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Title	**[Analysis of STFBC-OFDM for BWA in SUI channel]**	
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Re:	**Novel Design of STBC for OFDM/OFDMA using Frequency Diversity**	
Abstract	This document contains analysis and proposal for the OFDM STBC design for the 802.16a system.	
Purpose	This proposal should be used for the STBC-OFDM design	
Notice		
Release		
Patent Policy and Procedures		

Analysis of STFBC-OFDM for BWA in SUI channel

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References

[1] V. Erceg, K.V.S. Hari, M.S. Smith, D.S. Baum et al, "Channel models for fixed wireless applications", IEEE 802.16.3c-01/29r4, July, 2001.
[2] IEEE 802.16 Working Group, "Unapproved Working Document: Standard air Interface for fixed broadband wireless access systems", 802.16ab-01/01r2, Sep., 2001.
[3] PanYuh Joo, JungJe Son, and DaeEop Kang, " Novel Design of STBC for OFDM/OFDMA using Frequency Diversity", IEEE 802.16abc-01/59, Nov., 2001.

Introduction

In this contribution, an analysis of STFBC (Space-Time frequency block code)- OFDM for BWA in SUI channel is described. Also we show the way to estimate the amount of cyclic shift of the replica symbol. In STFBC design, the cyclic shift of the replica symbol is depending on the channel information, the amount of the cyclic shift of sub-carrier, which detected at the receiver. The cyclic shift value should be detected periodically and feedback to the transmission part for STFBC designs not frequently.

Background

In previous contribution we proposed space-time frequency block coded OFDM using two transmission antennas. This space-time frequency block code can simultaneously obtain space-time & frequency diversity gain, so that the performance of using two transmission antennas are almost equivalent to use 4 transmission antennas. ST-frequency code is composed of 2 parts: One for replica generator, which reproduces OFDM symbol to make frequency diversity. Another symbol is cyclically shift data in sub-carrier basis. The amount of cyclic shift is based on the stochastic properties of the channel environments. And then, to obtain space diversity two symbols made of replica generator are mapped into space-time block code. At the receiver the transmission signal is de-mapped with respect to reverse process. The de-mapper of Space-Time frequency block code is composed of 2 parts. The first de-mapping pass is done by enable the received signal to the space-time block encoder. Through the first pass the signal split into two symbols. Then cyclically "re-shift" the signal to replace the replica symbol. The de-mapping process is completed after the combination of such two symbols and decides to the nearest signal point using channel state information. After above procedure space-time frequency block code obtains order-2 space diversity and order-2 frequency diversity gain. After all, the mapping and de-mapping process of the STFBC is made of linear function and requires simple operation.

Covariance matrix of OFDM system

Channel impulse response of L multi-path frequency selective fading can be modeled as L-Tap FIR filter as,

$$g(t)=\sum_{i=0}^{L-1}h(i)\delta(t-\tau_i) \qquad (1)$$

where h(i) is attenuation factor of channel impulse response of i-th path τ_i is time delay of i-th path. In multiple transmission antenna system each channel coefficient is zero-mean independent gaussian random variable. And also assume power delay profile of channel is uniformly distributed.

Then, of the properties of OFDM system give the frequency response of the channel of the kth sub-carrier of the received OFDM signal after FFT at receiver as,

$$H(k)=\sum_{i=0}^{L-1}h(i)e^{-j2\pi ki/N}, 0\le k\le N-1 \qquad (2)$$

N is the total sub-carrier number of OFDM symbol. The channel correlation of the CIR of k-th and (k+Δk) -th sub-carrier for calculate the channel covariance matrix is as following,

$$\rho_{\Delta k}=E[H(k)H^*(k+\Delta k)]=\sum_{i=0}^{L-1}\sigma_i^2 e^{j2\pi\Delta ki/N} \qquad (3)$$

Because, each channel tap coefficients are uncorrelated to each other. σ^2 is variance of the i-th channel tap coefficients, and equivalent to power of i-th path. If all the channel power delay profiles are uniformly distributed, σ^2=1/L

$$\rho_{\Delta k}=\frac{1}{L}\sum_{i=0}^{L-1}e^{j2\pi\Delta ki/N}=\frac{1}{L}\frac{\sin\left(\frac{\pi\Delta kL}{N}\right)}{\sin\left(\frac{\pi\Delta k}{N}\right)}e^{j\pi\Delta k(L-1)/N} \qquad (4)$$

The channel vector is defined as,

$$H=[H(0)H(1)\cdots H(N-1)]^T$$

Then Covariance matrix is as following

$$C_H=E[H\ H^H]=\begin{bmatrix}\rho_0 & \rho_1 & \cdots & \rho_{N-1}\\ \rho_{-1} & \rho_0 & \cdots & \rho_{N-2}\\ \vdots & \vdots & \ddots & \vdots\\ \rho_{-N+1} & \rho_{-N+2} & \cdots & \rho_0\end{bmatrix} \qquad (5)$$

of the equation (4) $\rho_{\Delta k}$ have following properties

1. $\rho_{-\Delta k}=\rho_{\Delta k}^*$
2. $|\rho_{-\Delta k}|=|\rho_{\Delta k}|$

3. $\rho_{-\Delta k} = \rho_{N-\Delta k}$

from the property (1) and (3) the covariance matrix is expressed by cyclic hermite matrix.

To maximize the frequency diversity select optimum sub-carrier position

The basic concept of diversity is receive transmitted signal contain same symbol but independent fading channel. So realize diversity concept in OFDM system transmit two symbols, and each symbol have to allocate in different sub-carrier. But, to maximize the diversity gain each replica symbol should experience independent fading channel. Since, the sub-carriers of replica symbol is transmitted through uncorrelated sub-carriers.

Such uncorrelated sub-carrier can be found through the condition $\rho_{\kappa1\kappa2}$=0 in equation 4, and then the following equation should be satisfied,

$$\sin\left(\frac{\pi\Delta k_{12} L}{N}\right) = 0 \qquad (7)$$

where, $\Delta k_{12} \neq 0$. Finally Δk_{12} is the function of the distance of two sub-carriers. Then general solution of equation 7 is

$$\Delta k_{12} = \frac{mN}{L} \qquad (8)$$

where, m is none-zero integer. If let $\mathrm{k}_1 = 0$ then $1 \leq \Delta k_{12} \leq N-1$, so

$$\frac{L}{N}\pi \leq \frac{\pi\Delta k_{12} L}{N} \leq L\pi - \frac{L}{N}\pi \qquad (9)$$

and

$$\frac{L}{N} \leq m \leq L - \frac{L}{N} \qquad (10)$$

where m, L and N is positive integer, so,

$$1 \leq m \leq L-1 \qquad (11)$$

From equation 11 the number of sub-carrier uncorrelated to 0th sub-carrier is L-1. Include 0th carrier the number is L. According to the property 3 of the channel covariance matrix, the number of sub-carrier uncorrelated to arbitrary k-th sub-carrier is L in L-path fading channel environments.

Maximum frequency diversity achievable OFDM system structure

Three things have to be considered in the frequency diversity system.

1. Maximize diversity gain
2. Distance between all sub-carrier shall be maintained.

3. Robust property of channel correlation between sub-carrier.

When L=4 and N=64 the following figure is the magnitude of the correlation of sub-carriers respective to 0th sub-carrier.

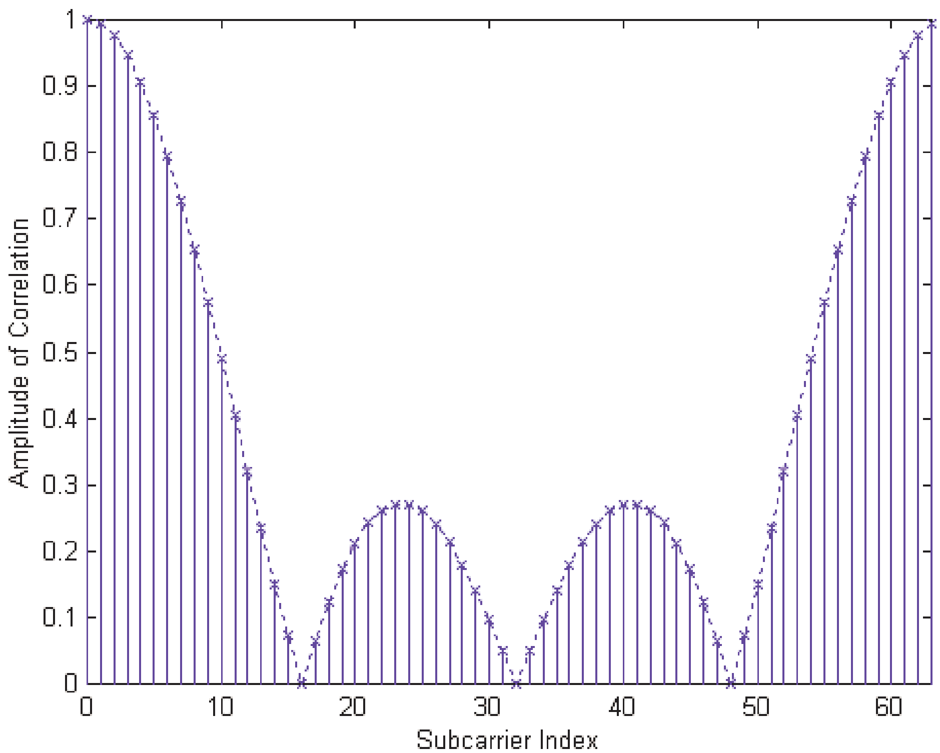

Figure 1. The magnitude of the correlation of sub-carriers respective to 0th sub-carrier.

As the figure indicate the maximum separation of sub-carrier is N/2. And in general, the optimum

$$\Delta k = d = \left\lfloor \frac{N}{L} \right\rfloor \cdot \left\lfloor \frac{L}{2} \right\rfloor \tag{12}$$

Where, $\lfloor x \rfloor$ is maximum integer not exceed x. According to channel covariance matrix property 3 the correlation vector is cyclically rotate to each other. So the maximum separable sub-carrier spacing k' is

$$k' = (k+d) \bmod N \tag{13}$$

where, mod is modulo operator.

Cyclic sub-carrier shift frequency diversity

An OFDM symbol s is composed of N modulation symbols

$$S=[s(0)\ \ldots\ s(N-1)]^T$$

Before the symbol transmission, we can generate another symbol using cyclic shift device. The amount of sub-carrier shift *d* is defined by equation (12). Then

$$X_1=s=[s(0),\ \ldots\ s(N-1)]^T$$

$$X_2=\ [s(N-d),\ldots\ s(N-1),\ s(0),\ldots s(N-d-1)]^T$$

Two symbols sequentially transmitted through STBC structure. Figure 3 is STFBC transmission block diagram and figure 4 is receiver block diagram.

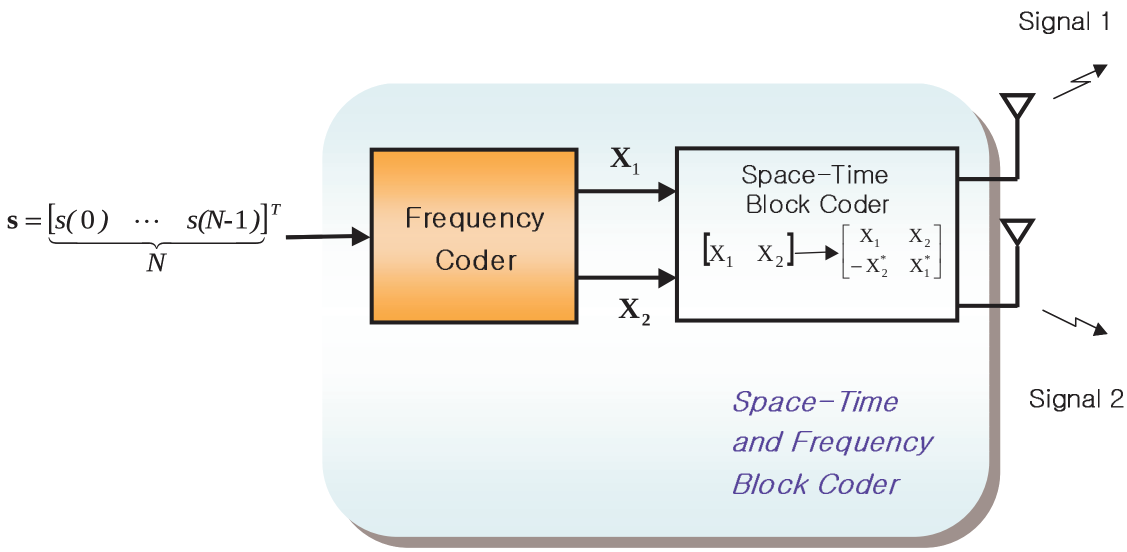

Figure 2 Transmission scheme of ST-frequency Block code

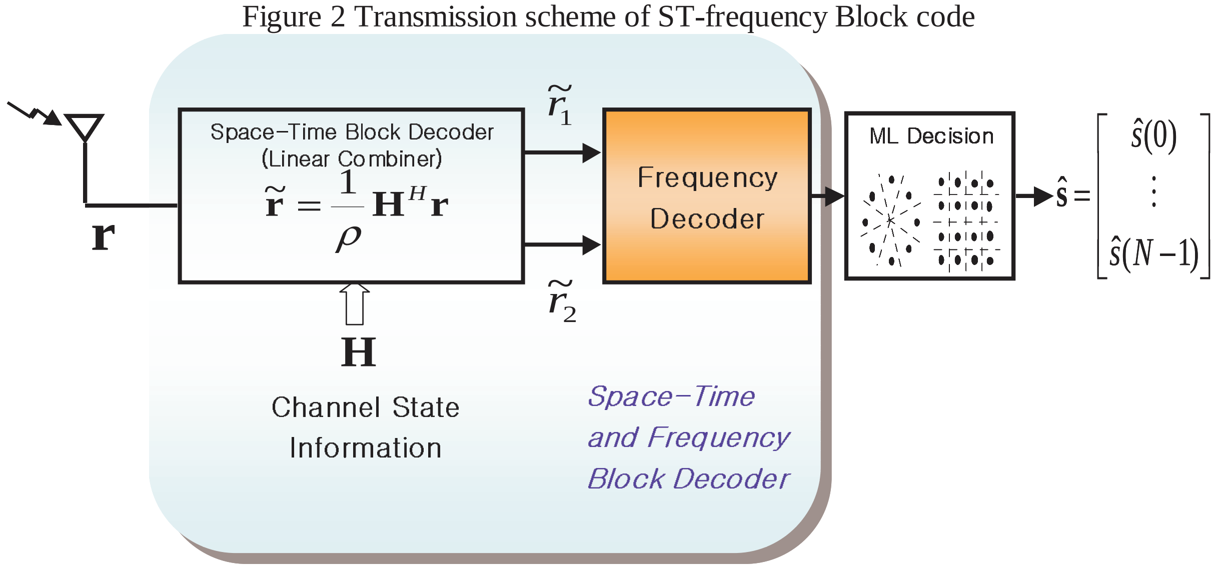

Figure 3 Rx scheme of ST-frequency Block code

Simulation results of Rayleigh fading channel

In this section we shall consider the case of simulation of STFBC(space-time frequency block code) under independent Rayleigh fading channels environments. The channel order is set to 10 and the modulation uses 16 QAM. It assumes the channel state & order information is given. In the case of simulation of STBC 4 tx antenna is compared to 2 tx antenna STFBC, same performance is shown in figure 4. Compare to 3 tx antenna using STBC in 10^{-4} SER(symbol error rate) it shows approx. 2.5dB SNR gain.

When we set the transmission rate constraints under same condition the STFBC shows further improvements. AS shown in figure 5 the STBC parameter is set to 2 tx antennas and 1 rx antenna, and the channel & order information is assumed perfectly estimated. Then using 16QAM in STFBC and QPSK in STBC results same transmission rate of 2bits/sub-carrier. In 10-5 BER, the performance improvements shown in figure 5 are approximately more than 5dB gain in EbN0. If correlation between transmission antennas increases, the performance also improves impressively

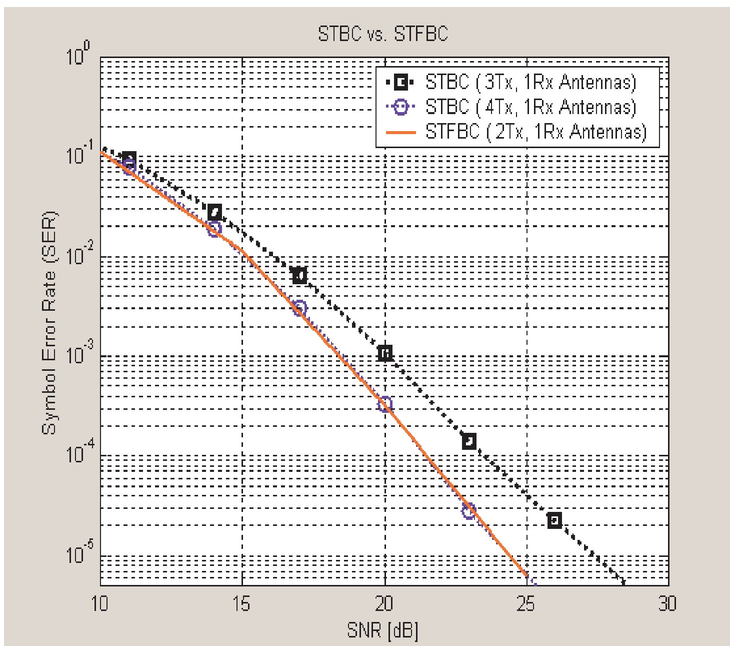

Figure 4 comparisons of performance of STBC and STFBC

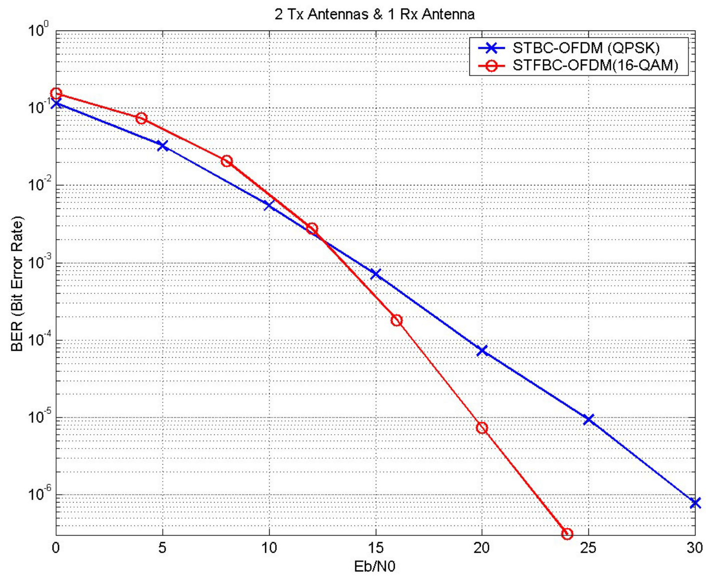

Figure 5 comparisons of STBC and STFBC in same transmission rate constraints

Simulation environments in SUI channel model

In BWA system, the BS/SS stations are fixed and the LOS (line of sight) exists on the transmission channel. Therefore the channel for BWA can be modeled as Ricean fading channel. And the Doppler effect can be almost ignored. The channel model is defined in the document 802.16.3c-01/29r4 as SUI 1~6[1].

In the first step, the SUI 3 channel shows relatively short delay spread just as Terrain Type B, which is defined in the table 1.

Table 1. SUI-3 channel parameter

SUI-3 Channel Terrain B				
	Tap1	Tap2	Tap3	Units
Delay	0	0.4	0.9	μs
Power(omni ant.)	0	-5	-10	DB
Doppler	0.4	0.3	0.5	Hz
Antenna Correlation	$\rho_{\mathrm{ENV}} = 0.4$			
SUI-1 Channel Terrain C				
	Tap1	Tap2	Tap3	Units
Delay	0	0.4	0.9	μs
Power (omni ant.)	0	-15	-20	DB
Doppler	0.4	0.3	0.5	Hz
Antenna Correlation	$\rho_{ENV} = 0.7$			

The channel simulator based on this parameter is shown in [1]. We will adapt this channel parameter to the STFBC-OFDM simulation parameter. The bandwidth assumed in this simulation is 6MHz[2].

Table 2. OFDM system parameter in MMDS 6MHz band

		OFDM
	F_S /(BW)	7/6
BW (MHz)	N_{FFT}	256
6	Δf (kHz)	27 11/32
	$BW_{Efficiency}$	91.60%
	$T_b\,(\mu s)$	36 4/7
	$T_g\,(\mu s)$	9 1/7

In this document the simulation results are based on the parameter of table 2 in order to compare the STFBC/STBC-OFDM performance evaluation in SUI channel model. In the previous results of ST-frequency block code [3], we assume the uniform delay spread in the Rayleigh fading channel. But for the property of delay spread of SUI-3 channel, the power of the delay spread is decreased as shown in figure 6.

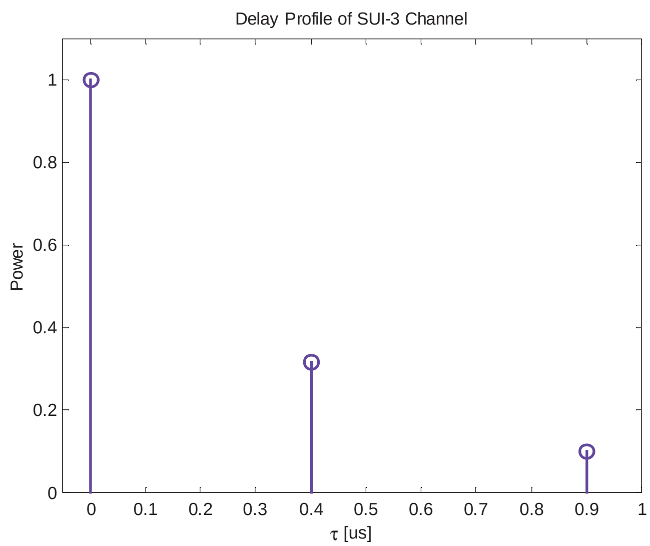

Figure 6. Delay Profile of SUI-3 channel

But it is not appropriate to directly enable the STFBC technique to BWA system under SUI channel model environments. In the SUI model, the STFBC-OFDM system should be redesigned under the condition of channel correlation between sub-carriers of symbol. In figure 2, the channel correlation of 0^{th} sub-carrier and n^{th} sub-carrier are shown.

As shown in figure 7, it is the 52^{nd} and the 204^{th} sub-carrier, which has the smallest amount of correlation with 0^{th} sub-carrier. However, in SUI 3 channel, zero correlation amplitude between any sub-carrier pairs in a OFDM symbol does not exist.

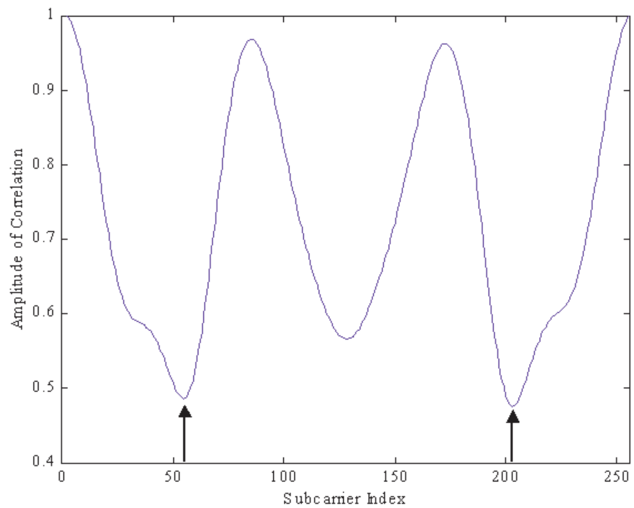

Figure 7. The amplitude of correlation of 0th sub-carrier and others

Since in the SUI 3 model the LOS affects to each TX path with certain amounts, so a little correlation value between each sub-channel is exists. Therefore, we cannot fully obtain 2nd order diversity. However, instead of getting the maximum frequency diversity, it still gives a certain amount of frequency diversity gain by transmit the cyclic shift the original symbol with the smallest correlated sub-carrier position as the replica symbol.

And in the previous contribution we have used the "Cyclic Shift property" of the sub-carrier to utilize frequency diversity in STFBC-OFDM. In order to stand for same property in SUI model, the correlation values between sub-carriers should be cyclically shifted in any ith sub-carrier. Some investigation on this property is taken in SUI-3 model. As shown in figure 8, the correlation between any ith sub-carrier and 0th, 10th, and 200th sub-carrier is plotted.

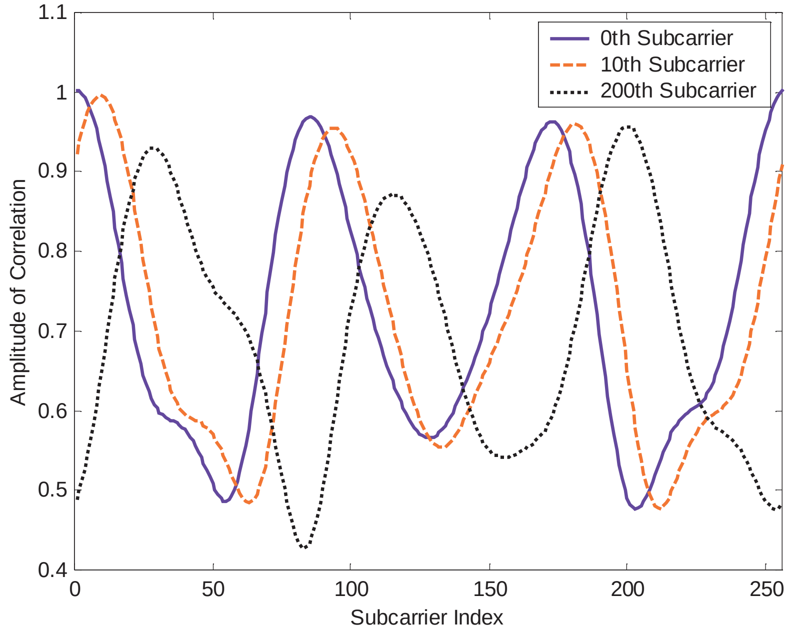

Figure 8. The correlation values between ith sub-carrier with 0th, 10th, 200th sub-carrier in SUI-3 model

An important property can be described in figure 8. Even for the cyclic shift property of OFDM symbol does not fully satisfied, but the cyclic shifting property of the correlation are still acceptable. The patterns of each correlation graphs still preserve the cyclic shifting property. Therefore, the frequency diversity scheme using cyclically shifting property is still valid for SUI model. Thus, using the scheme of cyclic shift of OFDM symbol between original symbol and replica symbol, the complexity of encoder/decoder of the STFBC can be reduced to symbol shift in frequency domain problem.

Based on these results, the STFBC for SUI-3 channel model is designed as following way. The correlation value of 52nd and 204th sub-carriers with respect to the 0th sub-carrier became the minimum, so cyclic shifting replica symbol 204 sub-carrier in frequency domain, therefore the STFBC-OFDM can get the maximum frequency diversity in SUI-3 channel. Thus, sub-carrier allocation of the replica symbol should be

$$k' = (k + 204) \bmod N ,$$

Thus, in the SUI-3 channel model, the same sub-carrier cyclic shift methods also can be applied to frequency diversity scheme. Figure 9 displays the instantaneous power variation of channel after combine the Space Time code with Frequency diversity in the receiver, which is compared with each of STBC-OFDM and OFDM. In this figure, the horizontal line of value 1 reveals ideal channel state without fading. In the case of the diversity of STBC-OFDM using 2 TX antenna and 1 Rx antenna have 2nd order diversity gain. Because of 2nd order diversity gain, it shows relatively reduced effects of null of the channel compared to OFDM only case. When the STFBC-OFDM are combined, it shows that the channel diversity gain evidently increased, the null of fading is almost reduced significantly and the channel variance is distributed very closely on the referenced horizontal line of value 1. Therefore, the assumption of the performance improvement through the frequency diversity in STFBC-OFDM can be proved.

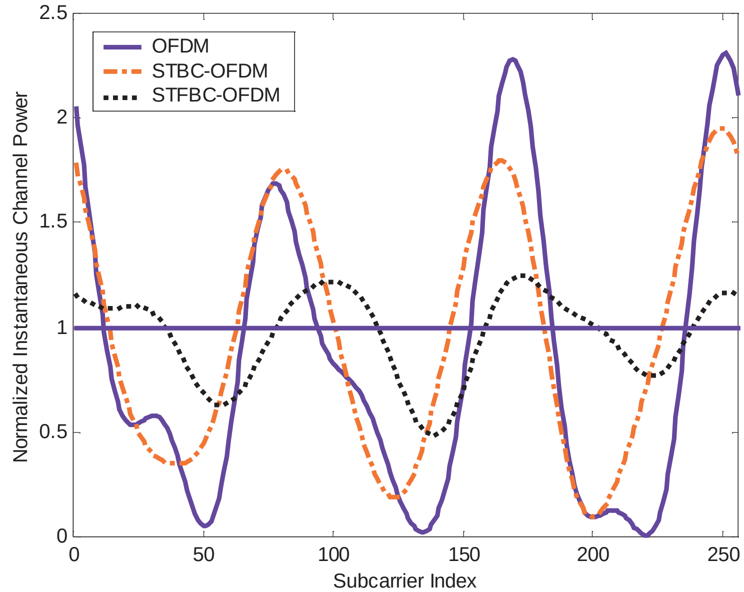

Figure 9. The normalized instantaneous power distribution of combining of inter-channel with respect to sub-carrier of OFDM, STBC-OFDM, STFBC-OFDM

Simulation Results of SUI channel model

Based on the proposed design method in this contribution, the simulation results of STFBC-OFDM in SUI channel are obtained. About the SUI-1 channel model it is also cyclically shifting 204 sub-carriers. The delay profile of two channel model is different in the power, but the amount of delays are same, so that the correlation value between the channel model is different in the value but the amount of shifting is still preserved equally.

This simulation is prepared under the OFDM system with MMDS bandwidth 6MHz. In figure 10 and figure 11 each of the results of SUI-1 and SUI-3 is shown. The performance of two simulations shows almost same in its pattern. First, in SUI-1 channel, since SUI-1 channel has significant LOS component, so the frequency diversity effects are not apparently revealed in the plot. In low Eb/N0, 16QAM STFBC-OFDM is worse than STBC, cause the noise influence more than diversity effects. But in high Eb/N0, the STFBC is better. Let’s consider BER 10^-5 as comparison point, STFBC-OFDM shows 3dB better performance than STBC-OFDM.

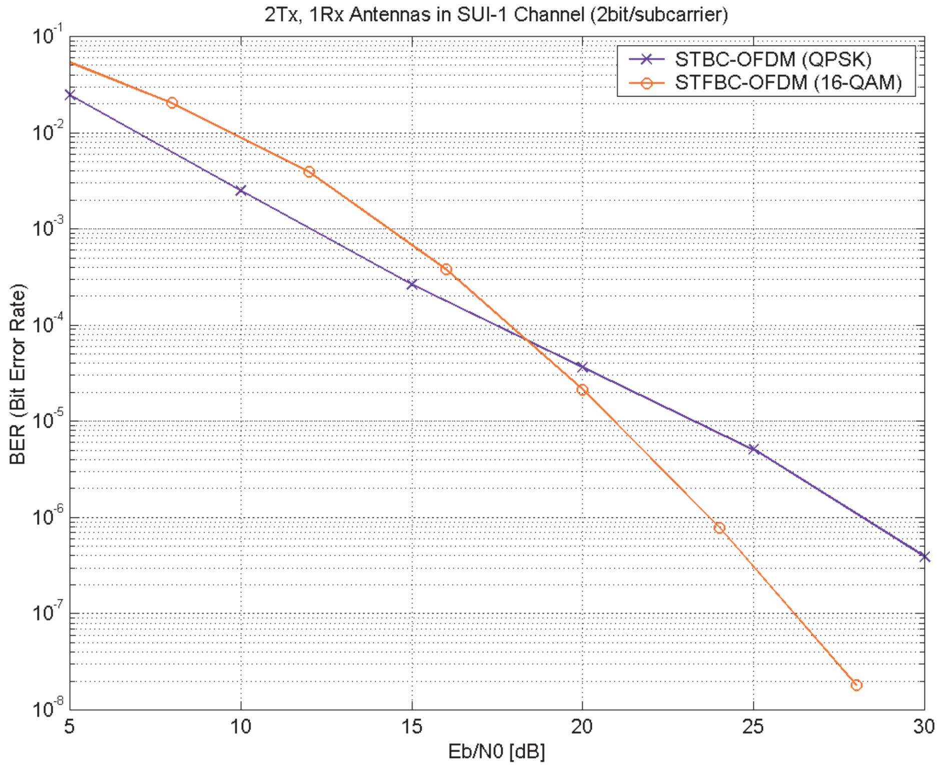

Figure 10. Transmission rate of 2bit/subcarrier in SUI-1 channel in the comparison of STBC-OFDM and STFBC-OFDM in BER vs. Eb/N0

In SUI-3 almost similar results are shown, but the LOS components of SUI-3 channel is not significant than SUI-1, the channel environments of SUI3 is worse than SUI-1, the diversity effect induces much more performance evolution. In SUI-3 channel, BER 10^-5 is considered; STFBC performs better than STBC about 4.5dB in Eb/N0. If move the BER curve further below the 10^-5 than the effects will be greater.

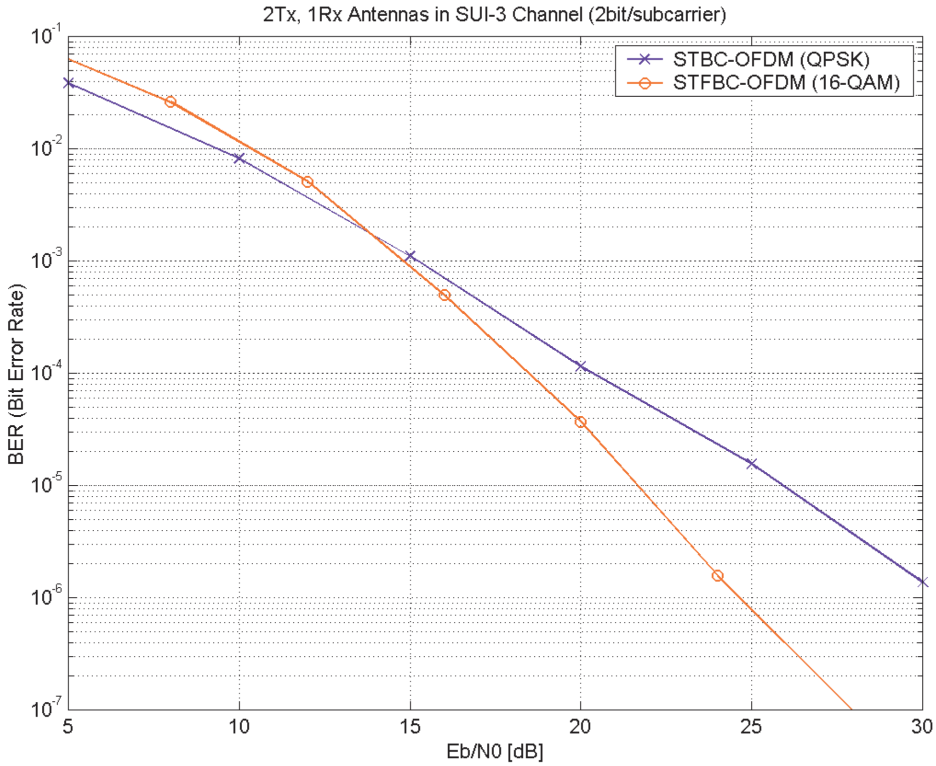

Figure 11. Transmission rate of 2bit/subcarrier in SUI-3 channel in the comparison of STBC-OFDM and STFBC-OFDM in BER vs. Eb/N0

About the replica symbol cyclic shifting value estimation

As described above, in the implementation of STFBC-OFDM, we should find the the shifting value for the STFBC system design. But the proposed design parameter is only suitable for the case SUI-1 and SUI-3 channel model only. In the case of SUI –2,4,5,6 model the cyclic shifting values may different from two results in this contribution.

Also in the real environments, we do not know the shift value a priori, using any predefined shifting value may give rise some problem to STFBC system. It results the system cannot fully utilized the frequency diversity. Maybe some degree of diversity gain can be obtained statistically.

Indeed proposed TX diversity does not required to know the entire channel state information of two channels in instantaneously and statistically. Only the cyclic shifting information is enough to design STFBC-OFDM transmission part. In the channel estimation process, at the receiver the statistical channel property can be acquired. After the amount of cyclical shifting information is obtained at the receiver, it should be feedback to the transmission part for generate the replica symbol.

Summary the feedback process

1. Acquire the channel correlation property at the receiver.
2. Find the sub-carrier smallest correlation in the sense of 0^{th} carrier.
3. Determine the amount of cyclical shift of the sub-carriers with respect to the sub-carrier found in step 2.
4. Feedback the determined amount of cyclic shift to the STFBC-OFDM TX diversity part.
5. Based on the feedback information determined in step 4, determine the STFBC-OFDM design parameter; the cyclic shift of sub-carrier.

In this way, we can use the STFBC-OFDM more conveniently doesn't matter with the channel state characteristics, Whether TDD or FDD; only the cyclic shifting value of OFDM symbol is required.

About the channel correlation property

To estimate the channel correlation is related to the implementation issue. It is not appropriate to treat it in this proposal. It is strongly desired to design efficient channel correlation detector. However, we have got powerful preamble, pilot symbols and strong detection algorithm for the replica symbol cyclic shifting value estimation. Samsung recommend the STFBC can be a strong candidate for the replacement of Alamouti STC transmission diversity in technically.

About the spectrum efficiency and coding, Interleaving

Indeed, STFBC sends one symbol when Alamouti STC sends two. But it has big potential for the frequency diversity effect in OFDM based system. It also can be a component technology for the future MIMO system based on ST diversity. Samsung think instead of spend some spectral efficiency, we can enhance the coverage range.

In another point of view, we can obtain 4^{th} order diversity with 2^{nd} order system, and also results in Eb/N0 reduction for same BER. However, there is no any evidence of the amount of reduced Eb/N0 will affect the coding & interleaving gain, though the simulation result are not provided. We don't think the concatenation of frequency diversity and frequency interleaving reduces performance in the information theoretical manner. It is shown in figure 12 and 13. Maybe some loss may come, but will not affect overall system performance significantly.

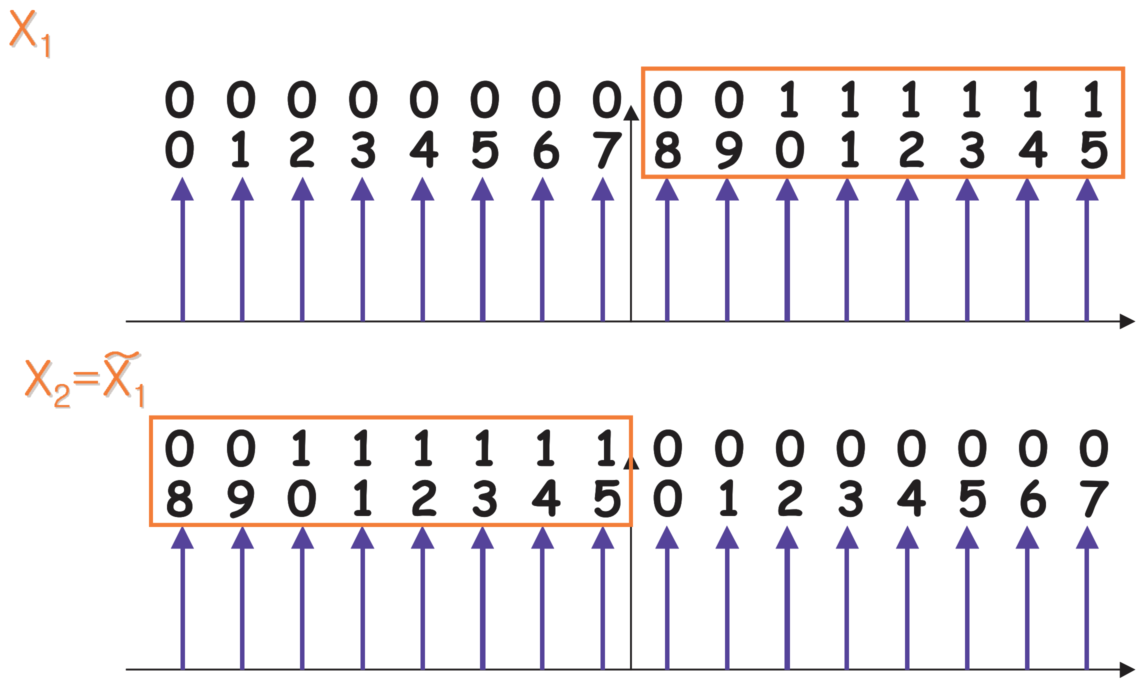

Figure 12. Concept of cyclic shift to achieve replica symbol

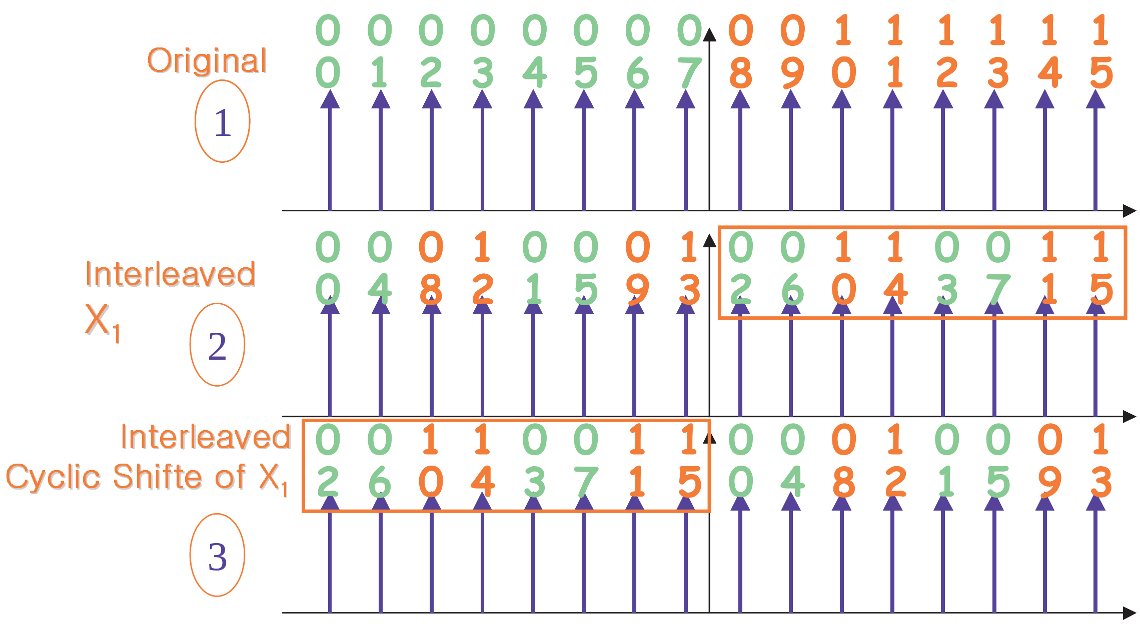

Figure 13. Comparisons of simplified original OFDM symbol X_1 / interleaved / interleaved cyclic shifted X_1

Conclusion

- Characteristics of Space-Time Block Coding (STBC)

It has simple structure and full space diversity gain. But there are many problems when using more than 3 antennas in OFDM system. The hardware and operational complexity is increase, and transmission rate decrease)

- Advantage of Space-Time and Frequency Block Coding (STFBC)

Novel structure of STBC using OFDM can overcome the problem of STBC-OFDM. This scheme not only maximizes Space Diversity but also frequency Diversity gain. And it is also because of using frequency diversity so that the number of tx antenna is not required to be increased.

- Compatible to existing STBC-OFDM

Proposed scheme also minimizes change of existing structure. The only added process is the cyclic shift of sub-carrier as replication of original symbols. And the length the channel impulse response L can be easily obtained from channel estimation process of the receiver end. A small amount of channel estimation error is not affect whole performance much. Finally, the frequency diversity process is a simple linear function, so further performance gain can be obtained from code combining and ARQ schemes.

- Tx diversity scheme for OFDM/OFDMA system is desirable to use the STFBC.