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Spectrum Sharing Analysis of Cognitive System Through Enery Harvesting and Interference Negligence Technique

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ABSTRACT

In this letter, a novel approach for solving the power and spectrum issues in wireless sensor network (WSN) has been proposed. Typically, a deployed sensor node is programmed to periodically send the data to the central base station (CBS). Moreover, most of the sensor nodes are deployed in a hostile environment where replacing a power supply may not be feasible. In the proposed work, we intend to solve the dual problem of spectrum and power for WSN by utilizing techniques such as cooperative spectrum sharing (CSS) and RF (radio frequency) energy harvesting, respectively. Specifically, by characterizing the WSN as an energy constrained secondary user, which will harvest power and spectrum from the primary user, we have shown that significant performance gains can be obtained for both primary and secondary users. Closed form expressions for outage prob- ability under a Nakagami fading channel have been derived for both primary and secondary users. Furthermore, the theoretical results have been compared with simulation results to validate the proposed analysis.

***Keywords:** Cooperative spectrum sharing, WSN, RF energy harvesting*

INTRODUCTION

Recently there has been growing impetus on developing smart cities thorough out the world [1], [2]. Smart city is an intelligent city that is able to integrate and synthesize data for many purposes which helps in improving the quality of life in cities. The smart city is an innovation of Information and Com- munication Technology (ICT), which is based upon Internet of thing (IoT), where the motivation is to connect different parts of the city by using sensors which will be useful in real-time monitoring of the public infrastructures such as bridges, roads, buildings as well as climate conditions [1]. Apart from above, the concept of "smartness" has also been brought in technolo- gies such as smart meters, smart grid, energy conservatism, recycling, waste management etc. [1]. In further boost to above technology, countries such as India has recently approved a proposal to invest heavily in smart city development [2]. For effective development of smart city, sensors have to be deployed in very large numbers and they have to be interconnected, so that the collected data can be transmitted to a CBS, where intelligent decisions based on this data can be made [1]. There are few issues identified in the aforementioned definition i.e. deployment of sensors throughout the city and transfer the collected information to the CBS which require both power and frequency spectrum. As the sensor nodes do not need to send the data all the time, therefore providing a dedicated spectrum to WSN is not an economically viable approach. Furthermore in case of WSN, providing energy storage mechanism is a critical issue in terms of space and location. In this paper, to alleviate the above issues, we propose a self-sustaining wireless sensor network that will utilize advance techniques such as cooperative spectrum sharing (CSS) [3] and RF energy harvesting (EH) to satisfy its requirement of spectrum and power respectively. In CSS, an unlicensed (secondary/cognitive) user is allowed to coexist in licensed spectrum of primary user (PU) on the condition that secondary user (SU) will assist the PU to achieve its target rate of communication [3]. Moreover, instead of using an internal battery or external recharging mechanism for its operation, it will prefer other sources of renewable energy like thermal, solar, wind, mechanical etc. The most reliable one, in case of WSN, is harvesting energy from the RF signals present in the environment, commonly known as RF or wireless EH. Various studies have shown that the wireless EH is the viable solution in solving the issues of energy constrained systems [4].

Hence in the proposed work, we characterize WSN as an energy-constrained SU, which will harvest energy and spectrum from PU, in return, it will ensure that PU meets its target rate of communication.

Some recent work have incorporated RF EH in cooperative relaying [5]–[7] where a single node operates for both EH and information processing. In [5] two relaying protocols are discussed for Rayleigh fading channel, namely power splitting- based relay (PSR) and time switching-based relay (TSR). In PSR, relay utilizes fraction of signal power coming from source for EH and remaining power for information processing. In TSR, relay will harvest energy in EH period and remaining time is used for information processing. Here, relay is used to amplify the source data and forward it to the destination. No spectrum sharing has been discussed. Both [6], [7] have discussed spectrum sharing protocol with EH but in underlay mode. Moreover, SU is not helping the PU in achieving the target rate of communication. In underlay mode, some power constraint on SU is superimposed so that SU will cause only an acceptable amount of interference at PU.

In this paper, a two phase protocol for energy as well as spectrum harvesting along with information transmission in overlay mode has been proposed for Nakagami fading channel. In the proposed protocol, a sensor node which acts as a decode- and-forward relay for the PU will harvest energy from primary transmission and will use that harvested energy to assist the PU in achieving the required rate of communication by transmitting its data to the destination. Moreover, part of the harvested energy will also be utilized by the node to send its own data to CBS. However, as compared to underlay mode of transmission, the proposed overlay protocol does not suffer from power constraint at the relay node [8].

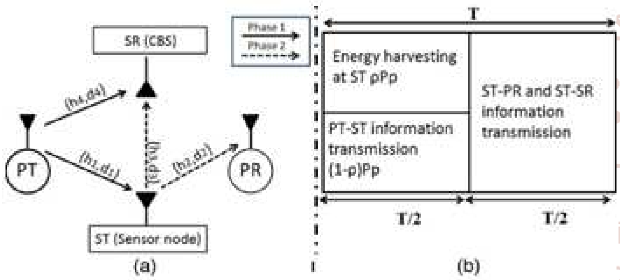

Fig. 1. (a) System model and (b) proposed protocol illustration for energy harvesting and information transmission at ST.

SYSTEM MODEL WITH MATHEMATICAL ANALYSIS:

In this architecture, primary and secondary system consists of transmitter receiver pair known as Primary Transmitter-Primary Receiver (PT-PR) and Secondary Transmitter-Secondary Receiver (ST-SR) respectively. For simplicity, we assume that the link between PT-PR fails, and primary user is not able to achieve its target rate of communication, Rp (due to physical obstacles, poor channel conditions etc.), in such case PT will require some cooperation from neighbouring nodes to forward its data to PR with target rate of Rpt. ST node (if it can) will assist PT by forwarding its data to PR and simultaneously transfer its own data to SR. As ST is self-sustaining sensor node, it will harvest the required energy from signal it received from PT. Therefore the whole protocol works as follow: In first phase, PT will broadcast PU's signal (x_p) which will be received by ST and SR only. After receiving the signal, ST will utilize ρ amount of signal power to harvest energy and remaining for signal decoding. In second phase, this harvested energy will be used to transfer both primary as well as secondary signal (x_s). ST will assign some (α) amount of power to xp and remaining to x_s, so that target rate at PR is met. As SR has prior knowledge of x_p from phase 1, so it can cancel the interference received in phase 2 and will extract only the required signal i.e. x_s. The information signal received at ST during the first phase is given by $y_{st} = \sqrt{P_p}h_1x_p + n_{st}$ where, Pp is the transmission power of PT. Here, ST works as a power splitting based relay, the power is split in the ratio of $\rho:(1-\rho)$, ρ is for energy harvesting and $(1-\rho)$ for information processing, $0 \leq \rho \leq 1$. Signal received by energy harvester is given by $\sqrt{\rho}y_{st} = \sqrt{\rho P_p}h_1x_p + \sqrt{\rho n_{st}}$. The harvested energy at ST for half of the block time of length T can be given by $E_h = \frac{\eta\rho P_p|h_1|^2T}{2}$ where, $0 \leq \eta \leq 1$ is the energy conversion efficiency. The power will be dispensed for remaining T/2 time and hence given by

$$P_h = \frac{E_h}{T/2} = \eta\rho P_p|h_1|^2.$$

The signal received by information receiver is given by

$$\sqrt{(1-\rho)}y_{st} = \sqrt{(1-\rho)P_p}h_1x_p + \sqrt{(1-\rho)}n_{st} + n_{rf}$$

Where, $n_{rf} \sim CN(0,\sigma_{rf}^2)$ is the sampled AWGN due to RF band to baseband signal conversion. Therefore, total AWGN noise at information receiver is $n_{ir} = \sqrt{(1-\rho)}n_{st} + n_{rf}$ and $\sigma_{ir}^2 = (1-\rho)\sigma_{st}^2 + \sigma_{rf}^2$. Consequently, the rate achieved at information receiver of ST can be given by

$$R_{ir} = \frac{1}{2}\log_2(1 + SNR_{ir}).$$

Where, $SNR_{ir} = \frac{(1-\rho)P_p\gamma_1}{\sigma_{ir}^2}$. In transmission phase 2, ST decodes the received signal (x_p) at information receiver and transmits it along with x_s by providing fraction of α and $(1-\alpha)$ power respectively. The signal received at PR is given by $y_{pr} - \sqrt{\alpha P_h}h_2x_p + \sqrt{(1-\alpha)P_h}h_2x_s + n_{pr}$ where, $n_{pr} \sim CN(0,\sigma_{pr}^2)$ is the AWGN received at PR and P_h.

After substituting P_h, we get

$$y_{pr} = \sqrt{\alpha\eta\rho P_p|h_1|^2}h_2x_p + \sqrt{(1-\alpha)\eta\rho P_p|h_1|^2}\,h_2x_s + n_{pr}$$

The rate achieved at PR is given by

$$R_{pr} = \frac{1}{2}\log_2(1 + SNR_{pr}).$$

Where $SNR_{pr} = \frac{\alpha\eta\rho P_p\gamma_1\gamma_2}{(1-\alpha)\eta\rho P_p\gamma_1\gamma_2 + \sigma_{pr}^2}$

OUTAGE PROBABILITY OF PRIMARY SYSTEM:

The outage probability for primary system can be given as

$$P_p^{out} = 1 - P\left[R_{ir} > R_{pt}\right]P\left[R_{pr} > R_{pt}\right]$$

Above equation shows that outage at PR will be declared if either ST or PR fails in decoding primary's signal with target rate of R_{pt}.

$$P\left[R_{ir} > R_{pt}\right] = 1 - P\left[\gamma_1 > \frac{\psi_p\sigma_{ir}^2}{(1-\rho)P_p}\right] = 1 - \frac{\left(k, \frac{\psi_p\sigma_{ir}^2}{\theta_1(1-\rho)P_p}\right)}{(k)}$$

Where , $\psi_p = 2^{2R_{pt}} - 1$, Γ(.,.) is the lower incomplete gamma function [1] and Γ(.) gamma function [2].

$$P\left[R_{pr} > R_{pt}\right] = 1 = P\left[\frac{\alpha\eta\rho P_p\gamma_1\gamma_2}{(1-\alpha)\eta\rho P_p\gamma_1\gamma_2 + \sigma_{pr}^2} < \psi_p\right]$$

Where, $z = \frac{\psi_p\sigma_{pr}^2}{\eta\rho P_p[\alpha - \psi_p(1-\alpha)]}$. Above equation can be rewritten as,

$$P\left[R_{pr} > R_{pt}\right] = \begin{cases} 1 - P[\gamma_1\gamma_2 < z] & \psi_p < \frac{\alpha}{1-\alpha} \\ 1 - P[\gamma_1\gamma_2 < z] = 0 & \text{Otherwise} \end{cases}$$

The second equality is because of the fact that for $\psi_p > \frac{\alpha}{1-\alpha}$, the z term will be negative and the probability of gamma distribution greater than a negative number is always 1. Moreover for $\psi_p > \frac{\alpha}{1-\alpha}$, z tend to $+\infty$ and the probability of product of gamma distribution less than $+\infty$ is also 1. Now solving for first equality when z is positive, using concept of product of two RVs, we obtain

$$P[\gamma_1\gamma_2 < z] = \int_0^\infty f_{\gamma_1}(x)P(\gamma_2 \le {}^{z}/_{x})dx$$
$$= \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty f_{\gamma_1}(x)P(\gamma_2 \le {}^{z}/_{x})dx$$

Using above equations we get,

$$P\left[R_{pr} > R_{pt}\right] = \begin{cases} 0 & 0 < \alpha \le \acute{\alpha} \\ 1 - \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)}e^{-\frac{x}{\theta_1}}\left(k,\frac{z}{x\theta_2}\right)dx & \acute{\alpha} < \alpha \le 1 \end{cases}$$

Where, $\acute{\alpha} = \frac{\psi_p}{\psi_p+1}$ Using (4.35),(4.36) and (4.40) we get ,

$$P_{p_z}^{out} = 1 - \left(1 - \frac{\left(k,\frac{\psi_p\sigma_{ir}^2}{\theta_1(1-\rho)P_p}\right)}{(k)}\right)\left(1 - \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)}e^{-\frac{x}{\theta_1}}\left(k,\frac{z}{x\theta_2}\right)dx\right)$$

Above Equation can be obtained in closed form

$$P_{p_z}^{out} = 1 - \left(1 - \frac{\left(k,\frac{\psi_p\sigma_{ir}^2}{\theta_1(1-\rho)P_p}\right)}{(k)}\right)\left(1 - \frac{1}{(\Gamma(k))^2}G_{1,3}^{2,1}\left[\left(\frac{z}{\theta_1\theta_2}\middle| \begin{matrix}1 & 1 & 1\\ k & k & 0\end{matrix}\right)\right]\right)$$

Where,G[.] is the Meijer G-function. For m=1 Nakagami fading reduces to Rayleigh Fading Channel and reduces to

$$P_{p_z}^{out} - 1 - \left(e^{-\frac{\psi_p\sigma_{ir}^2}{\theta_1(1-\rho)P_p}}\right)\left(\sqrt{\frac{4z}{\theta_1\theta_2}}k_1\left(\sqrt{\frac{4z}{\theta_1\theta_2}}\right)\right)$$

SIMULATION RESULTS AND DISCUSSION

In this section we have plotted outage probability for primary and secondary system with respect to location of the nodes in Fig. 2 and 3 respectively. We have considered $\frac{P_p}{\sigma_{ir}^2} = \frac{P_p}{\sigma_{pr}^2} = \frac{P_p}{\sigma_{sr}^2} = 40\,dB$. The path loss exponent (i.e. v) is considered to be 3. The target rate for both systems are considered to be 1 i.e. RP = RS = 1. The results are shown for:

- two different values of m i.e. m = 0.5 (half Gaussian pulse), 1 (Rayleigh fading)
- two different values of ρ i.e. ρ = 0.25, 0.75
- two different values of η i.e. η = 0.5, 1
- for α = 0.8
- distance of d (where, 0.1 ≤ d ≤ 0.9) between PT-ST node and (1-d) between ST-PR,

ST-SR links. PT-SR distance is assumed to be 1. It is very obvious that with increasing value of m, fading will become less severe; therefore outage probability decreases when m changes from 0.5 to 1 in both Fig. 2 and 3

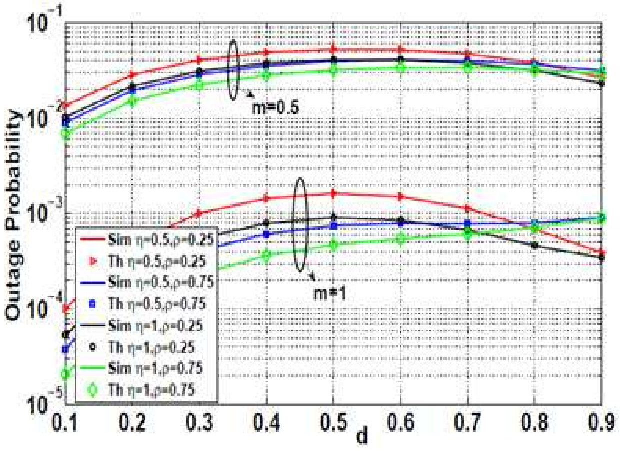

Fig. 2. Outage probability for primary system.

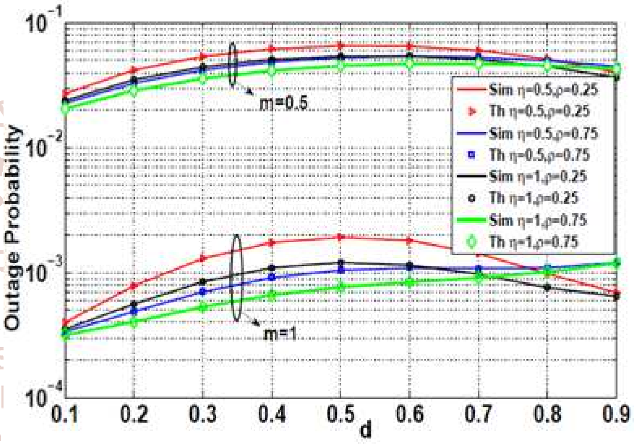

Fig. 3. Outage probability for Secondary system.

From Fig. 2 , it can be observed that when d is small, outage probability decreases with increasing ρ, as less value of d indicates PT and ST are closed enough and hence more energy can be saved by using large ρ. However, when d ≥ 0.8, we need to choose small value of ρ in order to have less outage probability. The reason for this is, as ST is moving away from PT, it will require more power for decoding the signal correctly. So proper choice of ρ depends on the location of nodes. Similarly, Fig. 3 illustrates the outage probability of secondary system with respect to d. The trend observed in secondary system is quite similar to that of primary system. This can be explained as follows. Since the outage probability of secondary system is also dependent on the successful decoding of primary signal by ST in Phase 1, hence as d (i.e.. distance between PT-ST) increases the probability of successful decoding of primary signal reduces hence the outage increases. Furthermore, when d ≥ 0.8, more power is required for decoding and less for transmission, hence outage probability decreases for ρ = 0.25.

CONCLUSION

In this paper, we proposed a self-sustaining protocol for WSN. In this protocol, WSN, which is characterized as a secondary user can harvest both energy and spectrum from primary signal transmission. In exchange for access to primary signal spectrum, it will help the primary user in achieving the target rate of communication. The excellent agreement between simulated results and the analytically

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