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Distributed MIMO Schemes for the Future Digital Video Broadcasting

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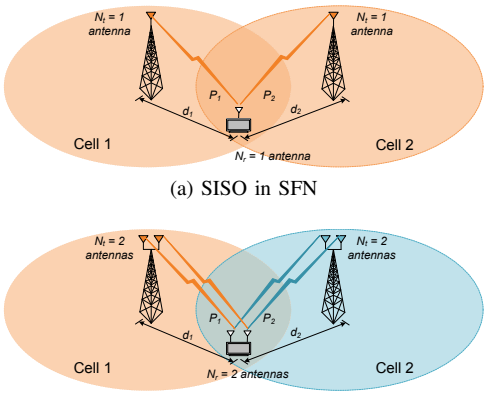
***Abstract*—This paper studies the application of distributed multiple-input multiple-output (MIMO), i.e. MIMO transmission over several geographically separated but cooperated transmitters, for future TV broadcasting systems. It is first shown that distributed MIMO is promising for the future broadcasting systems from a channel capacity perspective. Several STBCs that can be applied in the distributed MIMO broadcasting scenarios are then discussed. Through performance comparison and complexity analyses with realistic system settings and channel model, it can be concluded that simple STBCs are efficient for low data rate applications, while the sophisticated ones are more suitable to deliver high data rate services.**

I. Introduction

Nowadays, broadcasters are facing the challenge of delivering new services such as three-dimensional (3D) TV, Ultra High Definition TV (UHDTV) and mobile TV which require broadcasting systems being more efficient and reliable. Multiple-input and multiple-output (MIMO) technique has drawn much attention from both researchers and industries in the last decades. By using multiple antennas at both transmit and receive sides, MIMO can greatly increase the system throughput with improved reliability.MIMO technique has been widely applied in state-of-the-art communication systems, such as IEEE 802.11n, 3GPP Long Term Evolution (LTE) and WiMAX.

The Digital Video Broadcasting (DVB) project has also begun the research on the application of MIMO technique in TV broadcasting. The latest DVB-Terrestrial second generation (DVB-T2) [1] has integrated a transmit diversity option using Alamouti code [2]. Yet, it does not fully exploit the merits of MIMO technique, because only one antenna is used at the receiver side. The under-developing DVB-Next Generation Handheld (DVB-NGH) [3] system incorporates MIMO profile with two receive antennas in order to increase the efficiency and reliability of mobile TV broadcasting.

In this work, we study the application of MIMO technique with distributed implementation in the TV broadcasting. The advantage of distributed MIMO broadcasting over the traditional SFN broadcasting in terms of channel capacity is discussed in Section II. Several important space-time block codes (STBC) that are suitable for the distributed MIMO broadcasting are discussed in Section III. These STBCs are compared in terms of BER performances and ST decoding complexities with real system configurations and channel models in Section IV. Finally, some concluding remarks are drawn in Section V. $\mathbf{A}^T$ and $\mathbf{A}^{\mathcal{H}}$ are the transpose and Hermitian transpose of matrix $\mathbf{A}$; $\mathbb{E}\{a\}$ is the expectation of a.



(a) SISO in SFN

(b) Distributed MIMO

Fig. 1. Different broadcasting scenarios.

II. Distributed MIMO Broadcasting

A. SFN broadcasting

Single frequency network (SFN) is a popular and spectrally efficient network implementation in the modern digital TV broadcasting systems. Several geographically separated transmitters in SFN simultaneously transmit the same signal (TV program) in the same TV frequency band. Hence, SFN can easily achieve a large coverage without requiring extra frequency bands. Fig. 1a shows a simple SFN with two transmission sites. In the Orthogonal Frequency-Division Multiplexing (OFDM) based DVB system with N subcarriers, the received signal can be written in a frequency domain form:

$$\mathbf{Y} = \underbrace{(\lambda_1 \mathbf{H}_1 + \lambda_2 \mathbf{H}_2)}_{\mathbf{H}} \mathbf{X} + \mathbf{W}, \tag{1}$$

where $\mathbf{H}_j = \mathrm{diag}([H_j(1), \ldots, H_j(N)])$, $j = 1, 2$ are the channel matrices associated to the jth transmission site with $H_j(k)$ being the channel frequency response of the kth subcarrier. λ_1 and λ_2 are the factors scaling propagation path losses associated with the two channels, respectively. $\mathbf{X} = [X(1), \ldots, X(N)]^T$, $\mathbf{Y} = [Y(1), \ldots, Y(N)]^T$ and $\mathbf{W} = [W(1), \ldots, W(N)]^T$ are the transmitted signal, received signal and noise vectors. Given the overall transmission power P, the covariance matrix of the transmitted signal is $\mathbf{\Sigma} = \mathbb{E}\{\mathbf{X}\mathbf{X}^{\mathcal{H}}\} = \frac{P}{2N}\mathbf{I}_N$. $\mathbf{W}$ satisfies $\mathbb{E}\{\mathbf{W}\mathbf{W}^{\mathcal{H}}\} = \sigma_n^2 \mathbf{I}_N$.

The ergodic capacity of SFN channel is therefore:

$$C_{\text{SFN}} = \mathbb{E}\left\{\frac{1}{N}\log_2\left(\det\left(\mathbf{I}_N + \frac{1}{\sigma_n^2}\mathbf{H}\boldsymbol{\Sigma}\mathbf{H}^{\mathcal{H}}\right)\right)\right\}$$
$$=\mathbb{E}\left\{\frac{1}{N}\sum_{k=0}^{N-1}\log_2\left(1+\frac{P}{2N\sigma_n^2}\left(\lambda_1^2|H_1(k)|^2+\lambda_2^2|H_2(k)|^2\right)\right)\right\}. \quad (2)$$

B. Distributed MIMO broadcasting

Traditionally, MIMO is realized using several co-located transmit antennas on the same transmission site. In fact, MIMO transmission can also be implemented among multiple cooperated transmission sites. This yields the so-called distributed MIMO. Fig. 1b illustrates the distributed MIMO broadcasting scenario discussed in this paper. Two adjacent transmission sites cooperate with each other. Each site has two transmit antennas. Accordingly, the receiver has two receive antennas.

The received distributed MIMO signal can be written as:

$$\mathbf{Y} = \underbrace{[\mathbf{H}_1\ \mathbf{H}_2]}_{\mathbf{H}}\underbrace{\begin{bmatrix}\boldsymbol{\Lambda}_1 & 0\\ 0 & \boldsymbol{\Lambda}_2\end{bmatrix}}_{\boldsymbol{\Lambda}}\underbrace{\begin{bmatrix}\mathbf{X}_1\\ \mathbf{X}_2\end{bmatrix}}_{\mathbf{X}}+\mathbf{W}, \quad (3)$$

where $\mathbf{X}_j = [X_{j,1}(1),\ldots X_{j,N_t}(1),\ldots X_{j,1}(N),\ldots X_{j,N_t}(N)]^T$ and $\boldsymbol{\Lambda}_j = \lambda_j\mathbf{I}_{NN_t}$ $(j=1,2)$ are the transmitted signal and the path loss associated to the jth transmission site, respectively. $\mathbf{Y} = [Y_1(1),\ldots Y_{N_r}(1),\ldots Y_1(N),\ldots X_{N_r}(N)]^T$ and $\mathbf{W} = [W_1(1),\ldots W_{N_r}(1),\ldots W_1(N),\ldots W_{N_r}(N)]^T$ denote the received signal and noise components, respectively. $\mathbf{H}_1$ and $\mathbf{H}_2$ are channel matrices for $N_r \times N_t$ MIMO-OFDM system:

$$\mathbf{H}_j = \begin{bmatrix}\mathbf{H}_j[1] & \cdots & \mathbf{0}\\ \vdots & \ddots & \vdots\\ \mathbf{0} & \cdots & \mathbf{H}_j[N]\end{bmatrix}_{NN_r\times NN_t}. \quad (4)$$

The kth diagonal element of $\mathbf{H}_j$ is an $N_r \times N_t$ matrix whose (p,q)th element $H_{pq}(k)$ is the frequency response of the channel link from the qth transmit antenna to the pth receive antenna. Given the overall transmission power P and supposing that signals transmitted by different antennas have same power, the covariance matrix of the signal is $\boldsymbol{\Sigma} = \mathbb{E}\{\mathbf{X}\mathbf{X}^{\mathcal{H}}\} = \frac{P}{2NN_t}\mathbf{I}_{2NN_t}$.

The ergodic capacity of the distributed MIMO channel is expressed as:

$$C_{\text{MIMO}} = \mathbb{E}\left\{\frac{1}{N}\log_2\left(\det\left(\mathbf{I}_{NN_r} + \frac{1}{\sigma_n^2}\mathbf{H}\boldsymbol{\Lambda}\boldsymbol{\Sigma}\boldsymbol{\Lambda}^{\mathcal{H}}\mathbf{H}^{\mathcal{H}}\right)\right)\right\}$$
$$=\mathbb{E}\left\{\frac{1}{N}\log_2\left(\det\left(\mathbf{I}_{NN_r}+\frac{P}{2\sigma_n^2NN_t}\sum_{j=1}^{2}\lambda_j^2\mathbf{H}_j\mathbf{H}_j^{\mathcal{H}}\right)\right)\right\}. \quad (5)$$

C. Comparison

The advantage of using distributed MIMO broadcasting is shown by a simple example. Consider an area where there are two transmission sites denoted by 'A' and 'B' in Fig. 2. The distance between two sites is 15 km. The total transmission power P is 10 kW. Suppose that the signal experiences independent and identically distributed (i.i.d.) Rayleigh small-scale fading and signal power exponentially decays with respect to the distance between receiver and transmitter. The power decaying factor is chosen as 3.5 which represents the typical propagation scenario of the urban area [4]. The channel capacities of the two broadcasting scenarios given in (2) and (5) are evaluated in different geographical locations. Fig. 2 gives the ratios of the two channel capacities ($C_{\text{MIMO}}/C_{\text{SFN}}$) with different locations. It can be seen that the distributed MIMO broadcasting can achieve around twice channel capacity as much as the traditional SFN broadcasting with the same overall transmission power. The improvements are more significant in the boarder area of the two cells, which leads to a better coverage in the edges of the cells. This example shows that *the distributed MIMO broadcasting has better potential in terms of transmission efficiency*.

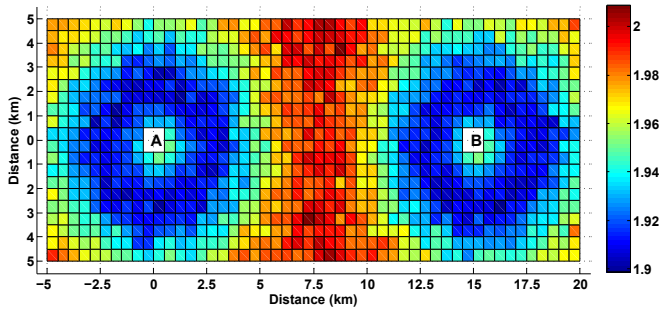
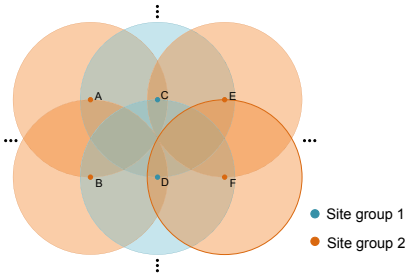


Fig. 2. Channel capacity improvement with respect to different geographical locations in distributed MIMO broadcasting. The color scale gives the ratio values of the two channel capacities, i.e. $C_{\text{MIMO}}/C_{\text{SFN}}$.

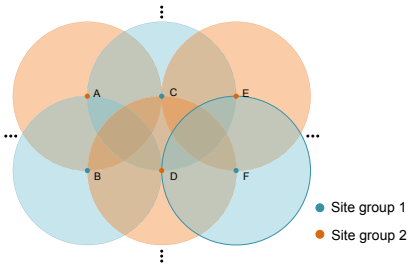
Note that, the discussion carried out in this paper is not limited to two-cell distributed MIMO structure depicted in Fig. 1b. An SFN with more transmission sites can be implemented based on the two-cell structure. In fact, the transmission sites of the network can be firstly divided into two groups. Then the distributed MIMO designed for the two-cell case are applied to the two site groups. For example, two implementations of distributed MIMO network are presented in Fig. 3. With proper planning of the locations of transmission sites, the broadcasting network can be easily extended to a large area. Therefore, it motivates us to study the two-cell-based distributed MIMO scenarios in the following parts.

III. STBC for Distributed MIMO Broadcasting

In this section, we discuss the space-time (ST) coding schemes for the distributed MIMO broadcasting. The signal sent in the broadcasting network is first encoded by ST coding scheme in a central station and is then fed to different transmission sites. The ST coding is performed not only for the signals of the same transmission cell but also for those of adjacent cells. It is carried out in a hierarchical manner. Signal of the same cell is coded by intra-cell ST coding scheme. The resulting ST codewords of adjacent cells are encoded by the inter-cell ST coding. If we have a close look at the



(a) Network type A



(b) Network type B

Fig. 3. Examples of distributed MIMO broadcasting network.

signal propagation situation, signals coming from different transmission sites experience different path losses. Therefore, the received signal exhibits power imbalances. On the other hand, signals coming from the same transmission site may have the same average power. In order to achieve good overall performance, it is important to select intra-cell and inter-cell ST coding schemes according to the propagation conditions.

A so-called *3D MIMO code* has been proposed for the distributed MIMO scenarios [5]. Alamouti scheme [2] is selected as the inter-cell ST coding because it is the most robust code against power imbalances. In addition, Golden code [6] is chosen for the intra-cell ST coding because it is the most efficient 2×2 ST coding scheme with balanced signal power. This combination preserves the efficiency of the Golden code while enabling strong resistance against power imbalances. The 3D MIMO code achieves a ST coding rate of 2 with high diversity. It has been shown recently that the 3D MIMO code can achieve low ML decoding complexity by exploiting the implicit Golden and Alamouti structure.

Besides the 3D MIMO code, there are several distributed STBCs that are also constructed in a hierarchical manner based on classical single cell STBCs. The simplest one is the spatial multiplexing (SM) [7] with SFN implementation. More precisely, two information symbols are simultaneously transmitted by two transmit antennas of the same cell, while two adjacent cells forming a SFN. The resulting *SM 4×2* scheme provides a ST coding rate of 2. Another simple distributed STBC is the *double Alamouti code*, also known as Alamouti multiplexing [8]. Each transmission site generates an independent Alamouti codeword. The two adjacent sites simultaneously transmit these two codewords. It is a spatial multiplexing of Alamouti codewords. This yields an overall ST coding rate of 2.

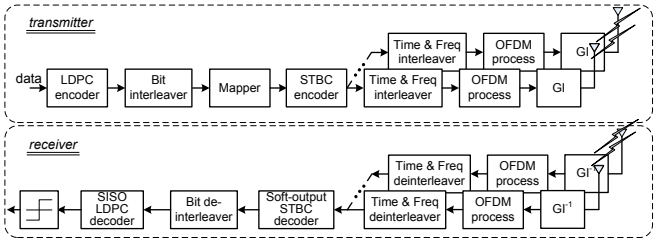


Fig. 4. Generic structure of the DVB-NGH system.

Several other STBCs with rate 2, namely *Srinath-Rajan* [9], *BHV* [10] and *DjABBA* [11] codes, are also considered in our study, even though they were not initially optimized for the distributed MIMO scenarios. The Srinath-Rajan code is constructed based on two CIOD codewords[1]. The BHV code is formed by two Jafarkhani codewords [13]. The DjABBA code is generated based on four Alamouti codewords. Among them, the Srinath-Rajan and BHV codes take the advantage of implicit CIOD and Jafarkhani structures, and can achieve low-complexity decoding.

The *Jafarkhani code* [13] can also be implemented in the distributed MIMO cases. The Alamouti scheme is applied in both inter-cell and intra-cell ST codings. In contrast to the previous STBCs, the Jafarkhani code provides a ST coding rate of 1. The quasi-orthogonal structure of Jafarkhani code enables low-complexity decoding. The *Ismail-Fiorina-Sari (IFS)* code [14] is another rate-1 STBC which is constructed based on complexity orthogonal code. Due to its partial orthogonal structure, IFS code needs the lowest decoding complexity among all STBCs considered in our study.

The most important characteristics of different STBCs are concluded in Table I for a clear comparison.

IV. Simulation and Comparisons

In this section, we will compare different STBCs with the DVB-NGH specifications. Fig. 4 demonstrates a generic block diagram of the DVB-NGH system. Simulation parameters are chosen according to the DVB-NGH specifications. More precisely, the FFT size is 4K. Guard interval length is $1/4$ of FFT size. The time interleaver length is 2^{18} cells. The 16200-length LDPC codes with rates $1/2$ and $5/6$ are used in the simulation. QPSK is used for the rate-2 STBCs and 16QAM is used for the rate-1 STBCs in order to achieve the same spectral efficiency in the comparison. The performance of STBCs is evaluated using the realistic DVB-NGH MIMO outdoor channel which simulates a cross-polarized 2×2 MIMO transmission in the UHF band [15]. To emulate the distributed MIMO scenarios, two uncorrelated DVB-NGH channel are generated with different average power levels representing different propagation path losses. The state-of-the-art soft-output sphere decoder with single tree search [16] is used as the ST decoding algorithm. Note that, the same ST decoding algorithm is used for all STBCs in order to perform

[1]Coordinate interleaved orthogonal design (CIOD) enables the ST decoding using single complex symbol [12].

TABLE I
STBCs FOR DISTRIBUTED MIMO BROADCASTING SCENARIOS.

Category	STBC	Structure of STBC				Worst-case ST decoding complexity [a]
		Nb. of info. symb.	Nb. of channel uses	Intra-cell ST coding	Inter-cell ST coding	
Rate one	Jafarkhani [13]	4	4	Alamouti	Alamouti	$\mathcal{O}(M^2)$
	IFS [14]	4	4	Based on orthogonal 4 Tx STBC		$\mathcal{O}(M)$
Rate two	SM 4×2	2	1	SM 2×2	SFN	$\mathcal{O}(M^2)$
	Double Alamouti [8]	4	2	Alamouti	SM 2×2	$\mathcal{O}(M^4)$
	Srinath-Rajan [9]	8	4	Based on 2 CIOD codes		$\mathcal{O}(M^{4.5})$
	BHV [10]	8	4	Based on 2 Jafarkhani codes		$\mathcal{O}(M^{4.5})$
	DjABBA [11]	8	4	Based on 4 Alamouti codes		$\mathcal{O}(M^6)$
	3D MIMO [5]	8	4	Golden	Alamouti	$\mathcal{O}(M^{4.5})$

[a] M is the size of constellation used by information symbols.

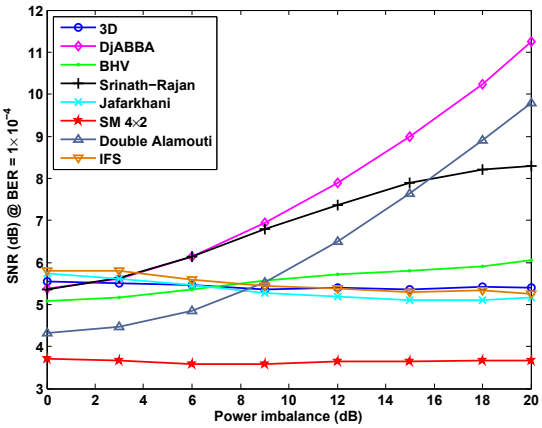


Fig. 5. Performance of distributed MIMO broadcasting using different STBCs in presence of power imbalances, soft-output sphere decoding, LDPC rate $4/9$, DVB-NGH MIMO channel with $f_d = 33.3$Hz.

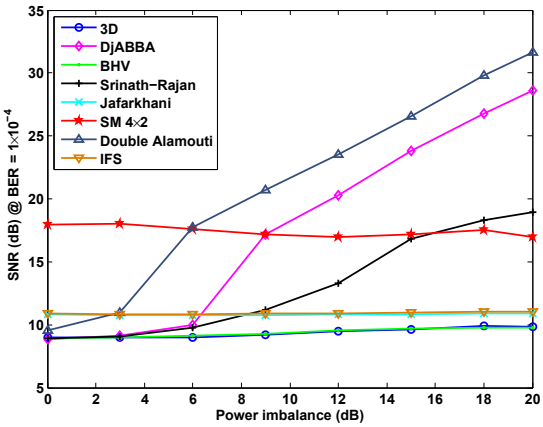


Fig. 6. Performance of distributed MIMO broadcasting using different STBCs in presence of power imbalances, soft-output sphere decoding, LDPC rate $5/6$, DVB-NGH MIMO channel with $f_d = 33.3$Hz.

a fair comparison. Finally, it is assumed that the receiver is perfectly synchronized and has perfect channel information.

A. Performance against power imbalances

Fig. 5 shows the performance of different STBCs in presence of received signal power imbalances. The vertical axis gives the required SNR to achieve a BER level of 1×10^{-4}. The horizontal axis presents the power differences of the signals sent by different transmission sites reflecting different path losses. This study investigates the influence of signal power imbalance on the BER performance of STBCs. It is very important for distributed MIMO broadcasting scenarios because broadcaster should guarantee equally good quality of service for all the users in the coverage no mater where they locate. It can be seen that double Alamouti, DjABBA and Srinath-Rajan codes can provide satisfactory performance when the received power is equal. Yet, they are not robust against the power imbalances. More precisely, given a 20 dB receive power imbalance, Srinath-Rajan, double Alamouti and DjABBA codes suffer performance degradations of 3.0 dB, 5.7 dB and 6.0 dB, respectively, compared with the balance power case. In contrast, the SM 4×2, Jafarkhani, IFS and 3D codes are robust against receive power imbalance. The performance losses are negligible. Interestingly, the simple SM 4×2 code outperforms the sophisticated ones, such as DjABBA, BHV, 3D and Srinath-Rajan codes, with a low channel coding rate. This can be ascribed to the strong error-correction capability of low-rate $(4/9)$ LDPC code. In combination with a long time interleaver, the LDPC decoding process extracts a high time diversity and can thus efficiently correct the errors occurred in the transmission. The effect of the diversity embedded in the STBC is less significant in such a configuration. In the contrary, the more information symbols stacked in one STBC codeword, the more difficult the STBC decoding process. Therefore, the SM 4×2 code is the more efficient when the soft-output sphere decoder and strong forward error correction (FEC) scheme are used.

Fig. 6 demonstrates the performance comparison with power imbalances using another FEC configuration. A weaker LDPC with a coding rate of $5/6$ is used. STBCs show similar power imbalance resistance behaviors as in Fig. 5. The 3D, SM 4×2, Jafarkhani, BHV and IFS codes are robust within a wide range of signal power imbalances, while double Alamouti, Srinath-Rajan and DjABBA codes suffer significant performance losses with high power imbalances. Compared with Fig. 5, it can be seen that the simple SM 4×2 code is not efficient with a weaker FEC scheme (LDPC rate $5/6$). Its performance is $7 \sim 9$ dB worse than the sophisticated 3D and BHV codes,

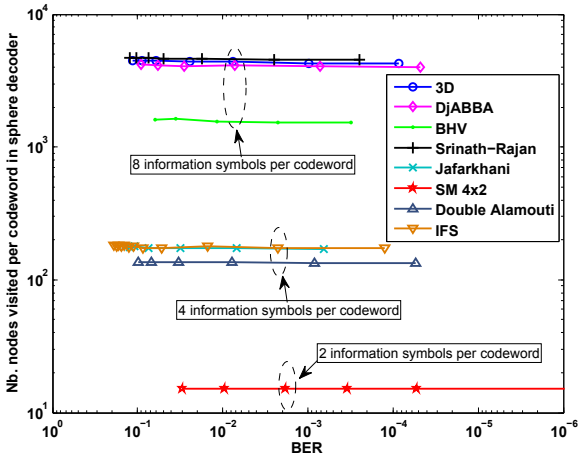


Fig. 7. Complexities of the soft-output sphere decoding, LDPC rate $4/9$, DVB-NGH MIMO channel with $f_d = 33.3$ Hz.

and $6 \sim 7$ dB worse than the rate 1 (IFS and Jafarkhani) codes. Because the diversity-extracting capability of the STBC plays an important role in the overall error-correction performance of the system when a weaker FEC scheme is adopted.

B. Complexity

The maximum likelihood (ML) decoding finds the best solution of the received STBC codewords through an exhaustive search over all possibilities. The sphere decoding simplifies this cumbersome traversal by restricting the search space within a hypersphere centered at the received signal point. Hence, the number of codewords to be examined can be greatly reduced. Fig. 7 shows the computational complexity of the sphere decoding in terms of the number of nodes (possible STBC codewords) "visited" during the search. It can be seen that the decoding complexity mainly depends on the number of information symbols that are stacked within one STBC codewords. For instance, the sphere decoder has to check about 13 possible codewords to decode each SM 4×2 codeword which contains two information symbols. This number increases to $130 \sim 180$ for those STBCs with four information symbols, such as double Alamouti, IFS and Jafarkhani codes. For those containing eight information symbols, the sphere decoder has to examine $1500 \sim 4500$ possibilities for each codeword. The more information symbols stacked in one codeword, the more complex the decoding process. In addition, the decoding complexities are notably reduced compared with the brutal-force ML search. Meanwhile, the SNR value (represented by different BER levels) does not significantly affect the decoding complexity.

V. Concluding Remarks

This paper discusses the application of distributed MIMO schemes for the future TV broadcasting. The distributed MIMO scheme is shown to outperform the traditional SFN broadcasting in terms of channel capacity.

Consequently, we investigate the STBCs that are suitable for the distributed MIMO broadcasting. From comprehensive simulations, it can be concluded that different types of STBCs have their own preferred application scenarios. Simple STBC such as SM 4×2 code is suitable for the low data rate services with portable or mobile receptions. To ensure the quality of the reception, such applications commonly adopt FEC and modulation combinations with strong error-correction capability. In addition, the portable devices require low decoding complexity. *Therefore,the combination of simple STBC and strong FEC is a suitable solution for low data rate services. On the other hand, the sophisticated STBCs such as 3D and BHV codes are more attractive for the high data rate applications.* High-rate channel coding schemes are used in these applications in order to achieve better system throughput. The STBCs' capability of extracting diversity becomes very important in such cases. Moreover, as the high-rate services are mainly delivered to stationary receivers belonging to family, business or public users, higher complexity and power consumption resulted by the decoding of the sophisticated STBCs are affordable by these receivers. In conclusion, the simple and sophisticated STBCs can offer mutually complementary application scenarios.

Acknowledgment

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