A Weight-Optimized Source Rate Optimization Approach in Energy Harvesting Wireless Sensor Networks

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***Abstract*—Using harvestable energy in Wireless Sensor Networks (WSNs) has gained considerable popularity recently. However, how to utilize the unstable power supply to achieve quality performance is still a challenge. In this paper, we propose a Weight-Optimized Source Rate Optimization (WOSRO) approach which allows the WSN system to adaptively control source coding rates by choosing the most valuable data packets to transmit. In this approach, the packet selection strategy is optimized by considering multimedia distortion reduction, energy cost, energy neutrality constraint and power saving efficiency. Simulation results show that the proposed data packet selecting strategy significantly improves data transmission quality by exploring harvesting-storage energy neutrality and multimedia data packet importance.**

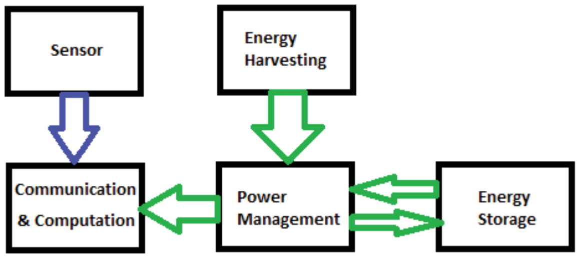

Fig. 1. System Model of WOSRO

I. INTRODUCTION

Energy Harvesting Wireless Sensor Network (EHWSN) has gained considerable popularity in various applications, for example, precision agriculture, environment monitoring, and surface water quality assurance. The EHWSN has the ability of building a connection between the physical worlds and computing infrastructures. On the other hand, the unlimited power supply from the environment (e.g. sun light, wind power, etc.) gathered by an energy harvest module makes the life time of the sensor network much longer than the traditional battery powered WSN. However, the instability of environmental power supply makes the EHWSN system running with low communication performance guarantee.

In this paper we propose a new Weight-Optimized Source Rate Optimization (WOSRO) approach to improve the data transmission quality (i.e. the data distortion reduction) for an EHWSN. The system model is illustrated in Figure 1, where environmental energy will be gathered by the energy harvesting module, and will be transferred to the power management module. The power management module switches the energy storage module between charge and discharge states. From this figure we show that WOSRO builds a relationship between energy cost and data packet transmission quality. By using the relationship, we can significantly improve data transmission quality.

Although there are a plethora of studies in sensor network energy management, research in optimized data packet selection adapting to harvestable energy input has seldom been reported. Research in [3] proposed a lifetime optimization scheme of the WSN under reliability constraint. The work in [4] used neural network dynamics to maximize the lifetime of the WSN without using any centralized computing nodes. Besides using battery as the power supply, many papers started to use energy harvesting inputs in their design [2] [5] [6]. In [2], the authors pointed out that information about future harvestable energy availability was required in the EHWSN study. Based on the condition of energy neutrality and practical power scaling method, research in [1] provided an adaptive duty cycling algorithm to seek higher environmental energy utilization. Our previous research in [7] focused on investigating the tradeoff between Automatic Repeat reQuest (ARQ) limit and the packet transmission error rate, but the source coding rate control was not considered in EHWSN. Some other related research also studied sensor network design strategies, including adjusting data packet length [8], improving node design [10][11], optimizing sleep/work time [6][9].

Fundamentally different from existing research, we build a simplified EHWSN source coding rate control model with energy neutrality and wireless transmission reliability constraints, and optimize the data packet selection by adapting the energy harvesting capability.

The rest of this paper is organized as follows. In Section

II, we mathematically formulate the problem as a constraint optimization problem. In Section III, the constraint and objective function are analyzed. In Section IV, we show numerical simulation results and in Section V we draw conclusion. Table I summarized the symbols used in equations in this paper.

TABLE I
SYMBOL DEFINITION

Symbol	*Notation*
S_{total}	distortion reduction of all transferred data during the total working time
S_i	distortion reduction of transferred data in time segment i
$S_{\min}$	distortion reduction of reliability required
E_i	energy cost in time segment i
E_i'	energy cost in time segment i if system work in charge mode
E_i''	energy cost in time segment i if system work in discharge mode
$\overline{E}_i$	energy produced by energy harvesting system in time segment i
B_0	the residue energy in the battery when system start
λ	Bit Error Rate (BER)
l_j	length of a certain data packet j
ρ_j	packet error rate of certain data packet j
q_j	distortion reduction of a certain data packet$j$
P_{on}	power of the energy consumed by system for sending data packet
P_{off}	denote the system energy cost in sleep mode or power saving mode
t_j	time cost for sending a certain data packet j
R	data transfer rate
w_j	weight of a certain data packet j
η	charging efficiency

II. PROBLEM STATEMENT

In this paper, we want to get the overall transmission quality as high as possible in such a low and unstable power supply. Here, we assume the total working time can be divided into several different segments. By optimization we mean to achieve the highest quality of transmission. The overall problem can be mathematically formulated as a packet selection problem in each segment with energy neutrality and reliability constraints.

In each segment, we assume the environment of wireless communication is stable for the short period of optimization time, and source nodes need to send data packets constantly. These data packets have different qualities (i.e. distortion reduction) and lengths which can be acquired in advance. Let S_{total} denote the expected value of all transferred data packets during the total working time, S_i denote the expected value of the transferred data packets in time segment i . The overall problem can be formulated as follows.

$$S_{total} = \sum_{i=0}^{N-1} S_i \tag{1}$$

Let $\overline{E}_i$ denote the energy produced by energy harvesting system in time segment i , E_i denote the energy cost of this node in time segment i , and B_0 denote the initial residue energy in the battery. Then the energy neutrality constraints of this system can be formulated as follows.

$$-\sum_{i=0}^{N-1} E_i + \sum_{i=0}^{N-1} \overline{E}_i + B_0 \geq 0 \tag{2}$$

Let $S_{\min}$ denote the lowest distortion reduction of reliability required. Then the reliability constraint can be formulated as

$$S_{\min} \leq S_i \tag{3}$$

In the next section, we will analyze the optimization problem and provide solutions to optimize data packet selection.

III. PROPOSED WOSRO SOLUTION

Let λ denote the Bit Error Rate (BER), l_j denote length of a certain data packet j. Then the packet error rate ρ_j can be estimated as the following equation.

$$\rho_j = 1 - (1 - \lambda)^{l_i} \tag{4}$$

We assume that in a certain segment i, regardless of the number of received data packets, there are m packets to be sent out. Let q_j denote the distortion reduction of the certain data packet j. Then the expected quality of the transferred packets in segment i can be formulated as

$$S_i = \sum_{j=1}^{m} q_j \left(1 - \rho_j\right) \tag{5}$$

Let P_{on} denote the power consumption for sending data packets, and let P_{off} denote the system energy cost in sleep mode or power saving mode, where $P_{off} << P_{on}$. For sending a data packet with length l_j, system active time is t_j. Let R denote the data rate between two nodes in the system. Let e_j denote the energy cost for sending a certain data packet j once, then it can be qualified as

$$e_j = P_{on} \times \frac{l_j}{R} \tag{6}$$

There are two different working modes for an EHWSN node: charge mode and discharge mode. When energy harvest module can produce enough power for the EHWSN system, node works in charge mode; otherwise, node works in discharge mode. In charge mode, system uses the power from the energy harvesting module directly, and the surplus power will be used to charge the energy storage module. In discharge mode, because of the energy harvesting module cannot provide desirable power, energy storage module will discharge to support the system. The output of energy harvesting module will charge the energy directly in this mode. In time segment i, assume the indices of the sent data packets are j ($1 \leq j \leq m$) . If the system works in charge mode, system energy consumption would be:

$$E_i' = \sum_{j=1}^{m} e_j + \int P_{off} dt - \sum_{j=1}^{m} P_{off} \frac{l_j}{R} \tag{7}$$

Let η denote the charge efficiency of charge and discharge. If the system works in discharge mode, system level energy consumption would be:

$$E_i'' = \frac{1}{\eta}(\sum_{j=1}^{m} e_j + \int P_{off}dt - \sum_{j=1}^{m} P_{off}\frac{l_j}{R}) \tag{8}$$

Since $P_{off} << P_{on}$, according to equations (6), (7) and (8), the system level energy consumption can be simplified as follows for charge mode:

$$E_i' = \frac{P_{on}}{R}\sum_{j=1}^{m} l_j \tag{9}$$

And for discharge mode, the energy consumption is:

$$E_i'' = \frac{P_{on}}{\eta R}\sum_{j=1}^{m} l_j \tag{10}$$

Then $E_i$will be E_i'if system works in charge mode and be E_i''if system works in discharge mode. Based on equations (4), (5), (9) and (10) we can quantify the relationship between S_i and E_i :

$$\frac{S_i}{E_i} = C\sum_{j=1}^{m} f(q_j, l_j) \tag{11}$$

In the above equation, the parameter C defined as $\frac{R}{P_{on}}$, is a constant value for a certain system. Let $w_j = f(q_j, l_j)$ denote the weight for a certain data packet j, when the system is running in charge mode:

$$w_j = \frac{q_j(1-\lambda)^{l_j}}{l_j} \tag{12}$$

When it is in discharge mode:

$$w_j = \frac{\eta q_j(1-\lambda)^{l_j}}{l_j} \tag{13}$$

Finally, our objective can be expressed as to send the data packet which has a higher weight (w_j). Algorithm 1 describes the details of the proposed WOSRO optimization process: how to get data packet weight and select the ones need to be sent at a higher priority.

Algorithm 1 Weight-Optimized Source Rate Optimization (WOSRO) Data Packet Selection

1: Define Input: energy harvesting profile P[i]; wireless channel bit error rate λ ; charge efficiency η; source data rate DR; segment count N; data packets quality q[R*N]; data packets lengths l[R*N]; radio transmission power P_{on}; data transmission rate R;segment time window length T.
Define Output: array OUTPUT, the index of data packets need to be sent out.
2: TotalEnergy = 0
  For i = 1 to N
    TotalEnergy = P[i]*T + TotalEnergy
  End
3: For i = 1 to N
    If workMode(i) == charge_mode Then
      For j = 1 to DR
        $k = (i-1)*j+j$
        $w[k] = \frac{q[k](1-\lambda)^{l[k]}}{l[k]}$
      End For
    Else
      For j = 1 to DR
        $k = (i-1)*j+j$
        $w[k] = \frac{\eta * q[k](1-\lambda)^{l[k]}}{l[k]}$
      End For
    End If
  End For
4: [Sorted_w, Sorted_Index] = Sort(w,'descend')
5: CurrentEnergy = TotalEnergy
  For i = 1 to N * DR
    If workMode(i) == charge_mode Then
      $e_i = \frac{P_{on}}{R}l_i$
    Else
      $e_i = \frac{P_{on}}{\eta R}l_i$
    End If
    If $e_i <$ CurrentEnergy Then
      CurrentEnergy = CurrentEnergy - e_i
      OUTPUT.Add(Sorted_Index[i])
    End If
  End For
6: Get the array of OUTPUT as results;

IV. SIMULATION

In this section we perform a numerical simulation study to explore the potential performance gain of the proposed approach. The performance is evaluated in terms of data transmission quality (i.e. distortion reduction). The energy neutrality and reliability conditions violation performance are also studied.

The simulation is performed with the following parameters. Radio transmission power is 20mW, circuit board power consumption in sleep mode is 0.01mW and transmission data rate is 19.2kb /s. The optimization period is 24 hours i.e. N =24 and each time segment is 1 hour. The source packet sample rate is 1000 packet/hour. Assume battery recharging efficiency is 0.8 and the wireless channel bit error rate is 0.0001. The proposed approach is denoted as "WOSRO", implementing the concept of unequal treatment for different data packets. For comparison, we also present the typical approach of data selection, which is First Come First Serve (FCFS). In the meanwhile, we also study the system reliability. We also compare the performance with a third approach which is based on FCFS, which assigns the same amount of energy to each segment. This approach is denoted as First Come First Serve with Energy Balance (FCFSEB).

The energy harvest profile over 24 hours in simulation is approximated based on results in [12], which were the statistical results of solar energy profile in Los Angeles form the beginning of June through the middle of August for a total 72 days. Here we assume the nodes run WOSRO data packet selecting program once every day in 9:00 am. Because of this, the solar energy profile in simulation will start at 9:00am (T = 1). We also assume the energy harvesting profile information and data packet distortion information can be acquired or predicted before applying optimization on wireless node. Table 2 summarizes the energy harvesting profile we used in simulation.

TABLE II
SOLAR ENERGY PROFILE

T	1	2	3	4	5	6	7	8
P(mW)	30	40	50	60	58	54	50	40
T	9	10	11	12	13	14	15	16
P(mW)	25	10	0	0	0	0	0	0
T	17	18	19	20	21	22	23	24
P(mW)	0	0	0	0	0	5	10	20

According to Table 2, system starts at T = 1 when solar energy is ample that the system is working in the charge mode. When T = [10, 23], solar power is smaller than radio transmission power (20mW), and the system works in the discharge mode. And when T = 24, solar energy is strong enough that system works in the charge mode again.

The residue energy versus time performance is illustrated in Figure 2. The results in this figure illustrate the violation of energy neutrality condition. From this figure we can see, FCFS consumes nearly all the energy gathered in current time segment. Since energy neutrality is not considered in the FCFS approach, the balancing between energy harvesting and energy consuming is not optimized. We can see the system running FCFS will stop working because of the power exhaustion.

Unlike FCFS, both WOSRO and FCFSEB save energy in charge mode. By planning utilization of harvested energy resource, WOSRO and FCFSEB succeed in avoiding the violation of energy neutrality constraint. We can see FCFSEB stores more power than WOSRO in charge mode. Obviously, during charge period, the consumption of system running in FCFSEB is lower than the one running in WOSRO; in discharge period, it is on the contrary.

Figure 3 is the illustration of transmission quality versus time. Since we are using the wavelet transform result of images as the sample data packets, distortion reduction is the transmission quality. Comparing FCFS and FCFSEB, in T = [1, 10], FCFS gains a higher distortion reduction by using more power in transmission. The result shows that, system running in FCFS stopped when T = [12, 21] because neither battery nor energy harvesting system can supply the power consumed by system. Considering reliability constraint, WOSRO and FCFSEB will much better than FCFS.

Regarding the transmission quality of WOSRO and FCF-SEB, WOSRO gets remarkably higher performance than FCF-SEB. It is due to two reasons. First, WOSRO uses weight to evaluate each data packet. When energy is not abundant, WOSRO can select the most valuable ones to send. Second, WOSRO not only takes harvested energy resource into consideration, but also takes account in the energy consumed in different working modes. In consideration of the energy con-

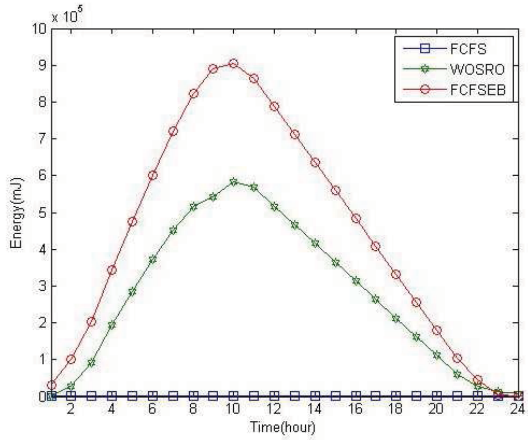

Fig. 2. Energy remaining in battery

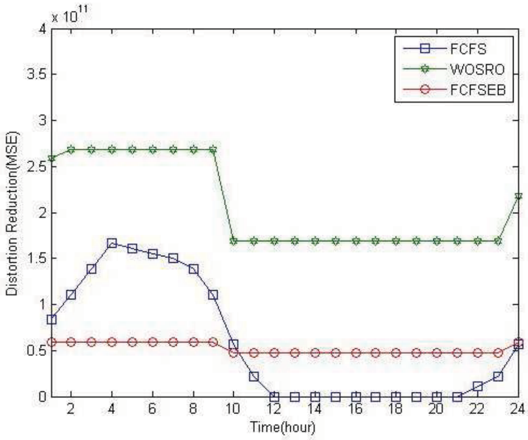

Fig. 3. Transmission quality

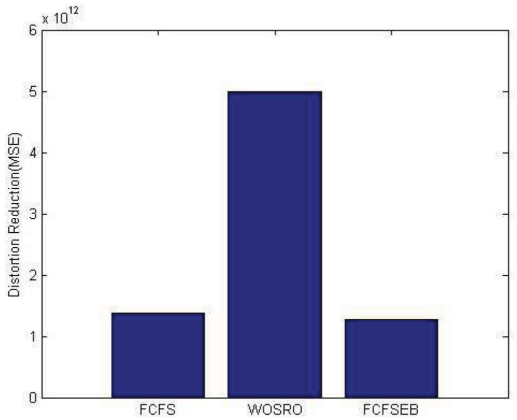

Fig. 4. Overall transmission quality

sumption in different working modes, the distortion reduction during the discharge mode (T = [10, 23]) is lower than that during charge mode.

Figure 4 summarizes the overview of the transmission quality of these three approaches. Even though FCFS has a higher overall quality than FCFSEB, it violates the energy neutrality and reliability constraint. WOSRO, on the other hand, approaches the highest overall transmission quality following the two constraints.

V. Conclusion

In this paper we have proposed a new WOSRO data packet selection approach to improve data transmission quality for energy harvesting wireless sensor networks. In the proposed approach, the data packet sending queue is sorted according to the packet distortion features and the energy harvesting profile. Energy neutrality and reliability constraints are considered in the optimization. We also use solar energy harvesting system as a simplified example to testify the proposed approach. Simulation results demonstrate that the proposed approach has improved the transmission quality significantly, while assuring the energy neutrality and reliability constraints.

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