Power Management Strategies in Energy-Harvesting Wireless Sensor Networks

Saîd El Abdellaoui [1,2], Youssef Fakhri [2,3]

[1] LAPSSII, High School of Technology, Cadi Ayyad University, B.P. 89, Safi, Morocco
[2] LRIT, Unité Associée au CNRST (URAC 29), Faculty of Sciences, Mohammed V University - Agdal, Rabat, Morocco
[3] LARIT, équipe Réseaux et Télécommunications, Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco.

Abstract: Power management strategies are extremely important in Wireless Sensor Networks (*WSNs*). The objective is to make the nodes operate as long as possible. In the same context, in this article, our aim is to provide the optimal transmission power to maximize the network lifetime using the Orthogonal Multiple Access Channel (*OMAC*) in Harvesting System (HS). We consider that the nodes have direct communication with a Fusion Center (*FC*) with causal Channel Side Information (*CSI*) at the sender and receiver.

We begin the analysis by considering a single transmitter node powered by a rechargeable battery with limited capacity energy. Afterward, we generalize the analysis with *M* transmitter nodes. In both cases, the transmitters are able to harvest energy from nature.

Eventually, we show the viability of our approach in simulations results.

Keywords: *WSN*, Energy-Efficiency, Harvest Energy, Orthogonal Multiple Access Channel, Lifetime, Optimal Power Allocation.

1. Introduction

Wireless Sensor Network (WSN) is composed of a large number of nodes distributed randomly in an area of interest that are deployed for environmental sensing, monitoring. Traditionally, a node is primarily powered by a non-rechargeable battery with a limited energy storage capacity [1-4]. Therefore, maximizing network lifetime is essential for ensuring the operation of the nodes as long as possible.

Several studies have addressed the problem of maximizing network lifetime for this kind WSN. Therefore, various approaches can be exploited to reduce the energy consumption [7]-[11].

According to the experimental measurements made by Li et al. [7], an optimal scheduling algorithm is proposed to minimize the data packet loss in the overall network with a fixed sink. While the authors, in [8], show that the energy-efficiency can be achieved through network processing (data aggregation) which consists to reduce the data amount to be transmitted to the sink. In [9], Sabet and Naji proposed a new clustering algorithm by building an optimal routing tree with the lowest transmission cost and showed that equilibrating intra-cluster and inter-cluster power consumption among Cluster Heads, avoid Cluster Head premature death near Base Station.

Zhuo et al demonstrate that Duty-cycle mechanisms can help to reduce the energy wastage, but they need to be designed carefully to be adaptive with low latency. Considering the power optimization in Incremental Redundancy (IR) based on Hybrid Automatic Repeat Request (HARQ) schemes, the authors [11], minimize the packet drop probability (PDP) under a total average transmit power constraint.

In [12], the authors have proposed a heuristic solution schema to resolve processing time, energy and computing resources optimization, at the same time, in MEC.

Conventional batteries cannot hold enough energy for the lifetime of the system which requires periodic replacement. Consequently, energy harvesting systems capture recently appears to collect the energy from nature to feed the battery such as solar, wind, and vibrations [5,6].

The recent works show that can greatly extend the lifetime of those rechargeable battery-powered nodes. This last requires specific design concepts, unlike traditional WSN, in order to efficiently use the dynamic energy levels instantly available. In other words, power allocation for these systems should take into account the battery charging process for nodes and maximum battery capacity.

Several contributions in the literature have considered the use of energy harvester as an energy source [13]-[22].

In [11] the authors optimize the harvesting duration to improve throughput using Nakagami fading channels with an uninformed fade figure. Power allocation has been studied in [13,14] to improve the throughput Multi-hop relaying as well as multiple inputs multiple outputs (MIMO) with EH has been suggested to benefit from spatial diversity [15]. The security aspect of EH systems has been investigated in [16] they maximize the achievable secrecy rate by jointly optimizing the distribution of energy for source and destination in [17].

The authors demonstrate that The Application of MIMO in non-orthogonal multiple access can improve the wireless energy transfer efficiency by beamforming and maximize also the throughput in [18,19].

Furthermore, the energy efficiency is also a key issue for routing protocols for WSN. In [22] the authors proposed a new routing optimal algorithm which improves the network lifetime, while satisfying the QoS requirements of networks, compared to the existing routing protocols.

The throughput maximization problem by a deadline is treated in [23] in a static channel conceding the energy harvesting nodes with finite energy storage capacity batteries.

In [24] the dynamic programming framework is used to calculate the optimal online policy for sensors with different energy budgets.

In our work, we focus on the problem of finding the optimal transmission policy for maximizing network lifetime for the energy-harvesting wireless sensor networks taking into account a set of constraints.

The remainder of this paper is organized as follows. Section 2 defines the terms used throughout the paper and presents the mathematical problem formulation. Section 3 discusses the experimental results whereas section 4 concludes the paper.

2. Power Management Strategies

2.1. Background and definitions

In this section, we define the terms used throughout this paper. We assume *M* sensors randomly dropping from an airplane in the area of interest (Figure 1). We consider that sensors transmit their data over Quasi-Static Rayleigh Fading Channels (QSRC) where the nodes have Channel State Information (CSI). All nodes have direct access to the FC using the Orthogonal Multiple Access Channel (OMAC). This channel type is based on the standard strategy of Time Division Multiple Access (TDMA) [26]. The temporal space is divided between all the transmitters, and the transmission can then be made on the same frequency band as it is alternately used by different transmitters. However, issuers must be synchronized to not use the channel at the same time.

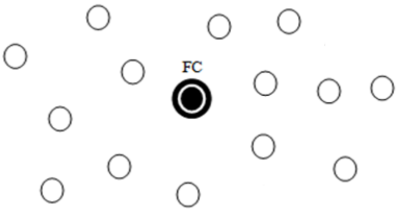

Figure 1: The area of interest

The source signal θ is collected by the *i-th* sensor with an Additive Complex Gaussian Noise $n_i \sim \mathcal{CN}(0,\sigma_{it}^2)$ where:

$$x_i = \theta + n_i \quad (1)$$

After, the observation x_i is amplified by w_i to be transmitted to the FC. Note that transmission power is written as $p_i = w_i^2\,(1+\sigma_{it}^2)$ assuming that $E[\theta^2] = 1$ where $E[:]$ is the mathematical expectation operator.

We assume that the channel condition measure is every T second and the number of transmissions before the network lacking in energy is N (the first node gets depleted). In the other hand, our objective is to maximize the network lifetime that is formulated as follows [28]:

$$L = N * T \quad (2)$$

We consider that the channel conditions are measured every second (T=1). Consequently, to maximize the network lifetime (L) it is adequate to maximize the number of transmissions.

On the other hand, the nodes are able to collect the energy of nature as long as the communication takes place in order to reload their batteries.

We assume that the fading levels change in different time instants which are indexed $\{t_1^h, t_2^h, \dots, t_n^h\}$ and the energy arrivals occur in $\{t_1^{En}, t_2^{En}, \dots, t_n^{En}\}$. Note that $h_i^{(j)}$ is the fading level in $[0, t_j^h]$ and $E_i^{(j)}$ arrivals energy amount in t_j^{En} for the sensor i (Figure 2). In addition, $h_i^{(j)}$ and $E_i^{(j)}$ are stochastic processes in time following Poisson Distribution with rates λ_h and λ_e, respectively.

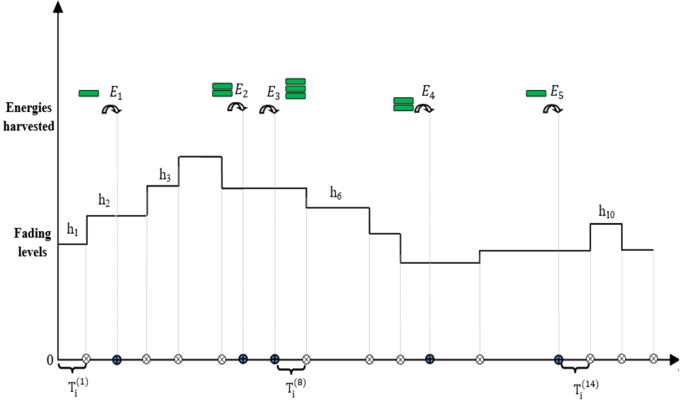

Figure 2: Fading levels and energy arrivals

To simplify, we note an epoch $T_i^{(j)}$ a time interval where a change is made, either at the fading channel level or the energy arrival for each sensor. In other words, $T_i^{(j)}$ is a time interval between two consecutive events.

Our analysis starts with a Single transmitter with a rechargeable battery (Figure 3) and is then extended to a multi-transmitter (Figure 4).

2.2. Single transmitter with rechargeable battery

Firstly, we consider the optimal power allocation problem for WSN with a rechargeable battery node where a single sensor transmits the noisy observation to the FC. We suppose that a Linear Minimum Mean Square-Error (LMMSE) detector is used at the receiver and the nodes have Channel State Information (CSI).

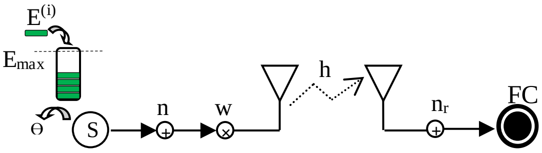

Figure 3: System Model (Single transmitter)

We suppose that the node S are able to collect the energy from their environment as long as the communication takes place. This energy ($E^{(j)}$) is stored in the battery of the refillable transmitter for later use.

2.2.1. System Model

The received signal at the FC is defined by:

$$y = h\,w\,(\theta + n) + n_r \quad (3)$$

Where h is the channel coefficient of the wireless link between the sensor S and FC and is known in the transmitter sensor; n_r is the noise component in the reception, and is assumed as additive complex Gaussian noise, with power spectral density given by σ_r^2 [28]. To control the transmission power for sensor S, we must take into account three constraints.

Constraint 1:

There is a sturdy relationship between the lifetime and the Quality of Service (QoS) in WSNs. Therefore, it is essential to integrate QoS into our lifetime definition. We allow for the quality constraint defined as the estimation of the SNR at the FC being greater or equal than a target value γ [28].

We express the SNR in terms of transmission power [31], we obtain:

$$SNR = \frac{p\,|\,h\,|^2}{\sigma_t^2 p|\,h\,|^2 + (1+\sigma_t^2)\sigma_r^2} \quad (4)$$

Constraint 2:

Due to the arrival of energy at random times, the second constraint on the power management policy is as follows:

$$\int_0^{t_j^{En}} p(u)du \leq \sum_{k=0}^{j-1} E^{(k)} \qquad \forall j \quad (5)$$

Where $E^{(0)}$ is the amount of energy available at the beginning for the sensor S. Supposing that the transmission power remains constant during each epoch $T^{(k)}$ the last equation can be writing as follows:

$$\sum_{k=1}^{l} T^{(k)} p^{(k)} \leq \sum_{k=0}^{l-1} E^{(k)} \quad \forall l \leq N \qquad (6)$$

Where $p^{(j)}$ is the transmission power for the sensor S in the *kth* period.

Constraint 3:

We assume that the storage battery capacity is limited. In this case, we must ensure that the energy level in the battery does not exceed the value E_{max} in times of energy arrival.
Then, the third constraint on the power management policy is as follows:

$$\sum_{k=0}^{l-1} E^{(k)} - \sum_{k=1}^{l} T^{(k)} p^{(k)} \leq E_{max} \quad \forall l \leq N \ (7)$$

After having quoted and determined the formulation of different constraints, it is time to formulate the problem mathematically.

2.2.2. Formulation Problem

The formulation of our problem, taking into account these last constraints, is:

$$\begin{cases} \qquad \qquad Max\ N \\ S.t \quad E\left[SNR^{(k)}\ \right] \geq \gamma\ k = 1, \dots \dots, N;\ p^{(k)} \geq 0 \\ \qquad \sum_{k=1}^{l} T^{(k)} p^{(k)} \leq \sum_{k=0}^{l-1} E^{(k)}\ \forall l \leq N \qquad (8) \\ \qquad \sum_{k=0}^{l-1} E^{(k)} - \sum_{k=1}^{l} T^{(k)} p^{(k)} \leq E_{max} \end{cases}$$

Using the weak law of large numbers [10], $E\left[SNR^{(k)}\ \right] \geq \gamma$ became $\sum_{k=1}^{N} SNR^{(k)} \geq N\gamma$ where γ is the average SNR at the FC over the network lifetime, given by:

$$\gamma \triangleq E\left[\frac{p\,|\,h\,|^2}{\sigma_t^2\, p\,|\,h\,|^2 + (1+\sigma_t^2)\sigma_r^2}\right] (9)$$

Maximizing the network lifetime is adequate to minimize the transmission power. Then, the formulation of our problem is becomes as follows:

$$\begin{cases} \qquad Min \sum_{k=1}^{N} P^{(k)} \\ S.t \ \sum_{k=1}^{N} SNR^{(k)} \geq N\gamma, P^{(k)} \geq 0 \\ \quad \sum_{k=1}^{l} T^{(k)} p^{(k)} \leq \sum_{k=0}^{l-1} E^{(k)} \\ \sum_{k=0}^{l-1} E^{(k)} - \sum_{k=1}^{l} T^{(k)} p^{(k)} \leq E_{max} \quad (10) \end{cases}$$

As can be seen, the set of constraints is convex. Therefore, the above equation (10) is a convex optimization problem with a unique solution. To find this last, we consider the Lagrangian method as an optimization method for this class of problem which is written as follows.

$$\begin{aligned} \mathcal{L}\,(p,\alpha,\beta,\lambda,\delta) = & \sum_{k=1}^{N} P^{(k)} - \sum_{k=1}^{N} \alpha^{(k)}\, P^{k} \\ & + \beta\left[N\gamma - \sum_{k=1}^{N} \frac{P^{(k)}|h^{(k)}|^2}{\sigma_t^2\, P^{(k)}|h^{(k)}|^2 + (1+\sigma_t^2)\sigma_r^2}\right] \\ & + \sum_{j=1}^{N} \lambda^{(j)} \left(\sum_{k=1}^{j} T^{(k)} p^{(k)} - \sum_{k=0}^{j-1} E^{(k)}\right) \\ & + \sum_{j=1}^{N-1} \delta^{(j)} \left[\sum_{k=0}^{j-1} E^{(k)} - \sum_{k=1}^{j} T^{(k)} p^{(k)} - E_{max}\right] (11) \end{aligned}$$

Then,

$$\begin{aligned} \frac{\delta\mathcal{L}\,(p,\alpha,\beta,\lambda,\nu)}{\delta P^{(l)}} = & \ 1 - \alpha^{(l)} \\ & - \beta\left[\frac{|h^{(l)}|^2(1+\sigma_t^2)\sigma_r^2}{[\sigma_t^2\, P^{(l)}|h^{(l)}|^2 + (1+\sigma_t^2)\sigma_r^2]^2}\right] \\ & + T^{(l)} \sum_{j=l}^{N} \lambda^{(j)} - T^{(l)} \sum_{j=l}^{N-1} \delta^{(j)} = 0 \ \ (12) \end{aligned}$$

We consider that the channel conditions are measured every one second (T=1s), then,

$$\begin{aligned} & \left[\frac{|h^{(l)}|^2(1+\sigma_t^2)\sigma_r^2}{[\sigma_t^2\, P^{(l)}|h^{(l)}|^2 + (1+\sigma_t^2)\sigma_r^2]^2}\right] \\ & \qquad = \frac{1}{\beta}\left[1 - \alpha^{(l)} + \sum_{j=l}^{N} \lambda^{(j)} - \sum_{j=l}^{N-1} \delta^{(j)}\right] (13) \end{aligned}$$

Finally,

$$\begin{aligned} P^{(l)} = & \frac{1}{\sigma_t^2|h^{(l)}|^2}\left[\sqrt{\frac{\beta|h^{(l)}|^2(1+\sigma_t^2)\sigma_r^2}{1-\alpha^{(l)} + \sum_{j=l}^{N} \lambda^{(j)} - \sum_{j=l}^{N-1} \delta^{(j)}}}\right. \\ & \left. \qquad - (1+\sigma_t^2)\sigma_r^2 \right]^{+} \ (14) \end{aligned}$$

Where $[x]^{+} = max\{x, 0\}$.
Satisfying the KKT conditions [31], we find $\alpha^{(l)} = 0$ and $\beta > 0, \lambda^{(j)}, \delta^{(j)} \geq 0$. Then,

$$P^{(l)} = \frac{1}{\sigma_t^2}\phi^{(l)}\left[\tau^{(l)} - \phi^{(l)}\right]^{+} \ (15)$$

Note that $\phi^{(l)} = \sqrt{\frac{(1+\sigma_t^2)\sigma_r^2}{\left|h^{(l)}\right|^2}}$ and $\tau^{(l)} = \sqrt{\frac{\beta}{1+\sum_{j=l}^{N} \lambda^{(j)} - \sum_{j=l}^{N-1} \delta^{(j)}}}$

2.3. Multi-transmitters with a rechargeable battery (Generalized)

In this subsection, we consider the same assumptions as in the previous subsection where we generalize the process by considering M transmitters nodes (Figure 4).

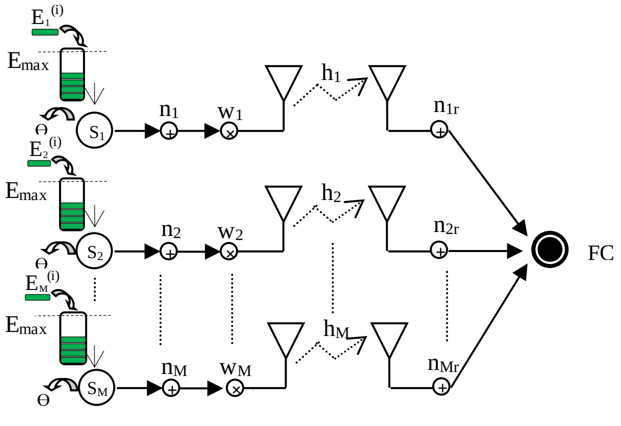

Figure 4: System Model (Multi-transmitter)

2.3.1. System Model

We use the orthogonal channels between the FC and each sensor. Then, the received signal at the FC is defined by:

$$y = \sum_{i=1}^{M} h_i w_i(\theta + n_i) + n_{ir} \qquad (16)$$

Where h_i is the channel coefficients of the wireless link between the sensor i and FC; n_{ir} is the noise component in the reception for the sensor i, and is assumed as additive complex Gaussian noise, with power spectral density given by σ_{ir}^2. We suppose that $|h_i|$ has a Rayleigh distribution where σ_{hi}^2 is known.

$$f(|h_i|) = \frac{|h_i| e^{\frac{-|h_i|^2}{2\sigma_{hi}^2}}}{\sigma_{hi}^2}$$

The use of the OMAC enables us to decompose our problem into a series of optimization problems for each sensor. To control the transmission power of each sensor, we must take into account those constraints.

Constraint 1:

Our goal is minimizing power consumption with regards to the estimation of overall SNR quality at FC. Since we use the orthogonal channels, the average SNR at the FC is the sum of all the required SNRs from each sensor which can be written as follows:

$$SNR = \sum_{i=1}^{M} SNR_i = \sum_{i=1}^{M} \left[\frac{p_i \mid h_i \mid^2}{\sigma_{it}^2 p_i \mid h_i \mid^2 + (1 + \sigma_{it}^2)\sigma_{ir}^2} \right] \quad (17)$$

Constraint 2:

The second constraint on the power management policy is as follows.

$$\int_0^{t_j^{En}} p_i(u)du \le \sum_{k=0}^{j-1} E_i^{(k)} \qquad \forall i, j \quad (18)$$

Where $E_i^{(0)}$ is the amount of energy available at the beginning for the *i-th* sensor. Since the transmission power remain constant during each epoch $T_i^{(j)}$ $\forall i$ the last equation can be writing as follows:

$$\sum_{j=1}^{l} T_i^{(j)} p_i^{(j)} \le \sum_{j=0}^{l-1} E_i^{(j)} \qquad \forall l, i \quad (19)$$

Where $p_i^{(j)}$ the transmission power for the *i-th* sensor for the *j-th* period.

Constraint 3:

The third constraint is ensuring that the energy level in the battery does not exceed the value E_{max} in times of energy arrival.

$$\sum_{j=0}^{l-1} E_i^{(j)} - \sum_{j=1}^{l} T_i^{(j)} p_i^{(j)} \le E_{max} \qquad \forall l, i \quad (20)$$

Our ultimate goal is to develop an algorithm that determines the transmission power versus time using causal knowledge of the system, namely, the state of instant energy, fading channel level, and quality of service required.

2.3.2. Formulation Problem

We assume M sensors randomly dropping from an airplane in the area of interest. The formulation of our problem is as follows:

$$\begin{cases} Min \displaystyle\sum_{i=1}^{M} \sum_{k=1}^{N} P_i^{(j)} \\ S.t \ E\left[\displaystyle\sum_{i=1}^{M} SNR_i^{(j)}\right] \ge \gamma;\ P_i^{(j)} \ge 0;\ j = 1, .., N \\ \displaystyle\sum_{j=1}^{l} T_i^{(j)} p_i^{(j)} \le \sum_{j=0}^{l-1} E_i^{(j)} \qquad \forall i \\ \displaystyle\sum_{j=0}^{l-1} E_i^{(j)} - \sum_{j=1}^{l} T_i^{(j)} p_i^{(j)} \le E_{max} \quad l = 1, \dots, N, \forall i \end{cases} \quad (21)$$

the $SNR_i^{(j)}$ is corresponding to the i-th sensor during the j-th transmission period.

We decompose our problem into a series of optimization problems. In other hand, we search to provide the optimum power consumption for each sensor independently. Using the weak law of large numbers also, we can rewrite the problem as [28]:

$$\begin{cases} Min \displaystyle\sum_{k=1}^{N} P_i^{(k)} \\ S.t \ \displaystyle\sum_{i=1}^{N} SNR_i^{(k)} \ge N\gamma_i \\ P_i^{(k)} \ge 0 \\ \displaystyle\sum_{j=1}^{l} T_i^{(j)} p_i^{(j)} \le \sum_{j=0}^{l-1} E_i^{(j)} \\ \displaystyle\sum_{j=0}^{l-1} E_i^{(j)} - \sum_{j=1}^{l} T_i^{(j)} p_i^{(j)} \le E_{max} \quad \forall l \end{cases} \quad (22)$$

As can be seen, that brings us to the previous section. Then, we use the Lagrangian method as an optimization method which is written as follows.

$$\begin{aligned} \mathcal{L}(p, \alpha, \beta, \lambda, \delta) = & \sum_{k=1}^{N} P_i^{(k)} - \sum_{k=1}^{N} \alpha_i^{(k)} P_i^k \\ & + \beta_i \left[N\gamma_i - \sum_{k=1}^{N} \frac{P_i^{(k)} |h_i^{(k)}|^2}{\sigma_{it}^2 P_i^{(k)} |h_i^{(k)}|^2 + (1 + \sigma_{it}^2)\sigma_{ir}^2} \right] \\ & + \sum_{j=1}^{N} \lambda^{(j)} \left(\sum_{k=1}^{j} T_i^{(k)} p_i^{(k)} - \sum_{k=0}^{j-1} E_i^{(k)} \right) \\ & + \sum_{j=1}^{N-1} \delta^{(j)} \left[\sum_{k=0}^{j-1} E_i^{(k)} - \sum_{k=1}^{j} T_i^{(k)} p_i^{(k)} - E_{max} \right] \quad (23) \end{aligned}$$

We follow the same procedure as the previous section, we obtain,

$$P_i^{(l)} = \frac{1}{\sigma_{it}^2 |h_i^{(l)}|^2} \left[\sqrt{\frac{\beta_i |h_i^{(l)}|^2 (1 + \sigma_{it}^2)\sigma_{ir}^2}{1 - \alpha_i^{(l)} + \sum_{j=l}^{N} \lambda^{(j)} - \sum_{j=l}^{N-1} \delta^{(j)}}} - (1 + \sigma_{it}^2)\sigma_{ir}^2 \right]^+ \quad (24)$$

Where $(x)^+ = max\{x, 0\}$. Satisfying the KKT conditions, we find $\alpha_i^{(l)} = 0$ and $\beta_i > 0$, $\lambda^{(j)}, \delta^{(j)} \ge 0$. Then,

$$P_i^{(l)} = \frac{1}{\sigma_{it}^2} \rho_i^{(l)} \left[\tau_i^{(l)} - \rho_i^{(l)}\right]^+ \quad (24)$$

Note that $\rho_i^{(l)} = \sqrt{\frac{(1+\sigma_{it}^2)\sigma_{ir}^2}{\left|h_i^{(l)}\right|^2}}$ and $\tau_i^{(l)} = \sqrt{\frac{\beta_i}{1+\sum_{j=l}^{N} \lambda^{(j)} - \sum_{j=l}^{N-1} \delta^{(j)}}}$

If $\delta^{(j)} = 0$ is equivalent to $E_{max_i} = \infty$, in this case $\tau_i^{(l)}$ is monotonically increasing. If $\delta^{(j)} = \tau_i^{(l)} = 0$ is equivalent to the sensors have a non-rechargeable battery.

We define our new algorithm in order to generate the transmission power which satisfies all conditions. The candidate solution is a member of a set of possible solutions that satisfies all constraints. The space of all candidate solutions is called feasible region.

Considering that the transmission power can only change when a new energy quantity arrives, or the status of channel changes and that the energy level in the battery never goes beyond battery capacity E_{max}.

We define two transmission powers sets $\left\{p_{min_i}^{(1)}, \ldots, p_{min_i}^{(n)}\right\}$ and $\left\{p_{max_i}^{(1)}, \ldots, p_{max_i}^{(n)}\right\}$ where $p_{min_i}^{(l)}$ and $p_{max_i}^{(l)}$ are the lower and upper boundary power levels in $T_i^{(n)}$. We can define the set P_i as $\{P_i^{(1)}, \ldots, P_i^{(n)}\}$ with $P_i^{(l)} = [p_{min_i}^{(l)}, p_{max_i}^{(l)}]$ where

$$p_{min_i}^{(l)} = \frac{\left(\sum_{j=0}^{l} E_i^{(j)} - E_{max_i}\right)^+}{T_i^{(l)}} \quad (25)$$

$$p_{max_i}^{(l)} = \frac{\sum_{j=0}^{l-1} E_i^{(j)}}{T_i^{(l)}} \quad (26)$$

Figure 5 presents the feasible region or the tunnel of transmission power required. The upper wall represents the cumulative energy harvested $\sum_{j=0}^{l-1} E_i^{(j)}$ which presents the upper limit of the total emission energy that can be spent. In the same way, the bottom wall is offset downwards by an amount of E_{max_i} of the upper wall: $\sum_{j=0}^{l} E_i^{(j)} - E_{max_i}$. This wall presents the lower limit of the total emission energy that can be spent, otherwise it will cause Overtake the capacity of the battery. Between these walls a region which present the solution to our system namely feasible region (FR).

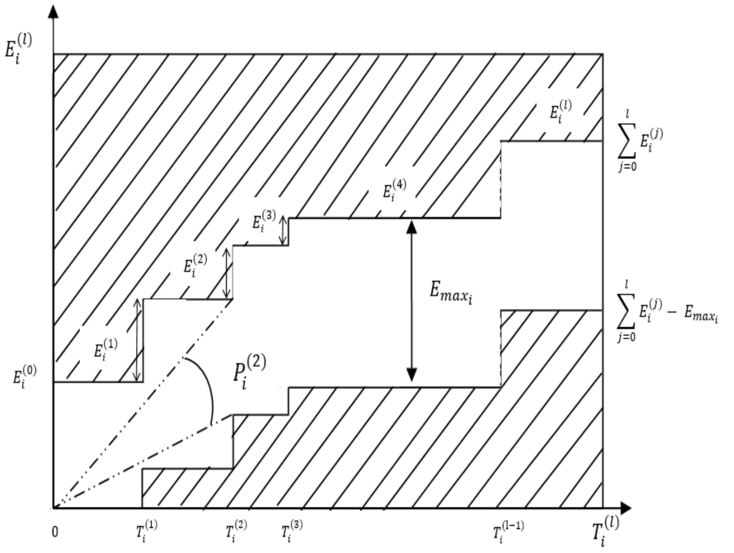

Figure 5: Tunnel of transmission power required

The required power consumption P_i must be full located inside the tunnel which forms a continuous curve. For simply, instead to test all of the infinite number of points in the feasible region it is only sufficient to consider the corner points. Therefore, in figure, the $p_{min_i}^{(l)}$ and $p_{max_i}^{(l)}$ correspond to the lines slopes passing through the origin and to each corner point in FR. For example, range $P_i^{(2)}$ is marked by an arc. In our algorithm, we use our solution (29) to calculate the optimal power, after we ensure that this power between $p_{min_i}^{(l)}$ and $p_{max_i}^{(l)}$.

3. Simulations

To evaluate the performance of our new algorithm, we compare our Optimal Power Allocation algorithm with Rechargeable Batteries (OPA-RB) with three other methods, namely the Equal Power Allocation (EPA) method wherein the power is allocated to each sensor based on its residual energy [29], the Partially Observable Markov Decision Process (POMDP) where the nodes are assumed to have prior information about the arrival of harvested energy [30] and Optimal Power Allocation with Non-Rechargeable batteries (OPANR) [28]. It is noted that the simulations have been performed using MATLAB.

The simulation parameters summarized in the table above are generated randomly by following a uniform distribution between ψ and φ (U [ψ, φ]).

Table 1: Simulations parameters

Estimate	Parameters
U[0.1,0.4]	σ_{hi}^2: The variances of channel estimation
U[0.02,0.2]	σ_{it}^2: The observation noise variances
U[0.2, 0.4]	σ_{ir}^2: The noise variances at the FC
U[400, 500]	E_{int} : The initial energy
U[50, 100]	$E_i^{(k)}$:The energy Quantity arrivals

In the first, we begin by th evaluation of the proposed method with single-transmitter using a rechargeable battery.

According to our simulations that are carried using MATLAB, we constate that our new method is more effective than the other methods concerning network lifetime (Figure 6). The batteries lifetime duration is extended by an average of 37.14% compared to EPA method and 39.13% compared to OPANR method and 92.01% compared to POMDP.

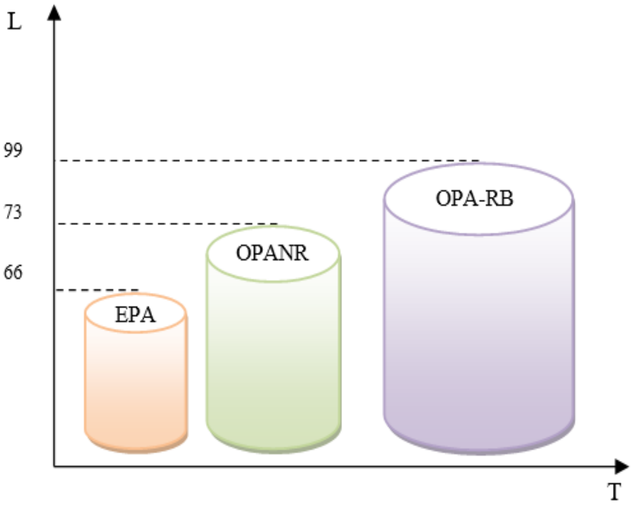

Figure 6: Comparison between our OPA-RB method and the PEA, OPANR methods concerning the network lifetime (Single-transmitter).

In the second, we evaluate the proposed method with Multi-transmitters using a rechargeable battery. Figure 7 illustrates the behavior of the network lifetime while increasing the number of nodes. As it can be seen, the suggested method increases the network lifetime by an average up to 187.80% compared to the results obtained of the other two methods using a rechargeable battery or even six times longer lifetime with the no-recharge battery method.

Indeed, the curves show that the network lifetime is plainly extended when the sensors number exceeds 50 nodes. Whereas less than 5 sensors, the extension of network lifetime is lower.

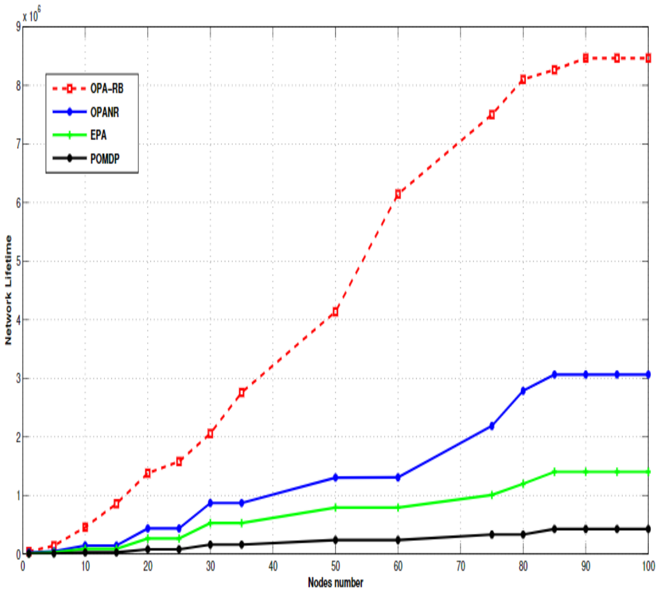

Figure 7: Comparison between our OPA-RB method and the PEA, OPANR and POMDP methods concerning the network lifetime (Multi-transmitters).

Previously, we have considered network lifetime is defined as the transmissions number before the first node gets depleted. In this sub-section, the network lifetime is defined as the transmissions number in the network until the exhaustion of the last node. Figure 8 illustrates the transmissions number until the last node gets depleted. The batteries lifetime duration is extended by an average of 222.03% compared to POMDP method and 493.81% compared to EPA method.

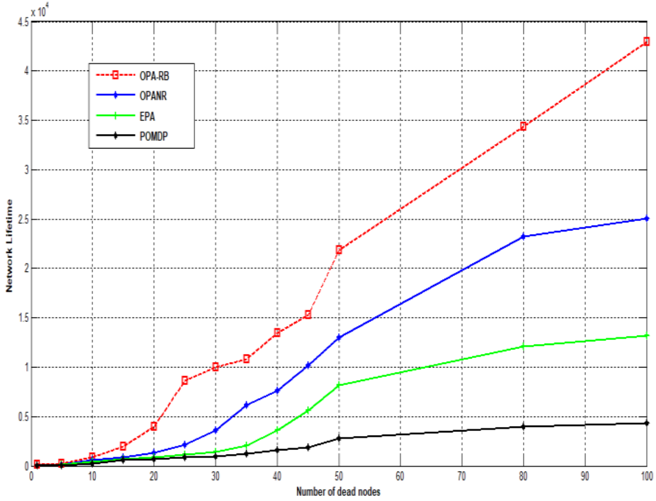

Figure 8: Comparison between our OPA-RB method and the PEA, OPANR and POMDP methods concerning the network lifetime until the last node gets depleted.

4. Conclusion

In this paper, we proposed a new algorithm in order to maximize the network lifetime for the energy harvesting system. The results showed that our algorithm OPA-RB achieved a much higher Lifetime than the others algorithm. Future work will concern the application of our method to a multi-hop model using a Non-Orthogonal Multiple Access Systems (NOMAS) with Partial Channel Information (PCI).

References

[1] Yetgin, Halil, et al. "A survey of network lifetime maximization techniques in wireless sensor networks," IEEE Communications Surveys & Tutorials, Vol.19 No.2 pp. 828-854.2017

[2] Khedikar, Rakhi, kapur, avichal, et survanshi, yogesh. “maximizing a lifetime of wireless sensor network by scheduling,” International Journal of Computer Science and Telecommunications, Vol. 2, No 8, pp. 1-6, 2011.

[3] Jin Ke-yin, Zhang Yao and Tian De-run, "Based on the Improvement of LEACH Protocol for Wireless Sensor Network Routing Algorithm," Second International Conference on Intelligent System Design and Engineering Application, pp. 1525 – 1528, 2012.

[4] Abdellaoui, S. E., Y. Fakhri, and D. Aboutajdine. "Optimum power allocation for Amplify-and-Forward cooperation strategy in WSN," Second International Conference on the Innovative Computing Technology (INTECH 2012). p. 230-234, 2012.

[5] Esu, Ozak O., et al. "Feasibility of a fully autonomous wireless monitoring system for a wind turbine blade." Renewable Energy Vol. 97 No 4, pp. 89-96, 2016

[6] Wan, Z. G., Y. K. Tan, and C. Yuen. "Review on energy harvesting and energy management for sustainable wireless sensor networks," 2011 IEEE 13th international conference on communication technology. IEEE, pp. 362-367, 2011.

[7] Li, Kai, et al. "Wireless power transfer and data collection in wireless sensor networks," IEEE Transactions on Vehicular Technology, Vol. 67, No 3, 2686-2697, 2017.

[8] Mohanty, Prabhudutta, and Manas Ranjan Kabat. "Energy efficient structure-free data aggregation and delivery in WSN," Egyptian Informatics Journal Vol. 17, No. 3, pp. 273-284, 2016.

[9] Sabet, Maryam, and Hamidreza Naji. "An energy efficient multi-level route-aware clustering algorithm for wireless sensor networks: A self-organized approach," Computers & Electrical Engineering, Vol. 56, pp. 399-417, 2016.

[10] Zhuo, Shuguo, et al. "Queue-MAC: A queue-length aware hybrid CSMA/TDMA MAC protocol for providing dynamic adaptation to traffic and duty-cycle variation in wireless sensor networks," 2012 9th IEEE International Workshop on Factory Communication Systems. IEEE, pp. 105-114. 2012.

[11] Chaitanya, Tumula VK, and Erik G. Larsson. "Optimal power allocation for hybrid ARQ with chase combining in iid Rayleigh fading channels," IEEE Transactions on Communications, Vol. 61, No.5, pp. 1835-1846, 2013.

[12] El Ghmary, Mohamed; Hmimz, Youssef; Chanyour, Tarik; Malki, Mohammed Ouçamah Cherkaoui.International Journal of Communication

Networks and Information Security; Kohat Vol. 12, No. 3, pp. 389-393, 2020.

[13] Babayo, Aliyu Aliyu, Mohammad Hossein Anisi, and Ihsan Ali. "A review on energy management schemes in energy harvesting wireless sensor networks," Renewable and Sustainable Energy Reviews, Vol. 76, pp. 1176-1184, 2017.

[14] Nadhir Ben Halima, and Hatem Boujemâa. "Wireless energy harvesting for Nakagami fading channels," International Journal of Sensor Networks, Vol. 33, No.2, pp. 55-62, 2020.

[15] Singh, Keshav, et al. "Toward optimal power control and transfer for energy harvesting amplify-and-forward relay networks," IEEE Transactions on Wireless Communications, Vol. 17, No.8, pp. 4971-4986, 2018.

[16] Fan, Rongfei, et al. "Throughput maximization for multi-hop decode-and-forward relay network with wireless energy harvesting," IEEE Access, Vol. 6, pp. 24582-24595, 2018.

[17] Huang, Yuzhen, et al. "Performance analysis of energy harvesting multi-antenna relay networks with different antenna selection schemes," IEEE Access, Vol 6, pp. 5654-5665, 2017.

[18] Nguyen, Tri Gia, et al. "Secrecy outage performance analysis for energy harvesting sensor networks with a jammer using relay selection strategy," IEEE Access, Vol. 6, pp. 23406-23419, 2018.

[19] Yao, Rugui, et al. "Secrecy rate-optimum energy splitting for an untrusted and energy harvesting relay network," IEEE Access, Vol. 6, pp. 19238-19246, 2018.

[20] Wang, Qiang, Hai-Lin Liu, and Fangqing Gu. "Relay node deployment for wireless sensor networks using evolutionary multi-objective algorithm," International Journal of Sensor Networks, Vol. 31, No. 3, pp. 189-197, 2019.

[21] Yang, Gang, Xinyue Xu, and Ying-Chang Liang. "Resource allocation in NOMA-enhanced backscatter communication networks for wireless powered IoT." IEEE Wireless Communications Letters, Vol. 9, No. 1, pp. 117-120, 2019.

[22] Nguyen, Thien Duc, Jamil Yusuf Khan, and Duy Trong Ngo. "A distributed energy-harvesting-aware routing algorithm for heterogeneous IoT networks," IEEE Transactions on Green Communications and Networking, Vol. 2, No 4, pp.1115-1127, 2018.

[23] Qian, Li Ping, Guinian Feng, and Victor CM Leung. "Optimal transmission policies for relay communication networks with ambient energy harvesting relays," IEEE Journal on Selected Areas in Communications Vol. 34, No 12, pp. 3754-3768, 2016.

[24] Ozel, Omur, et al. "Transmission with energy harvesting nodes in fading wireless channels: Optimal policies," IEEE Journal on Selected Areas in Communications Vol. 29, No. 8, pp. 1732-1743, 2011.

[25] Rakhi Khedikar, Avichal Kapur and Yogesh Survanshi, “Maximizing a Lifetime of Wireless Sensor Network by Scheduling,” in International Journal of Computer Science and Telecommunications, Vol. 2, No 8, pp. 1-6, 2011.

[26] Tumula V. K. Chaitanya and Erik G. Larsson, “Outage-Optimal Power Allocation for Hybrid ARQ with Incremental Redundancy,” IEEE Transactions on Wireless Communications, Vol. 10, No. 7, p. 2069-2074, 2011.

[27] J. P. Carmo, P. M. Mendes, C. Couto, and J. H. Correia, “A 2.4-GHz CMOS Short-Range Wireless-Sensor-Network Interface for Automotive Applications,” In IEEE Transactions on Industrial Electronics - IEEE TRANS IND ELECTRON , Vol. 57, No. 5, pp. 1764-1771, 2010.

[28] Abdellaoui, S. E., et al. "Increasing network lifetime in an energy-constrained wireless sensor network, " International Journal of Sensor Networks, Vol. 13, No. 1, pp. 44-56, 2013.

[29] Zhuo, W. U., and Hong-Bing Yang. "Power allocation of cooperative amplify-and-forward communications with multiple relays." The Journal of China Universities of Posts and Telecommunications, Vol. 18, No. 4, pp. 65-69, 2011.

[30] Mondal, Soumen, S. D. Roy, and Sumit Kundu. "Performance analysis of a cognitive radio network with adaptive RF energy harvesting," International Journal of Electronics Letters, pp. 1-14, 2019.

[31] Saîd, El, et al. "Maximizing Network Lifetime through Optimal Power Consumption in Wireless Sensor Networks," Image and Signal Processing, pp. 200-208, 2012.