Optimal Power Control in Green Wireless Sensor Networks With Wireless Energy Harvesting, Wake-Up Radio and Transmission Control

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***Abstract*—**

***Index Terms*—Communications Society, IEEE, IEEEtran, journal, LATEX, paper, template.**

I. Introduction

II. Prior Related Works, Motivation And Contribution

III. System Model And Problem Formulation

Consider a static wireless network modeled as an undirected graph G(V, L) where V is the set of nodes, and L is the set of links.The set, $V = N \cup S$, represents the source nodes N and sink nodes S. Sensor nodes collect data from the surrounding information field and deliver it to the sink node (collector node). Sensors communicate either in an uniformly distributed ring topology or randomly in a multi-hop ad-hoc topology as in [22].Two nodes i and j are connected if they can transmit packets to each other and the set of nodes connected to node i by a link is denoted as Ni . The set of outgoing links and the set of incoming links corresponding to a node i are denoted by O(i) and I(i) respectively.

For a network flow r, let r_{ij} denotes the rate of information flow from node i to node j. Let R_{ij} be the total information rate generated at source node i and this information needs to be communicated to the sink node. If there is no compression is performed at the source node, we have the flow equations at each node for time slot t as

$$\sum_{\mathrm{j}\in \mathrm{N}_i} (r_{ij}(t) - r_{ji}(t)) = R_{ij}(t), \forall i \in N, j \in N_i$$

$$0 \leq r_{ij} \leq Cl$$

Cl is the maximum flow that a link from node i to node j can support which is determined by the given transmit power of node and bandwidth of the channel. The lifetime of sensor nodes depends on the power consumption of the sensor node P_{i} per active duty cycle slot T_i of a node and the battery capacity as shown in [50].

Sensoring, processing, and communication which includes both receive and transmit are the primary behaviors of a sensor node.

Let $E_{RX}(t)$ denotes the receiver energy of the sensor node per bit per time slot and $E_{TX}(t)$ denotes the transmitter energy of the sensor node per bit per time slot. Then the communication energy per bit per time slot $E_{comm}(t)$ can be denoted as $E_{TX} + E_{RX}$.The power consumption in a time slot t is modeled as

$$P_{\mathrm{i}}(t) = \sum_{i\in N, j\in N_i} r_{ij}(t)E_{TX}(t) + \sum_{i\in N, j\in N_i} r_{ji}(t)E_{RX}(t) + \sum_{i\in N, j\in N_i} R_{ij}(t)E_{PR}(t) + \sum_{i\in N, j\in N_i} R_{ij}(t)E_{SN}(t)$$

Where $E_{\mathrm{PR}}(t)$ is the processing energy per bit per slot and $E_{\mathrm{SN}}(t)$ is the sensing energy per bit per time slot. As shown in [0], the transmitter energy for transmitting one bit of data from $i \in N$ to j $\in N_{\mathrm{i}}$ across distance d_{ij} can be modified as

$$E_{\mathrm{TX}} = a1 + a2 \cdot d_{ij}^{\gamma}$$

where γ ($\gamma \in [2, 6]$) is the path loss exponent, $a1$ and $a2$ are constants depending on the characteristics of the transceiver circuit.

IV. Packet Loss And Data Re-Transmission

Re-transmission consumes extra energy from the battery source of the sensor node, as often as the packets are failed to be delivered to the sink node. Error control coding (ECC) is a classic approach used to increase link reliability and lower the required transmitted power, thereby increasing its lifetime substantially. We assume a TDMA based MAC protocol where retransmission occurs till time-out after which the packet is dropped and use different error control codes to improve transmission reliability. Different encodings have different error correction capabilities, and the redundancy of each kind of code is also different. These are some kinds of error control codes we will use :

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We will evaluate the quality of each coding method by introducing a balance function in later section. Due to poor channel conditions and interference, packet loss often occurs and a re-transmission is required. A MAC layer ECC scheme was proposed and its flexibility and compatibility with IEEE 802.15.4 were shown in [11](“Reliable and low latency transmission in industrial wireless sensor networks”). We use the same framework to show the validity of our ECC schemes.

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Assuming that the transmission of the packets between the sensor node and sink node is in bursts of n-bit data, the packet loss rate at the sink node P_e^{ECC} can de given as

$$P_e^{ECC} = 1 - \left(1 - \sum_{i=e+1}^{n} \binom{n}{i} P_b^i (1-P_b)^{n-i}\right)^{\left\lceil \frac{Lp}{k} \right\rceil}$$

for a (n, k, e) e-error control code. Let P_e be the packet loss rate of ARQ or ECC schemes and $\mathrm{E}(Tr)$ denotes the expected number of re-transmissions for a single hop. Then the expected number of re-transmissions can be given as $\mathrm{E}(T_r) = 1/(1 - P_e)$. Accordingly, packet loss rate for end-to-end in a h-hop scenario assuming each node transmission is independent of the other as per the TDMA based MAC protocol in Section xx.

$$E(T_r, h) = \frac{h}{(1 - P_e)}$$

By applying error control coding scheme, the number of re-transmission is reduced with $n - k$ redundant bits. The power consumption in time slot t should be modified as

$$\begin{aligned} P_i(P_e, h_i, t) = & \sum_{i\in N, j\in N_i} r_{ij}(t)\mathrm{E}_{TX}(t)(1 + E(T_r, h_i)) \\ & + \sum_{i\in N, j\in N_i} r_{\mathrm{ji}}(t)\mathrm{E}_{RX}(t)(1 + E(T_r, h_i)) \\ & + \sum_{i\in N, j\in N_i} R_{ij}(t)\mathrm{E}_{PR}(t)(1 + E(T_r, h_i)P') \\ & + \sum_{i\in N, j\in N_i} R_{ij}(t)\mathrm{E}_{SN}(t) + \sum_{i\in O(i)} P_{LS}(t) \end{aligned}$$

Packet success rate $Ps(t)$ affects the sample rate in the rate flow constraint as

$$\sum_{j\in N_i} \sum_{t=1}^{T_i} \left(r_{ij}(t) - r_{ji}(t) + P_s(t)R_{ij}(t)\right) \leq 0, \forall i \in N, j \in N_i$$

Now, the problem of maximizing the network lifetime can be stated as

$$\begin{aligned} & \max_{t\geq 0, E_B(t)>0} T_i \\ & s.t. \quad \sum_{t=1}^{T_i} (P_i(P_e, h_i, t)) \leq \frac{1}{T_i} \centerdot E_B(t) \\ & \quad \sum_{j\in N_i} \sum_{t=1}^{T_i} \left(r_{\mathrm{ji}}(t) - r_{ij}(t) - P_s(t)R_{ij}(t)\right) \leq 0, \forall i \in N, j \in N_i \\ & \quad E_{TX} = a1 + a2 \centerdot d^\gamma, \gamma \in [2, 6] \\ & \quad 0 \leq r_{ij} \leq C_l \end{aligned}$$

Where, $\mathrm{E}_B(t) \leq \mathrm{E}_{B\max}$ ($\mathrm{E}_{B\max}$ is the maximum capacity of a battery) and $P_{\mathrm{i}}(t) < P_{\max}, \forall j \in N_{\mathrm{i}}, \forall t \in T_i$ ($\mathrm{P}_{\max}$ is the maximum power consumption due to hardware limitatios). Problem in (xx) is not convex. By substituting s = $1/T$, we obtain a convex maximization problem in s.

$$\begin{aligned} & \min_{s\geq 0} s_i \\ & s.t. \sum_{t=1}^{T_i} (P_{\mathrm{i}}(P_e, h_i, t)) \leq s_i \centerdot E_B(t), 1 \leq t \leq T_{\mathrm{i}} \\ & \quad 0 < E_B(t) \leq E_{Bmax}, 1 \leq t \leq T_i \end{aligned}$$

and with constraints above.

V. Wireless Energy Harvesting And Wake-Up Radio Scheme

A critical challenge in large scale implementation of WSNs technology and in a greater scope, IoT, is providing energy to the nodes. A more attractive energy harvesting approach is wireless (RF) energy harvesting which provides key advantages in virtue of being controllable, lower cost and smaller form factor implementation [15], [27]. In this section, enabling technologies for efcient wireless energy harvesting is presented. Also, an energy-efcient method to decrease the power consumption of nodes during the receive mode is discussed.

A. Wireless Energy Harvesting Networks

Energy can be harvested from the environmental sources such as wind energy, solar energy and vibration but aforementioned environmental sources dependents on the presence of the corresponding energy source. A more attractive energy harvesting approach is wireless radiofrequency (RF) energy harvesting which is wireless, cheap and readily available in the form of transmitted energy (TV/radio broadcasters, mobile base stations and hand-held radios).

Dedicated sources and Ambient sources are two kinds of different energy sources [27]. A dedicated RF source is deliberately deployed to supply energy to the nodes at a designated rate and optimum frequency (e.g., sink node). Ambient sources such as TV and radio towers (static ambient source) and WiFi access points (dynamic ambient source) is less predictable and happens to exist within the operation area of the network [28].

A generic wireless energy harvesting (WEH) enabled sensor node consists a rectifier, transceiver (RX, TX), sensors and sensor interface, storage unit (rechargeable battery), power management unit (PMU) and the processor. The core of the wireless energy harvesting unit is the RF-to-DC converter (also known as rectifier) which is used to convert the received RF power to a usable DC supply with some energy loss. Power conversion efficiency (PCE) of the rectifier is the ratio of the converted DC power to the RF input power. Using the Friis free space equation [29], the available harvested power can be given as

$$\mathrm{P}_H = P_{TX} \centerdot P_L \centerdot G_{TX} \centerdot G_{RX} \centerdot PCE \centerdot \frac{\lambda^2}{(4\pi d)^2}$$

where P_H is the available harvested power, P_{TX} is the transmitted power by the source, P_L is the path loss, G_{TX} is the transmitter antenna gain, G_{RX} is the receiver (node) antenna gain, PCE is power conversion efficiency of the rectifier, λ is the wavelength of the transmitted wave and d is the communication distance.

When a receiver node i is in the energy harvesting mode, the power harvested (P_{Hi}) from base station server source in a time slot t can be calculated as follows

$$\mathrm{P}_{Hi}(t) = \frac{\eta \centerdot P_{TX} \centerdot |H_{\mathrm{i}}(t)|^2}{d_{ij}^2}, 1 \leq t \leq T_{\mathrm{i}}$$

Where, η is PCE and H_i denotes the channel gain between source and receiver at time slot t.

B. Wake-Up Radio Scheme

The receiver unit constitutes a significant portion of the overall energy consumption of the system which keeps listening to the communication channel for the commands from the sink node and becomes active when its service is required. To decrease the energy consumption during the idle listening mode, we use the asynchronous duty cycling scheme in our wireless sensor notes system. In the asynchronous scheme we use wake-up radio (WUR) which is a simple and low-power receiver to keep listening to the channel and only wake up the main receiver when a request for transmission to the associated node occurs [33]. The listening mode power (P_{LS}) is related to the constant α ($0 < \alpha < 1$) which is a system parameter to be discussed in later section. The function in (11) in terms of α can be modified as

$$\begin{aligned}\mathrm{P_i}(P_e, h_i, t) = &\sum_{i\in N, j\in N_{\mathrm{i}}} r_{ij}(t)E_{TX}(t)(1 + E(Tr, h_{\mathrm{i}}))\\ &+ \sum_{i\in N, j\in N_{\mathrm{i}}} r_{ji}(t)E_{RX}(t)(1 + E(Tr, h_{\mathrm{i}}))\\ &+ \sum_{i\in N, j\in N_{\mathrm{i}}} R_{ij}(t)E_{PR}(t)(1 + E(Tr, h_{\mathrm{i}})P')\\ &+ \sum_{i\in N, j\in N_{\mathrm{i}}} R_{ij}(t)E_{SN}(t) + \sum_{l\in O(i)} \alpha(t)P_{LS}(t)\end{aligned}$$

Obviously, WUR scheme is more energy saving only when the power consumption of the WUR is much smaller than that of RX. WEH-enabled nodes provide a good opportunity for a very efficient implementation of WUR [34]. The rectifier block of the WEH unit can be used as a simple envelope detector and provide energy for the rest of WUR circuitry.

C. Medium Access Control For WEH-WSN

To complement our wake-up radio design, MAC protocols based on Time Division Multiple Access (TDMA) with wakeup and sleep periods are used in our wireless sensor nodes system. TDMA divides time into many fixed slots and nodes transmit data in their assigned slots to avoide collisions. TDMA is widely considered in wireless networks because of their low power consumption and collision free operation [36], [37], [38].

D. Modeling Energy Harvesting And Wake-Up Radio

Let $P^C_{Hi}(t)$ denote the cumulated harvested energy in all the slots of node i. For simplicity, we assume the harvested energy is available at the start of each interval t. We also assume that the battery has finite capacity and harvested energy can only recharge till the maximum capacity of battery E_{Bmax}.

$$P^C_{Hi}(t) = \sum_{x=1}^{t} P_{Hi}(x), (t \in 1, 2, \ldots.T_j)$$

$P^C_{Hi}(t)$ is a continuous increasing function that lies between points (0,0) and $(T_j, P^C_{Hi}(T_j))$ as shown in Fig. 6. The cumulative node energy $P^C_i(t)$ for all $(t \in 1, 2, \ldots.T_j)$ cannot be more than $P^C_{Hi}(t)$. Using this constraint, the dynamic charging and discharging of battery can be modeled as

$$E_B(t + 1) = E_B(t) - P_i(t) + P_{Hi}(t)$$

$$\mathrm{P}^C_i(t) \le P^C_{Hi}(t), \forall t \in 1, 2, \ldots.T_j$$

To find an optimal energy consumption $(P^C_i(t))^*$, we need to find the upper and lower bound of consumed energy. (19) gives the upper bound of the consumed energy. Further, $(P^C_i(t))^*$must satisfy that, the residual energy of nodes at all time slots i.e. $(P^C_i(t))^* - P^C_{Hi}(t)$ cannot exceed the battery maximum capacity E_{Bmax}, forms the lower bound of $(P^C_i(t))^*$ Thus the problem in (14), can be reformulated as

$$\begin{aligned}&\min_{s\ge0} s_{\mathrm{i}}\\ &s.t. \ \sum_{t=1}^{T_i}(P_i(P_e, h_i, t)) - \mathrm{s}_i \cdot E_B(t) - P_{Hi}(t) \le 0, 1 \le t \le T_i\\ &\quad 0 < E_B(t) \le E_{B\,\max}, 1 \le t \le T_i\\ &\quad P^C_{Hi}(t) - \mathrm{E}_{B\,\max} \le P^C_i(t) \le P^C_{Hi}(t), \forall t \in 1, 2, \ldots.T_j\end{aligned}$$

Constraints in (13), (16), (17) and (18) (20)

VI. Joint Utility and Network Lifetime Trade-off And Distributed Solution

We have known how to calculate the lifetime of the wireless sensor, and now we try to introduce the model of the utility function $U_i(\mathrm{R}_{ij}(t), P_s(t))$=$\log_2 R_{ij}(t) \cdot P_s(t)$. It is obvious that increasing the utility $U_i(\mathrm{R}_{ij}(t), P_s(t))$ of the sensor nodes often leads to a reduction in the lifetime of the sensor nodes which makes it difficult to achieve higher utility and lifetime at the same time. To solve this utility-lifetime trade-off problem,we introduce a balance function h

$$\sum_{t=1}^{Ti}\alpha(t)\sum_{i\in N}\sum_{j\in N_i} U_i(\mathrm{R}_{ij}(t), P_s(t)) - \sum_{t=1}^{T_i}(1 - \alpha(t))\left(\frac{1}{\epsilon + 1}\right) \cdot s_i^{\epsilon+1}$$

Where, S_i is the reciprocal of T_i, α is a constant between 0 and 1.

We note that the balance function h increases when the utility function U_i and the node lifetime function T_i increase when α is given . By maximizing the balance function, we can make both node utility and node lifetime be larger at the same time. The larger the constant α, the higher the effect of U_i on the balance function, and the smaller the effect of T_i on the balance function h. By changing the value of the constant α, we can change the impact of node utility and node lifetime on the balance function. In a real environment, If you are more concerned about the utility of the node, you can increase the value of α; if you pay more attention to the lifetime of the node, you can take a smaller α.

However, how to make the balance function h get the maximum value when constant α is given? From $U_i = \log_2(R_{ij}P_s)$, we can know that the balance function h is related to R_{ij}(source node rate) which is the sum of the number of bits of information generated by node i per second to be sent to other nodes, P_s, and S_i.

At the same time, the balance function h is also determined by S_i . By analyzing the formula

$$S_i \geq \frac{P_i - \mathrm{P}_{Hi}}{E_B}$$

, we know that the minimum value of S_i depends on P_i when the sensor battery capacity E_B and energy harvest power P_{Hi} are given.

Since

$$P_{H_i}^C(t) - E_{B\max} \leq P_i^C(t) \leq P_{H_i}^C(t)$$

and

$$\begin{aligned} P_i(P_e, h_i, t) = & \sum_{i \in N, j \in N_i} r_{ij}(t)\mathrm{E}_{TX}(t)(1 + E(T_r, h_i)) \\ & \sum_{i \in N, j \in N_i} r_{ij}(t)\mathrm{E}_{RX}(t)(1 + E(T_r, h_i)) \\ & \sum_{i \in N, j \in N_i} R_{ij}(t)\mathrm{E}_{PR}(t)(1 + E(T_r, h_i)P') \\ & \sum_{i \in N, j \in N_i} R_{ij}(t)\mathrm{E}_{SN}(t) + \sum_{i \in O(i)} \alpha(t)P_{LS}(t) \end{aligned}$$

, we can know that P_i is only related to r_{ij}, R_{ij}, $\mathrm{E}(T_r, h_i)$, $P'(P' = (n-k)/k)$ when the sensor to be chosen, energy harvest power, wake-up strategy, and constant α are given. Moreover, because $\mathrm{E}(T_r, h_i)$ (the number of retransmissions) is determined by P_s and r_{ij} is determined by R_{ij}, P_i is only related to R_{ij}, P_s, P' in fact.

In summary, in the case of selected sensors, energy harvest power, wake-up strategy and constant α are given, the value of the balance function h is only related to P_s , P', and R_{ij}.

Now we try to maxmize the balance function h.

(1) When P' and R_{ij} are constants, by increasing P_s, the lifetime and utility functions of the sensor node become larger at the same time which means that when R_{ij} and P_s are fixed, we should choose the encoding method that can increase P_s.

(2) When P_s and R_{ij} are constants, by decreasing P', the lifetime of the sensor node increases, and the value of the utility function does not change which means that when R_{ij} and P_s are constants, we should choose the encoding method that can reduce P'.

(3)Now, we try to solve the problem that how to maximize the balance function h when R_{ij} is a constant. To get the maximum value of h, we should make P_s as large as possible, and P' as small as possible. However, when P' takes the minimum value, P_s does not always get the maximum value at the same time. Conversely, reducing P' tends to result in a decrease in P_s. Therefore, in order to maximize the balance function h, choosing the appropriate P_s and P' is significant.

Since P_s and P' are only related to n, k, and e when the sensor to be chosen, energy harvest power, wake-up strategy, and constant α are given, we take n as the x-axis, k as the y-axis, and the balance function h as the z-axis, and plot the 3-d plot of the $n-k-h$ when $e = 1, 2, 3 \ldots$. Then filter some points by adding some constraints. Since n, k, and the encoding kind can determine the values of n, k, and e, we can also plot the 3-d plot of the $n-k-h$ under different kinds of encoding methods to find the best encoding strategy.

By observing the 3-d plot, we can get the most suitable encoding strategy to maximize the balance function h and the best n and k for each kind of encoding method.

VII. Simulation Results

1) Subsubsection Heading Here:

VIII. Conclusion

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Appendix A
Proof of the First Zonklar Equation

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Appendix B

Appendix two text goes here.

Acknowledgment

The authors would like to thank...

References

[1] H. Kopka and P. W. Daly, *A Guide to LATEX*, 3rd ed. Harlow, England: Addison-Wesley, 1999.

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Michael Shell Biography text here.

John Doe Biography text here.

Jane Doe Biography text here.