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Full Length Research Paper

Characterisation of impulse noise effects on space-time block-coded orthogonal frequency division multiplexing (OFDM) signal reception

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This correspondence presents the characterisation of impulse noise effects on the space-time block-coded orthogonal-frequency-division-multiplexing (STBC-OFDM) symbol reception, in which the conventional OFDM system is combined with the antenna-diversity/spatial-diversity in order to achieve the high data transmission rates. The weak impulse noise may be combated by the longer OFDM symbol duration, in which the total energy of noise spreads among the simultaneously transmitted OFDM sub-carriers irrespective of the impulse noise energy distribution. Specifically, the focus of the presented work is on "noise bucket" effect, in which the STBC-OFDM system is considered to be working in the impulsive environment. It is demonstrated by simulation results that for the occurrence of a significant number of impulses per symbol duration, the noise distribution at the input of the receiver's final decision device is approximately Gaussian. Therefore for simulation purpose, the impulsive environment may be generated by the mere incorporation of equivalent Gaussian noise. Besides, some simulation results are presented using 16-QAM / STBC-OFDM system to give some insight into the symbol error rate variations with respect to the different number of sub-carriers and characteristics of impulsive environment.

Key words: Impulse noise, space-time block-coded (STBC), orthogonal-frequency-division-multiplexing, Gaussian distribution, i nverse discrete Fourier transform (IDFT), M-ary QAM.

INTRODUCTION

Space-time block-coded Orthogonal-Frequency-Division-Multiplexing (STBC-OFDM) system is the advanced modulation technique used in the emerging broadband fourth generation wireless communication systems and high-definition-television (HDTV) broadcasting (Van Nee and Parsad, 2000), due to its high spectral efficiency and inherent robustness to the channel impairments. In the conventional approaches, the single carrier systems are forced to invert the channel characteristics, a problem that is aggravated by the multipath dynamics and packet waveform formats (Armstrong, 2009). However, the major which converts a frequency-selective fading channel into the parallel independent frequency-flat sub-channels using the computationally efficient inverse-fast-Fourier-transform (IFFT) (Armstrong et al., 2004). It is also an effective solution to intersymbol (ISI) caused by a dispersive channel using a form of guard interval, called cyclic prefix. The OFDM incorporates a cyclic extension to the sinusoidal basis functions, and the receiver effectively discards the intersymbol interference caused by the multipath propagation. Moreover, it efficiently transfers the complexity of transmitter and receiver from the analog domain to the digital domain.

To increase the capacity/data transmission rates of the conventional OFDM systems, the interest has peaked in different techniques to improve the signal-to-noise-ratio (SNR) at the receiver. In addition to the receiver antenna

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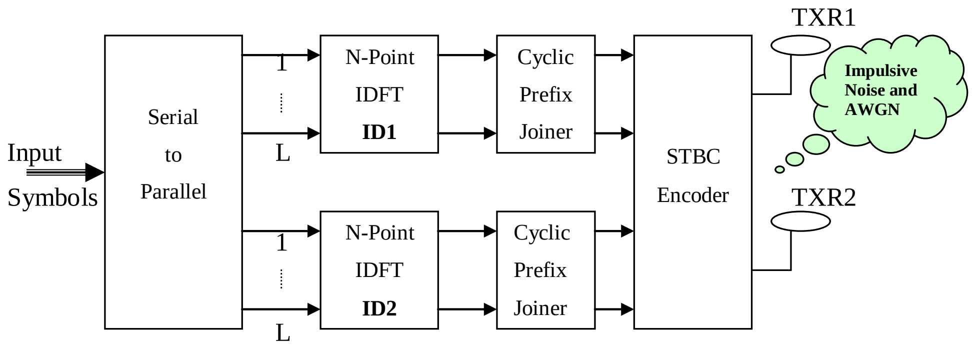

Figure 1. STBC-OFDM modulator/transmitter structure.

benefit that the OFDM offers over single carrier approaches is the resistance to the multipath fading, diversity schemes for better SNR, the STBCs have appeared as a break through in the field of high data transmission rate wireless communication systems. The pioneering work of Alamouti is based on the two transmitter antennas, which exploits the spatial diversity to improve the SNR without bandwidth expansion (Alamouti, 1998). However, the perfect knowledge of the mutually uncorrelated Rayleigh fading channels or channel state information (CSI) is assumed to be available at the receiver. Under these conditions, the OFDM technology is merged with STBC system to achieve the benefit of both schemes (Agrawal et al., 1998). A simple and efficient receiver structure may be used for STBC-OFDM systems, which do not require CSI (Uysal and Georghiades, 2000; Uysal et al., 2001).

The OFDM systems combat impulse noise better than the single carrier systems by using various techniques to mitigate the adverse effects of the impulse noise (Armstrong et al., 2004; Zhidkov, 2003). However, the impulsive environment appears as a serious problem in the digital-video-broadcasting (DVB) and in 4G OFDM services/systems due to the usage of various electrical and mechanical appliances and machines (major sources of impulse noise) (Wu, 1999; Poole, 2002). The transient short-duration disturbances uniformly distributed over the useful passband of the transmission system is impulse noise, which can affect the receiver functioning (Lind and Mufti, 1996). The results presented by Suraweera and Armstrong (2004) manifests that the performance degradation caused by the impulse noise in DVB systems depends only on the total noise energy within one OFDM symbol period, but it is not dependent on the details of distribution of the noise energy within the symbol. Moreover, the overall error rate does not depend on the noise in any one of the DFT output at the receiver (Armstrong et al., 2004), but on the statistics of the noise across all the DFT outputs, which is in close agreement with “Noise-Bucket-Effect” (NBE) investigated by Suraweera and Armstrong (2004). In this correspondence, we present the symbol-error-rate (SER) performance evaluation of the STBC-OFDM wireless systems to explain NBE by using the simulation results.

This paper is organised as follows. First, the details about the STBC-OFDM transmission under the wireless fading environment are described. We next discuss this STBC-OFDM reception scheme under the impulsive wireless environment. The main emphasis/focus is on the adverse effects of impulse noise on the STBC-OFDM systems. Subsequently, the simulation results are presented to characterize the impulse noise effects at the input of final decision device in the last stage of receiver, which are based on the symbol-error-rate (SER) performance of the STBC-OFDM wireless systems. Finally, the concluding remarks and future scope are given.

STBC – OFDM TRANSMISSION UNDER FADING ENVIRONMENT

At the wireless transmitter equipped with two antennas (TXR1 and TXR2), the binary bit stream (data) is first mapped to a sequence of the complex modulation information symbols using 16-QAM constellation scheme (Su and Xia, 2004). The resultant symbol sequence is then passed through a serial-to-parallel converter to generate L serial data streams of N information symbols in each transmitter branch as shown in Figure 1. Consider the l^{th} serial data stream in both branches, in which information symbols are represented by $X_l^1[k]$ and $X_l^2[k]$ corresponding to TXR1 and TXR2 respectively. An N-point inverse-Discrete-Fourier-Transform (IDFT) is performed on these serial data streams by using the following formulas as

$$x_{l,n}^1 = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_l^1[k] \exp\left(+j\frac{2\pi kn}{N}\right) \quad (1)$$
$$with \;\; n = 0,1, \; \ldots \; , N-1$$

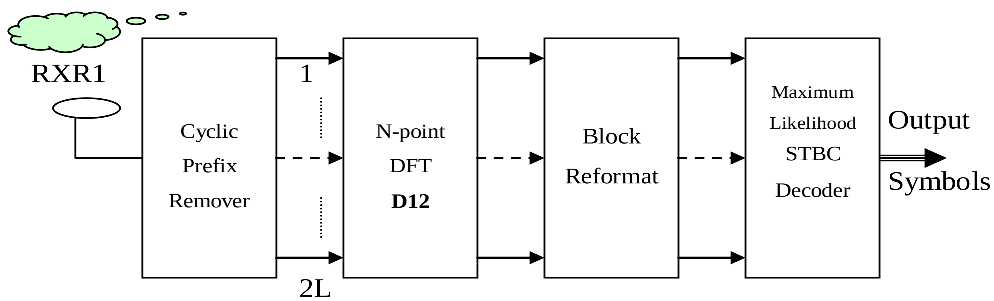

Figure 2. STBC-OFDM demodulator/receiver structure.

$$x_{l,n}^{2} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_l^{2}[k] \exp\left(+j\frac{2\pi kn}{N}\right) \quad (2)$$
$$with \quad n = 0,1, \ \dots \ , N-1$$

$\Rightarrow$In the first frame interval, the OFDM frame at the output of ID1 is

$$\left(X_l^1[0], \ \dots \ , X_l^1[N-1]\right) \xrightarrow{IDFT} \left(x_{l,0}^1, \ \dots \ , x_{l,N-1}^1\right) \quad (3)$$

The signal to be transmitted from the first antenna TXR1 is obtained after the incorporation of the cyclic prefix (CP) as

$$\left(x_{l,0}^1, \ \dots , x_{l,N-1}^1\right) \xrightarrow{CP} \left(\underbrace{x_{l,N-m}^1, \ \dots \ , x_{l,N-1}^1}_{Cyclic\,\mathrm{Pr}efix}, x_{l,0}^1, \ \dots , x_{l,N-1}^1\right) \quad (4)$$

Similarly in the first frame interval, the OFDM frame at the output of ID2 is

$$\left(X_l^2[0], \ \dots \ , X_l^2[N-1]\right) \xrightarrow{IDFT} \left(x_{l,0}^2, \ \dots \ , x_{l,N-1}^2\right) \quad (5)$$

The signal to be transmitted from the second antenna TXR2 is obtained after the incorporation of the cyclic prefix as

$$\left(x_{l,0}^2, \ \dots , x_{l,N-1}^2\right) \xrightarrow{CP} \left(\underbrace{x_{l,N-m}^2, \ \dots \ , x_{l,N-1}^2}_{Cyclic\,\mathrm{Pr}efix}, x_{l,0}^2, \ \dots , x_{l,N-1}^2\right) \quad (6)$$

We will now invoke Alamouti scheme for the STBCs to generate the STBC-OFDM signals at the transmitter in the time-domain using the complex constellation points (Alamouti, 1998), which is as follows.

In the next/second frame interval, the OFDM signal to be transmitted from the first antenna TXR1 is obtained by using the STBC encoder as

$$\left(\underbrace{-x_{l,N-m}^{2*}, \ \dots \ , -x_{l,N-1}^{2*}}_{Cyclic\,\mathrm{Pr}efix}, -x_{l,0}^{2*}, \ \dots \ , -x_{l,N-1}^{2*}\right) \quad (7)$$

Similarly, the OFDM signal to be transmitted from the second antenna TXR2 is obtained by using the STBC encoder as

$$\left(\underbrace{x_{l,N-m}^{1*}, \ \dots \ , x_{l,N-1}^{1*}}_{Cyclic\,\mathrm{Pr}efix}, x_{l,0}^{1*}, \ \dots \ , x_{l,N-1}^{1*}\right) \quad (8)$$

where, $(.)^* \ and \ (.)^T$ are the complex conjugate operator and the matrix transpose operator respectively, $m \geq channel\ memory\ length$ is the length of cyclic prefix. Although it introduces some redundancy and also reduces the over all data transmission rate (Hanzo et al., 2003), yet the usage of CP proves to be helpful in eliminating both intersymbol interference (ISI) and intercarrier interference (ICI) from the received signal (simple form of equalization). During the wireless transmission of $X_l^{Ant}[k]$ signal, $H^{Ant}[k]$ is the frequency response of the channel from the "Ant" transmitter antenna to the single receiver antenna at the k^{th} tone.

STBC – OFDM RECEPTION UNDER IMPULSIVE ENVIRONMENT

In addition to inevitable channel frequency response, the composite signal also encounters additive-white-Gaussian-noise (AWGN) and impulsive noise in between the transmitter and receiver pair. After the accurate/efficient removal of CP, the composite signal is passed through the N-point Discrete-Fourier-Transform (DFT) operation in D12 as shown in Figure 2. The received signal at the output of D12 in the vector form is represented as

$$\vec{R}[k] = \vec{X}[k]\vec{H}[k] + \underbrace{\vec{G}[k] + \vec{I}[k]}_{GI} \quad (9)$$

$$\vec{R}[k] = \vec{X}[k]\vec{H}[k] + \vec{GI}[k] \quad (10)$$

where, $\vec{R}[k] = \{\vec{Rs}_1[k] \ \ldots \ \vec{Rs}_v[k] \ \ldots \ \vec{Rs}_L[k]\}^T$ is the $2L \times 1$ dimensional received signal vector in frequency-domain, $\vec{X}[k] = \{\vec{Xs}_1[k] \ \ldots \ \vec{Xs}_v[k] \ \ldots \ \vec{Xs}_L[k]\}^T$ is the $2L \times 2$ dimensional transmitted signal matrix in the frequency-domain (3), (5), $\vec{H}[k] = \{H^1[k] \ H^2[k]\}^T$ is the 2×1 dimensional channel impulse response vector in the frequency-domain,

$\vec{G}[k] = \{G_1[k] \ \ldots \ G_l[k] \ \ldots \ G_{2L}[k]\}^T$ is the $2L \times 1$ dimensional AWGN signal sample vector in the frequency-domain with statistics defined by the Gaussian distribution $N_G(0, \ \sigma_{\eta g}^2)$,

$\vec{I}[k] = \{I_1[k] \ \ldots \ I_l[k] \ \ldots \ I_{2L}[k]\}^T$ is the $2L \times 1$ dimensional impulse noise sample vector in the frequency-domain with zero-mean and variance $\sigma_{\eta i}^2$. The total noise is defined by the $2L \times 1$ dimensional vector as $\vec{GI}[k] = \{GI_1[k] \ \ldots \ GI_l[k] \ \ldots \ GI_{2L}[k]\}^T$ with zero-mean and variance $\sigma_{\eta gi}^2$; it follows that

$$\frac{1}{2}E\left\{GI_l[k]GI_l[k]^*\right\} = \frac{1}{2}E\left\{G_l[k]G_l[k]^*\right\} + \frac{1}{2}E\left\{I_l[k]I_l[k]^*\right\} \quad (11)$$

where, $E\{.\}$ is the expectation operator. The received signal vector in the frequency-domain (10) can be explained by using

$$\vec{Rs}_v[k] = \begin{bmatrix} R_{2v-1} \\ R_{2v} \end{bmatrix}_{2\times 1}$$
$$where, \ v = 1, \ \ldots, L \ and \ k = 0, \ \ldots, N-1 \quad (12)$$

$$\vec{Xs}_v[k] = \begin{bmatrix} +X_v^1[k] & +X_v^2[k] \\ -X_v^{2*}[k] & +X_v^{1*}[k] \end{bmatrix}_{2\times 2} \quad (13)$$

The above equation (12) represents an orthogonal matrix in the frequency-domain at the k^{th} tone, which is proposed by Alamouti's scheme for the STBCs with the complex constellation points (Alamouti, 1998).

IMPULSE NOISE EFFECTS ON STBC – OFDM SIGNAL RECEPTION

To observe the impulse noise effects on STBC-OFDM signal reception, we consider the l^{th} sample of $\vec{R}[k]$ at the output of D12 that is,

$$R_l[k] = \sum_{Ant=1}^{2} X_l^{Ant}[k]H^{Ant}[k] + G_l[k] + I_l[k] \quad (14)$$

$$where, \ l = 1, \ \ldots, 2L \ and \ k = 0, \ \ldots, N-1$$

It is clear from (14) that the impulse noise component is

$$I_l[k] = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} i_l(n)\exp\left(-\frac{j2\pi kn}{N}\right) \quad (15)$$
$$for \ k = 0,1,2, \ \ldots, N-1$$

The above equation may be redefined as

$$I_l[k] = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} i_l(n,k) \quad (16)$$
$$for \ k = 0,1,2, \ \ldots, N-1$$

It is also apparent from (14) that the AWGN component is

$$G_l[k] = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} g_l(n)\exp\left(-\frac{j2\pi kn}{N}\right) \quad (17)$$
$$for \ k = 0,1,2, \ \ldots, N-1$$

The central limit theorem states that the probability distribution of I_l approaches the Gaussian distribution $N_G(0, \ \sigma_{\eta i}^2)$ in the limit (Papoulis, 2008) as $(1/N)$ approaches zero for a large number of sub-carriers.. Using (11) and (17), it can be shown that the variance of zero-mean Gaussian-plus-impulse noise is

$$\sigma_{\eta gi}^2 = \frac{1}{N}\sum_{n=0}^{N-1}\frac{1}{2}E\left\{gi_l(n)gi_l(n)^*\right\} \quad (18)$$

$$\sigma_{\eta gi}^2 = \frac{1}{N}\sum_{n=0}^{N-1}\sigma_{\eta g}^2 + \frac{1}{N}\sum_{n=0}^{N-1}\frac{1}{2}E\left\{i_l(n)i_l(n)^*\right\} \quad (19)$$

If N_i is the number of impulse noise occurrences within an OFDM symbol interval/period, then

$$\sigma_{\eta gi}^2 = \sigma_{\eta g}^2 + \left\{ \frac{N_i}{N} \right\} \sigma_{\eta i}^2 \quad (20)$$

The factor N_i/N represents the percentage of impulse noise energy per OFDM symbol, but it does not give any information about the impulse noise structure. However at the output of D12, the structure of impulse noise is approximately Gaussian due to the spreading effect of DFT operation. Moreover, the results presented in (Alamouti, 1998) manifest that the maximum-likelihood (ML) STBC decoder impose phase rotation on the noise components without affecting the signal-to-noise-ratio (SNR). In the presented work, when the $\vec{R}[k]$ (9) is processed in the ML STBC decoder as shown in Figure 2, the impulse noise sample vector $\vec{I}[k]$ also undergoes the phase rotation process, which in turn further randomizes the impulse noise components to bestow Gaussian characteristics. Major observations based on the simulation results that enlighten the approximate equivalence of impulsive noise with Gaussian noise at the output of DFT operator in the STBC-OFDM receiver are discussed. It is a well-known result that if the real and imaginary parts of a complex random process are independent wide-sense stationary Gaussian processes (Papoulis, 2008), then the magnitude and phase of this complex random process follow Rayleigh and uniform distribution respectively. Therefore, we will plot the magnitude and phase of the impulsive noise components at the output of D12 for its statistical characterisation, and we will also present the information symbol-error-rate (SER) performance results to observe the effects of impulsive noise on the final information symbol detection at the output of decision device at the last stage in the STBC-OFDM wireless receiver.

SIMULATION RESULTS

We investigate the details of noise bucket effect in the aforementioned STBC-OFDM system by simulations using the 16-QAM complex constellation signal scheme. For this purpose, we consider $N = 64$ for the number of sub-carriers, DFT, IDFT operations and the OFDM symbol duration. The random number of impulses N_i (both with negative as well as positive amplitude ensuring zero-mean) occurring within one OFDM symbol duration are assumed to be uniformly distributed over the interval $[0, N-1]$. The presented simulation results are based on the ensembled average of 250 independent trails. Therefore, the average symbol error rate is calculated by using the following formula:

$$SER_{Avg} = E\{SER(n)\} = \frac{1}{250}\sum_{n=1}^{250} SER(n) \quad (21)$$

Case 1

For comparison, we also consider the complex Gaussian noise with zero-mean and variance $\sigma_{\eta g}^2$ in the different setup for same STBC-OFDM system under the same conditions. The magnitude and phase/angle of the resultant impulse noise components at the output of DFT operator D12 are plotted in Figures 3 and 4 respectively. To characterize the impulsive noise, the magnitude and phase/angle of the resultant Gaussian noise components at the output of DFT operator D12 are also demonstrated in Figures 3 and 4 respectively. It is clear from the Figure 3 that the magnitude of impulsive noise follows the distribution approximately similar to the magnitude distribution of Gaussian noise with typical variance. It may also be inferred from the results presented in Figure 4 that the phase distribution of the impulsive noise and the Gaussian noise are approximately same that is, uniform phase distribution in the interval $[-\pi, +\pi)$. Therefore irrespective of the distribution of impulsive noise at the input of STBC-OFDM receiver, the distribution of impulsive noise at the output of D12 is approximately Gaussian due to the spreading effect of DFT operator under "NBE" (Suraweera and Armstrong, 2004). Moreover this fact is strengthened by the Alamouti STBC decoder (Alamouti, 1998), which boosts the Gaussianness of resultant impulsive noise component by phase rotation at the input of final decision device. However, the magnitude of impulsive noise energy per OFDM symbol period remains constant at the input and output of D12.

Case 2

We next observe the effects of impulse noise variance $\sigma_{\eta i}^2$ on the SER performance of the STBC-OFDM system. Therefore, the amplitude of impulse noise is varied from 0.5 to 3.0 to vary its variance. The value of signal to Gaussian noise ratio is kept constant at 20 dB. It is apparent from Figure 5 that the symbol error rate increases as the amplitude of noisy impulses increases, which is due to the increase in variance of the impulsive noise $\sigma_{\eta i}^2$ in (20). In addition to that the increasing number of impulses per OFDM symbol duration also deteriorates the SER performance of STBC-OFDM system due the increasing value of factor N_i/N in (20).

Case 3

Further, we keep the amplitude of the impulses constant at 1.25. The Gaussian-plus-impulsive noise variance $\sigma_{\eta gi}^2$ is calculated by using (20). The results presented in

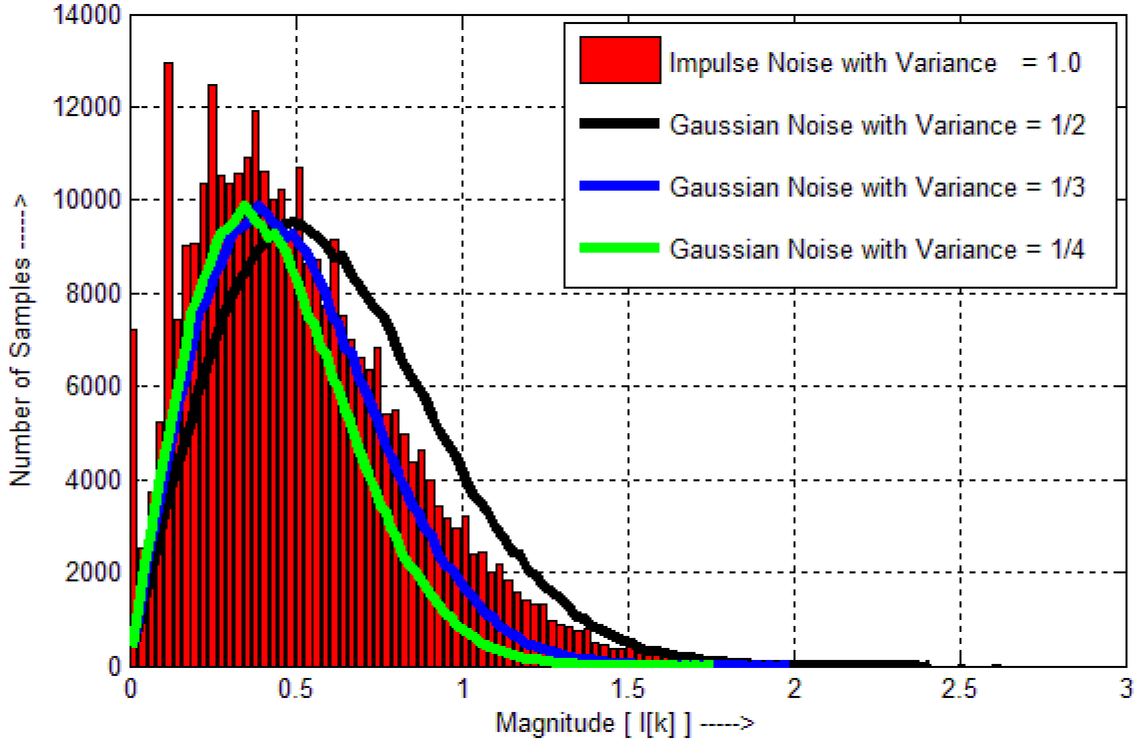

Figure 3. Distribution of the magnitude of received impulse noise at the output of D12.

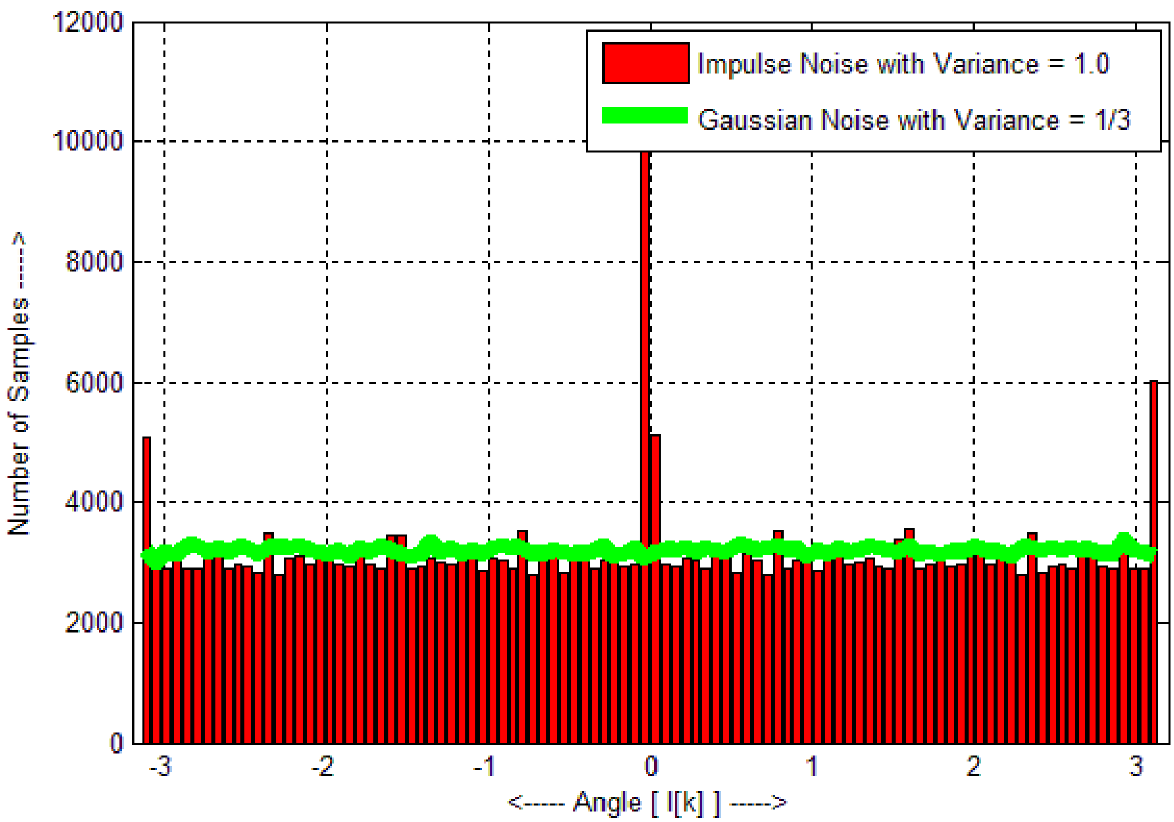

Figure 4. Distribution of the phase/angle of received impulse noise at the output of D12.

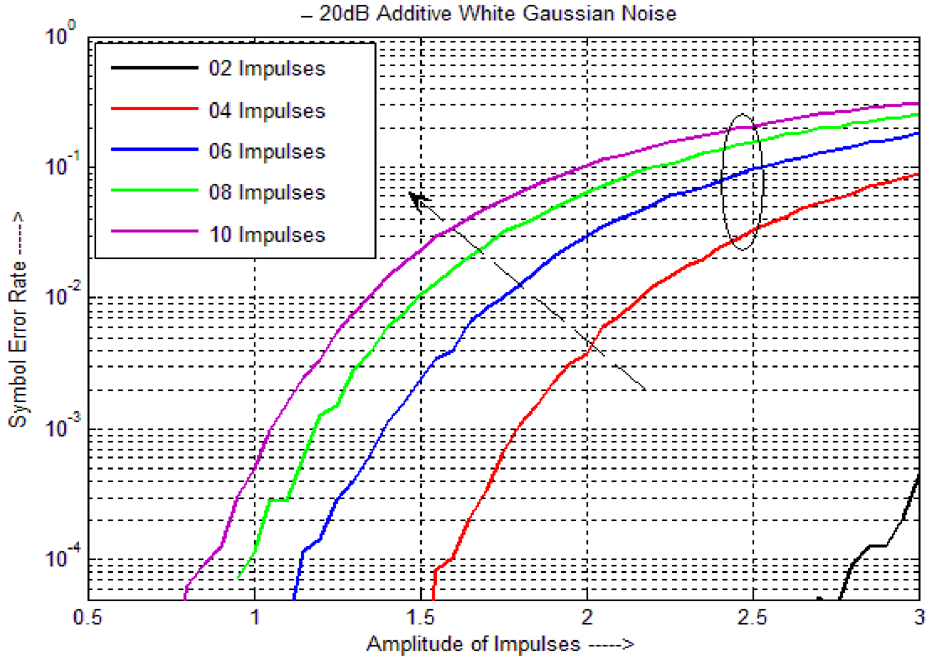

Figure 5. Symbol error rate at different values of the amplitude of noisy impulses.

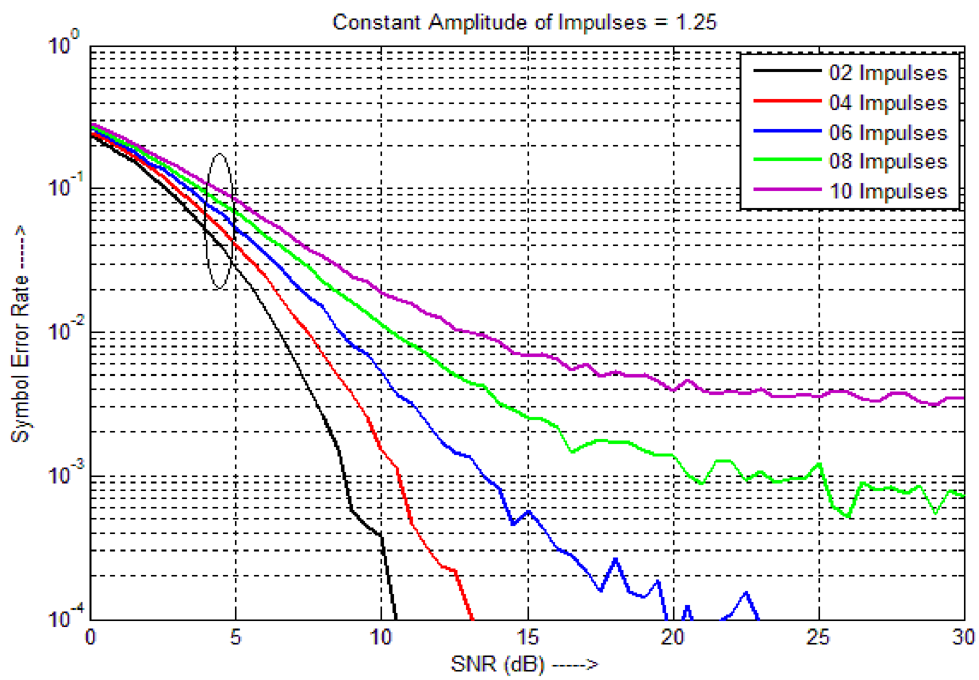

Figure 6. Symbol error rate at different values of the signal to Gaussian-plus-impulsive noise ratio in the presence of impulsive noise.

Figure 6 depict that as the signal to Gaussian-plus-impulsive noise ratio increases, the SER performance improves gradually; which in turn improves the data transmission rate. However, the total noise variance $\sigma^2_{\eta gi}$ in (20) can be reduced by increasing the OFDM symbol duration/the number of sub-carriers N, which reduces the factor N_i/N. For this simulation, we have

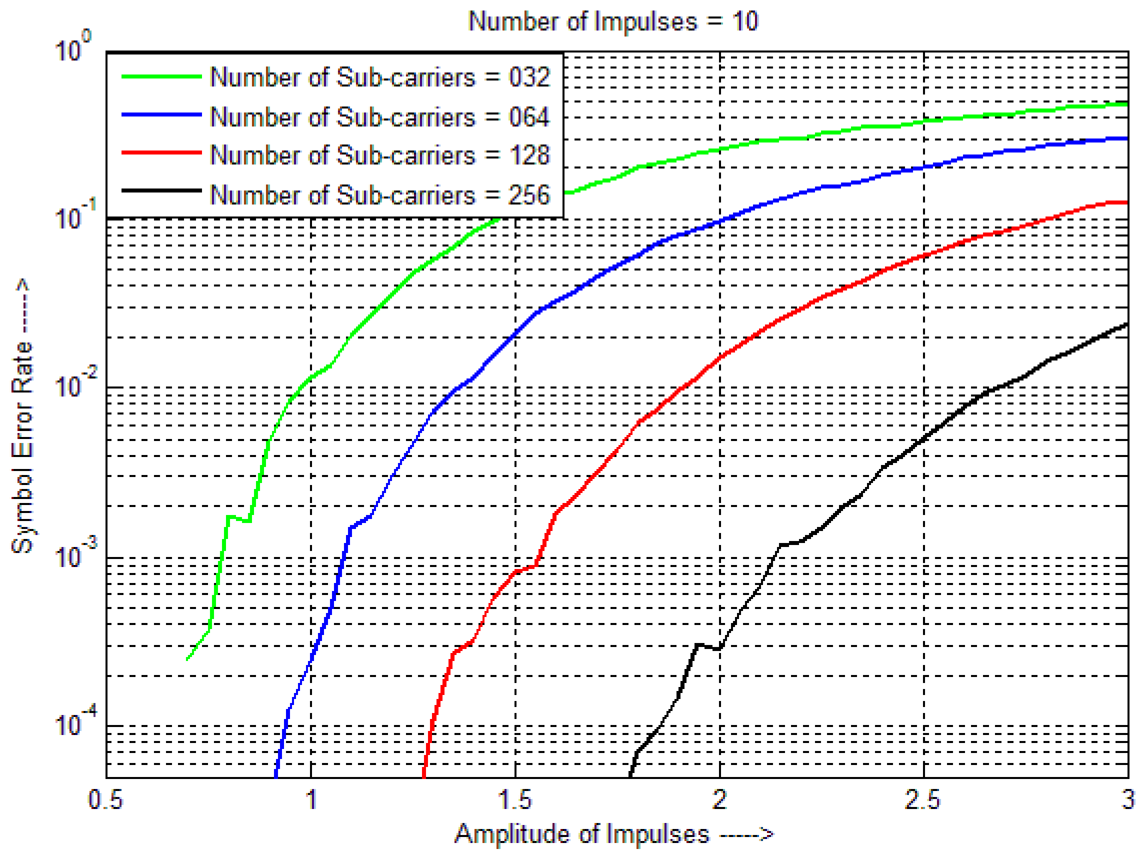

Figure 7. SER at different values of the amplitude of noisy impulses for varying number of sub-carriers.

fixed the maximum number of impulse noise occurrences per OFDM symbol duration $N_i = 10$. Here, we add $-20dB$ AWGN, and vary the amplitude of the impulse noise. The results plotted in Figure 7 demonstrate that as the value of N increases, the SER performance of the presented wireless system improves significantly because the long OFDM symbol duration reduces the total noise energy per symbol in contrast to the short OFDM symbol situation.

Conclusion

In this correspondence, the STBC and OFDM technologies are merged to achieve the benefits of both technologies working under the impulsive environment. The effects of impulse noise on this high data rate STBC-OFDM wireless systems are investigated, which particularly emphasis on the noise bucket effect. The presented simulation results manifest that the impulsive noise may be approximately characterized by the Gaussian distribution at the output of DFT operator due to the spreading effect of DFT, irrespective of the impulse noise distribution at the input of receiver antenna without any change in the impulsive noise energy per OFDM symbol duration. In addition, the phase distribution of the impulsive noise at the output of DFT operator is observed to be approximately uniform.

However the longer OFDM symbol duration leads to the spreading of impulse noise energy among the larger number of OFDM sub-carriers, which reduces the impulse noise energy per sub-carrier. Finally, the operation of ML STBC decoder further randomizes the impulse noise components to enhance its Gaussian characteristic. At the input of final decision device at the end stage of receiver, the total Gaussian-plus-impulse noise may be modelled as the zero-mean approximately Gaussian process with variance $\sigma^2_{\eta gi}$ (20). Therefore, the adverse effects of the impulse noise on the symbol error rate (SER) performance can be reduced by increasing the duration of OFDM symbol or the number of OFDM sub-carriers. Future scope includes the development of impulsive noise excision and mitigation techniques (Armstrong and Suraweera, 2004) for the STBC-OFDM wireless communication systems. Moreover, the data transmission rates may be further increased by using OFDM systems in combination with the high-rate full-diversity STBC systems (Grover and Kohli, 2011, 2012).

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