance matrix $\mathbf{I}/2$ where $1/2$ accounts for the power allocation of 2 antennas. As a result, the effective noise $\mathbf{n}_{\mathrm{eff}}[j] = (1-g)\sqrt{\mathrm{SNR}_u}\mathbf{H}_{(up)}\mathbf{b}[j] + \mathbf{n}[j]$.

For each received signal, the effective noise power can be approximated to be $1+(1-g)^2\mathrm{SNR}_u||[\mathbf{H}_{(up)}]_{n_m}||^2/2$, where $[\mathbf{H}_{(up)}]_{n_m}$ is the n_m-th row of $\mathbf{H}_{(up)}$.

For example, in the case of two channels e.g. $j = 1, 2$, the received signal can be written as

$$\begin{bmatrix}[\mathbf{y}_{(up)}[1]]_{n_m} \\ [\mathbf{y}_{(up)}[2]]^*_{n_m}\end{bmatrix} = g\sqrt{\mathrm{SNR}_u}\begin{bmatrix}[\mathbf{H}_{(up)}]_{n_m,1} & [\mathbf{H}_{(up)}]_{n_m,2} \\ [\mathbf{H}_{(up)}]^*_{n_m,2} - & [\mathbf{H}_{(up)}]^*_{n_m,1}\end{bmatrix} \cdot \begin{bmatrix}u_1 \\ u_2\end{bmatrix} + \begin{bmatrix}[\mathbf{n}_{\mathrm{eff}}[1]]_{n_m} \\ [\mathbf{n}_{\mathrm{eff}}[2]]_{n_m}\end{bmatrix}$$

where $\begin{bmatrix}u_1 & u_2\end{bmatrix}^T$ is the transmitted information symbols with power 1/2. And then, projecting the transmitted vector into k-th column of the channel matrix will result to a signal equal to

$$g\sqrt{\mathrm{SNR}_u}||[\mathbf{H}_{(up)}]_{n_m}||^2 u_k + w_k$$

where noise w_k has a power equivalent to $1 + (1-g)^2\mathrm{SNR}_u||[\mathbf{H}_{(up)}]_{n_m}||^2/2$. Finally, the SNR can be calculated as

$$\mathrm{SNR} = \frac{g^2 \cdot \mathrm{SNR}_u||[\mathbf{H}_{(up)}]_{n_m}||^2}{2(1 + (1-g)^2 \cdot \mathrm{SNR}_u||[\mathbf{H}_{(up)}]_{n_m}||^2/2)}$$

B. Conventional ISDB-T detection for Eq.(30)

The way the detection of conventional ISDB-T receiver is for every time instance. For example in time instance t at the received signal $y_1^{(t)}$, the received signal will be

$$y_1^{(t)} = g \cdot a \cdot h_{10} + (1-g) \cdot b_0 \cdot h_{10} + g \cdot a \cdot h_{11} + (1-g) \cdot b_1 \cdot h_{11} + (1-g) \cdot b_2 \cdot h_{12} + (1-g) \cdot b_3 \cdot h_{13} + n$$

The effective noise n_{eff} will be

$$n_{eff} = (1-g) \cdot b_0 \cdot h_{10} + (1-g) \cdot b_1 \cdot h_{11} + (1-g) \cdot b_2 \cdot h_{12} + (1-g) \cdot b_3 \cdot h_{13} + n.$$

The received signal can now be simplified as

$$y_1^{(t)} = g \cdot a \cdot (h_{10} + h_{11}) + n_{eff}.$$

Here we can measure the channel $(h_{10} + h_{11})$ because a contains the pilots based on Eq. 8. Dividing the whole equation above with $(h_{10}+h_{11})$ will result to a detection of $\tilde{a}$

$$\tilde{a} = \frac{y_1^{(t)}}{(h_{10} + h_{11})} = g \cdot a \cdot + \frac{n_{eff}}{(h_{10} + h_{11})}.$$

The value of g should be high enough for decent detection of a. The process above is also the same in other receive signals $y_1^{(t+1)}, ..., y_1^{(t+7)}$.

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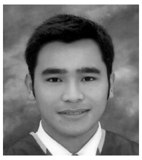

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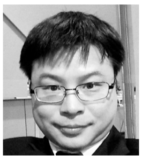

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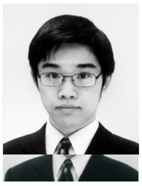

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