International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:6, No:11, 2012

Performance of Hybrid-MIMO Receiver Scheme in Cognitive Radio Network

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Abstract**—**In this paper, we evaluate the performance of the Hybrid-MIMO Receiver Scheme (HMRS) in Cognitive Radio network (CR-network). We investigate the efficiency of the proposed scheme which the energy level and user number of primary user are varied according to the characteristic of CR-network. HMRS can allow users to transmit either Space-Time Block Code (STBC) or Spatial-Multiplexing (SM) streams simultaneously by using Successive Interference Cancellation (SIC) and Maximum Likelihood Detection (MLD). From simulation, the results indicate that the interference level effects to the performance of HMRS. Moreover, the exact closed-form capacity of the proposed scheme is derived and compared with STBC scheme.

Keywords**—**Hybrid-MIMO, Cognitive radio network (CR-network), Symbol Error Rate (SER), Successive interference cancellation (SIC), Maximum likelihood detection (MLD).

I. Introduction

IN the present, the using of frequency band in wireless communication is continuously increased by the new applications such as WLAN, 3G and 4G. Consequently, the available spectrums are not enough used [1], the CR-network is established to solve this problem [2]. In CR-network, the spectrum sensing and the energy control are strictly operated by Fusion Center (FC) to eliminate the interference in Primary-network (PR-network) in common area. In Fig. 1, CR-network is a wireless communication that consumes the public frequency band commonly with PR-network during no PR-user is operated. CR-network can be simultaneously operated with PR-network in the common spectrum by adjusting the power under the enforcing threshold. Multiple-input multiple-output (MIMO) technique is an attracting choice for CR-networks because it can increase both capacity and diversity gain [3]-[6]. Normally, there are two schemes of MIMO technique including STBC [7], [8] and SM [9]. Hybrid-MIMO [10]-[12] is an efficient choice to apply in CR-network, because the receiver can detects both STBC and SM streams in the same time and the same frequency. Hence, it increases both the spectrum efficiency and the information rate. Generally, the Successive Interference Cancellation (SIC), Zero-Forcing (ZF), Minimum Mean Square Error (MMSE) detection and Maximum Likelihood Detection (MLD) are commonly used to separate each layer [13]. The closed-form capacity expression over MIMO fading channels has been presented in [14]. We proposed the HMRS technique in [15], the algorithm of detection and the performance are presented when the variety of both the antenna configuration and the detection techniques are applied to investigate the performance of HMRS technique.

In this article, we show the performance of HMRS when the system is effected by the interference of PR-user. When PR-user and FC are closely placed or the number of PR-user is increased, both the level of interference and the diversity gain are also changed. In addition, we show the varying of the CR-user energy and PR-user energy when CR-user moves directly to PR-network area under the limited threshold. The energy of CR-user can be adjusted to control the quality of information. Moreover, we derive an exact closed-form capacity expression over MIMO Rayleigh channels of HMRS by comparing with 2x2STBC technique.

This article is organized as follows. Section II discusses the CR-network environments that are modeled for simulation in section V. In section III, we present the construction of both 2x2STBC and HMRS. The exact closed-form capacity is derived in section IV. In section V, both SER under CR-network environment and capacity analysis are simulated. Finally, section VI summarizes the paper.

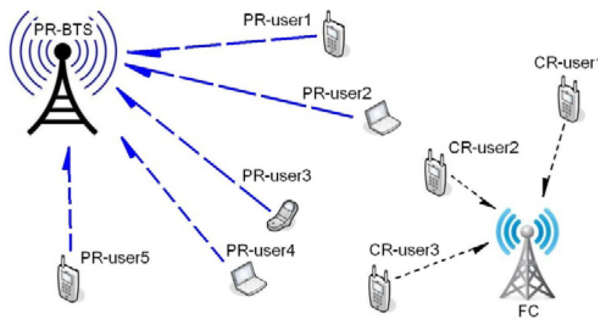

Fig. 1 Cognitive radio network

II. CR-Network Environment

In this section, we introduce an environment of CR-network that operates with PR-network in common area. All CR-users transmit signal according to HMRS encoding, the detection of FC can be done corresponding to HMRS algorithm. The energy of CR-user and the number of PR-user are considered for studying the effective result in HMRS system. In this section, the models of CR-network are used to simulate in

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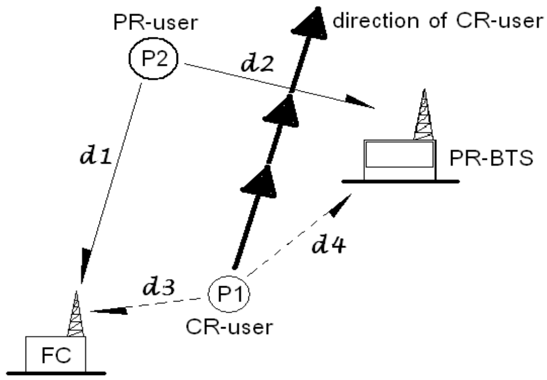

Fig. 2 The first model of CR-network in simulation

section V. In Fig. 2, the simulation model is assumed as follows. CR-user moves directly to PR-network (The biggest line represents the moving direction of CR-user), while other users do not move and all users operate simultaneously in the same spectrum band. Every time interval, CR-user moves closely into the center of PR-network, SNR and SER at FC are degraded. Therefore, the energy of CR-user is instantly increased for keeping the diversity order at FC. Presently, signal to noise ratio (SNR) at PR-base station (PR-BTS) is also decreased when CR-user moves closely. Therefore, the PR-BTS commands CR-network urgently to change the operating frequency or decrease the transmitted power. The received energy at FC can be described as

$$E_{FC} = d_3 E_1 + d_1 E_2 + \sigma_\omega^2 \quad (1)$$

where d_n denote a scaling constant of path loss for P1 and P2, E_1 denotes the transmitted symbol energy of CR-user, E_2 denotes the transmitted symbol energy of PR-user (we assigned E_2=1.3E_1) and another denotes the noise energy. SNR at FC can be expressed as

$$\text{SNR} = \gamma = \frac{d_3 E_1}{d_1 E_2 + \sigma_\omega^2} = \frac{d_3}{2d_1 + 1/\bar{\gamma}} \quad (2)$$

where d_1 = 0.01, d_3=[1, 0.9, 0.8,…,0.3] in each time interval and $\bar{\gamma}$ denotes the average SNR per received antenna.

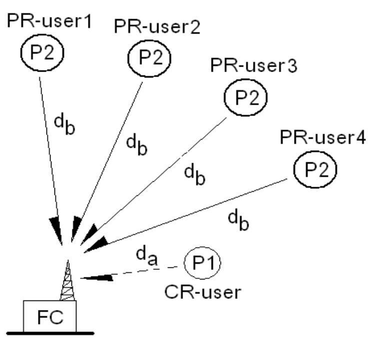

Fig. 3 The second model of CR-network in simulation

In Fig. 3, the simulation model is assumed as follows. All members in two networks operate on fixed position in common area. The interference powers of all PR-users are equally assigned as $d_b P_2$ by using the power control technique, where d_b =0.01, d_a =1 and P_1 denotes the power of CR-user. Therefore, the SNR at FC can be considered as

$$\text{SNR} = \gamma = \frac{E_1}{d_b N E_2 + \sigma_\omega^2} = \frac{1}{1.3 d_b N + 1/\bar{\gamma}}. \quad (3)$$

When the number of PR-user (N) increases, the interference level at FC is also changed. We will discuss this effect in section V.

III. System Model

In this section, we present the structure and signals in 2x2STBC and HMRS. The effective SNR of both schemes are explained.

A. Space-Time Block Code scheme

The received signal of 2x2STBC can be described as

$$\mathbf{Y} = \mathbf{H}_{2x2}\mathbf{G} + \mathbf{W} = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{bmatrix} \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \quad (4)$$

where **Y** denotes the vector of received signal, $\mathbf{H}_{2x2}$ is an 2x2 MIMO channel matrix, **G** is an 2x2 space-time block code matrix and W is an 2x1 vector i.i.d. complex circular Gaussian random variable. The received signal of each receiving antenna in each time interval can be written as

$$\begin{aligned} r_{t1}^1 &= h_{11} s_1 + h_{21} s_2 + w_1 \\ r_{t1}^2 &= h_{12} s_1 + h_{22} s_2 + w_2 \\ r_{t2}^1 &= -h_{11} s_2^* + h_{21} s_1^* + w_1 \\ r_{t2}^2 &= -h_{12} s_2^* + h_{22} s_1^* + w_2 \end{aligned} \quad (5)$$

where r_{tb}^a denotes the received signal of the a^th^ antenna in the b^th^ time interval in block. The combining signal can be expressed as

$$\begin{aligned} \tilde{s}_n &= r_{t1}^1 h_{11}^* + r_{t1}^2 h_{12}^* + r_{t2}^{1*} h_{21} + r_{t2}^{2*} h_{22} \\ &= \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) s_1 + n_1 h_{11}^* + n_2 h_{12}^* + n_1^* h_{21} + n_2^* h_{22} \end{aligned} \quad (6)$$

Hence, the transmitted symbol can be determined as $\hat{s}_n = \arg\min_{s \in A} \left|\tilde{s}_n - \|\mathbf{H}_{2x2}\|_F^2 s\right|^2$, where A denote the signal constellation. Therefore, the effective SNR per symbol after combining can be written as [14]

$$\gamma_{STBC} = \frac{\|\mathbf{H}_{2x2}\|_F^4 \mathbf{E}_0}{\|\mathbf{H}_{2x2}\|_F^2 \sigma_w^2} = \frac{\bar{\gamma}\|\mathbf{H}_{2x2}\|_F^2}{2} \quad (7)$$

where $\|\mathbf{B}\|_F$ denotes the Frobenius norm of matrix **B**. it can be defined as $\|\mathbf{B}\|_F \triangleq \sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}\left|B_{ij}\right|^2}$.

B. Hybrid-MIMO receiver scheme (HMRS)

In this paper, we provide two CR-users that use STBC and SM technique for transmitting signal to FC. In Fig. 4, each layer can be separated by using SIC and MLD at FC. The received signal at FC can be expressed as

$$\mathbf{Y} = \begin{bmatrix} h_{11} & h_{21} & h_{31} & h_{41} \\ h_{12} & h_{22} & h_{32} & h_{42} \\ h_{13} & h_{23} & h_{33} & h_{43} \\ h_{14} & h_{24} & h_{34} & h_{44} \end{bmatrix} \begin{bmatrix} s_1 & s_5 \\ s_2 & s_6 \\ s_3 & -s_4^* \\ s_4 & s_3^* \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} \quad (8)$$

$$\hat{\mathbf{Y}}_{SM} = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \\ h_{13} & h_{23} \\ h_{14} & h_{24} \end{bmatrix} \begin{bmatrix} \hat{s}_1 & \hat{s}_5 \\ \hat{s}_2 & \hat{s}_6 \end{bmatrix} \quad (9)$$

where $\hat{s}_n$ denotes the transmitted symbol of SM user that is detected by MLD in the first step at FC, the received signal of SM layer can be regenerated as (9). Then the received signal of STBC user can be approximated as

$$\hat{\mathbf{Y}}_{STBC} = \mathbf{Y} - \hat{\mathbf{Y}}_{SM} = \begin{bmatrix} r_{t1}^1 & r_{t2}^1 \\ r_{t1}^2 & r_{t2}^2 \\ r_{t1}^3 & r_{t2}^3 \\ r_{t1}^4 & r_{t2}^4 \end{bmatrix} \quad (10)$$

therefore, the combining signal can be expressed as

$$\tilde{s}_3 = r_{t1}^1 h_{31}^* + r_{t1}^2 h_{32}^* + r_{t1}^3 h_{33}^* + r_{t1}^4 h_{34}^* + r_{t2}^{1*} h_{41} + r_{t2}^{2*} h_{42} + r_{t2}^{3*} h_{43} + r_{t2}^{4*} h_{44}$$
$$\tilde{\mathbf{s}}_n = \left\|\mathbf{H}_{STBC}\right\|_F^2 s_n + \Delta s \mathbf{L} + \left\|\mathbf{H}_{STBC}\right\| w_n \quad (11)$$

where $\mathbf{H}_{STBC}$ is all elements in the 3rd and the 4th column of MIMO channels during two consecutive time in (8), $\Delta s = s_n - \hat{s}_n$ and L denotes the product of $|h|_{ij}$ in STBC combining process. From (11), the transmitted symbol of STBC user can be determined as $\hat{s}_n = \arg\min_{s\in A}\left|\tilde{s}_n - \left\|\mathbf{H}_{STBC}\right\|_F^2 s\right|^2$. Hence, the effective SNR per symbol after combining of HMRS STBC-user can be written as

$$\gamma_{HMRS}^{STBC} = \frac{\bar{\gamma}\left\|\mathbf{H}_{STBC}\right\|_F^2}{2\left(\dfrac{\left|\Delta s L\right|^2}{\sigma_\omega^2 \left\|\mathbf{H}_{STBC}\right\|_F^2} + 1\right)} \quad (12)$$

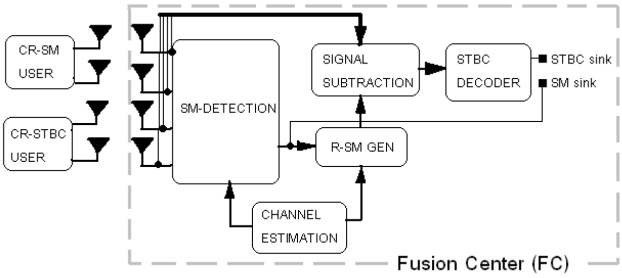

Fig. 4 Hybrid-MIMO receiver scheme (HMRS)

IV. Exact Closed-form Capacity

In CR-network, CR-user and FC communicate to each other over fading channels. The channel capacity can be represented as the maximum data rate that can be supported by channel without error. It can be used to indicate the merit of the communication system. In this section, we derive the exact closed-form ergodic capacity of both HMRS (STBC-user) and 2x2STBC (single user). The probability density function (pdf) of the effective SNR can be expressed as

$$p_{\gamma_n}(\gamma_n) = \frac{\gamma_n^{(n_T n_R)-1}}{\Gamma(n_T n_R)\bar{\gamma}_s^{(n_T n_R)}} e^{-\gamma_n/\bar{\gamma}_s} \quad (13)$$

where $\Gamma(\cdot)$ is the Gamma function that can be defined as $\Gamma(a) = \int_0^\infty x^{a-1} e^{-a} da$, the average SNR per channel can be expressed as $\bar{\gamma}_s = \gamma_n / \left\|H_n\right\|_F^2$, n_T and n_R denote the number of transmitted antenna and the number of received antenna, respectively. The ergodic capacity can be written as

$$C = R\int_0^\infty \log_2\left(1+\gamma_n\right) p_{\gamma_n}(\gamma_n) d\gamma_n \quad (14)$$

we can reduce the complexity of (14) by using the formula

$$\mathcal{I}(m,n) = \frac{n^m}{\Gamma(m)}\int_0^\infty ln(1+x) x^{m-1} e^{-nx} dx \quad (15)$$

or

$$\mathcal{I}(m,n) = \mathrm{P}_m(-n)\mathrm{E}_1(n) + \sum_{k=1}^{m-1}\frac{\mathrm{P}_k(n)\mathrm{P}_{m-k}(-n)}{k} \quad (16)$$

where $\mathrm{P}_m(\cdot)$ denotes the Poisson distribution, which can be defined as

$$P_m(x) \triangleq \sum_{k=0}^{m-1} \frac{x_k}{k!} e^{-x} \quad (17)$$

and $\mathrm{E}_1(\cdot)$ is the exponential integral function of the first order, which can be described as

$$\mathrm{E}_1(x) \triangleq \int_x^\infty \frac{e^{-t}}{t} dt, \qquad x > 0. \quad (18)$$

Under perfect CSI, the Shannon capacity of (14) can be

ISSN: 2517-9438
Vol:6, No:11, 2012

easily calculated [14] as following using (13) and (16)

$$C = \frac{R}{\ln(2)} \mathcal{I}(n_T n_R, q_n) \tag{19}$$

or

$$C = \frac{R}{\ln(2)} \left[\mathrm{P}_{n_T n_R}(-q_n)\mathrm{E}_1(q_n) + \sum_{k=1}^{(n_T n_R)-1} \frac{\mathrm{P}_k(q_n)\mathrm{P}_{(n_T n_R)-k}(-q_n)}{k} \right] \tag{20}$$

where R denotes the STBC code rate, $q_n = 1/\overline{\gamma}_s$, q_n of 2x2STBC and HMRS scheme can be obtained by using (7) and (12), respectively. Therefore, the ergodic capacity of 2x2STBC scheme and HMRS technique can be calculated by (21) and (22), respectively.

$$C_{STBC} = \frac{1}{\ln(2)} \left[P_4\left(-\frac{\|\mathbf{H}_{2x2}\|_F^2}{\gamma_{STBC}} \right) E_1\left(\frac{\|\mathbf{H}_{2\times 2}\|_F^2}{\gamma_{STBC}} \right) + \ldots \right.$$
$$\left. \ldots \sum_{k=1}^{3} \frac{P_k\left(\frac{\|\mathbf{H}_{2\times 2}\|_F^2}{\gamma_{STBC}} \right) P_{4-k}\left(-\frac{\|\mathbf{H}_{2\times 2}\|_F^2}{\gamma_{STBC}} \right)}{k} \right] \tag{21}$$

$$C_{HMRS} = \frac{1}{\ln(2)} \left[P_8\left(-\frac{\|\mathbf{H}_{STBC}\|_F^2}{\gamma_{HMRS}^{STBC}} \right) E_1\left(\frac{\|\mathbf{H}_{STBC}\|_F^2}{\gamma_{HMRS}^{STBC}} \right) + \ldots \right.$$
$$\left. \ldots \sum_{k=1}^{7} \frac{P_k\left(\frac{\|\mathbf{H}_{STBC}\|_F^2}{\gamma_{HMRS}^{STBC}} \right) P_{8-k}\left(-\frac{\|\mathbf{H}_{STBC}\|_F^2}{\gamma_{HMRS}^{STBC}} \right)}{k} \right]. \tag{22}$$

The exact closed-form ergodic capacities of two schemes are simulated in the next section.

V. System Performance

In this section, the SER of HMRS under the adjusting power of CR-user and the number of PR-user are presented by using Monte Carlo simulation method. QPSK modulation is applied to simulate SER. We consider the N number of PR-user that degrades the SER performance. In addition, the ergodic capacities of both HMRS and 2x2STBC are analyzed by applying (7), (12) and (20).

Fig. 5 presents the SER performance of each HMRS-user when PR-network is not operated, the SER performance of STBC-user is higher than SM-user about 2 dB at 10^{-4}. The average SER of both users are also presented.

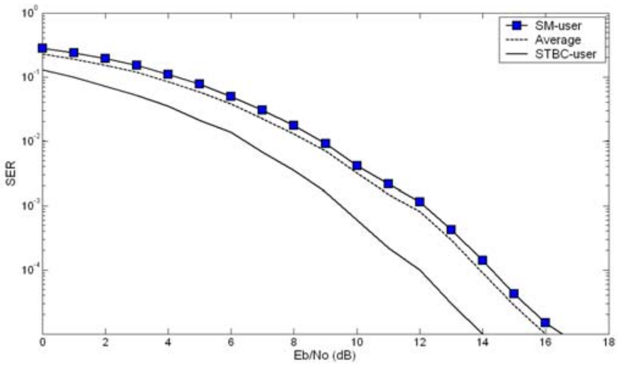

Fig. 5 Symbol error rate for HMRS technique

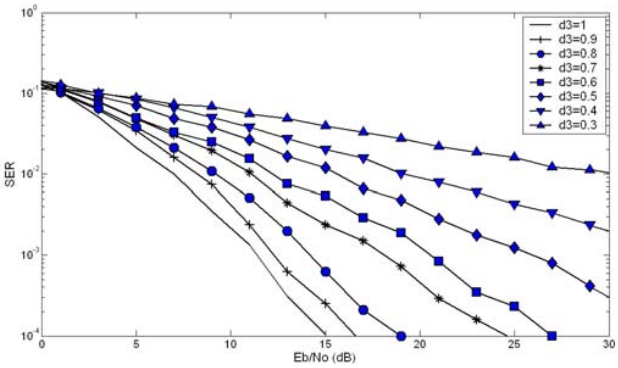

Fig. 6 Symbol error rate of FC when CR-user moves directly to PR-network area

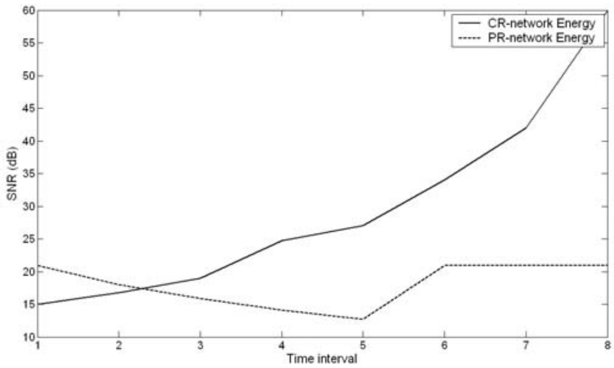

Fig. 7 The varying powers of the CR-network and the PR-network versus the time interval

Fig. 6 shows the SER performance under the situation of the first model in Fig. 2. The power of CR-user is increased for keeping the SER level, because the SNR at FC and the interference from PR-user are changed when CR-user moves directly to PR-network area. Every time interval, d_3 in (2) is increased about 0.1 times of the CR-user power. If FC wants to keep SER as 10^{-4}, the CR-user needs to increase the power continuously in every time interval. Initially, CR-user applies power at SNR=12dB for keeping SER=10^{-4}. Then in the 1st time interval, CR-user increases power until SNR=15dB. After that in the 2nd time interval, CR-user increases power until SNR=16.8dB. The power of CR-user is continuously increased until the CR-user stops his motion.

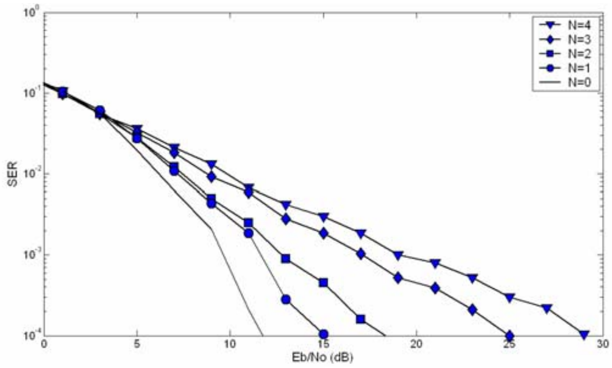

Fig. 8 Symbol error rate of FC when the number of PR-user (N) is increased

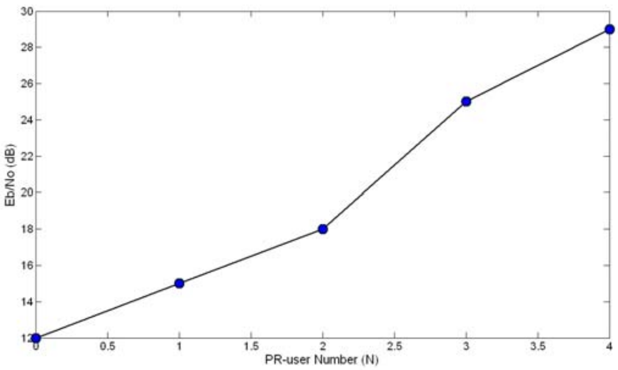

Fig. 9 The varying power of CR-user versus the number of PR-user

Fig. 7 illustrates the changing of both CR-user power and SNR at the PR-BTS versus time interval under the situation of the first model in Fig. 2. When CR-user moves continuously to the center of PR-network, the SNR at PR-BTS is also decreased because the interference in PR-network is increased versus the distance between CR-user and PR-BTS. At time interval=5, the SNR at PR-BTS is closely decreased to the threshold level (we assume threshold level=12dB). Hence, the PR-network commands CR-network urgently to change the operating frequency. Finally, the SNR at PR-BTS can be returned to the initial level (21dB) after CR-network changes the spectrum band.

Fig. 8 illustrates the varying of SER of HMRS when N number is increased. We assign d_b=0.01 in (3), the power from each PR-user is assigned by $E_2=1.3E_1$ in simulation. The distances between FC and each PR-user are assumed as the equal distance under the situation of the second model in Fig. 3. If CR-network wants to keep the quality of signal, CR-user needs to increase power according to the N number. The interfering level increases according to the number of PR-user. As the results, if the number of PR-user (N) is 1 then CR-user needs to increase power until SNR at FC is 15dB that differ from the case of no PR-user about 3dB at SER=10^{-4}. Similarly, if the number of PR-user (N) is 4 then CR-user needs to increase power until SNR at FC is 29dB that differ from the case of no PR-user about 17dB at SER=10^{-4}.

Fig. 9 presents the varying power of CR-user when the number of PR-user is increased under the situation of the

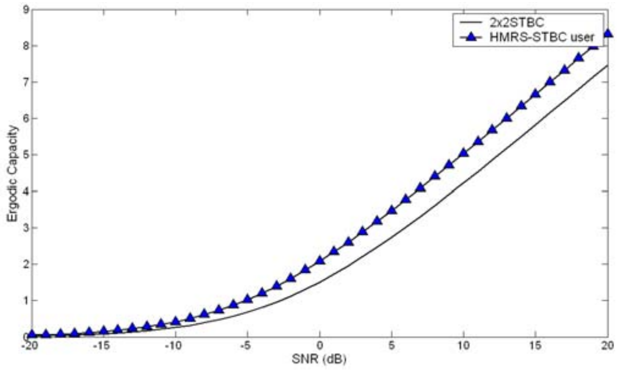

Fig. 10 Exact closed-form ergodic capacity of HMRS (STBC user) and 2x2STBC

second model in Fig. 3. The interference level in PR-network is changed according to the number of PR-user. The power of CR-user is needs increased for keeping the quality of information at SER=10^{-4}. Therefore, N number is an important factor for designing the CR-network.

Fig. 10 illustrates the exact closed-form ergodic capacity of 2x2STBC and HMRS by using (21) and (22), respectively. As the results, the maximum data rate that can be supported by channel without error of HMRS technique exceeds the data rate of 2x2STBC scheme. Therefore, the higher modulation order can be applied by HMRS technique.

VI. Conclusion

In this paper, we evaluate SER of HMRS in the model of cognitive radio network under the varying of both power and the number of PR-user. We apply HMRS technique for CR-network to investigate its performance in the environment of CR-network. As the results, the SER performance of HMRS is degraded by increasing the PR-user number corresponding to a far distance between FC and CR-user. In Fig. 7, the correlation between the power of CR-user and PR-user may be represented as a key for the energy handling in CR-network in future work. In addition, we derive an exact closed-form expression of the ergodic capacity of the HMRS technique compare with 2x2STBC scheme. We will investigate the HMRS performance in case of channel estimation error which can be written as a topic of future research.

References

[1] T. Yucek and H. Arslan, “A Survey of Spectrum Sensing Algorithms for CR Applications first quarter 2009,” University of South Florida, USA, Tech. Rep., 2009.
[2] S. Haykin, “Cognitive radio: Brain-empowered wireless communications”, *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–219, Feb 2005.
[3] Akin. S and Gursoy M.C.,”On the performance limits of cognitive radio MIMO channels”, *WCNC. 2011 IEEE*, pp. 1640-1645, 2011.
[4] Xiaoming Chen, Zhaoyang Zhang and Chao Wang, “Dual QoS Driven Power Allocation in MIMO Cognitive Network with Limited Feedback”, *WCNC. 2011 IEEE*, pp. 1829-1833, 2011.
[5] Sha Hua, Hang Liu, Mingquan Wu and Panwar, S.S., “Exploiting MIMO Antennas in Cooperative Cognitive Radio Network", *INFOCOM, 2011 Proceeding IEEE*, pp. 2714-2722, 2011.
[6] Jorswieck, E.A. and Jing Lv, “Spatial shaping in cognitive MIMO MAC with coded Legacy transmission”, *SPAWC, 2011 IEEE 12th*, pp. 451-455, 2011.

[7] S. Alamouti, "A simple transmit diversity technique for wireless communication", IEEE Journal of Selected Area in Communications, vol. 16, pp. 1451-1458, Oct 1998.
[8] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Transactions on Information Theory, vol.5,* pp.1456–1467, Jul 1999.
[9] G. J. Foschini, "Layered space-time architecture for wireless communications in a fading environment when using multiple antennas", *Bell Labs Tech. J.*, v.1, n.2, pp.41–59, 1996.
[10] Chee Wei Tan and A. Robert Calderbank, "Multiuser Detection of Alamouti Signals", *IEEE Transactions on Communications, Vol. 57, No. 7, 2009*, pp. 2080-2089, 2009.
[11] Walter da C. Freitas Jr., Francisco R. P. Cavalcanti and Renato R. Lopes, "Hybrid Transceiver Schemes for Spatial Multiplexing and Diversity in MIMO Systems", *Journal of Communication and Information systems, vol. 20, No. 3, 2005*, pp. 63-76, 2005.
[12] R.W. Heath Jr. and A. J. Paulraj, "Diversity versus multiplexing in narrow band MIMO channel: A tradeoff base on Euclidean distance", *IEEE trans. On Communication* submitted 2002.
[13] Yong Soo Cho, Jaekwan Kim, *MIMO-OFDM Wireless Communication with MATLAB*, John Wiley&Sons (Asia) Pte Ltd, 2010.
[14] Kyung Seung Ahn, Robert W. Heath Jr. and Heung Ki Baik, "Shannon Capacity and Symbol Error Rate of Space-Time Block Codes in MIMO Rayleigh Channels with Channel Estimation Error", IEEE Transactions on Wireless Communications, Vol. 7, No. 1, pp. 324-333, 2008.
[15] Tanapong Khomyat, Peerapong Uthansakul and Monthippa Uthansakul, "Hybrid-MIMO Receiver with Both Space-Time Coding and Spatial Multiplexing Detections for Cognitive Radio Networks", *ISPACS 2011 IEEE*, pp. 2011.