ISSN: 2278 – 909X
International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE)
Volume 6, Issue 7, July 2017

Study of STBC-OFDM: Consequences and Solutions

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***Abstract-* Space time block codes orthogonal frequency division multiplexing (STBC-OFDM) is the key technology of Chinese digital television terrestrial broadcasting (DTTB) standard. During digital television (TV) transition, analog signal disturbs digital terrestrial television (DTT) transmission in an area where a simulcast service is available. In the STBC-OFDM based DTTB system, the receiver is extremely sensitive to the co-channel interference (CCI) introduced by analog TV service. In this paper, a method of the time-domain autocorrelation of the received DTT signal is developed to detect the CCI, and it utilizes the line synchronization mechanism of analog TV signals. From the filtered signal, synchronization errors and channel responses can be estimated by means of conventional algorithms for STBC-OFDM. Also a review of algorithms for complexity and security is given.**

***Key words-* OFDM, STBC-OFDM, co-channel interference, security, complexity.**

1. INTRODUCTION

OFDM is exploited in broadband wireless scenarios, for instance, wireless local area network (WLAN), digital audio broadcasting (DAB), digital video broadcasting (DVB), and fixed wireless access, [1], [3], etc. To overcome frequency selective fading under multipath channels, orthogonal frequency division multiplexing (OFDM) is adopted. In OFDM the entire channel is divided into number of essentially flat sub-channels. Inter-symbol interference is introduced by multipath propagation. All systems mentioned above insert cyclic prefix (CP) as guard interval (GI) between adjacent OFDM symbols to evict inter-symbol interference (ISI) [1]. In conventional OFDM, CP has more than one advantage. First, it can be used as a guard interval between adjacent OFDM symbols to evict ISI. Second, it also converts linear convolution into circular convolution through channel propagation.

However, the CP consists of unknown data, so it is difficult to be exploited for channel estimation and synchronization. Subsequently, some known training sequences have been used instead of CP, in order to increase spectral efficiency remarkably. In accordance of this point, space time block codes OFDM (STBC-OFDM) with pseudo-noise (PN) training sequences have introduced between the OFDM data symbols. This is key technology used in Digital television/terrestrial multimedia broadcasting (DTMB), announced as the Chinese digital television terrestrial broadcasting (DTTB) standard. STBC-OFDM is exploited to achieve both fast and reliable synchronization and channel estimation.[4].

However, there are mutual interferences between the TS and the OFDM data block, in order to evict interferences an iterative interference cancellation has to be used in STBC-OFDM systems for CE and frequency-domain demodulation [6]. As the interference cancellation is iterative, it will result in the performance degradation under doubly selective fading channels [5], whereby the perfect removal of the IBIs is difficult to achieve [11]. In the United States advanced television systems committee (ATSC) standard, the co-channel analog TV interference (referred as the co-channel interference (CCI) hereafter) is detected. To eliminate it interference rejection is performed. Hence, in this paper we will concentrate on analyzing the effects of CCI on STBC-OFDM and give a solution to eliminate it [6]. Also a novel synchronization method is proposed that is robust to large CFO's in multipath channels [7]. OFDM cannot support secure transmission, which ultimately limits its application in military and commercial scenarios. To overcome this problem an encryption scheme is proposed for STBC-OFDM. This encryption scheme uses pseudo random constellation rotation and artificial noise insertion method [10].

The rest of the paper is organized as follows. Section II presents STBC-OFDM System Model and Description. Section III includes different techniques which consign solutions to the problems that appear in STBC-OFDM. Section IV includes the simulation results for above techniques. Then we conclude this paper in Section V.

2. SYSTEM MODEL AND DESCRIPTION OF STBC-OFDM

A. *System Model*

A typical STBC-OFDM system is shown in Fig. 2. The stream of data is divided into blocks of length N and modulated using an N-point inverse fast Fourier transform (IFFT). For the *i*th transmitted symbol sequence$\{X_k^{(i)}\}_{k=0}^{N-1}$, the time domain sequence of the output of the IFFT is

$$x_n^{(i)} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k^{(i)} \exp\{j \frac{2\pi kn}{N}\}, \ 0 \le n < N. \quad (1)$$

Here, the elements of the input symbol sequence $\{X_k^{(i)}\}_{k=0}^{N-1}$ are assumed to be independent identically distributed (i.i.d.) zero-mean random variables of variance $\sigma_X^2 = 1$. Similar PN sequence of length ν is inserted between data symbols of length N to give STBC-OFDM signal. The *i*th transmitted frame, $\{s_n^{(i)}\}_{n=0}^{N_2-1}$, is defined as the *i*th data block with a length-*ν* PN sequence. Namely,

$$s_n^{(i)} = \begin{cases} x_n^{(i)}, & 0 \le n < N \\ c_n, & N \le n < N_2 \end{cases} \quad (2)$$

where $\{x_n^{(i)}\}_{n=0}^{N-1}$, is the *i*th transmitted data block, $\{c_n\}_{n=0}^{v-1}$ is the PN sequence, and $N_2 = N + v$.

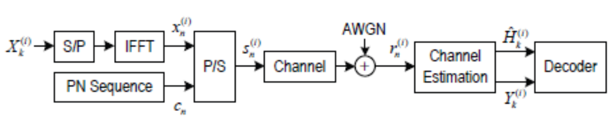

Fig. 2. Block Diagram of typical OFDM systems

B. *System Description*

Fig. 3 gives the baseband transmitter and receiver structures of the STBC-OFDM system. The symbol rate $1/T$ is identical for both Frame Sync and Frame Body (Fig. 3). In order to limit the bandwidth of transmitted signal, a square root raised cosine (SRRC) filter is used for the reason of pulse shaping. Denote $p(t)$ as the impulse response of the SRRC filter. The transmitted baseband signal $s(t)$ can be given as

$$s(t) = p(t) * [\text{PN}(k) + \text{IDFT}\,(s(k))] \quad (3)$$

where $*$ denotes convolution. At the receiver end, CA and STR are executed initially, then the PN sequence is removed after SRRC filtering. Finally the demodulated data $s'(k)$ is obtained by discrete Fourier transform (DFT).

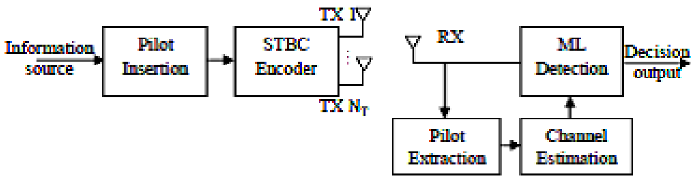

Fig. 3. STBC-OFDM transmitter and receiver

As shown in Fig. 4, STBC-OFDM system signal frame includes two parts, the frame head and the frame body. The L_{PN}-length frame head, serves as guard interval, and is composed of a pre-amble, a PN sequence and a post-amble. The frame head $PN(n)$ is a series of complex-valued symbols with QPSK constellation of which the real and imaginary parts are equal. The PN sequence with L_m samples is generated based on m-sequence, and the pre-/post-amble are cyclical extensions and has the length of L_{pre} and L_{post} , respectively. OFDM modulation is applied to the frame body, i.e. The N_c-length IFFT block.

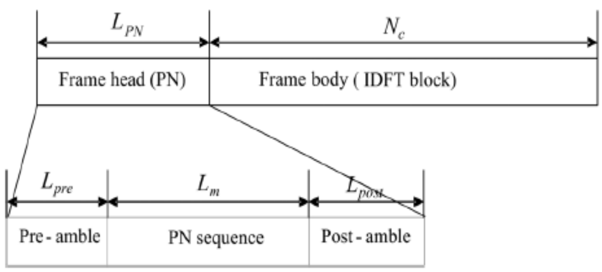

Fig. 4. STBC-OFDM signal frame

3. TECHNIQUES

I. Low Complexity Channel Estimation Method

The iterative process usually involves a lot of DFT and IDFT computation, which dramatically increases the complexity of the receiver also the system faces delay. To solve this problem, an approach is considered here that can prevent the elimination of interference in the frame header. The primary idea of given algorithm is to construct mixed correlation windows. Instead of using identical headers, PN sequences with different phases are adopted in each OFDM frame as the time domain pilots.

As shown in Fig. 4, each PN Guard interval can also be considered as a 420-lengthed part of successive PN sequences. It should also be noticed that, since the circular shift of PN sequences are still PN sequences, every 255-lengthed part of the frame header is a circular shift of the PN sequence, and thus it is also an PN sequence.

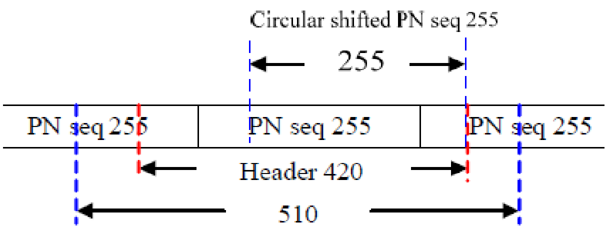

Fig. 4 another description of frame header

Most of the channel estimation methods using PN sequences mainly base on correlation. The process of this scheme can be briefly described as follows [4]:

Firstly, we model the radio channel as a finite linear filter. The impulse response is:

$$h(n) = \sum_{\tau=0}^{L-1} a(\tau)\delta(n-\tau) \qquad (4)$$

where $a(\tau)$ is the gain of corresponding channel profile. Assuming that the transmitted signal is s(n), the received signal y(n) can be expressed as:

$$y(n) = s(n) \otimes h(n) + N(n) \qquad (5)$$

Where $N(n)$ is AWGN and '$\otimes$' is linear convolution. We select part of the received signals $y(n), n \in [n_0, n_0 + 254]$ in the frame header which includes 255 symbols, as a correlation window $W(n), n \in [0,254]$. n0 is the starting index of the correlation window. The circular correlation between W(n) and PN255 sequence P(n) is expressed as:

$$C(n) = \sum_{k=0}^{M-1} P(k) W(n+k)_M$$

$$= \sum_{k=0}^{M-1} P(k) \{ \sum_{\tau=0}^{L-1} a(\tau) s[n_0 + (n+k)_M - \tau] + N[n_0 + (n+k)_M] \}$$

$$= \sum_{\tau=0}^{L-1} a(\tau) \sum_{k=0}^{M-1} P(k) s[n_0 + (n+k)_M - \tau] + \sum_{k=0}^{M-1} P(k) N[n_0 + (n+k)_M] \qquad (6)$$

where M is 255, and $(\,)_M$ donates the modular M process.

If the signal within the correlation window satisfies:

$$s[n_0 + (n+k)_M - \tau] = P(n+k-\tau)_M \qquad (7)$$

then *C(n)* with respect to correlation window start index n_0 becomes:

$$C(n, n_0) = \sum_{k=0}^{M-1} P(k) \{ \sum_{\tau=0}^{L-1} a(\tau) P(n+k-\tau)_M + N[n_0 + (n+k)_M] \}$$

$$= \sum_{\tau=0}^{L-1} a(\tau) \sum_{k=0}^{M-1} P(k) P(n+k-\tau)_M + \sum_{k=0}^{M-1} P(k) N[n_0 + (n+k)_M]$$

$$= \sum_{\tau=0}^{L-1} a(\tau) R_{pp}(n-\tau) + R_{pn}(n_0+n) \qquad (8)$$

Where $R_{pp}(n)$ is the auto-correlation of PN sequence and $R_{pn}(n)$ is the correlation between PN sequence and noise. If R_{pp} is ideal and satisfies:

$$R_{pp}(n-\tau) = \delta(n-\tau) \qquad (9)$$

then C_n is the estimation of the radio channel.

II. *CCI (co-channel interference)*

From the above CCI model, we know the energy of analog TV signal distributes mainly near three carriers - luma, chroma and audio. We consider the PAL(phase alternating line) as the CCI source for the calculation and design.

In STBC-OFDM systems, the CCI not only generates high-level narrow-band frequency interference as in CP-OFDM systems, but also destroys the correlation-peak-detection based parameter acquisition, which further deteriorates the system performance. since the CCI has significant effects on the PN-correlation based parameter estimation, we have to reject the CCI in the time domain at the receiver side. As shown in Fig. 5, the CCI is considered as the PAL signal and in the receiver the first step is to detect the CCI. Once the CCI is detected, the notch filter will be enabled, and the CCI-filtered signal is injected into a conventional STBC-OFDM receiver for demodulation and decoding.

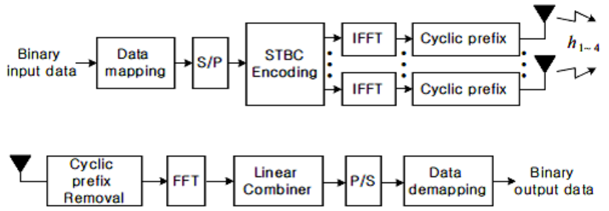

Fig. 5 Channel Model and STBC- OFDM Receiver with CCI processing

First stage of STBC-OFDM receiver should be detection and rejection of CCI. The line synchronizing pulse is periodical, which is utilized to detect the existence of the CCI in this paper. A correlator is hence designed to detect the periodical line synchronizing pulses, which is expressed as

$$R_{rc}(n) = \sum_{k=0}^{N_p-1} r^*(n+k)r(n+N_l+k) \quad (10)$$

where N_l is the minimal integer not less than T_l/T_s , T_s is the sampling period.

In Fig. 6, for a certain CCI level, the invariant level of line synchronizing pulse produces a stable correlation gain. Therefore, we can decide a threshold H_0, corresponding to the lowest CCI level we aim to detect, for the following judgment

$$F_{cci} = \begin{cases} 1, & A_m \geq H_0 \\ 0, & A_m < H_0 \end{cases} \quad (11)$$

where A_m stands for the magnitude of the correlation peak from $A(n)$'s. F_{cci} is set as one indicating the existence of the CCI, which enables the rejection of the CCI. The CCI rejection is implemented in the time domain by means of a method of notch filtering. Due to the unsymmetrical spectrum of the CCI in baseband complex signal, we have to design a notch filter with complex coefficients. Additionally, the filter is considered as a type of infinite-impulse-response (IIR) filter in order to make a low-complexity rejection scheme, while attenuating the CCI carriers deeply. We start the filter design with one notch at a given frequency ω_i. Given the 3-dB bandwidth $\Delta\omega_i$ of the notch as well as the filter gain A_i , we can obtain a filter's transfer function

$$H_i(z) = A_i \frac{1-e^{j\omega_i}z^{-1}}{1-\rho_i e^{j\omega_i}z^{-1}} \quad (12)$$

with $0 < \rho_i < 1$ ensuring a stable response of the IIR filter. According to the pole/zero pattern of $H_i(z)$, when is near the unit circle, the filter only attenuates the components close to the frequency ω_i of input signal, while other components pass through without visible attenuation. Since the designed notch filter does not affect the frequency components far away from ω_i, it is effective when rejecting some narrow-band interference. From the aforementioned analysis, the CCI is a type of narrow-band interference of which the energy mainly distributes near those three carrier frequencies. Hence, we can design a higher-order filter, i.e. with more notches, to filter out the components near the carriers of analog TV signal.

III. *Secure Communication*

Based on the conventional constellation rotation concept, this paper extends the application of constellation rotation to provide security from the physical layer point of view. Unlike the unique rotation angle, the pseudo random symbol-specific rotation angles are suggested for different constellation symbols, whereby the pseudo random angles can be treated as the secret key for physical layer encryption. As illustrated in Fig. 7 (b), a pseudo random rotation angle is assigned to each transmitted symbol as

$$S'_k = S_k \cdot e^{j\theta_k}, \quad 0 \leq k \leq N-1, \quad (13)$$

Where θ_k is the symbol-specific pseudo random rotation angle, which is generated by pseudo random sequence generator.

In STBC-OFDM system, both time-domain PN sequences and multi-carrier PN (PN-MC) sequences can be padded before the inverse discrete

Fourier transform (IDFT) block as the guard interval. The PN-MC sequence is the IDFT output of the binary sequence in frequency domain. As shown in Fig. 2, pseudo random constellation rotation can be applied to either PN-MC training sequence or IDFT block, or both of them.

Only the legal receiver can get the authentic rotation angle information, while the eavesdroppers without such information can only demodulate the information by enormous enumeration which is almost impossible to be realized in high-speed wireless communications.

4. CONCLUSION

In the STBC-OFDM-based DTTB system, the co-channel analog TV signal causes significant performance degradation. The high-level CCI not only disables the PN-correlation based synchronizer and channel estimator, but also generates the frequency-domain narrow-band interference to OFDM signal. The CCI is detected through searching for the peak of autocorrelation of the received baseband signal, based on the line synchronization mechanism of analog TV signal. The CCI is removed by a notch filter, which puts one notch at each carrier frequency of analog TV signal. For reducing complexity the conventional one-tap frequency-domain equalizer is applied to STBC-OFDM to separate the data part and the guard interval padded with PN sequence. The secure information can be encoded either in the training sequence, or in the IDFT block, or both of them, hence data can be secured.

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