Outage and Throughput Analysis of Spectrum Sharing Cognitive Radio Network Incorporating Energy Harvesting Hybrid Relay

Mousam Chatterjee, Banani Basu, Arnab Nandi, Chanchal Kumar De

Abstract. ***In this paper, cooperative spectrum sharing in cognitive radio (CR) network is incorporated with multi-antenna based RF energy harvesting relays (EH). The performance has been analyzed in the presence of multiple primary users. The relays can harvest energy from source signal and interference from primary transmitter. The relays follow adaptive hybrid protocol (AHR) for forwarding the received signal from source to destination. Outage probability and achievable throughput have been analyzed using a time-splitting relaying (TSR) scheme at the destination where best relay selection (BRS) strategy is used. The outage performances of energy harvesting and non-energy harvesting model have been compared. Throughput and outage performance comparison for AF, DF and AHR have been analyzed. The effect of the number of primary users is also investigated. A trade-off is shown between the number of relays and the number of antennas to achieve the desired throughput. The results depict that the use of energy harvesting strategy in cognitive radio network can result in an energy-efficient solution for future wireless communication.***

Keywords: Amplify-and-Forward (AF); Decode-and-Forward (DF); Adaptive Hybrid Relay (AHR); Energy Harvesting (EH).

I. INTRODUCTION

Energy consumption has become a major concern in designing and working of wireless network. For the past few years the main performance metric for optimization of wireless communication systems has been BER, throughput, latency etc. Recently energy consumption has become a major issue. The batteries at relay nodes drain quickly and replacing them is both a cumbersome and an expensive job. To address this problem energy harvesting circuit has been proposed. These energy harvesting circuit are placed at the relay nodes along with rechargeable battery. The first energy scavenging technique can be traced back to 1998 [1]. Most recently RF energy harvesting method has been proposed because of widespread use of wireless networks [2]. Wireless energy harvesting for point-to-point communication system has been proposed [3]. Recently, there is a great deal of research going on cognitive radio network to mitigate the spectrum insufficiency problem [4]. Energy harvesting in relay nodes of a cognitive radio network is a new area of intensive research. Authors in [5,6], investigate dual hop single relay EH network. Energy Harvesting in multiple user environment has become significant area of research. Recent work includes the use of MIMO [7,8,9] systems with EH relay nodes. Authors in [7] have considered multiple relay network working in DF mode. For energy harvesting and information processing, they have used time switching protocol at relays. In [8], the authors have worked on maximizing the sum-rate of a MIMO network interference alignment for simultaneous energy harvesting and information processing at relays working in DF mode. Authors in [9], has calculated the outage probability of EH multiple relay network with single secondary source. Works from [5,6,7,8,9] have not considered multiple primary users and multiple antenna at relays. The works from [2,3,4,5,6,7,8,9] has not used the AHR protocol. The work done in [10] includes the use of multi antenna relays, AHR protocol and multiple primary users, but energy harvesting and throughput performance evaluation has not been done.

In this paper, we have focused on the outage performance and throughput evaluation for energy harvesting relays in a spectrum sharing cognitive radio network in presence of multiple primary users. The proposed model consists of one secondary source S, multiple primary users communicating within themselves, K number of multi-antenna relays and one secondary destination D. The destination is assumed far from the primary users, thus having no interference on them. Energy is harvested from primary transmitter interference and from source signal by considering the relay nodes. It then stores the harvested energy and use it to forward the incoming signal to the destination. To achieve received signal diversity, several antennas are used in relays. The relays operate in AHR mode whose effect on outage and throughput performance is investigated. More specifically, the main contributions of this paper are summarized as follows: (i) Comparison of EH and non EH relay nodes working in AHR protocol in presence of multiple primary users. (ii) Evaluation and comparison of outage and throughput performance of considered system model using AF, DF and AHR relaying protocols. (iii) Evaluating the consequence of growth of the primary users on throughput. (iv) According to the deal between number of relays and number of antenna on throughput curve. (v) Progress of a MATLAB simulation test bed for the result analysis.

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* Correspondence Author

Mousam Chatterjee*, Department of Electronics and Communication Engineering, B. P. Poddar Institute of Management and Technology, Kolkata, India, E-mail: mousam.chatterjee@gmail.com

Banani Basu, Department of Electronics and Communication Engineering, National Institute of Technology, Silchar, India, E-mail: basu_banani@ieee.org

Arnab Nandi, Department of Electronics and Communication Engineering, National Institute of Technology, Silchar, India, E-mail: nandi_arnab@ieee.org

Chanchal Kumar De, Department of Electronics and Communication Engineering, Haldia Institute of Technology, Haldia, India, E-mail: wrt2chanchal@rediffmail.com

The rest of the paper has been organized as follows: Section II: Detailed explanation of system model, Section III: Description of the power allocation with mathematical analysis, Section IV: Different relaying protocols with derivation of expressions, Section V: Emphasize of the simulation model, and Section VI: Conclusions.

II. SYSTEM MODEL

As in Fig. 1, The emergence of network is considered as our system model. It composed of a secondary source S, a secondary destination D, L number of antennas at each relay (l = 1,2,...,L), K number of relays (R_{kl}; k = 1,2,…,K), M number of primary transmitters and receivers. The primary transmitters are taken as PU-Tx_m; m = 1,2,....,M and the primary receivers are taken as PU-Rx_m; m = 1,2,…,M.

It is expected that single antenna is considered at source, destination and primary users whereas at relays multiple antennas are considered. Therefore, the best link can be selected from source to relay. Due to severe shadowing, there is no direct link deliberated between source and destination. On this aspect, a non-identical Rayleigh fading channel has been considered. In our system model, the primary transmitters are present adjacent to the source S and the relays. The destination is assumed to be far from the primary users. That is why the interference due to primary transmitter is considered only at the source and relays but not at the destination.

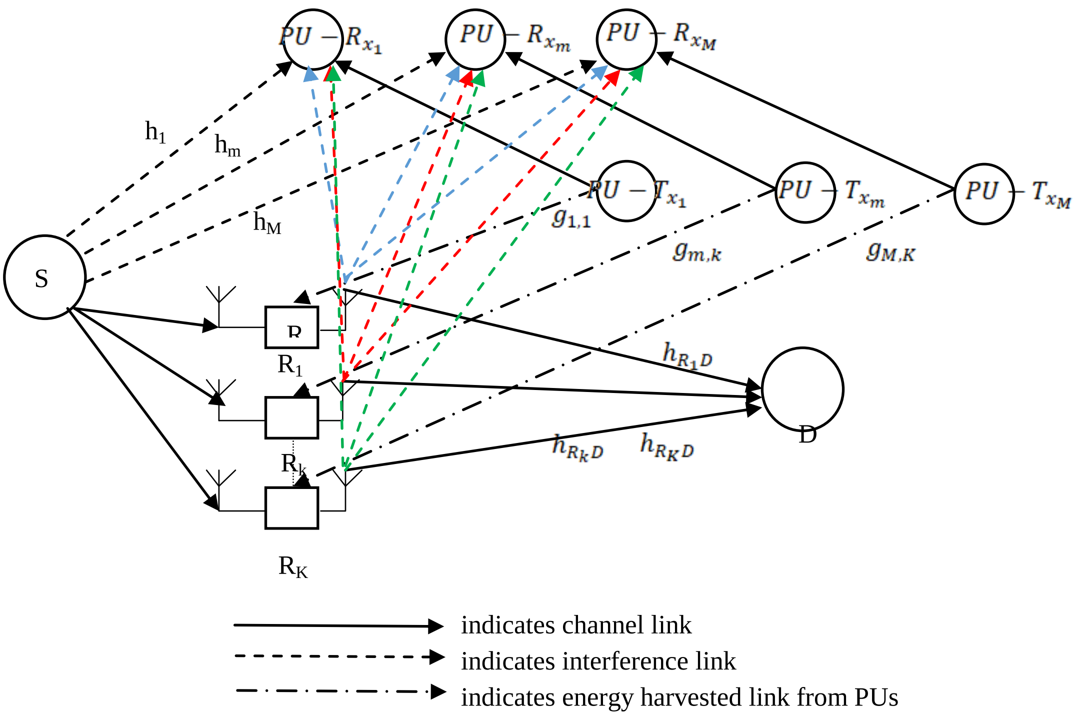

Fig. 1. System model of energy harvesting AHR in CSS CR network

The various channel links are specified: channel link S→ PU - Rx_m (m = 1,2,…,M) is defined by h_m, channel link S → l^{th} antenna of k^{th} Relay R_k is defined by $h_{SR_k,l}$, channel link k^{th} Relay R_k (k = 1,2,…K) → PU - Rx_m is defined by h_{R_km}, interference link PU-Tx_m (m = 1,2,M) → k^{th} Relay R_k (k = 1,2,…,K) is defined by $g_{m,k}$ and channel link k^{th} Relay R_k (k = 1,2,…,K) → D is defined by h_{R_kD}. The primary users can communicate within themselves with a fixed power P_{p_m}. The secondary source has to transmit information to the destination without hampering the communication between the primary users. This is done by setting the power of source S in such a way that it would maintain an interference constraint I_p. The relays are linked with energy harvesting circuits that also harvest energy from ambient RF waves. Here, it is considered that the relays can harvest energy from source signal and from interference due to primary transmitter because according to our system model the primary transmitter is near the relay network. For joint task of energy harvesting and information processing at relays we have considered Time Switching-based Relaying protocol. Fig. 2 shows TSR protocol. T is the total block considered for transmission of signal from S to D. The time fraction used for energy harvesting is designated as α ∈ (0,1) and the remaining time, i.e., (1 - α)T is used for information transmission. Out of the remaining time block $\frac{(1-\alpha)T}{2}$ is used for information transmission between source to relay and other half of it is used for information transmission between relay to destination. AHR process is applied for promoting the received signal at destination D from source S. According to AHR scheme, if the relay-received signal can be effectively decoded, then DF protocol is used else AF protocol is used. Hence, the mixing of both AF and DF schemes result is AHR, considering their impacts and utilize their advantages. The system model is divided into methodological sections to provide a clear understanding of our work.

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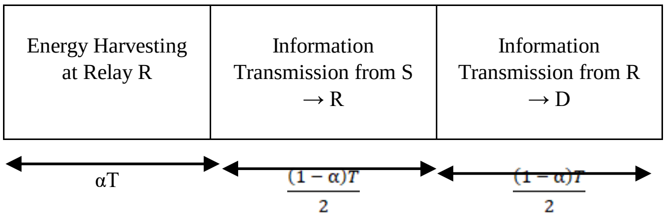

Fig. 2. TSR scheme for energy harvesting and information processing (Transmission block structure)

III. POWER ALLOCATION

This section explains the power allocation procedure in source and relay keeping in mind the use of energy harvesting in relays.

A. Power Allotment at secondary source S

The power allotment at source S should ensures that the interference between secondary source and primary receivers must not exceed the threshold I_p. So the power at secondary source S preserving the limitation of interference at m^{th} primary user is expressed by $P_{S_m} = \frac{Ip}{|h_m|^2}$ where m = 1,2….,M. Hence, preserving the limitation of interference for m^{th} primary receiver, the secondary source power is given by [10],

$$P_s = \min(P_{s_1}, P_2, \ldots \ldots, P_{s_m}) \tag{1}$$

B. Energy harvesting at relay

As stated before TSR protocol is used in this work. The received RF signal from source and interference due to primary transmitter is first sent to energy harvester circuit. The harvesting circuit process the RF signal and rectifies it to charge up the rechargeable battery already present. Let E_h^s be the energy harvested from secondary source signal and E_h^i be the energy harvested from interference due to primary transmitter. Thus the total energy harvested in k^{th} relay is given by

$$E_{hk} = E_h^s + E_h^i \tag{2}$$

The harvested energy due to source signal is given by [11]

$$E_h^s = \frac{\eta P_s \left|h_{SR_k}\right|^2 \alpha T}{d_1^n} \tag{3}$$

Similarly, the harvested energy due to interference from primary transmitter at k^{th} relay is given by [11]

$$E_h^i = \sum_{m=1}^{M} \frac{\eta P_{pm} \left|g_{m,k}\right|^2 \alpha T}{d_2^n} \tag{4}$$

where the energy conversion efficiency η varies between 0 and 1 depending on energy harvesting circuitry, n is the path loss exponent, d_1 is the distance between source and k^{th} relay, and d_2 is the distance between m^{th} primary transmitter and k^{th} relay.

C. Power allotment at relay

The transmit power at relay is decided by total harvested energy E_h. The harvested energy is stored in battery. The power developed from this energy must be less than the interference constraint for primary receivers. The transmit power at k^{th} relay is given by [11]

$$P_{R_k}^H = \frac{E_{hk}}{(1-\alpha)\frac{T}{2}} \tag{5}$$

Thus the maximum transmit power by virtue of harvested energy at any one of the relays satisfying interference constraint of all primary receivers is given by

$$P_R^H = \min_{k=1,2,\ldots,K} \{P_{R_k}^H\} \tag{6}$$

Now, at k^{th} relay by preserving the limitation of interference for all primary receiver PU - $R_x m$, the allocated power is

$$P_R^I \le \min_{m=1,2,\ldots,M} \left\{\frac{I_p}{\left|h_{R_k m}\right|^2}\right\} \tag{7}$$

Hence, the total power allotted at the relays

$$P_R = \min\{P_R^H, P_R^I\} \tag{8}$$

Now that the power allocation has been done successfully, we will evaluate the outage and throughput performance for AF, DF, and AHR protocols.

IV. RELAY PROTOCOL

This section explains the AF, DF and AHR transmitting protocols and derives the expression of outage probability and throughput for each of them.

A. AF Relay protocol

According to AF protocol the received signal from source is escalated at relay and forwarded to destination. This protocol acts as a signal amplifier. Major advantage of this scheme is easy implementation, but it comes with a serious drawback of noise amplification. Since no processing is done at relays the noise and information present in the received signal are amplified and this creates major decoding issues at destination.

The received signal from S to k^{th} relay R_k is expressed as

$$y_{k_D} = \sqrt{P_s} G_k h_{R_k D} h_{SR_k l} x + G_k h_{R_k D} n_{R_k} + n_{k_D} \tag{9}$$

where the channel coefficients $h_{SR_k l}$ and $h_{R_k D}$ of the links are S → $R_{k,l}$ (i.e., the link between source (S) and l^{th} antenna of k^{th} Relay) and R_k → D, respectively, n_{R_k} and n_{k_D} are the additive white Gaussian noise (AWGN) at R_k and D respectively, having the same power N_0.

The best channel between S and k^{th} relay R_k can be defined by using Selection Combining (SC) diversity and is expressed as

$$h_{SR_k} = \max_{l=1,2,\ldots,L} \left(h_{SR_k l}\right) \tag{10}$$

The gain G_k is expressed as,

$$\frac{1}{G_k^2} = \left|h_{R_k P}\right|^2 \left(\frac{\left|h_{SR_k}\right|^2}{|h_{SP}|^2} + \frac{N_0}{I_p}\right) \tag{11}$$

where, $h_{R_k P} = \max_{m=1,2,\ldots,M} \left(h_{SR_k m}\right)$ and $h_{SP} = \max_{m=1,2,\ldots,M} (h_m)$

Thus the SNR (end to end) for the link S → R_k → D is concerned with AF protocol and is provided by [12],

$$\gamma_k = \frac{\gamma_{SR_k} \gamma_{R_k D}}{1 + \gamma_{SR_k} + \gamma_{R_k D}} \tag{12}$$

where, $\gamma_{SR_k} = \bar{\gamma} \frac{\left|h_{SR_k}\right|^2}{|h_{SP}|^2}$, $\bar{\gamma} = \frac{I_p}{N_0}$ *and* $+\gamma_{R_k D} = \bar{\gamma} \frac{\left|h_{R_k D}\right|^2}{\left|h_{R_k P}\right|^2}$.

Thus, because of using of AF protocol, the received SNR (end-to-end) at D is given by

$$\gamma_D^{AF} = \max_{k=1,2,\ldots,K} \{\gamma_k\} \tag{13}$$

Thus, the AF outcome probability is provided by

$$P_{out}^{AF} = P_r(\gamma_D^{AF} \le \gamma_{th})$$
(14)

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where γ_{th} is the threshold SNR value preceding the instantaneous SNR at D cannot be exceeded.

Throughout of a communication network is described as the rate of successful information transmission over that communication channel. We have calculated the throughput at the destination. So the channel link $R_k \to D$ is considered.

Using the SNR obtained in equation (13) the ergodic capacity is derived by using Shannon's formula for $R_k \to D$ link.

$$C_r = E_r \log_2(1 + \gamma_D^{AF}) \quad (15)$$

where E_r is the expectation operator. Thus throughput for AHR at destination D is given by [11]

$$\tau = \frac{(1-\alpha)C_r}{2} \quad (16)$$

B. DF Relay protocol

Here in DF transmitting protocol, the relay-received signal is first decoded completely, then encoded again and finally forwarded to the destination. This is made possible by using powerful processors at the relay which can complete the whole process within seconds so as to avoid delay in the communication. Thus a major drawback is high decoding complexity and huge computational load on relays. But the silver lining in this scheme is no noise get transmitted at destination which ultimately leads to error less communication.

It is considered that at a given instant only a certain number of relays can successfully decode the incoming signal. Assume the set be ξ. Therefore the set can be explained as $\xi = \{\forall k \in (1,2,..K);\ \gamma_{SR_k} \geq \mu_{th}^R\}$ where $\gamma_{SR_k} = \frac{P_s}{N_0}$ is the instantaneous SNR. Only when $\gamma_{SR_k} > \mu_{th}^R$, the decoding process at R_k is successful. The instantaneous SNR (end to end) between the $S \to R_k \to D$ links may be expressed as

$$\gamma_{R_kD} = \frac{P_R}{N_0} \quad (17)$$

where P_R is the final power allocated at relay as in (8)

As per the ξ set, only one relay is chosen as in [12]

$$\gamma_D^{DF} = \max_{k\in\xi}\{\gamma_{R_kD}\} \quad (18)$$

The DF outage probability scheme may be expressed by

$$P_{out}^{DF} = \{\gamma_D^{DF} < \gamma th\} \quad (19)$$

where γ_{th} is the threshold SNR.

Here also we have described throughput at the destination and likewise the channel link $R_k \to D$ is considered. Using the SNR obtained in equation (18) the ergodic capacity is derived for $R_k \to D$ link.

$$C_r = E_r \log_2(1 + \gamma_D^{DF}) \quad (20)$$

where E_r is the expectation operator. Thus throughput for AHR at destination D is given by

$$\tau = \frac{(1-\alpha)C_r}{2} \quad (21)$$

C. Adaptive Hybrid Relay protocol

Mixing of both AF and DF protocol results AHR protocol. DF protocol is considered only if the incoming signal is successfully decoded in AHR protocol, otherwise AF protocol is considered. Thus AHR adaptively alterations between AF and DF protocols and results much better than individual AF and DF scheme. In this scheme no relay remains idle and each relay operating together creates a huge set of instantaneous SNR, which enhances the outcome performance of the considered system.

As stated in DF protocol, the decoding process at R_k is successful only when $\gamma_{SR_k} > \mu_{th}^R$, i.e., DF protocol is used, or else AF protocol is used. Perhaps, the following AF probability scheme is expressed as

$$P_{AF} = P_r\{\gamma_{SR_k} > \mu_{th}^R\} \quad (22)$$

So the following DF probability scheme is expressed as

$$P_{DF} = 1 - P_{AF} \quad (23)$$

Hence, the instantaneous SNR at R_k Hybrid Relay may be expressed by

$$\gamma_k^{AHR} = P_{AF}\gamma_k^{AF} + P_{DF}\gamma_k^{DF} \quad (24)$$

Utilizing the Best Relay Selection (BRS) scheme, one relay is preferred and the SNR (end-to-end) may be regulated as

$$\gamma_D^{AHR} = \max_{k=1,2,\dots,K}\{\gamma_k^{AHR}\} \quad (25)$$

Hence, the Adaptive Hybrid Relaying (AHR) probability scheme is denoted as

$$P_{out}^{AHR} = \{\gamma_{out}^{AHR} < \gamma_{th}\} \quad (26)$$

where γ_{th} is the outage threshold. As done in above mentioned protocols, the throughput is described at the destination. So the channel link $R_k \to D$ is considered. Using the SNR obtained in equation (21) the ergodic capacity is derived for $R_k \to D$ link.

$$C_r = E_r \log_2(1 + \gamma_D^{AHR}) \quad (27)$$

where E_r is the expectation operator. Thus throughput for AHR at destination D is given by

$$\tau = \frac{(1-\alpha)C_r}{2} \quad (28)$$

V. RESULTS AND DISCUSSIONS

In our work, we set the path loss exponent m is 2.7 and the energy harvesting efficiency η is set at 0.5. The distances d_1 and d_2 are regulated to unit value for simplicity.

Fig. 3 shows comparison of EH relay following AF, DF and AHR protocols in terms of outage performance. The system parameters are set as L = 4, K = 4 and PU = 3. It is observed that under similar conditions, the outage performance of AHR is better than individual AF and DF schemes. According to the AHR protocol, if the decoding process succeeds, then the relay regenerates the symbol and re-transmits it (i.e., it follows DF mode) to destination. Whereas if the decoding process fails, then the received signal is amplified and forwarded towards destination instead of remaining idle (i.e., AF mode). So, the relay selection diversity is improved as each and every relay works. Therefore, in case of individual AF and DF schemes, an improvement on performance is seen in case of AHR protocol.

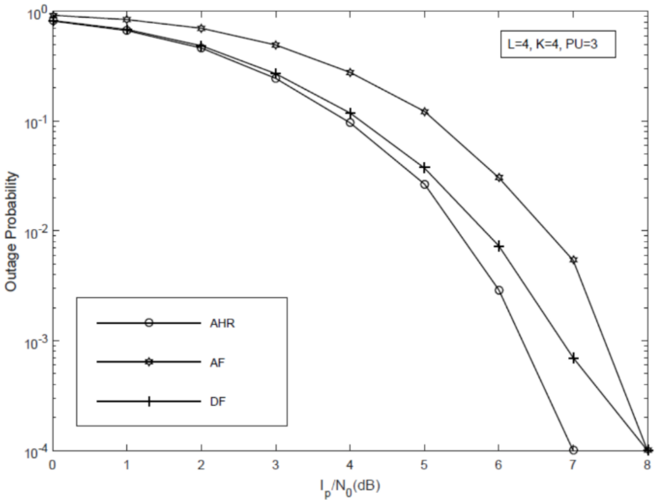

Fig. 3. Outage probability vs $\frac{I_p}{N_0}$ comparison for *EH AF, DF* and *AHR* protocol

Fig. 4 displays the comparison of EH relay following AF, DF and AHR protocols in terms of throughput performance. System parameters are kept constant such as L = 4, K = 4 and PU = 3. It is seen that the throughput attained by AF is maximum when α is 0 i.e., no time for energy harvesting. Then the throughput decreases linearly with increasing α. Thus it can be said that EH in relay has no noticeable effect on AF scheme. On the other hand, the AHR and DF witness optimizable throughput variation for changing values of α. Table 1 shows the performance of the network in terms of throughput for AHR, AF and DF schemes.

Time fraction (α)		0	0.2	0.4	0.6
Throughput (τ)	AHR	0.56	1	0.8	0.6
	AF	1.01	0.8	0.6	0.4
	DF	0.18	0.82	0.7	0.5

Table 1: Throughput for AHR, AF and DF schemes

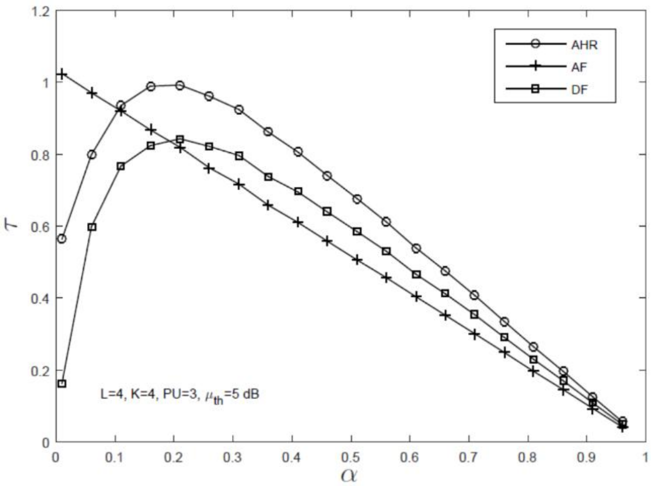

Fig. 4. Throughput τ vs α comparison for *EH AF, DF* and *AHR* protocol

The figure in Fig. 5 plots throughput vs α of considered CR network for increasing values of PU. The relays are operating in AHR mode. The values of L, K and PU are taken as L = 4, K = 4, and PU = 3. With increasing number of primary users, it is seen that the throughput increases over the range 0.2 < α < 0.6. As the throughput is a function of α and α is the time fraction for energy harvesting and information processing at relays, therefore it happens. Since, in our model, the relays are considered to harvest energy from both PU - T_x interference and the source signal, so a large amount of energy is harvested from increasing primary users. Thus, we see increase in throughput with increase in number of primary users.

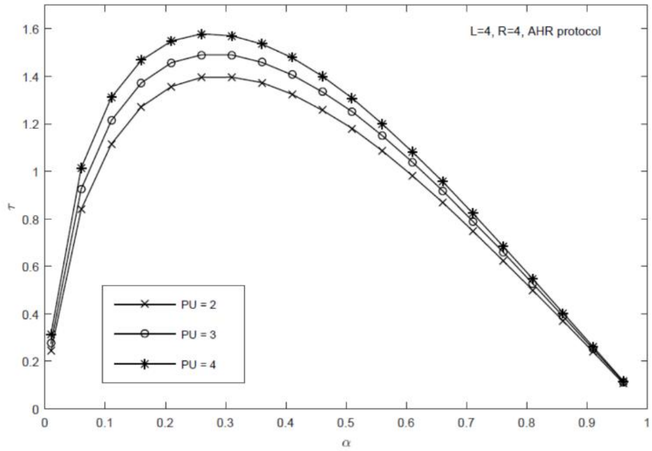

Fig. 5. Throughput τ vs α for increasing primary users

Fig. 6 shows τ vs α for two combinations of L and K. The number of primary users are fixed at 3. It is seen that the throughput is better in case of L = 1 with K = 4 compared to the case where L = 4 and K = 1. Thus, it can be concluded that if the number of antennas increases at each relay, then the increasing number of relays has more effect on throughput. Table 2 shows the performance of the network in terms of throughput for different combinations of L and K.

Time fraction (α)		0.3	0.4	0.5	0.6	0.7
Throughput (τ)	L = 1, K = 4	1.42	1.35	1.8	1	0.7
	L = 4, K = 1	1.35	1.25	1.5	.9	0.6

Table 2: Throughput for different combinations of L and K

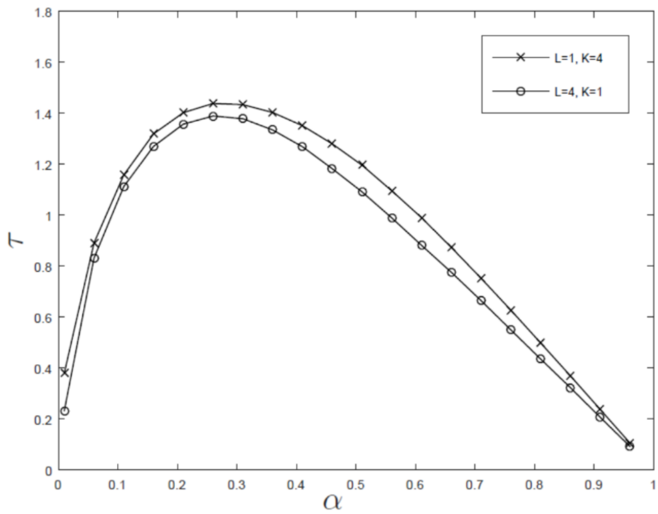

Fig. 6. Throughput τ vs α for two combinations of L and K

Throughput τ vs I_p performance is compared for AF, DF and AHR protocol in Fig. 7. The

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network parameters are taken as L = 4, K = 4 and PU = 3.

It is seen that the throughput obtained in case of AHR protocol is more fruitful than individual AF and DF protocol. Till 7.5 dB of I_p, the comparison is noticeable for the three protocols but after this point the performance of AHR and DF becomes similar, whereas the performance of AF is better than AHR and DF protocol. Since the I_p value should be set low in practical purposes to avoid primary user interference, so we can say that AHR protocol is more applicable than AF and DF protocols.

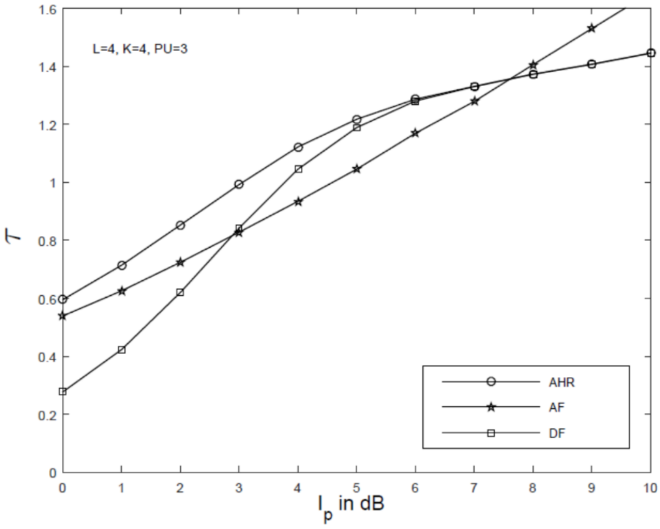

Fig. 7. τ vs I_p for *AF, DF* and *AHR* protocol

VI. CONCLUSSIONS

Outage probabilities and throughput of a CSS CR network are incorporated with EH relays following AHR protocol and the performance is evaluated. The throughput and outage performance using energy harvesting AF, DF and AHR protocols have been compared and it is shown that AHR protocol is the best among the three. It is seen that throughput performance of AF is better for α = 0 and then linearly degrades as α increases while AHR and DF protocol shows a subsequent increase and then decrease in throughput performance. Thus, we can get optimizable throughput for specific value of harvesting time α. The effect of an increasing number of primary users on the throughput of the system is also shown. It is also seen that the throughput increases for a certain interval of α as the number of primary user increases. A trade-off between the number of relays and the number of antennas at each relay is also shown. It is concluded that the increasing number of relays produces better results than the rising count of antennas.

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AUTHORS PROFILE

Mr. Mousam Chatterjee is currently working as Assistant Professor in B. P. Poddar Institute of Management & Technology under MAKAUT. He obtained B.E. in Electronics & Communication Engineering from Jalpaiguri Govt. Engineering College, North Bengal University in 2004. He secured his M. Tech Degree in Radio Physics & Electronics from Institute of Radio Physics & Electronics, Calcutta University in 2008. He is in teaching profession for more than 11 years. He is a life member of ISTE and FOSET. His main areas of teaching interest include Signals and Systems and Communication Engineering and research interest include Wireless Network. Till date he has published 2 papers (book chapter) in International Conferences and 1 paper in National Conference.

Presently, **Dr. Basu** is working as an Assistant Professor, Dept. Electronics and Communication Engineering in National Institute of Technology Silchar, Assam, India. Prior to that, she worked as Assistant Professor in Thapar University, Patiala and National Institute of Technology, Arunachal Pradesh. She published 42 numbers of research articles in International Journals & Conferences. She has also authored 4 books and 2 book chapters. Her research interest includes Antenna Design, Soft Computing Techniques in Antenna Array Design, Wireless Networks, Optimization of Wireless Sensor Networks, Signal Processing etc.

Dr. Nandi is an Assistant Professor in the Dept. of Electronics and Communication Engineering (ECE), National Institute of Technology (NIT) Silchar since December 2015. Prior to that, he worked as an Assistant Professor in the Dept. of ECE at NIT Meghalaya and NIT Arunachal Pradesh. He published 43 numbers of research articles in International Journals & Conferences. He has also authored 4 books and 1 book chapter. His research interest includes Wireless Sensor

Networks (WSNs), Wireless Networks, Optimization of WSNs, Antenna Design, RF MEMS Design, Signal Processing etc.

Dr. Chanchal Kumar De was born in Bankura, India, in 1981. He received the Ph.D. degree in 2015 in Wireless Communication Engineering from NIT Durgapur, India. He is currently Associate Professor in Electronics and Communication Engineering department at Haldia Institute of Technology, Haldia, India. His research interests include cooperative relay networks, OFDM technology, and cognitive radio networks. He has published 20 research papers in various Internationals journals and Conferences. Communication Engineering department at Haldia Institute of Technology, Haldia, India. His research interests include cooperative relay networks, OFDM technology, and cognitive radio networks. He has published 20 research papers in various Internationals journals and Conferences.

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