Down Link: Error-Rate Performance of Cognitive D-STTD MC-IDMA System

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Abstract. 5G wireless network has promised to offer high speed data transmission along with quality of service. Cognitive radio network (CRN) with multiple-input-multiple-output system have potential to offer higher bandwidth with high data rate. We present physical layer design of double-space-time-TD (D-STTD)-Transmit Diversity aided MIMO-MC-IDMA system invoking Cognitive spectrum. CRN is a modern device which entreat unused TV-band available spectrum and distribute such spectrum strongly to BS (base station). The fragments subdivided frequency-band of CRN is distributed for secondary users and is utilized for multi-carrier transmission-DSTTD system consists of two STBC block units and we invoke such system to obtain better error-rate performance. We detect signals at each mobile station using block-Nulling detection decoding algorithm. We present error-rate results of CRN defined D-STTD MC-IDMA for standard channel specifications. We observe from the error-rate results that D-STTD assisted MC-IDMA system enhances data rate with better performance while extracting higher bandwidth from CRN network.

Keywords: Block-Nulling detection algorithm · BCJR decoding algorithm · Maximum likely-hood detection (ML) · (MMSE) detection algorithm · Multi-user detection (MUD) · Space-time transmit diversity (S-TTD) · Zero-forcing algorithm (ZF)

1 Introduction

Multiple-Input-Multiple-Output system (MIMO) is a optimistic transmission technique in wireless network by which we can enhance spectral efficiency without expecting additional bandwidth. By incorporating multiple antenna system at receiver and transmitter, we can enhance bit-error rate performance along with data rate and quality of service in wireless transmission. In general, MIMO system is exploited in two possible ways; Space-time transmit diversity (STBC) is aimed to enhance error-rate performance by reducing deep fading effect. Spatial Multiplexing is designed to uplift data rate. In other words, STBC enhances capacity of system while we are invoking higher spectral efficiency using spatial Multiplexing V-BLAST architecture and the advantage of spatial multiplexing is achieving higher gain by scheme. Bell Laboratories introduced V-BLAST architecture which focus on spatial multiplexing and Alamouti introduced the

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concept of STBC. Many detection algorithms have been focused on MIMO detection such as Maximum likely hood algorithm, ZF and MMSE algorithm. Researchers [1] elucidated the benefits of adaptive MIMO scheme by switch over between V-BLAST structure and STBC. Prof. Lee in [2] explained the basic principles of D-STTD detection algorithm using Block-Nulling algorithm. Prof. Iruthayanathan [3] explained D-STTD - OFDM system for mitigation of multi-path fading effects in underwater signal transmission. Spreading code specific CDMA was introduced by Prof. Frenger et al. [4] and such scheme adds advantages over low-rate channel encoding with DSSS techniques by which we can obtain superior performance. Ping in [5] proposed the concept of new accessing scheme called IDMA: Interleave Division Multiple Access scheme to allow more users in a wireless channel. Many research article have addressed the advantages of IDMA that the proposed scheme can mitigate rich scattering effects of multi-path environments thereby offering higher error-rate performance with less $\boldsymbol{E_b} / \boldsymbol{N_0}$. This scheme is referred as low-rate spreading code CDMA. Hence it exploits all the benefits of CDMA. Prof. Viterbi elucidated in [6] that by allocating full bandwidth for low-rate channel coding, achieves high coding gain along with necessary processing gain with higher capacity in the context of multi-user signal transmission. Research article, authors [7] have addressed benefits of IDMA scheme to get higher error-rate results in multi-path environments. Prof. Hanzo elucidated in [8] Multi-carrier IDMA offers better error-rate results for down-link signal transmission.

The demand for data rate is increasing day by day for specific purpose such as live video telecast system, still image transmission and other relevant multi-media services etc., At present limited frequency-band are accessible for users to transfer data. In the recent past, many research articles focused on Cognitive Radio (CR) un-used TV band spectrum which can be extracted for mobile communication to overcome limitation of bandwidth. It is elucidated in [9] that we can allocate this spectrum for secondary users for huge data transfer application such as human being movements and activities observing system in hospital using IoT etc., Federal Communication Commission (FCC) is being originated to exploit Television-band spectrum for the application of mobile communication.

Turbo code is recommended as preeminent channel encoder for wireless LAN, 5G network. The authors in [10] addressed mathematical model for turbo decoder considering serial concatenated and parallel concatenated convolutional encoder. Prof. Wang and his team [11] explained iterative turbo decoder for CDMA system. Prof. Le Goff and his team [12] explained the benefits of iterative decoding for wireless signal transmission. In literature [13], Benedetto and his team explained bandwidth efficiency of parallel-concatenated style of turbo code in wireless network. In [14], Robertson explained modulation scheme employing turbo code. In [10], Prof. Benedetto explained benefits of channel encoder of serial concatenated type and also decoding technique. In the most of above-mentioned literature, author expressed benefits of MIMO, IDMA scheme along with iterative decoder and Multi-Carrier Communication.

In this treatise, we encapsulate our contribution: -

1. We realize D-STTD style of MIMO structure at Base station to exploit both spatial multiplexing and spatial diversity

2. We implement CRN with TV-Band spectrum of 80 MHz to 800 MHz for utilization of secondary users.
3. At each Mobile station, block-Nulling detection algorithm realization is made to estimate information considering lesser SNR
4. We decode received signals using Maximum Log-Maximum-a-posteriori probability-based detection algorithm.
5. We analyze and present results for CRN assisted D-STTD MC-IDMA system considering SUI Model & LTE channel specifications

Research work is summarized as Sect. 2 describes system model configuration with mathematical modelling. Section 3 explains mathematical structure of D-STTD detection algorithm at the receiver and decoded signals. Section 4 details simulated results observation and exploration. Finally, Conclusion are detailed in Sect. 5.

2 System Model

2.1 Signal Transmission from BS

Considering D-STTD style of MIMO system with N_t - TX from BS-Base Station and N_r - RX antennas at each MS-Mobile Station, we contemplate Cognitive defined Coded MIMO MC-IDMA system with 'K' - DL users in the Fig. 1. We presume that $N_t = N_r =$ 4 antennas for calculation in our system. We construct D-STTD using two parallel form of STBC block unit at BS. At each MS, we realize Block-Nulling detection algorithm to decode transmitted sequence in the presence of licensed user interferences known as Primary PR-MUI & Secondary-SE-MUI-Multiple User Interference and noise. We allocate CR frequency-band for secondary users according to the need of users assign SE-users dynamically to utilize CR-Spectrum that ranges 80 MHz– 800 MHz.

Let $\boldsymbol{u}_l$ represents bit-data stream of $\boldsymbol{l}^{th}$ user which undergo turbo code encoding

Let $\boldsymbol{e}_l$ be encoded bit stream where

$$\boldsymbol{e}_l = [e_{l1}, e_{l2}, \ldots, e_{lm}]^T, \quad l = 1, 2, \ldots, L \tag{1}$$

Indicating 'm' as total no. of bits.

Let $\boldsymbol{s}_l$ be the frequency-domain (FD) spreading sequence with respect to l^{th} user

$$\text{Where } \boldsymbol{s}_l = \frac{1}{\sqrt{N}}\left[s_{l0}, s_{l1}, \ldots, s_{l(N-1)}\right]^T \tag{2}$$

Indicating N as spreading length.

The FD spreading matrix $Nm \times m$ is represented as $\boldsymbol{S}_l$ where

$$S_l = diag\left\{\boldsymbol{s}_l, \boldsymbol{s}_l, \boldsymbol{s}_l, \ldots, \boldsymbol{s}_l\right\} = \boldsymbol{I}_m \otimes \boldsymbol{s}_l, \quad l = 1, 2, \ldots, L \tag{3}$$

$$\text{where } Nm = N.\, m \tag{4}$$

Consequently, the spreaded sequence is interleaved by user-defined interleaving pattern.

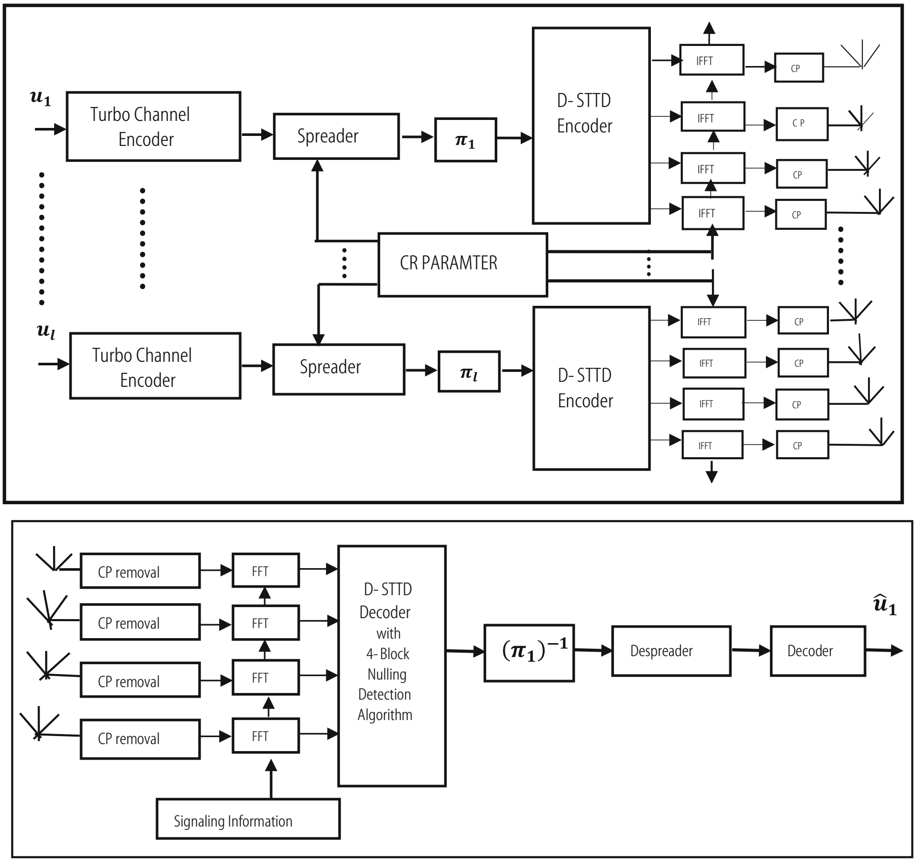

Fig. 1. Transceiver structure for Cognitive defined D-STTD model Coded MIMO MC-IDMA system

Let $\boldsymbol{d}_l$ be interleaved spread sequence and is expressed as

$$\boldsymbol{d}_l = \boldsymbol{S}_l \, \boldsymbol{e}_l \tag{5}$$

The interleaved spread signal of all users is represented as

$$d = \sum_{l=1}^{L} \boldsymbol{S}_l \, \boldsymbol{e}_l \tag{6}$$

We encode bit stream using D-STTD encoder considering each block having four consecutive bit sequences. Then we transmit Mb size of block from each antenna after carrying multi-carrier modulation.

We now represent MC-modulation (Multi-Carrier) matrix as

$$\boldsymbol{MC} = diag\{exp(j2\pi\, f_1\, t), exp(j2\pi\, f_2 t), \ldots, exp(j2\pi\, f_{Mb} t)\} \tag{7}$$

We add Cyclic prefixes for 20% to relieve the effects of inter-carrier interference before transmission from each antenna.

We transmit multi-user sum signals in multi-path channel environments with channel specifications as in the Table 1. Considering N - tap delay spread channel matrix connecting r^{th} - RX t^{th}- TX Antenna are represented as

$$h_{rt}(t) = \sum_{n=1}^{N} h_{rt}^{n} \partial(t - \tau_n) \tag{8}$$

where h_{rt}^{n} - random process which is Gaussian and zero mean with variance $\psi(\tau_n)$.

2.2 Signal Reception

At each MS, we remove cyclic prefix and carry out multi-carrier demodulation. In this article, we have assumed that the CSI is known to MS. Relation between input and output as assumed to be

$$Y = (\boldsymbol{H}_{\perp})\boldsymbol{D} + \boldsymbol{\eta} \tag{9}$$

Where Y - received vector

$(\boldsymbol{H}_{\perp})$ - Channel Matrix connecting Mobile Station and Base Station and $\boldsymbol{\eta}$ - indicating both PR-MUI and SE-MUI in addition to the noise. The received matrix at $\boldsymbol{l}^{th}$. Mobile Station is given by $N_r \times 2$ component matrix received after two symbol durations are expressed.

3 D-STTD Detection Algorithm

$$\boldsymbol{Y}_l = (\boldsymbol{H}_{\perp})_l \boldsymbol{D} + \boldsymbol{\eta} \tag{10}$$

Where

$$\boldsymbol{Y}_l = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \\ y_{31} & y_{32} \\ y_{41} & y_{42} \end{bmatrix}, \ N_r \times 2 \text{ component received matrix} \tag{11}$$

$$\boldsymbol{D} = \begin{bmatrix} d_1 & -d_2^* \\ d_2 & d_1^* \\ d_3 & -d_4^* \\ d_4 & d_3^* \end{bmatrix} N_t \times 2 \,\text{Component transmitted matrix} \tag{12}$$

$$(\boldsymbol{H}_{\perp})_l = \begin{bmatrix} (h_{\perp})_{11} & (h_{\perp})_{12} & (h_{\perp})_{13} & (h_{\perp})_{14} \\ (h_{\perp})_{21} & (h_{\perp})_{22} & (h_{\perp})_{23} & (h_{\perp})_{24} \\ (h_{\perp})_{31} & (h_{\perp})_{32} & (h_{\perp})_{33} & (h_{\perp})_{34} \\ (h_{\perp})_{41} & (h_{\perp})_{42} & (h_{\perp})_{43} & (h_{\perp})_{44} \end{bmatrix}, \ N_r \times N_t \,\text{component} \tag{13}$$

$$\boldsymbol{\eta} = \begin{bmatrix} \eta_1 & -\eta_2^* \\ \eta_2 & \eta_1^* \\ \eta_3 & -\eta_4^* \\ \eta_4 & \eta_3^* \end{bmatrix}, \ N_r \times 2 \text{ component noise Matrix} \tag{14}$$

We have to re-arrange the above equation to imply Block-Nulling Signal Estimation Algorithm [2]. Hence the above equation is modified as

$$\left(\overline{\boldsymbol{Y}}_e\right)_l = \left(\overline{\boldsymbol{H}}_e\right)_l \overline{\boldsymbol{D}} + \overline{\boldsymbol{\eta}}_l \tag{15}$$

Where

$$\left(\overline{\boldsymbol{Y}}_e\right)_l = \begin{bmatrix} y_{11} \\ y_{12}^* \\ y_{21} \\ y_{22}^* \\ y_{31} \\ y_{32}^* \\ y_{41} \\ y_{42}^* \end{bmatrix} 2N_r \times 1 \text{ component received vector} \tag{16}$$

$$\left(\overline{\boldsymbol{H}}_e\right)_l = \begin{bmatrix} (h_\perp)_{11} & (h_\perp)_{12} & (h_\perp)_{13} & (h_\perp)_{14} \\ (h_\perp)_{12}^* & -(h_\perp)_{11}^* & (h_\perp)_{14}^* & -(h_\perp)_{13}^* \\ (h_\perp)_{21} & (h_\perp)_{22} & (h_\perp)_{23} & (h_\perp)_{24} \\ (h_\perp)_{22}^* & -(h_\perp)_{21}^* & (h_\perp)_{24}^* & -(h_\perp)_{23}^* \\ (h_\perp)_{31} & (h_\perp)_{32} & (h_\perp)_{33} & (h_\perp)_{33} \\ (h_\perp)_{32}^* & -(h_\perp)_{31}^* & (h_\perp)_{34}^* & -(h_\perp)_{33}^* \\ (h_\perp)_{41} & (h_\perp)_{42} & (h_\perp)_{41} & (h_\perp)_{44} \\ (h_\perp)_{42}^* & -(h_\perp)_{41}^* & (h_\perp)_{44}^* & -(h_\perp)_{43}^* \end{bmatrix} 2N_r \times N_t \text{ component matrix} \tag{17}$$

$$\overline{D} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix} N_t \times 1 \text{ component vector} \tag{18}$$

$$\text{And } \ \overline{\eta}_l = \begin{bmatrix} \eta_{11} \\ \eta_{12}^* \\ \eta_{21} \\ \eta_{22}^* \\ \eta_{31} \\ \eta_{32}^* \\ \eta_{41} \\ \eta_{42}^* \end{bmatrix} 2N_r \times 1 \text{ component noise vector} \tag{19}$$

We pre-multiply above equation with $\left(\overline{\boldsymbol{H}}_{\boldsymbol{e}}\right)_l^H$ to express in simple form

$$\left(\overline{\boldsymbol{Y}}\right)_{\boldsymbol{l}} = \overline{\boldsymbol{H}}_{\boldsymbol{l}}\,\overline{\boldsymbol{D}} + \overline{\eta}_{\boldsymbol{l}} \tag{20}$$

Where

$$()^H \text{ - Indicates Hermitian transpose} \tag{21}$$

$$\left(\overline{\boldsymbol{Y}}\right)_{\boldsymbol{l}} = \left(\overline{\boldsymbol{H}}_{\boldsymbol{e}}\right)_{\boldsymbol{l}}^{\boldsymbol{H}} \times \left(\overline{\boldsymbol{Y}}_{\boldsymbol{e}}\right)_{\boldsymbol{l}} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} N_r \times 1 \text{ component vector} \tag{22}$$

$$\overline{\boldsymbol{H}}_{\boldsymbol{l}} = \left(\overline{\boldsymbol{H}}_{\boldsymbol{e}}\right)_{\boldsymbol{l}}^{\boldsymbol{H}} \times \left(\overline{\boldsymbol{H}}_{\boldsymbol{e}}\right)_{\boldsymbol{l}} = \begin{bmatrix} \boldsymbol{\upsilon_1} & \boldsymbol{0} & \boldsymbol{\sigma} & \boldsymbol{\omega} \\ \boldsymbol{0} & \boldsymbol{\upsilon_1} & -\boldsymbol{\omega}^* & \boldsymbol{\sigma}^* \\ \boldsymbol{\sigma}^* & -\boldsymbol{\omega} & \boldsymbol{\upsilon_2} & \boldsymbol{0} \\ \boldsymbol{\omega}^* & \boldsymbol{\sigma} & \boldsymbol{0} & \boldsymbol{\upsilon_2} \end{bmatrix} N_r \times N_t \text{ channel gain} \tag{23}$$

Expressing $\boldsymbol{\sigma}$, $\boldsymbol{\omega}$, $\boldsymbol{\upsilon}_1$, and $\boldsymbol{\upsilon}_2$-channel gain, We have

$$\boldsymbol{\sigma} = \sum_{w=1}^{4}\left(\left(\boldsymbol{h}_{w1}^* \times \boldsymbol{h}_{w3}\right) + \left(\boldsymbol{h}_{w2} \times \boldsymbol{h}_{w4}^*\right)\right) \tag{24}$$

$$\boldsymbol{\omega} = \sum_{w=1}^{4}\left(\left(\boldsymbol{h}_{w1}^* \times \boldsymbol{h}_{w4}\right) - \left(\boldsymbol{h}_{w2} \times \boldsymbol{h}_{w3}^*\right)\right) \tag{25}$$

$$\boldsymbol{\upsilon}_1 = \sum_{w=1}^{4}\left(|\boldsymbol{h}_{w1}|^2 + |\boldsymbol{h}_{w2}|^2\right) \tag{26}$$

$$\boldsymbol{\upsilon}_2 = \sum_{w=1}^{4}\left(|\boldsymbol{h}_{w3}|^2 + |\boldsymbol{h}_{w4}|^2\right) \tag{27}$$

And

$$(\overline{\eta})_l = \left(\overline{H}_e\right)_l^H \times \left(\overline{\eta}_l\right) = \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \end{bmatrix} N_r \times 1 \text{ component noise vector} \tag{28}$$

If STBC block-1 component consisting of d_1 and d_2 are having stronger signals strength than STBC block-2 unit comprising d_3 and d_4, then we detect d_1 and d_2 initially using ML algorithm as given below

$$\hat{\boldsymbol{d}}_i = \underset{d_i \in \{1, -1\}}{arg\,min} \left|\boldsymbol{y}_i - (\overline{\upsilon}_i \times d_i)\right|^2 \tag{29}$$

Where

$$\overline{\upsilon}_i = \upsilon_1 - \left(\frac{|\sigma^2| + |\omega^2|}{\upsilon_2}\right) \tag{30}$$

After estimating STBC block-1 unit, we can estimate second STBC block-2 unit using simple expression

$$\begin{bmatrix} \hat{\boldsymbol{d}}_3 \\ \hat{\boldsymbol{d}}_4 \end{bmatrix} = \begin{bmatrix} y_3 \\ y_4 \end{bmatrix} - \begin{bmatrix} \sigma^* & -\omega \\ \omega^* & \sigma \end{bmatrix} \begin{bmatrix} \hat{\boldsymbol{d}}_1 \\ \hat{\boldsymbol{d}}_2 \end{bmatrix} \tag{31}$$

Presuming that STBC block-2 unit having signal component d_3 and d_4 are stronger in signal strength than STBC block-1 unit having d_1 and d_2, we detect signals d_3 and d_4 using ML algorithm based on

$$\hat{d}_i = \underset{d_i \in \{1, -1\}}{arg\,min} \left|\boldsymbol{y}_i - (\overline{\boldsymbol{\upsilon}}_i \times d_i)\right|^2 \tag{32}$$

where

$$\overline{\upsilon}_i = \upsilon_2 - \left(\frac{|\sigma^2| + |\omega^2|}{\upsilon_1}\right) \tag{33}$$

Consequently, we detect STBC block-1 unit with signals d_1 and d_2 using expression

$$\begin{bmatrix} \hat{d}_1 \\ \hat{d}_2 \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} - \begin{bmatrix} \sigma^* & \omega \\ -\omega^* & \sigma \end{bmatrix} \begin{bmatrix} \hat{d}_3 \\ \hat{d}_4 \end{bmatrix} \tag{34}$$

Finally, we de-spread the estimated information and de-interleave followed by turbo decoder [15] to obtain $\hat{\boldsymbol{u}}_l$ - $\boldsymbol{l}^{th}$ user information.

4 Result Discussion and Performance Analysis

Simulation results are represented of coded D-STTD assisted MIMO-MC-IDMA scheme exploiting Cognitive spectrum for SUI-1 [16] and LTE-Vehicular Channel-Model [17]. We summarize channel model in Table 1 and simulation parameter in Table 2.

Table 1. Channel Parameters Model & power delay profiles Specifications for SUI and LTE channels

Path no.	Channel	SUI-1		LTE extended vehicular	
		Delay (μ-microsec)	Power (dB)	Delay (μ-microsec)	Power (dB)
1		0	0	0	0
2		0.4	−15	30	−1.5
3		0.9	−20	150	0
4				310	−1.5
5				370	−0.6
6				710	−9.1
7				1090	−7
8				1730	−12
9				2510	−16.9

Channel desp^{n}	Doppler shift frequency (Hz)	Antenna correlation	Vehicular speed (km/h)
SUI-1	0.5	0.7	-
LTE-extended vehicular channel model	300	0.7	162

We simulate error-rate results for SUI-1 model with DS-Doppler-Shift of 2.5 Hz along antenna correlation for D-STTD architecture of 0.7 for SUI-1 channel and Doppler shift of 300 Hz with moving vehicle speed of velocity of 162 km/hr considering LTE-extended vehicular model for channel respectively.

Table 2. Parameters for simulation

Parameters	Attributes
Carrier Frequency	Cognitive Spectrum - 80 MHz to 800 MHz
BW-Bandwidth	6 MHz
No's of Channel Realizations	25000
Modulation Technique	BPSK
Channel Models	SUI-1, LTE Extended Vehicular Channel Model Specifications
No's of Transmitter Antenna	4
No's of Receiver Antenna	4
Channel encoder and decoder	Turbo code and log-MAP iterative decoding

We exploit Cognitive spectrum ranging from 80 MHz to 800 MHz Evidently, we have implicated sub-band frequency with bandwidth of 6 MHz of channel for each user. We present simulation of 25000 channel realizations results for each SNR. We have replicated for F-domain spreading sequence length of 8192 with 16-users.

Figure 2 dictates bit error-rate results with SNR for Cognitive D-STTD MC-IDMA system with model of SUI-1 specification. Figure 2 graph, we observe that D-STTD system with MC-IDMA requires 1 $\boldsymbol{Eb/No}$ to generate 10^{-5} of bit error rate. Our considered system offers better bit-error-rate results for lesser SNR while achieving higher processing gain using IDMA system and higher bandwidth using CRN.

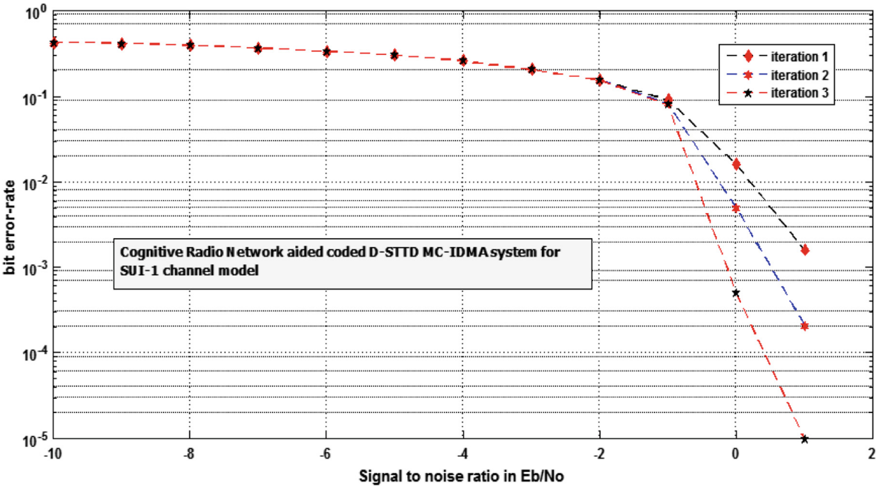

Fig. 2. Bit error performance results of D-STTD MC-IDMA system for SUI-1 channel specification

Figure 3, dictates the error-rate performance with SNR for our system with LTE-vehicular channel specification. The error-rate curve reveals that to reproduce 10^{-5} of bit error rate, the system requires approximately 1 $\boldsymbol{Eb/No}$. Hence our system provides better results with less number of computation while achieving higher data rate in the rich scattering effects.

From our analysis, we would like to clarify that D-STTD type of MIMO profile achieves both spatial multiplexing and diversity gain. Also the system need three iteration to achieve better results for both channel model. In the first iteration, there is BER of almost 10^{-3} for SUI-1 channel model, 10^{-2} for LTE-vehicular channel model for 1 $\boldsymbol{Eb/No}$. Clearly, there is no appreciable Bit-Error-Rate performance of our coded system for both channel specifications in first iteration. In the third iteration, iterative turbo decoding algorithm gives appreciable enhancement in terms of Bit-Error-Rate. After three iteration, there is no further improvement in BER results. Hence we have shown up to three iteration results in the graph. Further, we demonstrated from mathematical analysis that Block-Nulling detection techniques [2] offers better estimation technique with less number of computations when compared to MMSE detection algorithm. Furthermore, error-rate curve reveals that coded cognitive radio system achieves better bit

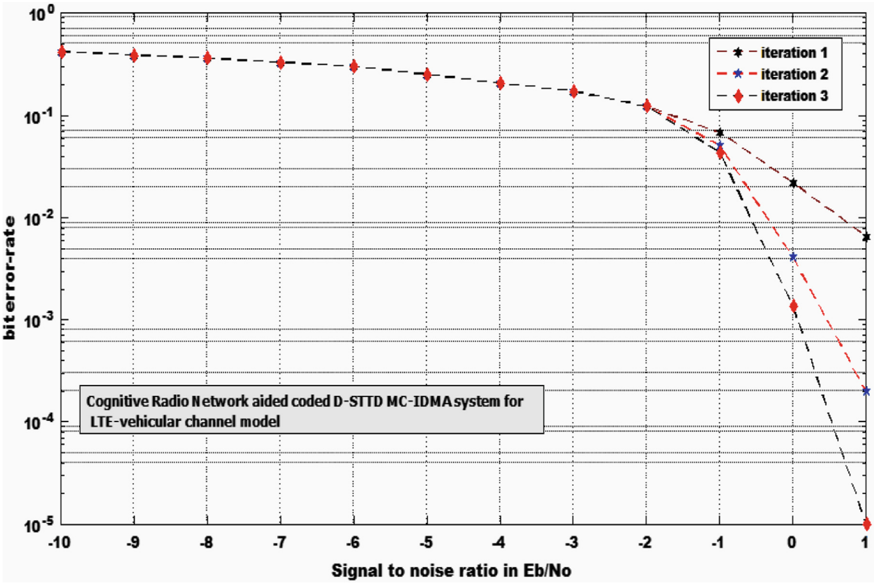

Fig. 3. Bit error-rate performance of D-STTD MC-IDMA system for LTE-vehicular specification

error-rate with lesses SNR even though our Mobile unit is traveling at high speed of 162 km per hour. The error-rate performance reveals that with low value of SNR, we obtain higher performance while exploiting higher bandwidth using Cognitive spectrum.

5 Conclusion

This research work presented performance-analysis of coded cognitive radio network D-STTD aided MIMO MC-IDMA system. The proposed transceiver structure for down-link communication enables to obtain higher performance irrespective of channel condition while offering higher bandwidth by invoking unused TV-band spectrum. Our considered D-STTD MC-IDMA system also supports more user-population by mitigating adverse effects of PR-MUI and SE-MUI with support of D-STTD decoder and iterative style of channel decoder. Further the system reveals that we can confront demand for high data rate using D-STTD structure with minimum number of computation while packing bandwidth efficiency using CRN.

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