Online Transmission Policy for Energy Harvesting Sensor Node with Energy Loss

Arpita Jaitawat, and Arun Kumar Singh

Abstract—**This letter considers a point-to-point data transmission scheme over a fixed number of slots where the energy harvesting transmitter operates in harvest-use-store (HUS) mode and an imperfect supercapacitor with storage loss and energy leakage loss is used as an energy storage device. For these settings, the dynamic programming (DP) method is known to achieve the optimal throughput, but the '*curse of dimensionality*' necessitates the search of schemes that allow for an improved performance-complexity trade-off. The work focuses on deriving a computationally efficient online transmission policy that achieves the optimal or near-optimal throughput. This letter presents a novel computationally efficient *uniform thresolding* based online transmission policy that achieves near-optimal throughput. The work also presents numerical results which demonstrate that the proposed policy with supercapacitor-based energy storage achieves better or the same performance as compared to the battery-based energy storage, thus allowing for a longer lifetime of sensor networks.**

Index Terms—**Energy harvesting, throughput maximization, Dynamic programming, uniform threshold, transmission policy**

I. INTRODUCTION

Energy harvesting (EH) has emerged as a prominent solution for continuous power supply to enhance the lifetime of wireless sensor networks (WSN), without the need to replenish the battery. But the limited charge-discharge cycles of battery limit the network lifetime. Over time, supercapacitor (SC) has emerged as a potential solution for improving the network lifetime because it can sustain a large number of charge-discharge cycles [1]. But the high self-discharge rate of SC brings in a critical aspect of *energy management*, where to improve the communication performance (throughput and efficiency), the EH device has to exploit the available resources correctly [2]. In this letter, the two imperfections considered for the SC are storage loss[1] and energy leakage[2] [3].

Most of the EH systems consider *harvest-use* (HU) and *harvest-store-use* (HSU) architecture [4]. The HSU architecture is justified for the system with an ideal energy storage device (ESD), but for imperfect ESD, HSU leads to loss of harvested energy. Thus for a system with lossy ESD, the energy-efficient *harvest-use-store* (HUS) architecture is preferred, where the harvested energy is primarily used for data transmission and the extra energy is stored into or used from the ESD [5].

For the maximization of mutual information, an opportunistic transmission policy that exploits the good channel and spreads the energy evenly throughout the communication duration is needed [6]. For an online scheduling model considering the statistical knowledge of fading channel and harvested energy, Dynamic Programming (DP) is the optimal online policy [7], where the process identifies the blocks for opportunistic transmission based on the expected future values stored as state space. The numerical solutions by DP are typically obtained with a high computational complexity, which is impractical for real implementation [8]. A low-complexity heuristic online approach is proposed in [7], with no performance guarantee. There is a need to determine a low complexity online transmission policy that can exploit channel fluctuation for the system's advantage by avoiding energy overflow in ESD.

This letter considers a point-to-point communication over K slots under channel fluctuations and energy variations for EH-WSN with imperfect SC of finite capacity working in HUS architecture. The proposed transmission policy determines the transmit energy based on the precalculated threshold values, which remain the same throughout the communication session, reducing the computational complexity. The quantitative comparison of the proposed scheme with the DP reflects a near-optimal performance with a significantly lower computational cost. The presented simulation results also establish the SC's suitability as ESD for EH sensor nodes, as SC achieves higher or comparable performance compared to a battery with a much longer life expectancy.

II. SYSTEM MODEL AND PROBLEM FORMULATION

Point-to-point data transmission between transmitter (Tx) and receiver (Rx) is considered over a finite session of K time slots (TS) with slot length of t_{bc} seconds, where the Tx sensor node operates in HUS mode, as shown in Fig. 1(a). The Tx power supply unit is modified and consists of an EH unit, a supercapacitor with maximum storage capacity S_{max}, and a decision device to schedule the energy between harvested energy and SC energy for data transmission. The SC is considered to be non-ideal with the storage efficiency, $\eta_{sc} < 1$ and a self-discharge rate, $\epsilon_{sc} > 0$. It is assumed that the total energy (i.e., harvested energy and the supercapacitor energy) is available for data transmission, considering the sensing and signal processing cost to be negligible. Also, it is assumed that data is always available for transmission so that we can only focus on the effect of the EH profile on the power transmission policy. The Tx is equipped with perfect causal channel state information (CSI) feedback to update channel fade level change.

Just like [5], the energy harvesting is modelled as a discrete process, where the amount of energy harvested $E_k \sim \mathcal{U}(0, 2P)$

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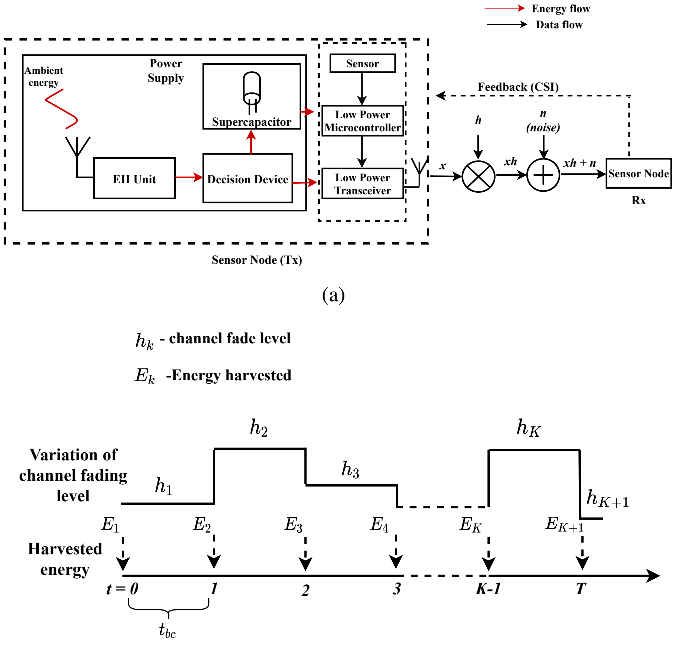
[1] Although loss occurs at both the charging as well as discharging time, but, from a mathematical point of view, both the imperfections are clubbed together as storage loss at the time of charging.

[2] When the charging and discharging times are small, the energy leakage happens due to charge redistribution.



(a)

(b)

Fig. 1. (a) System model for HUS energy harvesting communication system under fading channel with supercapacitor. (b) Fading channel and energy arrival in time duration T

is a uniform random variable with mean value P and is available for consumption at the starting of each k^{th} TS. Based on the harvested energy, SC operates in different modes, which can be defined by rectifier function $[D_k]^+$, where

$$[D_k]^+ = \begin{cases} D_k, & D_k \geq 0 \\ 0, & D_k < 0 \end{cases} \tag{1}$$

and $D_k = E_k - E_k^T$. E_k^T is the transmit energy in each k^{th} TS. If $D_k > 0$, SC operates in the charging mode and the TS is known as charging TS. Similarly, if $D_k < 0$ or $D_k = 0$, then the SC is in the discharging or neutral mode respectively, and the corresponding TS is known as discharging and neutral TS. Thus, the SC energy level at the end of each TS k is given by

$$S_k = S_0 + \eta_{sc}\sum_{i=1}^{k}[D_i]^+ - \sum_{i=1}^{k}[-D_i]^+ - \sum_{i=1}^{k}\epsilon_{sc}\sqrt{t_{bc}}, \forall k \in [1, K] \tag{2}$$

where S_0 represents the initial energy state of the SC, $\eta_{sc}\sum_{i=1}^{k}[D_i]^+$ and $\sum_{i=1}^{k}[-D_i]^+$ represents the amount of energy stored into and taken from the SC at the end of each TS k respectively, and $\sum_{i=1}^{k}\epsilon_{sc}\sqrt{t_{bc}}$ represents the total energy leakage at the end of each TS k.

Considering the HUS architecture and the randomness of the harvested energy, the consumption of energy from the SC is constrained by the energy profile. The first constraint states that the SC must meet the causality constraint i.e., the energy drawn from the SC cannot exceed the energy stored in the SC up to any TS, which can be written as

$$S_0 + \eta_{sc}\sum_{i=1}^{k}[D_i]^+ - \sum_{i=1}^{k}[-D_i]^+ - \sum_{i=1}^{k}\epsilon_{sc}\sqrt{t_{bc}} \geq 0, \forall k \in [1, K] \tag{3}$$

The second constraint is due to the maximum storage capacity of the SC, which states that at any TS k, the energy stored in SC cannot exceed S_{max}, which can be written as

$$S_0 + \eta_{sc}\sum_{i=1}^{k}[D_i]^+ - \sum_{i=1}^{k}[-D_i]^+ - \sum_{i=1}^{k}\epsilon_{sc}\sqrt{t_{bc}} \leq S_{max}, \forall k \in [1, K] \tag{4}$$

Therefore, the distribution and storage of energy are strictly to be controlled.

The channel between Tx and Rx is Rayleigh block fading, where the fading coefficient h_k remains constant for the k^{th} TS, as shown in Fig. 1(b).The received signal is given by

$$y_k = h_k x_k + n_k \tag{5}$$

where, x_k is the data transmitted in the k^{th} TS, $h_k \sim \mathcal{CN}(0, \sigma^2)$ is a circularly symmetric zero mean complex variable with variance σ^2 and $n_k \sim \mathcal{CN}(0, N_0)$ is a circularly symmetric complex variable with zero mean and unit variance ($N_0 = 1$). In this case an effective channel SNR is defined as $\gamma_k = |h_k|^2/N_0 = |h_k|^2$. During each TS, Tx encodes the bits to be transmitted into data symbols, ensuring that the block length of each symbol is large enough to guarantee reliability.

In this work, the objective is to allot energy E_k^T over K TS such that the overall rate is maximized, for which the optimization problem is given by [9]

$$\begin{aligned} \max_{E_k^T \geq 0} \quad & \mathcal{R} = \sum_{k=1}^{K} R_k = \sum_{k=1}^{K} t_{bc} log_2(1 + \frac{\gamma_k E_k^T}{t_{bc}}) \\ \text{s.t.} \quad & 0 \leq S_k \leq S_{max}, \forall k \leq K \end{aligned} \tag{6}$$

where $R_k = t_{bc} log_2(1 + \frac{\gamma_k E_k^T}{t_{bc}})$ is the achievable instantaneous rate in TS k.

III. ONLINE TRANSMISSION POLICY

The transmission policy where the Tx chooses the transmit energy value based on the harvested energy and channel state up to that point of time, i.e., causal information, is known as *online policy*. In this section, we discuss optimal online policy and develop an online policy with lower complexity.

A. Optimal Online Policy

The optimal online policy can be solved by dynamic programming, formulated using simplified Bellman equation [7]

$$\begin{aligned} V(S_{k-1}, E_k, \gamma_k, k) = & \max_{\phi} R(\phi(S_{k-1}, E_k, \gamma_k, k), \gamma_k) \\ & + \mathbb{E}[V(S_k, E_{k+1}, \gamma_{k+1}, k+1)] \end{aligned} \tag{7}$$

which means that taking action $e_k = \phi(S_{k-1}, E_k, \gamma_k, k)$, the system achieves a throughput $R(e_k, \gamma_k)$ in time slot k. The value function $V(S_{k-1}, E_k, \gamma_k, k)$, is the achieved throughput in time slot k and the expected future throughput of the system after time slot k. (7) can be computed using value iteration, where starting from $k = K$, optimal action e_K and value function $V(S_{K-1}, E_K, \gamma_K, K)$ are calculated, considering $V(S_K, E_{K+1}, \gamma_{K+1}, K+1) = 0$. These values are further used to calculate the optimal action and value function at $k = K - 1$ from (7), and the process is repeated for all $k = K -$

Algorithm 1 Proposed Uniform Thresholding based Transmission Policy

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Initialization: $\sigma$, $S_{max}$, $N_{opt}$, $K$, $t_{bc}$ and $x$
Determine the threshold values from equation (8).
Repeat for $k = 1 \rightarrow K$
    Determine the channel fade level position using Interpolation search method by (9), and allocate the transmit energy $E_k^T$ from equation (10).
    Calculate $R_k$.
end for
Calculate the average sum throughput $R$ (equation (6)).
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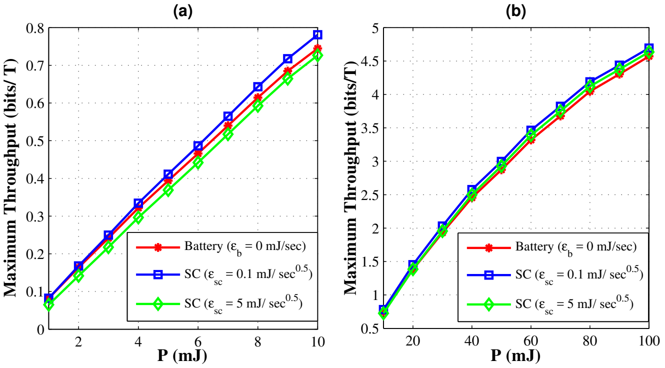

Fig. 2. Performance analysis of the battery (η_b = 0.8 and ϵ_b = 0 mJ/sec) and the two supercapacitors SC1 and SC2 (η_{sc} = 0.95, $\epsilon_{sc,1}$ = 0.1 mJ/$\sqrt{sec}$ and $\epsilon_{sc,2}$ = 5 mJ/$\sqrt{sec}$) for the proposed policy at different P.

$2, K-3, ..., 1$. The calculated values of $V(S_{k-1}, E_k, \gamma_k, k), \forall k$ are recorded as look-up table at the Tx. At each slot k, depending on γ_k and total available energy $E_k^{total} = S_{k-1} + E_k$, the Tx transmits with optimal energy E_k^T.

B. Proposed Online Policy

The high computational complexity of the DP solution burdens the sensor node with the requirement of substantial computation resources. Thus, it is natural to forgo performance for less complex online policies. In this subsection, a computationally efficient transmission policy that achieves near-optimal throughput performance is proposed. The proposed policy's objective is to decide the transmit energy at each TS k based on the channel fade state. To determine the channel fade state, N_{UP} threshold values are determined by dividing the x-sigma range for the exponentially distributed channel gain into partitions, such that the partition size is $\Delta(x, \sigma, N_{UP}) = \frac{(x+1)\sigma^2}{N_{UP}+1}$ and the threshold values are

$$\lambda_n = n * \Delta(x, \sigma, N_{UP}), \forall n \in [1, N_{UP}] \tag{8}$$

The next step is to find the position of γ_k in the uniformly distributed threshold values. This is done by rounding the position found by the optimal interpolation search method [10] to the nearest integer threshold index as

$$n = min\{N_{UP}, \lfloor 1 + \frac{(\gamma_k - \lambda_1)(1 - N_{UP})}{\lambda_{N_{UP}} - \lambda_1} \rfloor\} \tag{9}$$

Based on the value of n, the transmit energy is given as

$$E_k^T = \frac{n}{N_{UP}} * E_k^{total} \tag{10}$$

Note that the transmission is subject to energy availability and S_{max} constraint. The pseudo-code for the proposed policy is elucidated in Algorithm 1.

IV. NUMERICAL RESULTS

In this section, numerical results are presented to demonstrate the potential performance analysis of optimal and proposed policy for sensor node equipped with imperfect SC. The results are compared with imperfect battery equipped sensor nodes, to find out the suitability of SC as ESD. The analysis is carried out for the WSN application scenario with σ = 3 dB [11] and the energy is harvested from the RF sources where P = 1-100 mJ [12]. For ease of calculation t_{bc} is considered to be 1 sec. Also, N_{UP} = 25 is considered for the analysis. The sensor node is equipped with SC of maximum capacity S_{max} = 250 mJ with initial charge $S_0 = S_{max}$, operating voltage V = 2 Volt and the corresponding capacitance C = 125 mF. The imperfections of SC for the considered capacitance value are η_{sc} = 0.95 [13] and $\epsilon_{sc} \in$ [0.1 mJ/$\sqrt{sec}$-5 mJ/$\sqrt{sec}$] [14]–[16]. For analysis we consider two SC, one with low self-discharge rate (SC1 with $\epsilon_{sc,1}$ = 0.1 mJ/$\sqrt{sec}$) and the second with the maximum self-discharge rate (SC2 with $\epsilon_{sc,2}$ = 5 mJ/$\sqrt{sec}$). Also, for the battery, with the same maximum capacity as SC, η_b = 0.8 [17] and since the leakage rate is very low, ϵ_b = 0 mJ/sec is considered. Further, x = 2 is considered for $x-$sigma range as it considers 95% of channel realizations [18]. The results are simulated using Monte Carlo simulations. The DP solution is performed for N_{DP} discretized steps of $S_{max} + 2P$, where the step size ΔS is considered to be 0.5 mJ. Also, the energy state equation for battery can be used from [16].

The results for the throughput performance of the sensor node equipped with SC or battery at different values of P for the proposed policy are shown in Fig. 2. It can be analyzed that for lower values of P (Fig. 2(a)), the self-discharge rate for SC1 is so low that it does not affect the performance with η_{sc} dominating the performance. On the other hand, the self-discharge rate for SC2 is higher than the amount of energy harvested, resulting in a loss of energy. Thus, the performance of SC1 and SC2 is better and worse, respectively, as compared to a battery. With an increase in P (Fig. 2(b)), the effect of the self-discharge rate decreases, resulting in better performance for SC1 and SC2, as compared to the battery.

In Fig. 3(a), the performance of the proposed policy is compared with the optimal policy (DP) and state-of-the-art policy (double threshold method) [7] for SC1 at different values of P. The proposed policy gives a near-optimal performance compared to the sub-optimal policy, for all P values for the defined system parameter. The proposed policy's near-optimal performance can be supported by the transmit energy graph over the TS, as shown in Fig. 4.

From equation (2), it can be deduced that the amount of energy loss depends on t_{bc}, which affects the mutual information (equation (6)), as shown in Fig. 3(b). The analysis is carried out by increasing the t_{bc} for K = 10. For SC1,

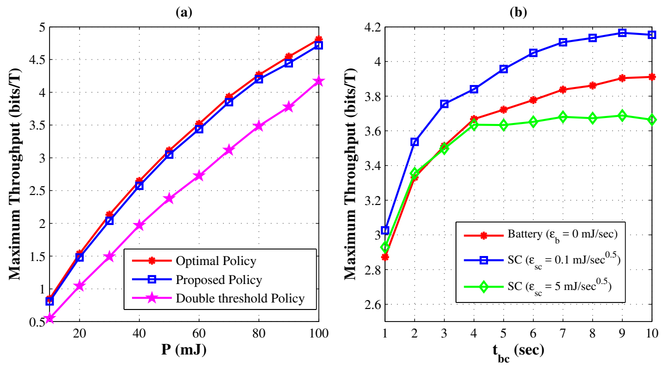

Fig. 3. (a) Performance comparison of the policies for SC1 ($\eta_{sc} = 0.95$ and $\epsilon_{sc,1} = 0.1$ mJ/$\sqrt{sec}$) at different values of P. (b) Performance comparison for sensor node equipped with SC1, SC2 or battery for different t_{bc} at $P =$ 50 mJ and $K = 10$ for proposed policy.

the self-discharge rate is negligible wrt the amount of energy harvested; as a result, the performance loss is negligible. On the other hand, the self-discharge rate is high for SC2, so the performance decreases with an increase of t_{bc}. But still, for SC2, the performance is equivalent to the performance of the battery-equipped sensor node.

The computational complexity of the optimal and the proposed policy depends on how the transmit energy is determined from the precalculated threshold values. In DP, $N_{DP}+1$ energy states are linearly searched to find the optimal transmit energy. Thus, the computational complexity to calculate sum-throughput over K time slots is given by $K * (N_{DP} + 1)$. On the other hand, for the proposed policy, the channel states are uniformly divided by N_{UP} threshold values, and the optimal interpolation method is used to find the transmit energy. Thus, the computational complexity to calculate sum-throughput over K time slots is given by $K * log(log(N_{UP} + 1))$. Since $N_{DP} + 1 >> log(log(N_{UP} + 1))$, the proposed policy is less complex as compared to the optimal policy.

V. CONCLUSION

A low complexity energy management scheme for an online scheduling energy harvesting system is developed to solve the mutual information maximization problem. The numerical results show that the supercapacitor displays better or equivalent performance than the battery as an ESD because of high storage efficiency despite the high self-discharge rate. Also, it can be analyzed that the proposed transmission policy performs close to the optimal policy, with a significant decrease in the computational complexity as compared to the optimal policy. Thus, the sensor node equipped with a supercapacitor as an energy storage device and employing the proposed policy is a better choice for energy harvesting low power sensor nodes to improve sensor node lifetime.

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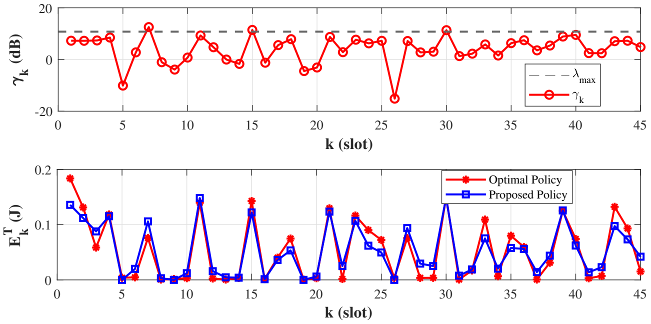

Fig. 4. Trajectory of system parameters : Top: γ_k; Bottom: E_k^T, for SC1 ($\eta_{sc} = 0.95$ and $\epsilon_{sc,1} = 0.1$ mJ/$\sqrt{sec}$) at $P = 50$ mJ

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