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Rao, Yepuri Sudhakara; Madhukumar, A. S.

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Optimal algorithms for energy harvesting based systems with circuit power considerations

Yepuri Sudhakara Rao

School of Computer Science and Engineering
Nanyang Technological University
Singapore
Email: sudhakar001@ntu.edu.sg

A.S.Madhukumar

School of Computer Science and Engineering
Nanyang Technological University
Singapore
Email: asmadhukumar@ntu.edu.sg

Abstract—Recently, an elegant method to alleviate the shortcomings of battery-powered (BP) sensor nodes has been introduced in the form of energy harvesting (EH), where the nodes scavenge the energy from ambient sources. Optimal scheduling algorithms, either to minimize transmission completion time or to maximize short-term throughput, for such networks under the deterministic energy and data arrival profiles are extensively studied in the literature. In this work, we revisited the existing optimal algorithms under practical energy cost considerations: circuit power consumption and sleep-to-wakeup power consumption. Next, we found that the direct application of the state-of-the-art algorithms led to sub-optimality. Finally, we proposed suitable adaptations to regain optimality.

I. INTRODUCTION

The early work related to battery-powered (BP) wireless networks [1], [2] as well as energy harvesting (EH) based networks [3], [4] completely ignored the power dissipation associated with circuitry, such as micro-controllers, sensing circuitry, filters, power supply subsystem, and so on. However, it is vital to consider these overheads in the optimization algorithms to make them viable in the real world. In this paper, all these overheads are referred as "processing cost". If one includes significant processing cost, it is possible that the optimal algorithms proposed in the literature might turn sub-optimal.

As the wireless devices rely on batteries for energy, and also the battery power is finite, it is highly desirable to reduce the power consumption of a wireless node during all the modes of operation: Active, Idle, and Sleep. However, the power consumption in the idle mode is substantial while adding nothing to overall data throughput [5]. It is always recommended to put the node to sleep while it is not being used for transmission [5]. Also, in the case of sensor networks, the time and the energy to wake-up is also significant [6]. Therefore, it is essential to consider sleep-to-wakeup power consumption while deriving optimal algorithms.

The amount of energy needed to transmit fixed amount of information decreases with increase in transmit-duration. In other words, it is always optimal to reduce the transmission power by increasing the transmit duration [1]. In [7], author established a significant information-theoretic result relating capacity per unit cost and the channel capacity for stationary

Fig. 1. EE-SE trade-off for circuit power overhead scenario [9]

memoryless channels. This result can be extrapolated to include the processing costs associated with the transmission. It is showed that signaling, which is not bursty either in frequency or in time cannot achieve the minimum cost per bit [8]. This implication goes against the lazy scheduling algorithms [1], [4].

A. related work

Apart from maximizing energy efficiency (EE) (bits-per-joule), maximizing Spectral efficiency (SE) (bits-per-second-per-Hz) is tantamount in today's data-hungry applications. It is important to study the interplay between these two important metrics instead of going unilaterally in one particular direction. The trade-off between EE and SE, where EE is a monotonically decreasing function of SE is derived in [1]. However, once we include circuit overhead, the relation is no longer monotonic but follows the curve shown in Fig. 1

[9]. The circuit processing cost is incorporated in the system model and solved for an optimal solution using calculus in [10]. Authors in [9], [11] solved the same using two-step algorithm. However, in all their work, they considered fixed processing power but ignored the crucial overhead: sleep-to-wakeup power consumption.

B. contributions

This work adapts the state-of-the-art algorithms for more practical power consumption scenarios that include circuit power consumption and non-zero sleep-to-wakeup costs. To that end, the following are the significant contributions of this paper:

- Shown that the existing algorithms become suboptimal for the considered power consumption scenario
- Resolved the performance difference by adapting the state-of-the-art solutions.

The remainder of the paper is organized as follows. Preliminary system model is presented in II. Single user capacity with overheads for BP communication system is considered in Section III. Section IV solves the transmission completion time minimization problem for EH based sensor networks with various overheads. Section V provides the numerical simulation study and finally we summarize the results and also provides possible future directions in Section VI.

II. SYSTEM MODEL WITH OVERHEADS

The average energy consumption for transmitting a packet of data for a sensor radio is given by the equation below [6]

$$E = \frac{(p + \alpha)L}{R} + \alpha T_{start} + \beta T_{sleep}. \quad (1)$$

α is the power consumption of the circuitry, p is the transmit power which drives the RF antenna, L is the size of the data packet (in bits), R is the data rate (in bits per second, bps), T_{start} is the time it takes to wake up from the sleep state, β is the power consumption in sleep mode, and T_{sleep} is the time during which the system is in sleep mode. The only component which contributes to the data transmission is p and the rest is the overhead.

In practice, β is much smaller compared to α and thus can be ignored for simplicity. This work assumes fixed circuit processing power, α , which is independent of p . We denote processing cost related to sleep-to-wakeup with ϵ which is equal to αT_{start} . This simplification enables us to solve a tractable problem which throws valuable insights w.r.to the influence of overheads over scheduling algorithms. We use the following rate function for the analytical study,

$$r(p(t)) = W \log_2 \left(1 + \frac{hp(t)}{WN_0} \right), \quad (2)$$

where $r(p(t))$ is the instantaneous achievable data rate for transmit power p at time t , W is the channel bandwidth, N_0 is the Noise power spectral density, and h is the attenuation power loss. In this model, we can get an immediate insight by replacing the cost of transmitting a symbol with $(P + \alpha) * l_{on}$,

Fig. 2. Single link BP System model with all the data available at $t=0$.

Fig. 3. Power vs rate for Single link BP System model with all the data available at $t=0$ and with processing cost, α .

where l_{on} is equal to L/R . It is visible that the increase in l_{on} drives the overhead cost ($\alpha * l_{on}$) higher. Based on this, one can deduce that the transmitting at extremely low power for longer duration in the presence of non-zero circuit power is inefficient w.r.to energy efficiency. To start with, we consider a wireless node that needs to transmit B_0 bits of data using E_0 units of energy to its counterpart by a deadline T as shown in Fig. 2. The resultant problem definition as follows:

$$\begin{aligned} & \underset{\mathbf{p}, \mathbf{l}}{\text{minimize}} && T \\ & \text{subject to} && E(t) \leq E_0, \quad 0 \leq t \leq T \\ & && B(T) = B_0 \end{aligned} \quad (3)$$

Where $\mathbf{p}$ and $\mathbf{l}$ are the transmission power vector and the corresponding duration vector respectively. $E(t)$ and $B(t)$ are the energy consumed and the transmitted data respectively up to time t . Optimal solution to the above optimization problem can be found by solving for p in the equation below

$$B_0 = \frac{E_0 - \epsilon}{p + \alpha} W \log_2 \left(1 + \frac{hp}{WN_0} \right) \quad (4)$$

For example, given $B_0 = 55.8$ Mbits, $E_0 = 4.5$ J, $\epsilon = 0.25$ J, $\alpha = 0.1159$ W, $W = 1$ MHz, $h = -80$ dB, and, $N_0 = 10^{-16}$ W/Hz, the rate function (4) is shown in Fig. 3. We have to select the solution with the higher power to minimize T , i.e., $p = 0.236$ W and $l = 4.25 / (0.236 + 0.1159) = 12.07$ s. The most important inference from the Fig. 3 is that the maximum energy efficiency can be achieved at unique optimum power, $p_{opt} = 0.079$ W, unlike in the system with no overheads. p_{opt}

Fig. 4. BP: System model with intermittent data availability

can be derived by maximizing the rate function given in (4). p_{opt} and α are related by the following equation [8],

$$p_{opt} = \frac{\alpha - 1}{W(e^{-1}(\alpha - 1))} - 1, \quad (5)$$

where the W is the Lambert W-function [12].

III. BP: SINGLE USER CHANNEL WITH PROCESSING COSTS

In this section, we consider the optimal scheduling algorithm which minimizes the energy consumption [1]. Data arrives during transmission in M discrete time instants as shown in Fig. 4, and the objective is to transmit all the data by deadline T while consuming minimum energy:

$$\begin{aligned} & \underset{r, l}{\text{minimize}} && E(T) \\ & \text{subject to} && B(t) \leq \sum_{i: t_i < t} B_i, \quad 0 \leq t \leq T \\ & && B(T) = \sum_{i=0}^M B_i \end{aligned} \quad (6)$$

In the absence of processing costs, the solution to the above problem follows the throughput maximization algorithm proposed in [1] as shown below:

$$r_0 = \min_{k \in \{0, \dots, M\}} \left\{ \frac{\sum_{i=0}^k B_i}{t_{k+1}} \right\}, \quad (7)$$

$$k_0 = \min \left\{ k : \frac{\sum_{i=0}^k B_i}{t_{k+1}} = r_0 \right\} + 1, \quad l_0 = t_{k_0} \quad (8)$$

For $j \geq 0$,

$$r_{j+1} = \min_{k \in \{0, \dots, M-k_j\}} \left\{ \frac{\sum_{i=0}^k B_{k_j+i}}{t_{k_j+1} - t_{k_j}} \right\}, \quad (9)$$

$$k_{j+1} = k_j + \min \left\{ k : \frac{\sum_{i=0}^k B_{k_j+i}}{t_{k_j+1} - t_{k_j}} = r_{j+1} \right\} + 1, \quad (10)$$

$$l_{j+1} = t_{k_{j+1}} - t_{k_j} \quad (11)$$

where $k \in \{1, \dots, M - k_j\}$ and $t_{M+1} = T$. The pair r_j and l_j , $j \in \{1, \dots, J\}$, defines the optimal schedule of transmission rates and transmission times respectively. Where $J = \min \{j : k_j = M\}$. However, if we consider non-zero α , this algorithm becomes suboptimal because the optimum transmission power is no longer towards zero but is unique based on the processing cost (5). In developing the optimal algorithm for this problem, one need to consider the optimum transmission rate, r_{opt} corresponding to p_{opt} apart from the

causality constraints. The adaptation needed to bring back the optimality in the presence of circuit processing costs are as follows:

$$\begin{aligned} & \text{if } r_j \leq r_{opt}, \quad j \in \{1, \dots, J\} \\ & \text{then } r'_j = r_{opt}, \quad l'_j = l_j - l_{j_{sleep}}. \end{aligned} \quad (12)$$

Where the pairs (r'_j, l'_j) , $j \in \{1, \dots, J\}$ are the optimum transmission rate and transmission time respectively, and $l_{j_{sleep}}$ represents the length of time during which the system is in sleep mode in j th transmission interval. As we can observe from (13), it is no longer suboptimal to put the transmitter in sleep mode.

The above two phase on-off solution turns sub-optimal for non-zero T_{start} because of recurrent sleep-to-wakeup transitions. This issue can be resolved by consolidating all the sleep intervals in (13) as follows:

$$\begin{aligned} r''_0 &= 0, \quad l''_0 = \sum_{j=1}^J l_{j_{sleep}}, \\ r''_j &= r'_j, \quad l''_j = l_j - l_{j_{sleep}}. \end{aligned} \quad (13)$$

Where the pairs (r''_j, l''_j) , $j \in \{0, \dots, J\}$ are the optimum transmission rate and transmission time respectively.

IV. EH: SINGLE USER CHANNEL WITH PROCESSING COSTS

Optimal algorithms for transmission completion time minimization and short-term throughput maximization for EHWSNs was thoroughly investigated in [4]. However, authors assumed the overhead, α as zero. In this work, we study the short-term throughput maximization problem for single user communication system considering non-zero overhead costs.

A. System Model and Problem Formulation

The system model with energy-arrival information is shown in Fig. 5. For non-zero α , the optimization problem can be

Fig. 5. Simplified system model with initial data availability

reformulated as:

$$\min_{p, l} \quad T \quad (14)$$

$$\text{s.t.} \quad \sum_{i=1}^i (p_i + \alpha) l_i \leq \sum_{i: t_i < t} E_i, \quad 0 \leq t \leq T \quad (15)$$

$$B(T) = B_0 \quad (16)$$

Where T is the transmission completion time, E_i is the quantum of energy harvested at time instant t_i , $i \in \{0, \dots, N-1\}$. Every proposed transmission policy should satisfy the energy-causality constraints given in (15). The goal of the optimal

algorithm is to minimize T using the available harvested energy.

The procedure proposed by authors in [4, Algorithm 1] cannot be used directly for the system with overheads as it unilaterally follows the lazy scheduling procedure. However, the basic tenets [4, Lemma 1,2,3] can still be used to find the optimal algorithm. To solve the above EH problem, we can use the results obtained in the BP model developed in the earlier section.

If we consider a single epoch case, then the above problem turns into a battery-powered case where all the energy and data are available at $t = 0$. The optimal transmission power, p_{opt} for a given α is given by (5) and the corresponding transmit duration is $l_{on}^* = E_0/(p_{opt} + \alpha)$. In the case of multiple epochs, the algorithm given in [4] need to be adapted to cater to the scenario with processing costs as shown in the theorem below:

Theorem 1: For a given B_0 and α , the policy is optimal if and only if it has the following structure:

$$\sum_{n=1}^N r(p_n) l_n = B_0 \quad (17)$$

and for $n \in \{1, 2, \dots, N\}$,

$$i_n = \arg \min_{i: s_i \leq T} \left\{ \frac{\sum_{j=i_{n-1}}^{i-1} E_j}{s_i - s_{i_{n-1}}} \right\} \quad (18)$$

$$p_n = \max \left\{ \frac{\sum_{j=i_{n-1}}^{i_n-1} E_j}{s_{i_n} - s_{i_{n-1}}}, p_{opt} \right\} \quad (19)$$

$$l_n = s_{i_n} - s_{i_{n-1}} - l_{n_{sleep}} \quad (20)$$

Where $l_{n_{sleep}}$ is the sleep interval during n^{th} transmit slot. The adapted algorithm in (1) performs exactly like that of the algorithm given in [9, Table I]. However, similar to the BP case in section III, once we include the sleep-to-wakeup costs, the on-off algorithm turns suboptimal. This issue can be resolved by aggregating all the sleep intervals in (20) as follows:

$$p'_0 = 0, l'_0 = \sum_{n=1}^N l_{n_{sleep}} \quad (21)$$

$$p'_n = p_n, l'_n = s_{i_n} - s_{i_{n-1}} - l_{n_{sleep}}, n \in \{1, \dots, N\}$$

Where the pairs $(p'_n, l'_n), n \in \{0, \dots, N\}$ are the optimum transmission power and transmission time respectively. Likewise, the discussion can be extended to the system in which packets arrive during transmission.

V. SIMULATION RESULTS

In this section, we consider two distinct possibilities. In one case, sleep-to-wakeup is infinitesimally small ($\epsilon = 0$) while in the other case it is considered to be substantial. For both the scenarios, we compute the total power vector, $\mathbf{p}_{tot}$ and the associated duration vector, $\mathbf{l}_t$ which minimizes the transmission completion time. In this example, B_0 is set as 55.8 Mbits and the α as 115.9 mw. The energy arrival times, $\mathbf{t}=[0, 4, 6, 11, 14, 16, 18]$ s and the corresponding energy quantum, $\mathbf{E}=[0.5, 0.5, 0.5, 1, 0.5, 0.75, 0.5]$ J are considered

Fig. 6. Scheduling policies for zero sleep-to-wakeup cost (a) Allocation policy in [4] (b) Allocation policy in [9] (c) Optimal allocation policy

Fig. 7. Scheduling policies for non-zero sleep-to-wakeup cost ($\epsilon = 58mJ$): (a) Allocation policy in [4] (b) Allocation policy in [9] (c) Optimal allocation policy

respectively.

- $\epsilon = 0$

As shown in Fig. 6(a), the scheduling algorithm proposed for the ideal system (with no overheads) [4] becomes suboptimal. It takes $T = 20s$ to

complete the transmission and the associated vectors are: $\mathbf{p}_{\text{tot}} = [0.125, 0.14285, 0.3, 0.31264]w$, and $\mathbf{l}_t = [4, 7, 5, 4]s$. This suboptimality has been resolved for $\epsilon = 0$ by a two-phase solution in [9]. As shown in Fig. 6(b), two-phase algorithm finishes the transmission in 18.07s and its respective power and duration vectors are: $\mathbf{p}_{\text{tot}} = [0.195, 0, 0.195, 0, 0.3, 0.375, 7.143]w$, and $\mathbf{l}_t = [2.56, 1.44, 5.12, 1.88, 5, 2, 0.07]s$. The optimal total-power and duration vectors for the algorithm proposed in this paper are $\mathbf{p}_{\text{tot}} = [0, 0.079, 0.184, 0.259, 7.03]w$, and $\mathbf{l}_t = [3.32, 7.68, 5, 2, 0.07]s$ respectively. As shown in Fig. 6(c), this scheduling also achieves optimality.

- $\epsilon = 58mJ$

In this example, sleep-to-wakeup time, T_{start} is chosen as 0.5s. The resultant overhead, ϵ , is 58mJ. As can be observed from Fig. 7(b), two-phase algorithm [9] outperforms the scheduling policy proposed in [4]. The respective power and duration vectors are: $\mathbf{p}_{\text{tot}} = [0.195, 0, 0.1159, 0.195, 0, 0.1159, 0.32, 0.375, 0.8305]w$, and $\mathbf{l}_t = [2.56, 1.44, 0.5, 4.83, 1.67, 0.5, 4.5, 2, 0.6]s$. However, due to the recurrent sleep-to-wakeup events, this algorithm turns suboptimal. It is resolved by our proposed algorithm by aggregating the sleep intervals as shown in Fig. 7(c). This procedure completes the transmission in 18.18s and the associated vectors are: $\mathbf{p}_{\text{tot}} = [0, 0.1159, 0.195, 0.3, 0.375, 2.8]w$, and $\mathbf{l}_t = [3.07, 0.5, 7.43, 5, 2, 0.178]s$.

VI. CONCLUSION

In this work, the transmission algorithms considered circuit processing cost along with transmission power. The analysis started with BP case and found the minimum critical power based on the non-zero circuit overhead with the help of LambertW function. It also found that the critical power is independent of transmitting power, and it depends only on the given overhead. We used this result to optimize the algorithms for EH systems (with processing cost). For the ease of exposition, the analysis in this paper considered the same performance metrics (transmission completion time or maximum throughput) as in the state-of-the-art, to compare the classic algorithms with the adapted algorithms. Adaptation of the algorithms for dynamic circuit power consumption is left as a future work.

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