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Joint Utility-lifetime Trade-off Problem of Wireless Sensor Networks with Wireless Energy Harvesting, Wake-Up Radio, and Error Control Coding

Abstract

Wireless sensor networks (WSNs) are composed of a large number of spatially distributed autonomous sensor nodes with limited computation and sensing capabilities, to monitor physical or environmental conditions, and to cooperatively pass their data to a sink. The flexibility, fault tolerance, high sensing fidelity, low-cost, and rapid deployment have made them widely used in military, disaster relief, environment monitoring, and healthcare, etc. In this paper, we use both the transmission rate and delivery reliability to denote the utility of the sensor nodes. The utility and network lifetime are two fundamental but conflicting design objectives in energy-constrained WSNs which means maximizing one will degrade the other. By introducing the weight parameters, we combine the optimization objectives of rate, reliability, and lifetime into a single objective to characterize the trade-off among them. Wireless energy harvesting (WEH) is used to prolong the lifetime of the sensor nodes. Wake-up radio (WUR) scheme is considered as an efficient solution to address the idle listening energy dissipation of sensor nodes. Error control coding (ECC) is proposed to improve the reliability of the transmission and reduce re-transmission, hence, reducing energy consumption. We also find that a suitable error control coding scheme is the key to solve the joint utility-lifetime trade-off problem and we find a way to choose the most suitable error control code according to the realistic application's requirements. Simulation and experiments results evaluate the effectiveness of the proposed schemes in prolonging the node lifetime and increasing the utility of the sensor node.

Keywords Wireless sensor networks (WSNs), wireless energy harvesting (WEH), wake-up radio (WUR), error control coding (ECC), joint utility-lifetime trade-off problem

1 Introduction

A wireless sensor network (WSN) is a collection of wireless sensor nodes with limited energy capabilities that are located randomly on a dynamically changing environment and are capable of wirelessly communicating with each other in a multihop fashion. The development of WSNs was motivated by military applications such as the detection of enemies in remote jungle areas. Today such networks are usually used to monitor and record the physical conditions of the environment, such as temperature, sound, pressure, pollution levels, humidity, wind, and so on. Then, the collected data will be transmitted to a central location through the network. With the development of Internet-of-Things (IoT), a wide range of intelligent and tiny wireless sensing devices have been used in such areas like environmental sensing, health care monitoring, industrial monitoring, and so on.

Although the WSN systems possess tremendous potential in these areas, there are still some main barriers in the way of implementing such a great scheme. The devices used in a WSN usually have a low processing speed, a small memory unit, and a limited communication bandwidth. Moreover, since the nodes are battery powered, the finite battery capacity limits both the lifetime and the utility of the sensor nodes [1]. Motivated by the emerging concept of Green Wireless Sensor Network (GWSN) in which the lifetime and utility of the sensor nodes are maximized while minimizing the carbon footprints, we use WEH, WUR, and ECC to enhance the utility and lifetime of the system, in the meantime we formulate the utility-lifetime trade-off problem incorporating WEH, WUR, and ECC by balance function H . What is more, we try to get the most suitable encoding strategy to solve the utility-lifetime trade-off problem by analyzing the three most important parameters of the ECC—n, k, and e. For a given ECC system, k is defined as the number of information bits, n is defined as the total number of bits (i.e. information plus redundancy bits), and e

means the number of errors that can be corrected in a given communication package.

The remainder of this paper is organized as follows: In Section II, we review the related work and introduce our contributions. In Section III, we introduce the model of our WSN system and give the math model of the power consumption in a time slot t — P_i. Section IV describes our error control coding based data transmission control. In Section V, we improve our system model with the WEH and WUR schemes. In Section VI, we formulate the joint utility-lifetime trade-off problem by balance function H and find a way to solve the utility-lifetime trade-off problem by choosing a suitable error control code. Section VII shows our simulation plots and Section VII shows our experiment on practical sensor nodes. Finally, conclusions are drawn in Section IX.

2 Related Works

In the literature, there are numerous papers on optimizing the network lifetime of WSNs in a number of different ways. Yang et al. [2] jointly consider link scheduling, transmission power and transmission rate in a proposed optimization problem with the adoption of time division multiple access (TDMA) schedules and solved the optimization problem with an iterative algorithm. Madan and Lall [3] maximized the network lifetime by using subgradient algorithms in a distributed manner, whereas Tashtarian et al. [4] solved the lifetime optimization problem using Alternating Direction Method of Multipliers. Ehsan et al. [5] designed energy and cross-layer aware routing schemes for multichannel access WSNs that account for radio, MAC contention, and network constraints, aiming to maximize the network lifetime. However, all these works did not consider decrease in the utility of the sensor nodes due to decrease in rate flows. Practically, the network lifetime and utility are two fundamental, yet conflicting, design objectives in WSNs. Chen et al. [6] analyzed the utility-lifetime trade-off in WSN for flow constraints. He et al. [7] followed a cross-layer design approach. Both of these papers do not take some special approaches to ensure the reliability of the system. Fei et al. [8] provided a tutorial and survey of multi-objective optimization (MOO) in WSNs. As showed in [8], many papers aimed to solve the lifetime-rate trade-off problems in WSNs but no work considered the data rate, reliability and network lifetime together and studied the trade-off among them. Lun et al. [9] improved the reliability of the system by introducing error control schemes into the sensor nodes with multipath routing. The automatic repeat request (ARQ) as well as a hybrid ARQ scheme is used by Yu et al. [10]. The ARQ scheme improves the reliability of the system by re-transmission which increases the energy consumption of nodes in the meantime. In fact, we can improve the reliability of the system and decrease the number of re-transmission by using some suitable error control codes. Xu et al. [11] describes a rate-reliability and lifetime trade-off for WSNs by taking theoretical end to end error probability of packets. Similarly, Zou et al. [12] has taken a joint lifetime-utility-rate-reliability approach for WSNs taking a generic error coding processing power model. However, models in both [11] and [12] do not include the encoding/decoding powers of the error control codes.

Energy harvesting is proposed as a useful way to improve the lifetime of WSNs by He et al. [13], Magno et al. [14], Deng et al. [15], and Kamalinejad et al. [16]. Recently, dynamics of traffic and energy replenishment incorporated in the network power model has been an active research topic. Some of the challenges are addressed by [17], [18], and [19]. They assume battery energy to be zero at start, which may not be practical for many application scenarios that has sensors with rechargeable batteries. Challenges caused by packet loss due to interference has also not been addressed.

In this paper, the lifetime, rate, and reliability of the WSNs are all taken into account in our system model and we combine the optimization objectives of rate, reliability, and lifetime into a single objective to characterize the trade-off among them. We also find that a suitable error control coding scheme is the key to solve the joint utility-lifetime trade-off problem and we find a way to choose the most suitable error control code according to the realistic application's requirements.

3 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 [20]. Two nodes i and j are connected if they can transmit packets to each other and we use N_i to denote the set of nodes that are connected to node i by a link.

As showed in Fig. 1, s is a sink node and (i_1, i_2, i_3) are three sensor nodes. Specially, node i_2 also acts as a relay node for delivering nearest neighbor's data to the sink node s. There are six communication links $(l_1, l_2, l_3, l_4, l_5, l_6)$ in the system and 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. In Fig. 1,

$O(i_2)$ is (l_3, l_6) and $I(i_2)$ is (l_4, l_5). The communication between i_3 and s is a multi-hop transmission whereas communication between i_1 and s is a single-hop transmission. Some parameters that will be used in this paper are showed in Table 1.

Table 1 System parameters

Symbol	Description
N	Set of Sensor Nodes
S	Set of Sink Nodes
i	Outgoing Sensor Node
j	Incoming Sensor Node
r_{ij}	Rate of Information Flow between i & j
R_{ij}	Source Node Rate
Cl	Capacity of Link
$T_{network}$	Lifetime of Network
E_{TX}	Transmit energy [J/bit]
γ	Pass Loss exponent
d	Communication distance
E_{RX}	Receive energy [J/bit]
E_{PR}	Processing energy [J/bit]
E_{SN}	Sensoring energy [J/bit]
P_e	Packet Loss Rate
P_s	Packet Success Rate
P_b	Bit error rate
L_P	Length of Packet
$E(T)$	Expected number of retransmissions
h	Number of hops
P_{LS}	Listening Power [W]
E_B	Battery energy of Sensor
P_H	Harvested Power
α	System design parameter
$\in$	Lifetime approximation constant
H	balance function

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

$$\sum_{j \in N_i} (r_{ij}(t) - r_{ji}(t)) = R_{ij}(t), \forall i \in N, j \in N_i, 0 \le r_{ij} \le Cl \tag{1}$$

Where, 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 [21].

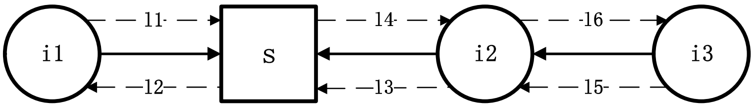

Fig. 1 A simple example of a WSN

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

Let $E_{RX}(t)$ denotes the energy consumed by the receiver of the sensor node per bit per time slot and $E_{TX}(t)$ denotes the energy consumed by the transmitter 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

$$P_i(t)=\sum_{i\in N, j\in N_i} r_{ij}(t)E_{TX}(t)+\sum_{i\in N, j\in N_i} r_{ji}(t)E_{RX}(t)+\sum_{i\in N, j\in N_i} R_{ij}(t)E_{PR}(t)+\sum_{i\in N, j\in N_i} R_{ij}(t)E_{SN}(t) \quad (2)$$

Where $E_{PR}(t)$ is the processing energy consumed by the sensor node per bit per time slot and $E_{SN}(t)$ is the sensing energy consumed by the sensing equipment per bit per time slot. WSNs have usually a dynamic topology and each node has a type of sensing equipment to analyze a given phenomenon (e.g., temperature, luminosity). Through this device, it can capture the phenomenon occurred, and transmit it to a sink node, responsible for disseminating the data to the observer (or the Internet). As shown in [21], the transmitter energy for transmitting one bit of data from $i\in N$ to $j\in N_i$ across distance d_{ij} can be modified as

$$E_{TX}=a_1+a_2\cdot d_{ij}^{\gamma} \quad (3)$$

where γ ($\gamma\in[2,6]$) is the path loss exponent, a_1 and a_2 are constants depending on the characteristics of the transceiver circuit.

4 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 re-transmission 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. BCH and RRNS are two kinds of error control codes that we will use in our simulation. RRNS is a error coding scheme on the theoretical basis of Redundant residue number systems (RRNS). An analysis of RRNS code has been done in [22].

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 [10]. We use the same framework to show the validity of our ECC schemes. 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 for a (n,k,e) e-error control code — P_e^{ECC} can be given as [23]

$$P_e^{ECC}=1-\left(1-\sum_{i=e+1}^{n}\binom{n}{i}P_b^i\left(1-P_b\right)^{n-i}\right)^{\left\lceil \frac{Lp}{k}\right\rceil} \quad (4)$$

and the package success rate can be calculated by

$$P_s=1-P_e^{ECC} \quad (5)$$

Let P_e be the packet loss rate of ARQ or ECC schemes and $E(Tr)$ denotes the expected number of re-transmissions for a single hop. Then the expected number of re-transmissions can be given as $E(T_r) = 1/(1-P_e)$. Assuming each node transmission is independent of the other, the expected number of re-transmissions in a h-hop scenario per the TDMA based MAC protocol in Section V can be given as

$$E(T_r, h) = \frac{h}{(1-P_e)} \tag{6}$$

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

$$\begin{aligned} P_i(P_e, h_i, t) = &\sum_{i\in N, j\in N_i} r_{ij}(t)E_{TX}(t)(1+E(T_r, h_i)) + \sum_{i\in N, j\in N_i} r_{ji}(t)E_{RX}(t)(1+E(T_r, h_i)) + \\ &\sum_{i\in N, j\in N_i} R_{ij}(t)E_{PR}(t)(1+E(T_r, h_i)P') + \sum_{i\in N, j\in N_i} R_{ij}(t)E_{SN}(t) + \sum_{i\in O(i)} P_{LS}(t) \end{aligned} \tag{7}$$

where $P' = (n-k)/k$ and $P_{LS}(t)$ is the listening mode power at time slot t which will be discussed in Section V.

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

$$\sum_{j\in N_i}\sum_{t=1}^{T_i}\left(r_{ij}(t) - r_{ji}(t) + P_s(t)R_{ij}(t)\right) \le 0, \forall i \in N, j \in N_i \tag{8}$$

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

$$\begin{aligned} &\max_{t\ge 0, E_B(t)>0} T_i \\ &s.t. \sum_{t=1}^{T_i}(P_i(P_e, h_i, t)) \le \frac{1}{T_i}\cdot E_B(t) \\ &\sum_{j\in N_i}\sum_{t=1}^{T_i}\left(r_{ji}(t) - r_{ij}(t) - P_s(t)R_{ij}(t)\right) \le 0, \\ &\forall i \in N, j \in N_i \end{aligned} \tag{9}$$

Where, $E_B(t) \le E_{B\max}$ ($E_B(t)$ is the total residual energy left in a sensor node operated by battery at time slot t, $E_{B\max}$ is the maximum capacity of a battery) and $P_i(t) < P_{\max}, \forall j \in N_i, \forall t \in T_i$ ($P_{\max}$ is the maximum power consumption due to hardware limitations). Problem in Eq. (9) is not convex. By substituting $s = 1/T$, we obtain a convex maximization problem in s.

$$\begin{aligned} &\min_{s\ge 0} s_i \\ &s.t. \sum_{t=1}^{T_i}(P_i(P_e, h_i, t)) \le s_i \cdot E_B(t),\ 1 \le t \le T_i \\ &0 < E_B(t) \le E_{Bmax},\ 1 \le t \le T_i \end{aligned} \tag{10}$$

and with constraints above.

5 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 [16], [24]. In this section, enabling technologies for efficient wireless energy harvesting is presented. Also, an energy-efficient method to decrease the power consumption of nodes during the receive mode is discussed.

5.1 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 radio frequency (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 [24]. 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 [25].

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 [26], the available harvested power can be given as

$$P_H = P_{TX} \cdot P_L \cdot G_{TX} \cdot G_{RX} \cdot PCE \cdot \frac{\lambda^2}{(4\pi d)^2} \tag{11}$$

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 wave length 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

$$P_{Hi}(t) = \frac{\eta \cdot P_{TX} \cdot |H_i(t)|^2}{d_{ij}^2}, 1 \le t \le T_i \tag{12}$$

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

5.2 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 [27]. The listening mode power (P_{LS}) is related to α $(0 < \alpha < 1)$ which is a system parameter to be discussed in later section. The function in Eq. (7) in terms of α can be modified as

$$\begin{aligned} P_i(P_e, h_i, t) = & \sum_{i \in N, j \in N_i} r_{ij}(t) E_{TX}(t)(1 + E(Tr, h_i)) + \sum_{i \in N, j \in N_i} r_{ji}(t) E_{RX}(t)(1 + E(Tr, h_i)) + \\ & \sum_{i \in N, j \in N_i} R_{ij}(t) E_{PR}(t)(1 + E(Tr, h_i)P') + \sum_{i \in N, j \in N_i} R_{ij}(t) E_{SN}(t) + \sum_{l \in O(i)} \alpha(t) P_{LS}(t) \end{aligned} \tag{13}$$

where $\alpha(t)$ is the the value of α at time slot t .

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 [28]. The rectifier block of the WEH unit can be used as a simple envelope detector and provide energy for the rest of WUR circuitry.

5.3 Medium Access Control For WEH-WSN

To complement our wake-up radio design, MAC protocols based on Time Division Multiple Access (TDMA) with wake-up 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 [29], [30], [31].

5.4 Modeling Energy Harvesting And Wake-Up Radio

Let $P_{Hi}^{C}(t)$, denotes 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} .

$$P_{Hi}^{C}(t)=\sum_{x=1}^{t}P_{Hi}(x),(t\in 1,2,....T_j) \tag{14}$$

$P_{Hi}^{C}(t)$ is a continuous increasing function that lies between points (0,0) and $(T_j, P_{Hi}^{C}(T_j))$. The cumulative node energy $P_i^{C}(t)$ for all $(t\in 1,2,....T_j)$ can not be more than $P_{Hi}^{C}(t)$. Using this constraint, the dynamic charging and discharging of battery can be modeled as

$$E_B(t+1)=E_B(t)-P_i(t)+P_{Hi}(t) \tag{15}$$

$$P_i^{C}(t)\le P_{Hi}^{C}(t),\forall t\in 1,2,....T_j \tag{16}$$

To find an optimal energy consumption $(P_i^{C}(t))^*$, we need to find the upper and lower bound of consumed energy. Eq. (16) gives the upper bound of the consumed energy. Further, $(P_i^{C}(t))^*$ must satisfy that, the residual energy of nodes at all time slots i.e $(P_i^{C}(t))^*-P_{Hi}^{C}(t)$ can not exceed the maximum battery capacity E_{Bmax} , forms the lower bound of $(P_i^{C}(t))^*$. Thus the problem in Eq. (10), can be reformulated as

$$\begin{aligned}
&\min_{s\ge 0}\quad s_i\\
&s.t.\quad \sum_{t=1}^{T_i}(P_i(P_e,h_i,t))-s_i\cdot E_B(t)-P_{Hi}(t)\le 0, 1\le t\le T_i\\
&\qquad 0<E_B(t)\le E_{B\max}, 1\le t\le T_i\\
&\qquad P_{Hi}^{C}(t)-E_{B\max}\le P_i^{C}(t)\le P_{Hi}^{C}(t),\forall t\in 1,2,....T_j\\
&\qquad \text{Constraints in } Eq.(9),\ Eq.(12),\ Eq.(13),\ \text{and } Eq.(14)
\end{aligned} \tag{17}$$

6 Joint Utility and Network Lifetime Trade-off Problem and the Solution

We have known how to calculate the lifetime of the wireless sensor nodes, and now we try to introduce the model of the utility function $U_i(R_{ij}(t),P_s(t))=\log_2 R_{ij}(t)\cdot P_s(t)$ .It is obvious that increasing the utility $U_i(R_{ij}(t),P_s(t))$ 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

$$H=\sum_{t=1}^{Ti}\alpha(t)\sum_{i\in N}\sum_{j\in N_i}U_i(R_{ij}(t),P_s(t))-\sum_{t=1}^{T_i}(1-\alpha(t))\left(\frac{1}{\in+1}\right)\cdot s_i^{\in+1} \tag{18}$$

Where, s_i is the reciprocal of T_i , α is a constant between 0 and 1, $\alpha(t)$ is the the value of α at time slot t .

We note that the balance function H increases only when the utility function U_i and the node lifetime function T_i increase. By maximizing the balance function H , 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 H . 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 P_s, s_i, and R_{ij} (the sum of the number of information bits generated by node i per second to be sent to other nodes).

At the same time, the balance function H is also determined by s_i. By analyzing the formula

$$s_i \geq \frac{P_i - P_{Hi}}{E_B} \tag{19}$$

, 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

$$P_{H_i}^C(t) - E_{B\max} \leq P_i^C(t) \leq P_{H_i}^C(t) \tag{20}$$

and

$$\begin{aligned} P_i(P_e, h_i, t) = &\sum_{i \in N, j \in N_i} r_{ij}(t) E_{TX}(t)(1 + E(T_r, h_i)) + \sum_{i \in N, j \in N_i} r_{ij}(t) E_{RX}(t)(1 + E(T_r, h_i)) + \\ &\sum_{i \in N, j \in N_i} R_{ij}(t) E_{PR}(t)(1 + E(T_r, h_i) P') + \sum_{i \in N, j \in N_i} R_{ij}(t) E_{SN}(t) + \sum_{i \in O(i)} \alpha(t) P_{LS}(t) \end{aligned} \tag{21}$$

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

In summary, in the case of the 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 fixed, 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 given, 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, the most suitable encoding strategy which can maximize the balance function H and the best n and k for each kind of encoding method will be known.

7 Simulation

To solve the joint utility-lifetime trade-off problem in terms of source node rate R_{ij}, packet success rate P_s, the reciprocal of lifetime s_i, and system parameter α, a WSN is showed in Fig. 2 with seven nodes distributed over a square region of 100m × 100m. s_1 acts as the sink node and the other six nodes are taken as the source nodes which are used to monitor the environment and transmit the collected data to the sink node s_1. Specially, nodes i_3, i_6 also act as relay nodes for delivering nearest neighbor's data to the sink node s_1 . Some parameters taken for the simulation are given in Table 2.

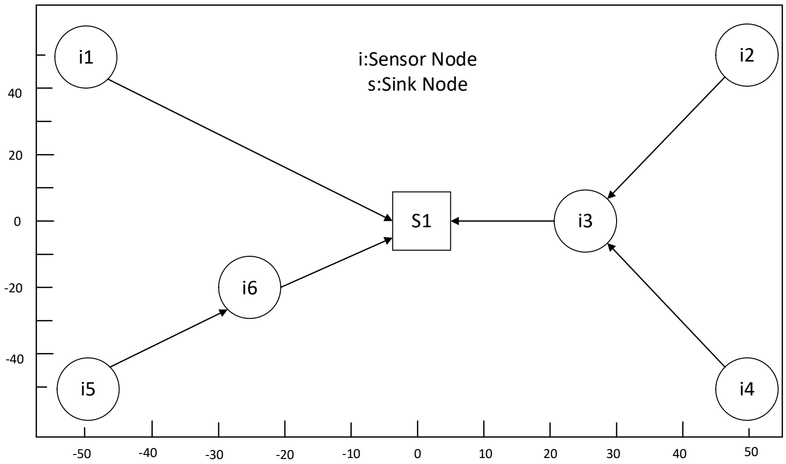

Fig. 2 WSN topology

Table 2 Simulation parameters

Parameter	Description	Value
a_1	Transceiver Constant	10^{-7} J/bit
a_2	Transceiver Constant	$0.1 \cdot a_1$ J/bit
γ	Pass Loss Exponent	4
$\in$	Lifetime Approximation Constant	20
ERX	Receiver energy per bit	$1.35 \cdot 10^{-7}$ J/bit
EPR	Processing energy per bit	$5 \cdot 10^{-8}$ J/bit
ESN	Sensoring energy per bit	$5 \cdot 10^{-8}$ J/bit
PLS	listening power	1mW
EB	Battery energy of sensor node	1J

The value of a_1, a_2 are chosen from [3] and the value of γ is taken as 4 in our simulation. The bit error rate P_b for sensor nodes in IEEE 802.15.4 is given in [23]. We will use these data to calculate E_{TX} by Eq. (3). E_{RX} and E_{SN} are taken from [32]. Processing energy E_{PR} is assumed to be the same as the sensing energy E_{SN} . Also, the initial battery energy E_B in all the nodes at start t_0 is taken as 1 J.

In Section VI, we formulated the joint utility-lifetime trade-off problem by balance function H as showed in Eq. (18) and we find that the balance function H is only related to n , k and e when the sensor node to be chosen, energy harvest power P_{Hi} , wake-up strategy, system parameter α , and source node rate R_{ij} are given. Now, the most important thing to do for a given sensor node is finding a suitable error control code. Some error control codes that we will use in our simulation are showed in Table 3.

Table 3 Some Error Control Codes for Our Simulation

Coding Schemes	n	k	e
BCH	63	16	11
BCH	127	57	11
BCH	127	8	31
RRNS	64	28	16
RRNS	128	60	32

We will take n as the x-axis, k as the y-axis, and the balance function H as the z-axis, then plot the 3-d plot of the $n-k-H$ for the different kinds of coding schemes showed in Table 3. 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. To get a better solution, we can use more kinds of coding schemes to plot the 3-d plot of $n-k-H$. In Fig. 3, source node rate R_{ij} is taken as $250Kbps$, system parameter is taken as 0.9 with coefficient $\in=20$. The error in measuring the lifetime with respect to the coefficient ∈ — $\left|s-\frac{1}{\in+1}s^{\in+1}\right|$ decreases when the parameter ∈ increases. Paper [21] has proved that we get less than 10% error in measurement of lifetime at $\in=10$ and less than 5% error at $\in=20$.

In order to conveniently observe the data, we use $-\lg(-H)$ instead of H to plot Fig. 3 and the value of H is showed in Table 4. As shown in Fig. 3, we can find that the value of balance function for RRNS (128, 60, 32) is larger than the others which means RRNS(128, 60, 32) is more suitable for the sensor node when $\alpha=0.9$ and $R_{ij}=250Kbps$.

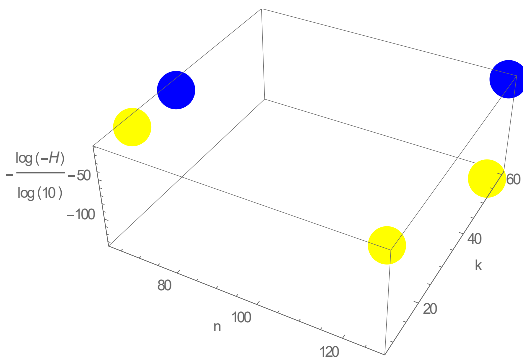

Fig. 3 This figure shows the value of balance function $-\lg(-H)$ for different coding schemes. The yellow balls represents the BCH code and the blue balls represents the RRNS code.

By adjusting the value of system parameter α, we can change the impact of nodes utility and nodes lifetime on the balance function H. You can increase the value of system parameter α to get more nodes utility or make the lifetime of nodes smaller by decreasing the value of system α.

Adjusting system parameter α, the coding scheme that can maximize the balance function H will be changed. We can calculate the lifetime and utility of the sensor nodes under different α and choose the most suitable coding scheme based on the desired performance of the system.

Table 4 Values of H for Different Coding Schemes

Coding Schemes	n	k	e	H
BCH	63	16	11	-2.98641×10^{17}
BCH	127	57	11	-3.49914×10^{133}
BCH	127	8	31	-5.04504×10^{11}
RRNS	64	28	16	-4.90086×10^{11}
RRNS	128	60	32	-4.70793×10^{11}

When $\alpha=0.9$ and the data is coded with RRNS(128, 60, 32), we plot the lifetime of the sensor node for different cases with source node rate R_{ij} varying from $0\sim250Kbps$ as shown in Fig. 4. Fig. 5 shows the utility of the sensor node versus source node rate R_{ij}. To visualize the impact of WEH & WUR on the balance function H, we plot the value of $-\lg(-H)$ for different cases with α varying from $0\sim1$. When $H<0$, $-\lg(-H)$ is an increasing function of H which means that we can use $-\lg(-H)$ instead of H to plot Fig. 6. Fig. 4, Fig. 5, and Fig. 6 all verify the effectiveness of WEH & WUR in prolonging the node lifetime and increasing the utility of sensor nodes.

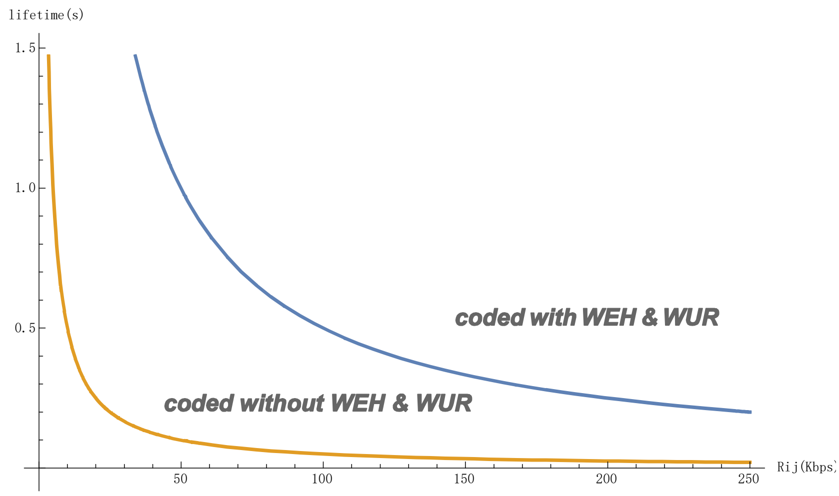

Fig. 4 This figure shows the lifetime of the sensor node for different cases with source node rate R_{ij} varying from $0\sim250Kbps$ when $\alpha=0.9$ and the data is coded with RRNS(128, 60, 32).

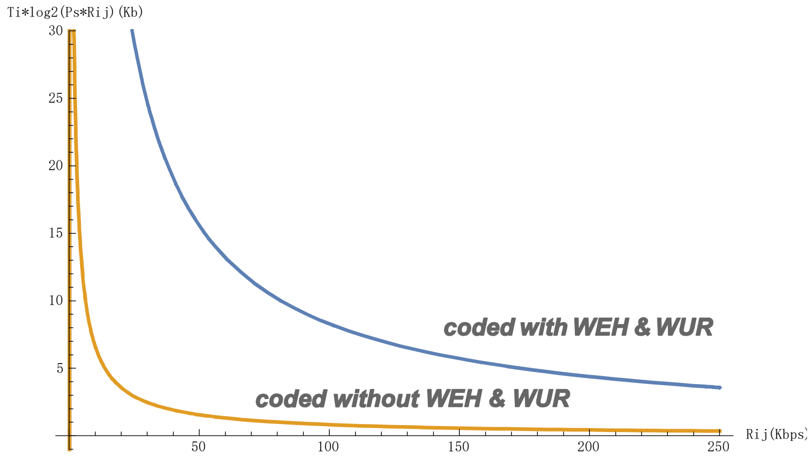

Fig. 5 This figure shows the utility of the sensor node for different cases with source node rate R_{ij} varying from $0 \sim 250Kbps$ when $\alpha = 0.9$ and the data is coded with RRNS(128, 60, 32).

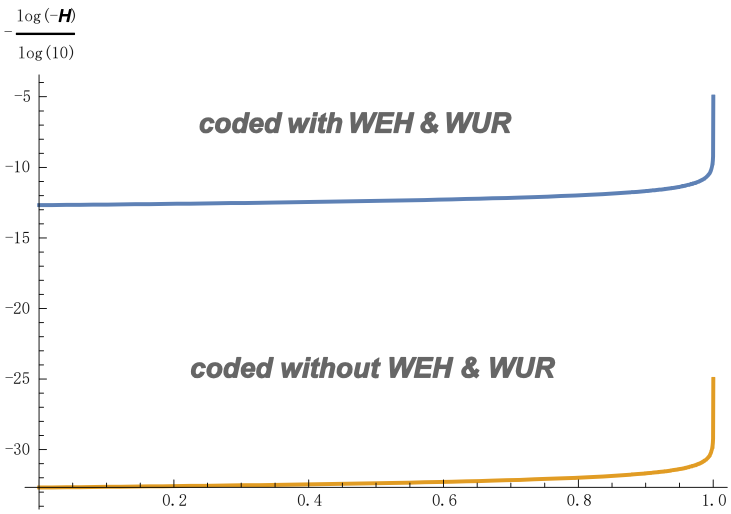

Fig. 6 This figure shows the value of the balance function $-\lg(-H)$ for different cases with α varying from $0 \sim 1$ when source node rate $R_{ij} = 250Kbps$ and the data is coded with RRNS(128, 60, 32).

8 An experiment on practical sensor node TelosB

In Section VI, we formulated the joint lifetime-rate-reliability trade-off problem by introducing the weight parameters α as showed in Eq. (18) and we found that a suitable error control coding scheme is the key to solve the joint lifetime-rate-reliability trade-off problem by our analysis. In Section VII, we proposed a method about how to choose the most suitable coding scheme according to the realistic application's requirements. As showed in Fig. 3, the value of the balance function H is larger than the others when $\alpha = 0.9$ and $R_{ij} = 250Kbps$ which means that RRNS (128, 60, 32) is more suitable for the desired system performance. To verify the effectiveness of the proposed method in pratical sensor nodes, we plot the lifetime of sensor mote TelosB using different coding schemes when $\alpha = 0.9$ and $R_{ij} = 250Kbps$ as showed in Fig. 7. TelosB is a IEEE 802.15.4 compliant sensor mote that runs a TinyOS operating system with a CC2420 radio ($http://www.willow.co.uk/TelosB\_Datasheet.pdf$) and the battery power of the sensor node is taken as 9000 milli-Amphere-Hour (capacity of 2 standard 1.5-volt batteries used in sensors). By observing Fig. 7, we can find that RRNS (128, 60, 32) has better lifetime than the other four coding schemes and the sensor node utility of RRNS (128, 60, 32) which is calculated by $\log_2(R_{ij}P_s)$ is also the largest among these five coding schemes, which have verified the effectiveness of the proposed method in finding the most suitable error control coding scheme and solving the joint lifetime-utility trade-off problem.

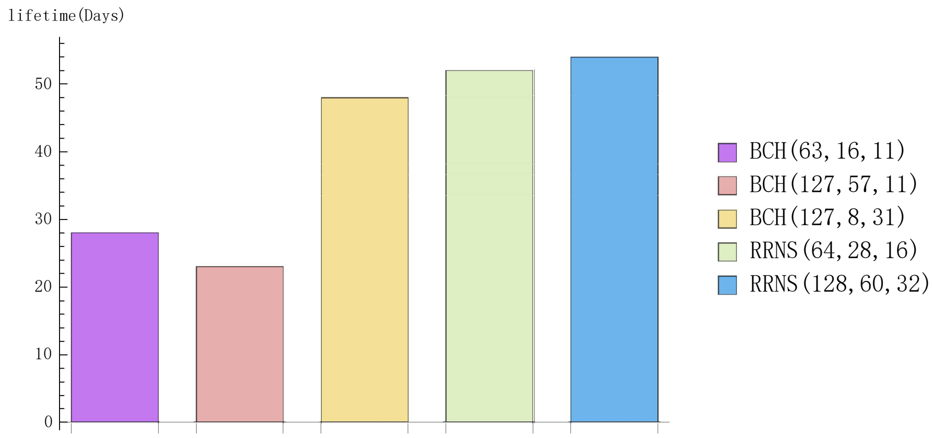

Fig. 7 This figure shows the lifetime of sensor mote TelosB for different coding schemes when α=0.9 and $R_{ij} = 250Kbps$.

9 Conclusion

A dedicated RF source which is wireless, cheap and readily available in the form of transmitted energy is deliberately deployed to supply energy to the nodes at a designated rate and optimum frequency. Wake-up radio scheme is proposed to decrease the idle listening energy consumption of sensor nodes. Error control coding is used to improve the reliability of the transmission and prolong the lifetime of sensor nodes by reducing re-transmission. A joint utility-lifetime trade-off problem incorporating WEH, WUR and ECC schemes is formulated and solved by choosing the suitable error control code to maximize the balance function H . Simulation results verify the effectiveness of the proposed schemes in prolonging the lifetime and improving the utility of the system.

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