Performance Analysis Of Adaptive MIMO-Of Dmcognitive Wireless System With Joint Rate, MIMO Profile, And Power Adaptation

Santosh Itraj, Dr. Uttam Bombale, Pravinkumar Patil, Dr. Meenakshi Patil

Abstract— The cognitive radio resolves the spectrum scarcity issue in wireless communication networks by utilizing the spectrum in an opportunistic way. The CR network yet inflicts peculiar challenges because of the dynamic spectrum, high quality of service requirements and the higher data rate. Integration of the multiple input multiple output-orthogonal frequency division multiplexing (MIMO-OFDM) with the cognitive radio offers robustness and the diversity gain in a hostile wireless environment. In this treatise, we propose a link adaptation strategy for the MIMO-OFDM based cognitive radio system. In our adaptation scheme, Cognitive radio-adaptive modulation coding, MIMO profile, power controller (CR-AMCMPPC) adapts the MIMO profile space-time block code (STBC) or spatial division multiplexing (SDM) along with the modulation coding scheme (MCS) and the transmit power. This adaptation works on each of the packets to be transmitted on the selected channel. The novel power-adaptation scheme time-domain water-filling power adaptation (TWFPA) is proposed. The TWFPA adapts transmit power to improve energy efficiency instead of the throughput of the system. We evaluate the performance of the adaptive MIMO-OFDM cognitive system. We perceive through the simulation results that the proposed adaptation scheme procures significant enhancement in the throughput of the system with an efficient power utilization under the constraint of targeted bit error rate (BER) and the transmit power. We consider both the interweave and underlay cognitive schemes in the proposed controller. System performance is investigated for the interweave channel sharing scheme.

Index Terms— BER, Cognitive radio, Interweave scheme, MIMO-OFDM, SDM, STBC, Throughput.

1 Introduction

The prominent resources in the wireless communication network are bandwidth and energy. The scarcity of these resources limits the performance of the wireless system in terms of quality of service and the channel capacity. The most eminent solution to deal with the scarcity of these resources is a cognitive radio (CR) technology. It can utilize these resources in the most intelligent and efficient manner [1]. The CR allows secondary users (SUs) to access the licensed spectrum owned by the primary users (PUs) in an opportunistic manner under the constraint of maintaining the quality of service for the primary user. Cognitive radio shares channel in either interweave or underlay manner [2]. Cognitive radio enables secondary users to not only select the best available channel but also to adapt the transmission parameters like modulation, coding rate, transmit power, etc. quickly. This allows enhancement in the performance of the system in a hostile wireless environment [1]. However, to ensure further performance improvement integration of MIMO-OFDM with CR technology can be the best possible solution.

- *Santosh Itraj is currently pursuing a Ph.D. in Electronics Engineering at Shivaji University Kolhapur, Maharashtra, India., PH-9422405192. E-mail: ssitraj@yahoo.com*
- *Dr. Uttam Bombale received the Ph.D. in Electronics Engineering from the (D.A.I.I.C.T.), Gandhinagar, Gujarat, India Presently he is working as a Professor in D.O.T. Shivaji University, Kolhapur, India. E-mail: uttam_bombale@rediffmail.com*
- *Pravinkumar Patil is currently pursuing a Ph.D. in Electronics Engineering at VTU, Belgavi, India. E-mail: pspatil108@gmail.com*
- *Dr. Meenakshi Patil is Principal at Jain AGMIT Jamkhandi, VTU, India, received a Ph.D. degree from Shivaji University, India. E-mail: meenakshipatil@gmail.com*

MIMO provides multiple benefits such as capacity enhancement without extra bandwidth [3], dramatic boost in the transmission reliability using space-time coding [4], and the minimal co-channel interference in the multi-user communication environment [5]. There has been immense research work in various domains of CR technology with an objective of improving the capacity and energy efficiency of the cognitive network. One of the areas of interest of many researchers is the adaptation of various parameters or resources in a cognitive system. However, no much more attention has been given to exploit the benefits of MIMO technique in the CR network. In [6], the author has given a focus on the various research activities on energy efficiency improvement in wireless communication. It can be seen that the link adaptation in a wireless communication system using MIMO-OFDM technology results in an energy-efficient solution. The parameters that can be adapted include MIMO mode, modulation, code rate, and the transmit power. However, most of the research work considered the non-cognitive single-user and single-channel environment. The MIMO-OFDM schemes in the multi-channel and the multi-user cognitive environment need to be further investigated. S. Hua et al. [7] proposes a novel MIMO co-operative cognitive radio network (CCRN) framework. This system consists of MIMO SUs. These act as relaying nodes and co-operates PUs in relaying their traffic. Concurrently SUs use the same channel for communicating their own data. The motive behind the design of the system was to optimize spectrum efficiency of PUs and SUs. It has been proved that both primary and secondary networks give enhanced performance in MIMO-CCRN. However, authors have considered only power adaptation and discussed the relay node selection in an optimum way to enhance the capacity of the cognitive network. It can be realized that many researchers [8], [9] have focused on the enhancement of energy efficiency of cognitive radio with or without MIMO technology. In [9], authors have addressed the joint optimization problem with reference to spectrum sensing duration and the transmit power of the cognitive users to improve energy efficiency. The authors in [10] used singular value decomposition technique to optimize the capacity of the secondary network by adapting transmit power. However, it is computationally complex in case of MIMO-OFDM CR system. Authors in [11] investigated the joint dynamic channel and rate selection in the CR system to optimize the throughput. The considered system is a single antenna-based system and with the assumption that channels are primary user free. In [12], underlay single antenna CR system is validated with power adaptation. In [13], authors have investigated the single input single output (SISO) system performance with rate and power adaptation. In [14], authors have proposed a link adaptation scheme for MIMO cognitive multi-carrier code division multiple access (MC-CDMA) system. System performance is investigated by adapting MIMO mode (STBC/SDM) and modulation (16QAM/QPSK) in single-user and single-channel environment. As evident from the above discussion, it can be seen that the link adaptation with MIMO-OFDM in CR optimizes the performance of the system. However, in most of the proposals for MIMO CR either power or MIMO mode is adapted. Power adaptation distributes total power among the channels based on the channel condition to enhance the capacity of the system. In addition, most of the work considers the single-channel environment and underlay cognitive scheme. Motivated by these facts, in this treatise, we investigate the performance of adaptive MIMO-OFDM cognitive system. We propose the novel link adaptation algorithm (CR-AMCMPPC) adapting MCS, MIMO profile and the transmit power based on channel state information (CSI) and the status of the primary users. In this algorithm, the MCS and MIMO profile adaptation scheme is proposed for throughput optimization, whereas power adaptation scheme is proposed for improving the energy efficiency of the system. We consider the multi-user and a multi-channel cognitive system with interweave as well as underlay channel-sharing schemes.

2 System Model

2.1 System environment

The cognitive system environment as illustrated in Fig. 1 constitutes two secondary users *SU1* and *SU2*, two primary users *PU1* and *PU2* with multiple antennas at both transmitter and receiver forming a (2 x 2) MIMO system. *PU1* is a licensed user of CH1 whereas *PU2* is a licensed user of CH2. *PU2* always allow *SU1* to communicate with *SU2* on *CH2*. In the presence of *PU2*, there is a constraint on the transmit power of *SU1* to minimize the interference to the primary user. Use of CH2 in the presence of the *PU2* by secondary users defines underlay channel sharing scheme in CR. However, *PU1* allows secondary users to use CH1 in an opportunistic manner i.e. in his absence. Thus, *SU1* uses CH1 only in absence of the *PU1*, while communicating with SU2. This defines the interweave channel sharing scenario. *SU1* is assigning the highest priority to CH1. Secondary nodes in the system are assumed to be operating in the full-duplex mode. The system performance can be evaluated for different channel detection probabilities.

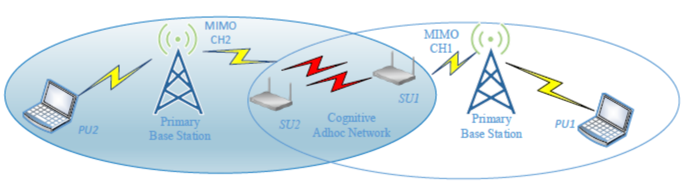

Fig. 1. *System Environment.*

2.3 System description

The architecture of the secondary user transceivers in the proposed MIMO-OFDM based adaptive cognitive system is shown in Fig. 2. We consider that *SU1* communicates with *SU2* by using the spectrum owned by *PU1* and *PU2* either in interweave or underlay schemes. The transmitter at the *SU1* detects the availability of the CH1 and if it is available then selects it to communicate with *SU2* otherwise, *SU1* continues data transmission on CH2. The system design and simulation parameters are based on the 802.11n (WLAN) protocol and are depicted in Table 1 [15]. The transmitter at the *SU1* constructs high throughput (HT) packets and transmits them to *SU2* on the selected channel. Transmitter selects MIMO mode STBC or SDM along with MCS for each of the packet for optimizing the throughput of the system over the selected channel. Transmitter also adapts the transmit power per packet to improve the energy efficiency of the system. Transmitter uses the control information fed back by *SU2* receiver to select the transmit parameters. We consider the Rayleigh distributed multipath frequency selective fading MIMO channels TGn-D (CH1) and TGn-B (CH2). OFDM converts these channels into flat fading channels. The system design ensures that these channels behave as slow fading channels. The receiver at the SU2 estimates the channel using a minimum mean square error (MMSE) detector. This estimate of the channel gain at the receiving end is used to compute the signal to noise ratio (SNR) estimate. This reflects the channel state information (CSI). The CR-AMCMPPC at the receiver uses the CSI and the soft information about the status of the primary users to define the MIMO mode, MCS, and the average transmit power for the next packet to be transmitted. This control information is fed back to the transmitter for adapting the transmit parameters over the selected channel.

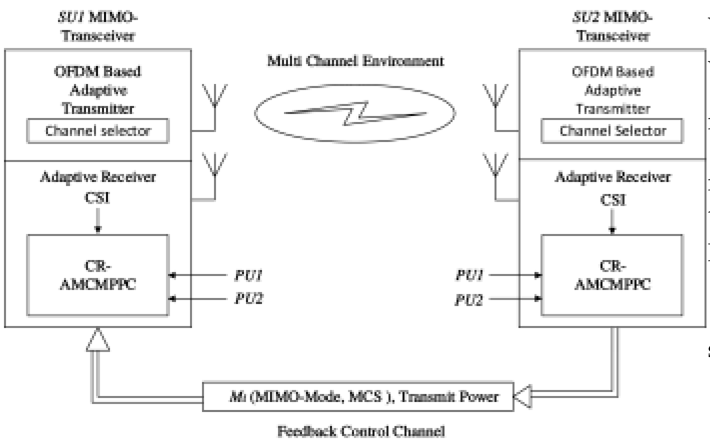

Fig. 2 System Model

TABLE 1
SYSTEM DESIGN PARAMETERS

No.	System parameter	Specification
1	WLAN standard	802.11n HT mode
2	Modulation	OFDM-56 carriers
3	Constellations	BPSK, QPSK, 16-QAM, 64-QAM
4	Code rates	1/2, 2/3, 3/4, 5/6
5	PSDU length	1000 bytes
6	Guard interval	800 ns
7	OFDM symbol period	4 µs
8	Maximum packet period	1.3 ms
9	Channels	TGn-B, Tgn-D
10	Fading effect	Flat and slow
11	Channel bandwidth	20 Mhz
12	MIMO modes	STBC (2×1), SDM (2×2)

2.3 Mathematical Model

We consider a CR-MIMO system with two flat fading MIMO channels CH1 (TGn-D) and CH2 (TGn-B). The MIMO system consists of N_t transmit antennas and N_r receive antennas. In the proposed system $N_t = N_r = 2$. The transmit power is assumed to be equally distributed among the transmit antennas. In the proposed system, *SU1* transmits the signal X_m to *SU2* over the selected MIMO channel either CH1 or CH2. The received signal at *SU2* on the m^{th} channel is [16]

$$Y_m = H_m X_m + N_m \tag{1}$$

Where m = 1, 2 specifies channel number.

Where H_m is a $(N_t \times N_r)$ channel matrix and in our case, it is of size (2×2). The element $h_{m\_ij} = h_{m\_12}$ of the channel matrix is the gain of the m^{th} channel between the first transmit antenna and the second receive antenna.

Here X_m is a transmit OFDM symbol vector of size $(N_t \times 1)$ i.e. it is (2×1) in our case. Y_m is a received symbol vector of size $(N_r \times 1)$ i.e. it is (2×1) in this case.

N_m is a $(N_r \times 1)$ noise vector and n_{m_i} is a white Gaussian noise with zero mean and variance σ^2_{mn}.

Further, n_{m_i} are IID i.e. independent identically distributed.

The proposed system operates in either STBC or SDM mode depending on the channel condition.

2.3.1 STBC-MIMO (2×1)

In this mode of operation the number of space-time streams is $N_{ss} = 1$, and $N_t = 2$, $N_r = 1$.

The proposed MIMO model uses Almouti coding while transmitting a symbol in this mode of operation. This ensures a diversity gain of two and thus enhances the reliability of the system. Let x_{m_1} and x_{m_2} denote the symbols transmitted from transmit antenna $Tx1$ and $Tx2$ respectively during the first symbol period $t1$. During the second symbol period $t2$, $Tx1$ transmits $-x^*_{m\_2}$ and $Tx2$ transmits $x^*_{m\_1}$. Combining the received symbols during $t1$ and $t2$, the net system model becomes

$$\begin{pmatrix} y_{m\_1} \\ y_{m\_2} \end{pmatrix} = \begin{pmatrix} h_{m\_1} & h_{m\_2} \\ h^*_{m\_2} & -h^*_{m\_1} \end{pmatrix} \begin{pmatrix} x_{m\_1} \\ x_{m\_2} \end{pmatrix} + \begin{pmatrix} n_{m\_1} \\ n^*_{m\_2} \end{pmatrix} \tag{2}$$

Where the effective channel matrix with orthogonal columns is

$$H_m = \begin{pmatrix} h_{m\_1} & h_{m\_2} \\ h^*_{m\_2} & -h^*_{m\_1} \end{pmatrix} \tag{3}$$

Noise vector matrix is

$$N_m = \begin{pmatrix} n_{m\_1} \\ n^*_{m\_2} \end{pmatrix} \tag{4}$$

The diversity order for (2×1) MIMO with Almouti STBC coding is

$$L = N_t - N_r + 1 \tag{5}$$

Thus, this mode provides diversity gain with the full coding rate ($R = 1$). This ensures mitigation of BER without affecting data rate.

2.3.2 SDM-MIMO (2×2)

Spatial multiplexing in MIMO ensures data transmission at a higher rate than diversity based MIMO systems. The system model for the m^{th} channel can be represented as

$$\begin{pmatrix} y_{m\_1} \\ y_{m\_2} \end{pmatrix} = \begin{pmatrix} h_{m\_11} & h_{m\_12} \\ h_{m\_21} & h_{m\_22} \end{pmatrix} \begin{pmatrix} x_{m\_1} \\ x_{m\_2} \end{pmatrix} + \begin{pmatrix} n_{m\_1} \\ n_{m\_2} \end{pmatrix} \tag{6}$$

This is a matrix form representation of the (1).

2.3.3 Signal Detection

The received signal Y_m is recovered at the receiver by using the MMSE detector in which it minimizes mean square error. MMSE minimizes total power of noise and inter symbol interference (ISI) components in the recovered signal. Considering Y_m and X_m to be zero mean

$$MSE = E\left\{\left(\hat{X}_m - X_m\right)^2\right\} \tag{7}$$

Here, X_m is a transmitted signal vector. $\hat{X}_m$ is an estimated signal vector and is given as

$$\hat{X}_m = W Y_m \tag{8}$$

Here Y_m is a received signal vector. W is an MMSE weight matrix to maximize signal to interference plus noise ratio (SINR) after detection and is given as

$$W = \left(H_m^{\;H} H_m + \sigma_{mn}^2 I\right)^{-1} H_m^{\;H} \tag{9}$$

Here H_m is a channel matrix. m^{th} is a matrix Hermitian. I is an identity matrix. σ_{mn}^2 is a noise variance given as

$$\sigma_{mn}^2 = E\left\{N_m^{\;H} N_m\right\} \tag{10}$$

In the proposed system adaptive controller (CR-AMCMPPC) adapts MCS, MIMO profile (STBC/SDM) and the average transmit power by using CSI i.e. SNR estimate at the receiver. We consider the average SNR_e to reflect the MIMO channel condition and is computed by using channel estimate $h_{m\_est}(k)$ for N subcarriers (k varies from one to N). The average signal power estimate at the receiver is defined as

$$S_{m\_avg\_est} = \frac{1}{N}\sum_{k=1}^{N}\left|h_{m\_est}(k)\right|^2 \tag{11}$$

Here $h_{m\_est}(k)$ is the m^{th} channel coefficient estimate for k^{th} subcarrier. N Defines the total number of subcarriers and for STBC and SDM it is defined as

$$N = N_{STBC} = 112 \tag{12}$$

$$N = N_{SDM} = 224 \tag{13}$$

Hence the SNR ratio at the receiver is

$$SNR\_ratio = \frac{S_{m\_avg\_est}}{n_{m\_var\_est}} \tag{14}$$

Here $n_{m\_var\_est}$ is noise variance σ_{mn}^2 at the receiver.

Thus the average SNR estimate in dB is

$$SNR_{avg\_est} = 10\log_{10}\left(SNR\_ratio\right) dB \tag{15}$$

2.3.4 Performance Metrics

The performance of the system is investigated by computing the throughput of the system under the constraint of the targeted BER and the average transmit power. The approximate expressions for the BER for different modulation and coding schemes and L independent identically distributed Rayleigh paths are depicted [17]. The average BER for BPSK is

$$P_b = \frac{1}{\log_2 M}\left[\frac{1}{\pi}\int_0^{\frac{\pi}{2}}\left(M_{\gamma_b}\left(\frac{-g}{\sin^2\phi}\right)\right)^L d\phi\right] \tag{16}$$

Where $M_{\gamma_b}(s)$ is the moment generating function (MGF) of the average SNR per bit $\overline{\gamma}_b$ for all L channels and for Rayleigh fading channel it is given as

$$M_{\gamma_b}(s) = \left(1 - s\overline{\gamma}_b\right)^{-1} \tag{17}$$

Here

$$s = -\frac{g}{\sin^2\phi} \tag{18}$$

Here g is of value one for coherent BPSK constellation.

Average BER for QPSK is defined as

$$P_b = \frac{1}{\log_2 M}\left[\frac{1}{\pi}\int_0^{\frac{3\pi}{4}}\prod_{l=1}^{L} M_{\gamma_{bl}}\left(\frac{-g}{\sin^2\phi}\right) d\phi\right] \tag{19}$$

Here $g = .5$ for QPSK constellation. Where $M_{\gamma_{bl}}$ is MGF of the SNR per symbol γ_{bl} of the path l and for Rayleigh channel, it is defined as

$$M_{\gamma_b l}(s) = \left(1 - s\overline{\gamma}_{bl}\right)^{-1} \tag{20}$$

Here

$$s = -\frac{g}{\sin^2\phi} \tag{21}$$

Average BER for M – QAM is given as

$$P_b = \frac{4}{\pi\log_2 M}\left(P_{b1} - P_{b2}\right) \tag{22}$$

Where P_{b1} and P_{b2} are defined as

$$P_{b1} = \left(1 - \frac{1}{\sqrt{M}}\right)\int_0^{\frac{\pi}{2}}\prod_{l=1}^{L} M_{\gamma_{bl}}\left(\frac{-g_{QAM}}{\sin^2\phi}\right) d\phi \tag{23}$$

$$P_{b2} = \left(1 - \frac{1}{\sqrt{M}}\right)^2\int_0^{\frac{\pi}{4}}\prod_{l=1}^{L} M_{\gamma_{bl}}\left(\frac{-g_{QAM}}{\sin^2\phi}\right) d\phi \tag{24}$$

Here

$$g_{QAM} = \frac{3}{2(M-1)} \tag{25}$$

MGF $M_{\gamma_{bl}}$ is as defined in (20). In the defined BER equations $L = 2$ for (2×1) STBC and in case of (2×2) SDM $L = 1$. All the above equations of the BER can be expressed in terms of SNR and coding gain by replacing $\overline{\gamma}_b$ by

$$\overline{\gamma}_b = \left(\frac{B}{R_b} SNR \right) R_c d_{\min} \tag{26}$$

Where $B = 250$ KHz defines the signal bandwidth. R_b is the maximum achievable bit rate depending on the modulation technique. $R_c d_{\min}$ is a coding gain in which R_c is a code rate and $d_{\min}$ is the free distance defined by the code rate.

The throughput of the system is

$$Thru = (1 - PER) \tag{27}$$

Where PER is given as

$$PER = \left(1 - (1 - BER)^{P_l}\right) \tag{28}$$

Here P_l is a packet length.

The proposed MIMO cognitive system uses CH1 in an opportunistic manner and hence it operates on both CH1 and CH2. Hence, the average throughput of the proposed system is given as

$$Thru = (P_{d1})(Thru1) + (P_{d2})(Thru2) \tag{29}$$

$Thru1$ reflects the average throughput of the system when communication is over CH1.r signifies the average throughput of the system while communicating over CH2. P_{d1} and P_{d2} are channel detection probabilities for CH1and CH2 respectively.

3 ALGORITHMS

3.1 CR-AMCMPPC Algorithm

This is a novel algorithm used to optimize the performance of MIMO cognitive system. This algorithm at the secondary receiver deals with the tradeoff between the throughput and the energy efficiency of the system. It invokes the AMC-AMP algorithm to optimize the average throughput of the system. Further, this throughput of the system is retained and energy efficiency is improved by calling TWFPA algorithm. This algorithm supports both interweave and underlay channel sharing schemes in a cognitive radio environment. For adapting MCS, MIMO profile and average transmit power over the selected channel in the multi-channel environment this algorithm uses the CSI and the soft information about the activities of the primary users. The channel selection is based on the availability of the channels as described in Table 2. For example if primary user1 is absent (PU1 = 0) and primary user2 is present (PU2 = 1) then CH1 is available (A1 = 1) and CH2 is available (A2 = 1). Then, in this case, CH1 is selected for communication. These algorithmic steps are applied for each of packet being transmitted i.e. to all the symbols in a packet.

TABLE 2

CHANNEL AVAILABILITY STATUS

$PU1$	$PU2$	$A1$	$A2$
0	0	1	1
0	1	1	1
1	0	0	1
1	1	0	1

Algorithm 1 CR-AMCMPPC

Input: σ_m^2, σ_{mn}^2, CH, $PU1$, $PU2$
Output: M_i, G

1: *Initialisation* :
2: $G \leftarrow 1.41$
3: $M_i \leftarrow 0$
4: *Function call* :
5: AMC-AMP(M_i)
6: TWFPA(G)
7: **return** M_i, G

3.2 Adaptive Modulation Coding and MIMO Profile Selection Algorithm (AMC-AMP)

This proposed algorithm is applied to the 802.11n (WLAN) based MIMO cognitive system. AMC-AMP algorithm in the controller adapts modulation, coding rate and MIMO profile (STBC/SDM) by comparing SNR estimate SNR_e with the empirically found SNR thresholds SNR_t. It selects higher MCS in the best channel condition to enhance the throughput of the system. It also defines the MIMO mode based on the channel condition. It ensures reliability in lower SNR range by selecting diversity mode (2×1) STBC and in higher SNR range it goes for (2×2) SDM mode to optimize the throughput of the system. The operating modes defining modulation coding MIMO index with concern parameters are illustrated in Table 3. The algorithm considers CSI i.e. SNR_e and the information about the status of the primary users for adapting the transmit parameters. The information about these parameters is generated in the form of single MCS and MIMO profile index as MCMI index i.e. M_i. This ensures minimum overhead on the feedback channel to the transmitter. The SNR threshold used in this algorithm defines the minimum SNR required to ensure the maximum throughput with BER less than the targeted BER. Hence for optimum throughput

$$\begin{aligned} &If \quad BER \le BER_{target} \\ &Then \quad SNR_t = SNR_{\min} \end{aligned} \tag{30}$$

TABLE 3

MCS-MIMO PROFILE

MCMI Index(M_i)		Modulation	Rate	$N_{ss} = N_r$	
STBC	SDM			STBC	SDM
0	8	BPSK	1/2	1	2
1	9	QPSK	1/2	1	2
2	10	QPSK	3/4	1	2
3	11	16-QAM	1/2	1	2
4	12	16-QAM	3/4	1	2
5	13	64-QAM	2/3	1	2
6	14	64-QAM	3/4	1	2
7	15	64-QAM	5/6	1	2

Algorithm 2 AMC-AMP

Input: SNR_e, l is integer between 1 to 16
Output: M_i

```
function AMCMP(SNR_e, l)
Initialisation :
    M_i ← 0
    SNR_L ← [SNR_1, SNR_2, ..., SNR_l]
    M_L ← [M_1, M_2, ..., M_l]
LOOP Process
    for t = 1 to l do
        if (SNR_t ≤ SNR_e < SNR_{t+1}) then
            M_i ← M_t
        end if
    end for
    return M_i
end function
```

M_i is defining the control parameters MCS, N_{ss} (Number of space-time streams) and the number of receiving antennas N_r i.e. MIMO profile.

3.3 Time-domain Water Filling Power Adaptation Algorithm (TWFPA)

In this treatise, we propose the novel simple power adaptation algorithm for multi-user and multi-channel MIMO cognitive system. We assume that the maximum average transmit power in the system is two. The conventional water filling power adaptation algorithm operates in the frequency domain. It distributes the constraint power among subcarriers as well as the MIMO channels based on the channel condition with an objective of throughput optimization. In this existing technique, the average transmit power remains constant. This conventional approach is based on the SVD technique and is mathematically complex. However, we have modified water filling power adaptation scheme and it operates in the time domain i.e. per-packet basis in spite of per channel. This computing power after receiving a packet is used for all symbols in the next packet to be transmitted. The proposed power adaptation scheme inserts maximum power within the specified limit in best channel condition and assigns minimum power to the symbol when the channel goes worst. Thus it minimizes the transmit power without affecting the throughput of the system. Thereby proposed power adaptation scheme improves energy efficiency without affecting the throughput of the system. This effect is realized in the simulation results. The average power to be inserted for transmission of the next packet over the selected MIMO channel is

$$P_{m\_t} = P_{m\_sym} = \begin{cases} \frac{1}{\lambda} - \frac{\sigma_{mn}^2}{\sigma_m^2}, & For\ \frac{1}{\sigma_m^2} \le \frac{1}{\lambda \sigma_{mn}^2} \\ 0, & otherwise \end{cases} \tag{31}$$

In this case σ_m^2 is the average channel power for the received packet over m^{th} the channel. λ is Langrage multiplier defined by the power constraint. σ_{mn}^2 is noise variance at the receiving end.

Algorithm 3 TWFPA

Input: σ_m^2, σ_{mn}^2, CH, $PU1$, $PU2$, λ
Output: G

```
function TWFPA(σ_m^2, σ_mn^2, CH, PU1, PU2, λ)
Initialisation :
    G ← 1.41
    if (CH = 1 and PU1 = 0) then
        if (1/σ_m^2 ≤ 1/(λσ_mn^2)) then
            P_m_t ← 1/λ − σ_mn^2/σ_m^2
        else
            P_m_t ← 0
        end if
    else if (CH = 1 and PU1 = 1) then
        P_m_t ← 0.1
    else if (CH = 2 and PU2 = 0) then
        if (1/σ_m^2 ≤ 1/(λσ_mn^2)) then
            P_m_t ← 1/λ − σ_mn^2/σ_m^2
        else
            P_m_t ← 0
        end if
    else if (CH = 2 and PU2 = 1) then
        P_m_t ← 1
    end if
    G ← √P_m_t
    return G
end function
```

6 SIMULATION RESULTS

This section depicts the simulation results for the adaptive MIMO cognitive system. The performance of the system is evaluated with CR-AMCMPPC. This performance evaluation compares the different link adaptation strategies for the proposed system. The simulation environment considers transmission on the single and fixed channel as well as transmission on both channels CH1 and CH2 according to the channel detection probabilities P_{d1} and P_{d2} . In this case, the use of CH1 is in an opportunistic manner. Table 1 summarizes the simulation parameters involved in the system analysis. The system performance analysis computes the average throughput, average transmit power and BER over the selected channel CH1 or CH2 or both CH1 and CH2 ($P_{d1} = P_{d2} = 50\%$) i.e. CH12. The adaptation strategies considered in performance evaluation of the system are

1. Effect of the AMC-TWFPA algorithm
2. Effect of the AMC-AMP algorithm
3. Effect of the CR-AMCMPPC algorithm

4.1 Effect of the AMC-TWFPA Algorithm

In this case, the system performance is evaluated by applying adaptive modulation and coding algorithm (AMC) along with the time domain water filling power adaptation algorithm (TWFPA). The system performance evaluation considers SDM MIMO mode. Fig. 3 and Fig. 4 illustrate the throughput and BER curves of MIMO-OFDM cognitive system in two different cases. In the first case, computation of the throughput is with AMC and the constant power (CP) and in the second case; throughput computation is with AMC-TWFPA. Table 4 illustrates the numerical values associated with the average throughput for constant power and adaptive power. The performance is evaluated over different channels CH1 or CH2 or CH12 (CH1 and CH2 both with ($P_{d1} = P_{d2} = 50\%$)). From Fig. 3 and Table 4, it can be seen that TWFPA scheme improves the energy efficiency of the system. It successfully maintains the throughput of the system to the level as that of the throughput with the constant power, that too by using less average transmit power. This improvement in energy efficiency is observed in all three-channel cases. For example in the case of the transmission over CH1, the average throughput of the system is 51.98 Mbps with a constant power of two. However, with adaptive power (TWFPA) the average throughput of the system is 51.79 Mbps and the average transmit power is 1.7W. This shows 15% power saving is achieved with TWFPA scheme. The performance evaluation of the system also considers a noisy channel (NCH2). Fig. 5, Fig. 6, and Fig. 7 illustrate the curves corresponding to this performance. The average throughput of the system over a noisy channel (NCH2) is 41.35Mbps with a constant power of 2W. However, with TWFPA scheme throughput is 41.32Mbps and the average transmit power is 1.35W. This shows the significant improvement in the energy efficiency of the system as the channel becomes worst.

TABLE 4

AMC-TWFPA: THROUGHPUT-MEAN-AVERAGE-POWER

Channel	Detection probabilty %		Average throughput Mbps		$P_{mavg-mean}$ (W)	
	P_{d1}	P_{d2}	CP	TWFPA	CP	TWFPA
CH1	100	0	51.98	51.79	2	1.70
CH2	0	100	46.52	46.22	2	1.72
CH12	50	50	49.09	49.06	2	1.71
NCH2	0	100	41.35	41.32	2	1.35

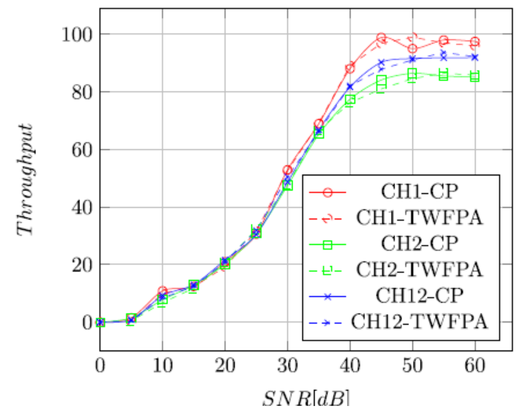

Fig. 3. *AMC-TWFPA: Throughput v/s SNR.*

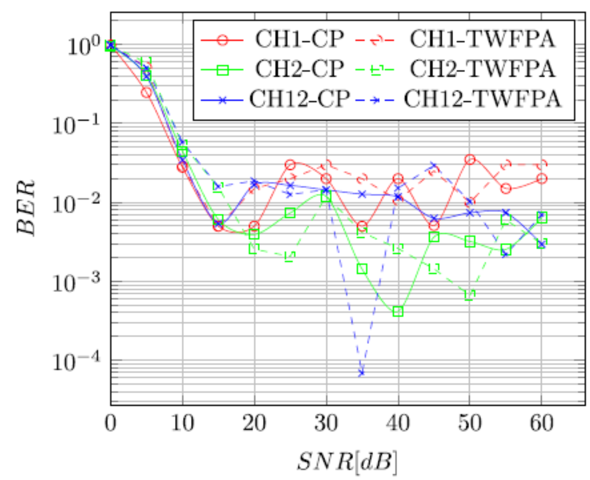

Fig. 4. *AMC-TWFPA: BER v/s SNR.*

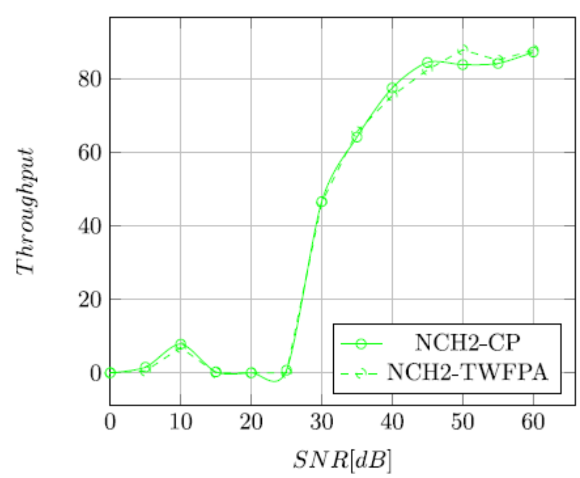

Fig. 5. *AMC-TWFPA: Throughput v/s SNR over noisy channel CH2*

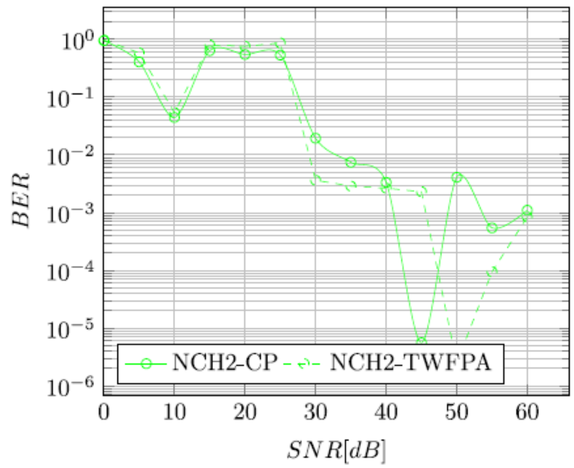

Fig. 6. *AMC-TWFPA: Throughput v/s SNR over noisy channel CH2*

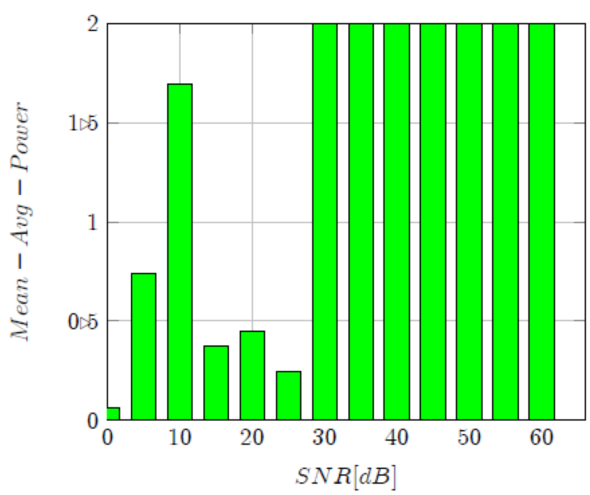

Fig. 7. *AMC-TWFPA: Mean-Avg-Power v/s SNR over noisy channel CH2*

4.2 Effect of the AMC-AMP Algorithm

To analyze the effect of AMC-AMP, the rate adapted MIMO system is operated in three different modes STBC, SDM, and STDM (adaptive selection between STBC and SDM). The system performance in these three modes is compared. Fig. 8 and Fig. 9 illustrate the throughput and BER curves corresponding to these modes. Table 5 summarizes the concern numerical values. In this case, the transmit power is constant and is having a value of two. The performance investigation considers communication over CH1, CH2 or CH12 (CH1 and CH2 both with $P_{d1} = P_{d2} = 50\%$). From Fig. 8 it can be realized that AMC-STBC offers higher performance in lower SNR range. However, AMC-SDM outperforms in higher SNR range. Hence, further enhancement in the throughput of the MIMO system is possible with adaptive MIMO profile selection as shown in Fig. 8. For example in the case of transmission over CH1, the average throughput of the system with AMC-STBC is 33.39 Mbps, AMC-SDM is 51.98 Mbps, and AMC-STDM is 53.39 Mbps. It signifies that adaptive MIMO profile selection outperforms STBC or SDM transmission in the cognitive environment.

TABLE 5

AMC-AMP: MIMO PROFILE

Channel	Detection probabilty %		Average throughput (Mbps)		
	P_{d1}	P_{d2}	STBC	SDM	STDM
CH1	100	0	33.39	51.98	53.39
CH2	0	100	33.63	46.52	47.84
CH12	50	50	33.33	49.09	49.95

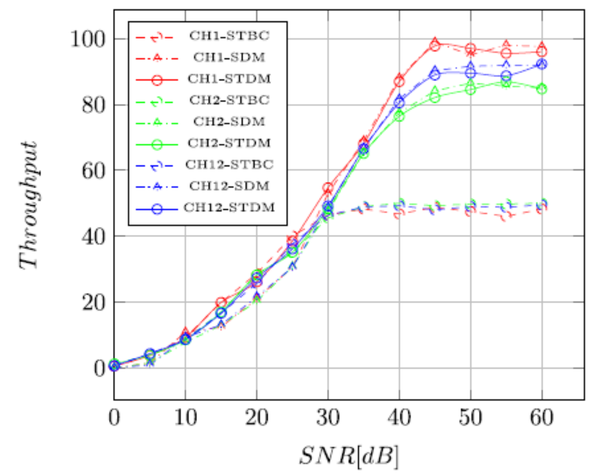

Fig. 8. AMC-AMP: Throughput v/s SNR

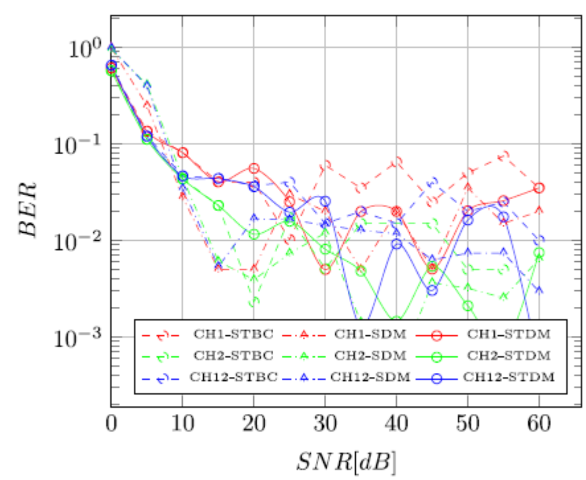

Fig. 9. AMC-AMP: BER v/s SNR

4.2 Effect of the CRAMCMPPC Algorithm

Fig. 10 and Fig. 11 illustrate the throughput and BER performance of the adaptive cognitive system with (CR-AMCMPPC) controller adapting modulation, coding, MIMO profile and the average transmit power. Table 6 illustrates the corresponding numerical values. The performance evaluation considers communication on CH1, CH2, and CH12 (CH1 and

CH2 both with $P_{d1} = P_{d2} = 50\%$). It can be seen that this adaptive cognitive system outperforms with respect to the throughput of the system and the average transmit power. In this controller algorithm, AMC-AMP (Adaptive MCS and MIMO profile) optimizes the throughput of the system whereas TWFPA algorithm ensures throughput retention with the minimal average transmit power. For example, referring the case of the transmission over both channels CH1 and CH2 with channel detection probabilities of 50% (Interweave channel-sharing scheme), the throughput of the system as illustrated in Table 6 is 50.21 Mbps with the average transmit power of 1.77W. However, from Table 5 it can be seen that with constant average transmit power of two the throughput with AMC-AMP is 49.95 Mbps. This signifies the improvement in the throughput and energy efficiency of the cognitive system is possible with the adaptive controller (CR-AMCMPPC).

TABLE 6

AMC-CRAMCMPPC: THROUGHPUT-MEAN-AVERAGE-POWER

Channel	Detection probabilty %		Average throughput Mbps	$P_{mavg-mean}$ (W)
	P_{d1}	P_{d2}	STDM	
CH1	100	0	53.58	1.75
CH2	0	100	47.34	1.80
CH12	50	50	50.21	1.77

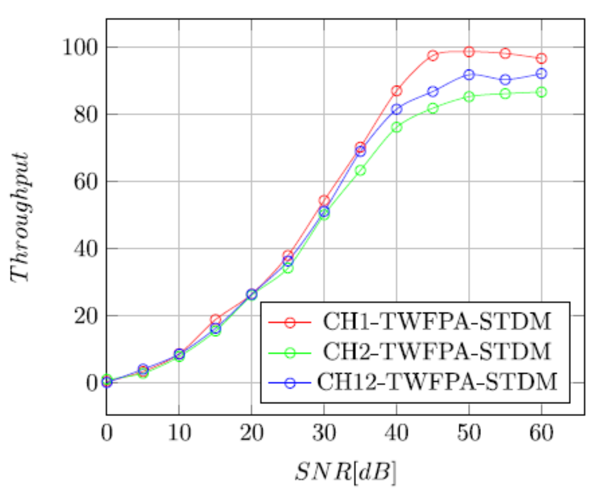

Fig. 10.CR- AMCMPPC: Throughput v/s SNR

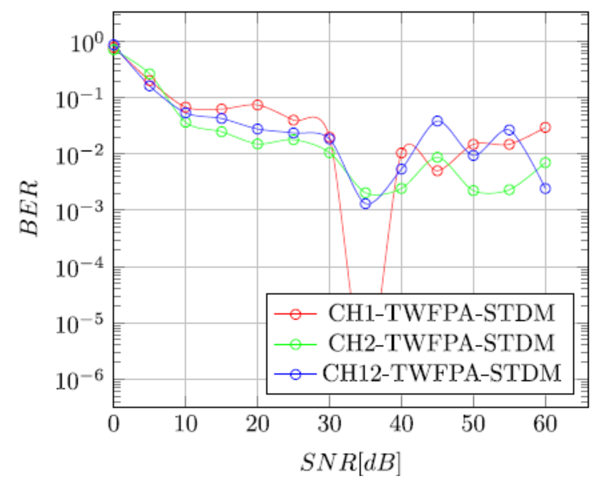

Fig. 11.CR- AMCMPPC: BER v/s SNR

CONCLUSION

The work presented in this treatise represents a novel design of adaptive MIMO-OFDM based cognitive radio system. We design the adaptive controller CR-AMCMPPC to adapt MCS, MIMO profile (STBC/SDM) and the average transmit power based on the channel condition for multi-user, multi-channel Cognitive system. In the designed system AMC scheme ensures the improvement in the throughput of the system. Further enhancement in the performance of the system with respect to the reliability and throughput is observed using MIMO profile adaptation. The simulation results reflect significant improvement in the throughput of the system with joint AMC-AMP algorithm. Capacity and energy efficiency trade-off play a vital role in defining the performance of the cognitive wireless system. Therefore, we have suggested a novel packet-based TWFPA scheme for adapting the average transmit power to optimize energy efficiency rather than the throughput of the system. Simulation results show that significant power saving is achieved in the worst channel condition without affecting the throughput of the system. Further, system performance is investigated with CR-AMCMPPC controller and it is observed that there is a significant improvement in the throughput of the system with 10% to 20% energy saving by adapting the transmit power of the system. The system performance is analyzed in a single and fixed channel (CH1 or CH2) as well as dynamic channel switching environment (CH12-Interweave case) based on the status of the primary users. In all these cases, the system shows improvement in the performance in terms of throughput and energy efficiency. In the future, this controller can be used at multiple secondary nodes in the cooperative cognitive ad-hoc networks. In such networks, these intelligent nodes can act as virtual antennas and assist in boosting the performance of the entire network.

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