Energy Harvesting and Spectrum Sharing Protocol for Wireless Sensor Networks

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***Abstract*—In this letter, a novel approach to solve the power and spectrum issues in wireless sensor network (WSN) has been proposed. Typically a deployed sensor node is programmed to send the data to the central base station (CBS) periodically. Moreover, most of the sensor nodes are deployed in hostile environment where replacing a power supply may not be practically 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 WSN as 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 user. Closed form expressions for outage probability under a Nakagami fading channel has been derived for both primary and secondary user. Furthermore, the theoretical results have been compared with simulation results to validate the proposed analysis.**

***Index Terms*—Cooperative spectrum sharing, WSN, RF energy harvesting**

I. 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 ICT (Information and communication technology), which is based upon IoT (Internet of thing), 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 technologies 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 PSR (Power splitting-based relay) and TSR (Time switching-based relay). 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].

II. 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 as shown in Fig. 1a). For simplicity, we assume that the link between PT-PR fails, and primary user is not able to achieve its target rate of communication, R_p (due to physical obstacles, poor channel conditions etc. [5]), in such case PT will require some cooperation from neighbouring nodes to forward its data to PR with target rate of R_p. 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 (x_p) as well as secondary signal (x_s). ST will assign α amount of power to x_p 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 channels between the nodes are modeled as frequency non-selective Nakagami block fading. The channel coefficient between PT-ST, ST-PR, ST-SR, PT-SR, is h_1, h_2, h_3, h_4 respectively. Here, $h_i \sim$ Nakagami (m, Ω_i) where, m is the shape parameter and Ω is the controlling parameter. $\Omega_i = d_i^{-v}$ where, v is the path loss exponent and d_i is the distance between the corresponding link. The instantaneous gain of each channel is given as $\gamma_i = |h_i|^2$. γ_i is the random variable given by Gamma (k, θ_i) where, k=m and θ_i is the scale parameter, defined as $\theta_i = \frac{\Omega_i}{m}$. The additive white Gaussian noise (AWGN) at receiver is represented as $r \sim \mathcal{CN}(0, \sigma^2)$ which indicates zero mean and σ^2 variance. x_p and x_s are assumed to be independently circularly-symmetric complex Gaussian (CSCG) distributed with zero mean and unit variance, i.e. $x_p \sim \mathcal{CN}(0,1)$ and $x_s \sim \mathcal{CN}(0,1)$. R_p and R_s represents the target rate at primary and secondary receiver respectively.

The information signal received at ST during the first phase is given by $y_{st} = \sqrt{P_p} h_1 x_p + n_{st}$ where, P_p is the transmission power of PT and $n_{st} \sim \mathcal{CN}(0, \sigma_{st}^2)$ is the AWGN received at ST. Here, ST works as a power splitting based relay as shown in Fig. 1b), 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 $\sqrt{\rho} y_{st} = \sqrt{\rho P_p} h_1 x_p + \sqrt{\rho} n_{st}$. The harvested energy at ST for half of the block time of length T can be given by $E_h = \frac{\eta \rho P_p |h_1|^2 T}{2}$ 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

$$P_h = \frac{E_h}{T/2} = \eta \rho P_p |h_1|^2. \tag{1}$$

The signal received by information receiver is given by

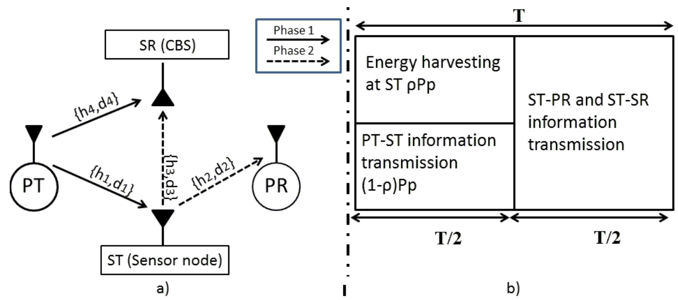

Fig. 1. a) System Model b) Proposed protocol illustration for energy harvesting and information transmission at ST

$$\sqrt{(1-\rho)} y_{st} = \sqrt{(1-\rho) P_p} h_1 x_p + \sqrt{(1-\rho)} n_{st} + n_{rf} \tag{2}$$

where, $n_{rf} \sim \mathcal{CN}(0, \sigma_{rf}^2)$ is the sampled AWGN due to RF 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

$$R_{ir} = \frac{1}{2} \log_2(1 + SNR_{ir}) \tag{3}$$

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 $y_{pr} = \sqrt{\alpha P_h} x_p h_2 + \sqrt{(1-\alpha) P_h} x_s h_2 + n_{pr}$ where, $n_{pr} \sim \mathcal{CN}(0, \sigma_{pr}^2)$ is the AWGN received at PR and P_h is defined in(1). After substituting P_h, we get $y_{pr} = \sqrt{\alpha \eta \rho P_p |h_1|^2} x_p h_2 + \sqrt{(1-\alpha) \eta \rho P_p |h_1|^2} x_s h_2 + n_{pr}$. The rate achieved at PR is given by

$$R_{pr} = \frac{1}{2} \log_2(1 + SNR_{pr}) \tag{4}$$

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

III. Outage Probability of Primary System

The outage probability for the primary system can be given as

$$P_p^{out} = 1 - P[R_{ir} > R_p] \, P[R_{pr} > R_p]. \tag{5}$$

(5) shows that outage at PR will be declared if either ST or PR fails in decoding primary's signal with target rate of R_p. Using (3),

$$P[R_{ir} > R_p] = 1 - P\left[\gamma_1 < \frac{\psi_p \sigma_{ir}^2}{(1-\rho) P_p}\right] = 1 - \frac{\Gamma(k, \frac{\psi_p \sigma_{ir}^2}{\theta_1 (1-\rho) P_p})}{\Gamma(k)} \tag{6}$$

where, $\psi_p = 2^{2R_p} - 1$, $\Gamma(.,.)$ is the lower incomplete gamma function[1] and $\Gamma(.)$ is the complete gamma function[2]. Using (4),

$$P\left[R_{pr} > R_p\right] = 1 - P\left[\frac{\alpha\eta\rho P_p\gamma_1\gamma_2}{(1-\alpha)\,\eta\rho P_p\gamma_1\gamma_2 + \sigma_{pr}^2} < \psi_p\right]. \tag{7}$$

Defining $z = \frac{\psi_p\sigma_{pr}^2}{\eta\rho P_p[\alpha-\psi_p(1-\alpha)]}$, (7) can be rewritten as,

$$P\left[R_{pr} > R_p\right] = \begin{cases} 1 - P[\gamma_1\gamma_2 < z] & \psi_p < \frac{\alpha}{1-\alpha} \\ 1 - P[\gamma_1\gamma_2 > z] = 0 & \text{otherwise} \end{cases}. \tag{8}$$

The second equality in (8) 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 tends 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

$$\begin{aligned} P[\gamma_1\gamma_2 < z] &= \int_0^\infty f_{\gamma_1}(x) P(\gamma_2 \le z/x)dx \\ &= \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)}e^{-\frac{x}{\theta_1}}\Gamma\left(k, \frac{z}{x\theta_2}\right)dx. \end{aligned} \tag{9}$$

Using (7), (8) and (9) we get

$$\begin{aligned} &P\left[R_{pr} > R_p\right] \\ &= \begin{cases} 0 & 0 \le \alpha \le \hat{\alpha} \\ 1 - \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)}e^{-\frac{x}{\theta_1}}\Gamma\left(k, \frac{z}{x\theta_2}\right)dx & \hat{\alpha} < \alpha \le 1 \end{cases} \end{aligned} \tag{10}$$

where, $\hat{\alpha} = \frac{\psi_p}{\psi_p+1}$. Substituting (6) and (10) in (5), we obtain

$$P_p^{out} = \begin{cases} P_{p_1}^{out} = 1, & 0 \le \alpha \le \hat{\alpha} \\ P_{p_2}^{out}, & \hat{\alpha} < \alpha \le 1 \end{cases} \tag{11}$$

where,

$$\begin{aligned} P_{p_2}^{out} &= 1 - \left(1 - \frac{\Gamma(k, \frac{\psi_p\sigma_{ir}^2}{\theta_1(1-\rho)P_p})}{\Gamma(k)}\right) \\ &\left(1 - \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)}e^{-\frac{x}{\theta_1}}\Gamma\left(k, \frac{z}{x\theta_2}\right)dx\right). \end{aligned} \tag{12}$$

(12), can be obtained in closed form using ([9], Eq.(7)),

$$\begin{aligned} P_{p_2}^{out} &= 1 - \left(1 - \frac{\Gamma(k, \frac{\psi_p\sigma_{ir}^2}{\theta_1(1-\rho)P_p})}{\Gamma(k)}\right) \\ &\qquad \left(1 - \frac{1}{(\Gamma(k))^2} G^{\,2\;1}_{\,1\;3}\left[\frac{z}{\theta_1\theta_2}\middle|\begin{matrix}1\\ k,k,0\end{matrix}\right]\right) \end{aligned} \tag{13}$$

where, G[.] is the Meijer G-function.

[1] $\Gamma(k,x) = \int_0^x t^{k-1}e^{-t}dt$
[2] $\Gamma(k) = \int_0^\infty t^{k-1}e^{-t}dt$

IV. Outage Probability of Secondary System

The signal received by SR in transmission phase 1 is given by

$$y_{sr_1} = \sqrt{P_p}h_4x_p + n_{sr} \tag{14}$$

where, $n_{sr} \sim \mathcal{CN}(0, \sigma_{sr}^2)$ is the AWGN received at SR. At SR, an estimate of x_p is obtained as $\widehat{x_p} = \frac{y_{sr_1}}{\sqrt{P_p}h_4} = x_p + \frac{n_{sr}}{\sqrt{P_p}h_4}$. In transmission phase 2, signal received at SR from ST is given by

$$y_{sr_2} = \sqrt{\alpha P_p\eta\rho\left|h_1\right|^2}h_3x_p + \sqrt{(1-\alpha)P_p\eta\rho\left|h_1\right|^2}h_3x_s + n_{sr} \tag{15}$$

The estimate $\widehat{x_p}$ is used to cancel the interference component from (15), to obtain $\widehat{y}_{sr_2} = \sqrt{(1-\alpha)P_p\eta\rho\left|h_1\right|^2}h_3x_s + n_{sr}$. The achieved rate between ST and SR, conditioned on successful decoding of x_p at both ST and SR in the first transmission phase, is given by

$$R_{sr} = \frac{1}{2}\log_2\left[1 + SNR_{sr}^{df}\right] \tag{16}$$

where, $SNR_{sr}^{df} = \frac{(1-\alpha)\eta\rho P_p\gamma_1\gamma_3}{\sigma_{sr}^2}$. Moreover, using (14) the rate achieved at SR in phase 1 is given by

$$R_{sd} = \frac{1}{2}\log_2\left[1 + \frac{P_p\gamma_4}{\sigma_{sr}^2}\right]. \tag{17}$$

Outage is declared if ST and SR are not able to decode x_p, and therefore the outage probability of the secondary signal transmission with target rate R_s is given as

$$P_s^{out} = 1 - P\left[R_{ir} > R_p\right]P\left[R_{sd} > R_p\right]P\left[R_{sr} > R_s\right]. \tag{18}$$

Using (17),

$$P\left[R_{sd} > R_p\right] = 1 - P\left[\gamma_4 < \frac{\psi_p\sigma_{sr}^2}{P_p}\right] = 1 - \frac{\Gamma(k, \frac{\psi_p\sigma_{sr}^2}{\theta_4P_p})}{\Gamma(k)}. \tag{19}$$

Using (16),

$$P\left[R_{sr} > R_s\right] = 1 - P\left[R_{sr} < R_s\right] = 1 - P\left[\gamma_1\gamma_3 < y\right]$$

where, $y = \frac{\psi_s\sigma_{sr}^2}{(1-\alpha)\eta\rho P_p}$ and $\psi_s = 2^{2R_s} - 1$. Therefore,

$$\begin{aligned} P\left[R_{sr} > R_s\right] &= 1 - \int_0^\infty f_{\gamma_1}(x)P(\gamma_3 \le y/x)dx \\ &= 1 - \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)}e^{-\frac{x}{\theta_1}}\Gamma\left(k, \frac{y}{x\theta_3}\right)dx. \end{aligned} \tag{20}$$

Substituting (6), (19) and (20) in (18), we obtain

$$\begin{aligned} P_s^{out} =& 1 - \left(1 - \frac{\Gamma(k, \frac{\psi_p\sigma_{ir}^2}{\theta_1(1-\rho)P_p})}{\Gamma(k)}\right)\left(1 - \frac{\Gamma(k, \frac{\psi_p\sigma_{sr}^2}{\theta_4P_p})}{\Gamma(k)}\right) \\ &\left(1 - \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)}e^{-\frac{x}{\theta_1}}\Gamma\left(k, \frac{y}{x\theta_3}\right)dx\right). \end{aligned} \tag{21}$$

(21), can be obtained in closed form using ([9], Eq.(7)),

$$P_s^{out} = 1 - \left(1 - \frac{\Gamma(k, \frac{\psi_p \sigma_{ir}^2}{\theta_1 (1-\rho) P_p})}{\Gamma(k)}\right) \left(1 - \frac{\Gamma(k, \frac{\psi_p \sigma_{sr}^2}{\theta_4 P_p})}{\Gamma(k)}\right) \left(1 - \frac{1}{(\Gamma(k))^2} G^{\,2\ 1}_{\,1\ 3}\left[\frac{y}{\theta_1 \theta_3}\middle|\,{}^{1}_{k,k,0}\right]\right) \quad (22)$$

where, G[.] is the Meijer G-function.

V. Simulation Results and Discussion

In this section, the simulation results for the outage probability of the primary and secondary system with the proposed scheme has been shown. For ease of analysis, all the nodes PT, SR, ST and PR are assumed to be collinear [8]. The distance between PT and PR is assumed to be 100 meters and ST is at distance d from PT. All other distances are defined with respect to d i.e. PT-SR, SR-ST and ST-PR have distance of $d/2$, $d/2$ and $(100 - d)$ respectively. Transmit power at PT, i.e. P_p is 30 dBm whereas noise variance at all receivers is -110 dBm. The path loss exponent (i.e. v) is 3 and the target rate for both systems is considered to be 1 i.e. $R_p = R_s = 1$. The results are shown for: a) two different values of *m* i.e. *m* = 0.5 (half Gaussian pulse), 1 (Rayleigh fading) b) two different values of ρ i.e. ρ = 0.25, 0.75 c) two different values of η i.e. η = 0.5, 1 and d) α = 0.8.

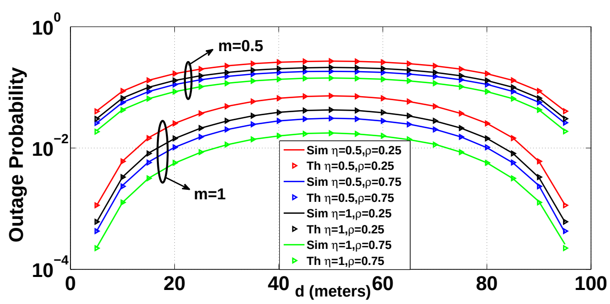

Fig. 2. Outage probability for Primary System

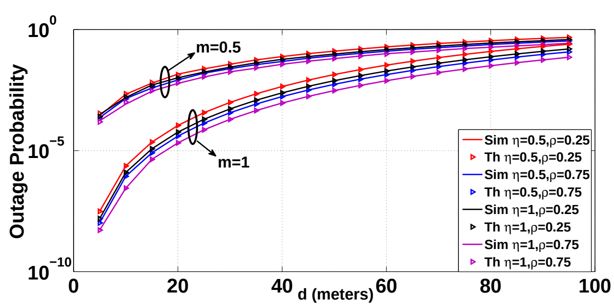

Fig. 3. Outage probability for Secondary System

In Fig. 2, the outage probability of primary system is plotted against d. From graph, we can observe that initially outage probability increases with d, however, when $d > 50$m it starts decreasing. This can be explained as follows: the total outage probability of primary system is the function of successful decoding of primary signal at ST in phase 1 as well as at PR in phase 2. As PT-ST has a distance of d and ST-PR has a distance of $(100-d)$, therefore when $d \leq 50$m, PT-ST is more dominant link, and hence with increasing d, the probability of successful decoding of primary signal at ST decreases. However, for $d > 50$m, ST-PR link is more dominant and as d increases, ST start moving closer to PR and outage decreases. Moreover, the performance for $\rho = 0.75$ is better than $\rho = 0.25$ i.e. performance improves if more power is given for harvesting rather than decoding at ST. However, any further increase in ρ (i.e. $\rho > 0.75$) will not have any significant impact on outage as less power will remain for decoding of primary signal at ST. Furthermore, as *m* increases, fading will become less severe, therefore outage probability decreases.

Similarly, Fig. 3 illustrates the outage probability of secondary system with respect to d. The trend observed in secondary system is quite different to that of primary system. This can be explained as follows. Since the outage probability of secondary system is dependent on the successful decoding of primary signal by ST and SR in phase 1 and also on successful decoding of secondary signal at SR in phase 2. Therefore, as d increases all corresponding links will start moving away from each other and hence outage will increase.

VI. Conclusion

In this letter, 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 obtained closed form expressions validated the theoretical analysis presented in the paper.

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