An Energy Management Scheme for Solar-Powered Wireless Visual Sensor Networks toward Uninterrupted Operations

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Abstract — Energy harvesting is required for the uninterrupted operation of Wireless Visual Sensor Networks (WVSNs). Solar energy is considered one of the effective energy harvesting sources for WVSN applications. In this paper, we propose an efficient energy management scheme for solar-powered WVSNs. The proposed scheme aims to maximize the overall quality of captured video while maximizing the network operation time. Our energy management is based on the prediction of energy supply and demand. The simulation results show that the proposed method achieves higher sampling quality of video data and longer WVSN operation time by 26.66% on average (up to 33.14%) compared to the greedy energy distribution approaches.

Keywords – energy management; event occurrence prediction; solar energy harvesting; wireless visual sensor network

Introduction

Deep concerns about security, safety, and environmental monitoring issues give rise to increasing demands on wireless visual sensor networks (WVSNs). Especially, WVSN that is comprised with clusters and each cluster has several sensor nodes connected by wired links can be used for monitoring construction health and safety, oil or/and gas pipeline security, and other social infrastructure status.

Researchers have exerted great efforts in energy minimization and lifetime maximization problems in WVSNs [1]-[4]. System-level energy-aware design methods including hierarchical event detection considering energy and accuracy trade-off were proposed [2]. And power-rate-distortion optimization for video encoder were employed to achieve minimal energy consumption in WVSN nodes [3,4]. In spite of these huge efforts, proposed methods have limitations to solve energy problems in WVSNs.

Energy harvesting from surroundings needs to be employed to tackle the problem fundamentally. There are plenty of works about energy harvesting [5]. The solar energy harvesting has been a popular topic in wireless sensor networks [6]-[8]. To design efficient system, various components have to be considered as well as solar energy harvester [6]. M. Minami et al. implemented the solar-powered wireless sensor network system for environmental monitoring [7]. Besides, due to fluctuation of solar energy, efficient energy allocation schemes are proposed to allocate uniform amount of energy even for nighttime [8].

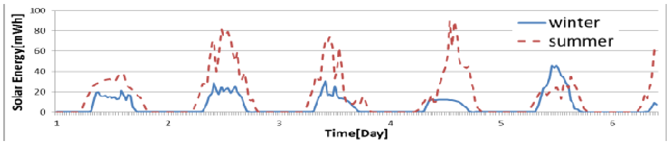

Fig 1. An example of solar radiation energy change by time

In this paper, we propose an efficient energy management algorithm in solar-powered WVSNs for maximum operation time while pursuing the quality of video data. A careful energy management method coupled with prediction scheme of energy supply and demands is needed.

Our contributions are two folds. Firstly, we applied solar energy harvester to WVSNs consisting of sensor node-clusters with two communication channels: in forms of wired and wireless links. Secondly, we proposed efficient dynamic energy management scheme in node-level as well as cluster-level coupled with an energy demand and supply prediction method to maximize the WVSN lifetime.

A Solar-Powered Wireless Visual Sensor Node Overview

A. Solar Energy Harvester

We select solar radiation energy for energy harvesting because it provides high energy density which satisfies energy demand of our WVSN system [5]. Solar energy has two characteristics: periodicity and fluctuation as shown in Fig 1. Daily period of solar energy is typically 24 hours. Yearly period reflects seasonal solar radiation changes. Furthermore, solar energy dynamically varies even throughout a day. It is affected by the amount of clouds in the sky or other weather conditions.

B. Single Node Architecture

As shown in Fig. 2, our sensor node operates by battery. Most of the blocks in a sensor node normally sleeps deeply except event detector which wakes up the system when events occur to capture, encode, and store the captured video data.

The stored image data are transmitted to base station by wireless transmitter or it may be sent to other nodes by wired transmitter. We divide the operation time into equal-sized time slots. For each time slot, we can apply different operation parameters for each node energy management. The energy consumption of each node can be dynamically controlled by changing the video sampling rates for every time slot. The video sampling rate for time slot i (ψ^i) is defined as the product of image width (n_w^i), image height (n_h^i), and frame rate (r_{fr}^i). Energy demand of our sensor node is as follows.

$$E_{dmd}^i(\psi^i) = E_{ed} + R_{ev}^i \cdot (E_{cis} + E_{ctr} + E_{enc}) + R_{ev}^i \cdot \psi^i \cdot R_{enc} \\ \cdot (E_{fla,w} + E_{fla,r} + E_{tx})$$

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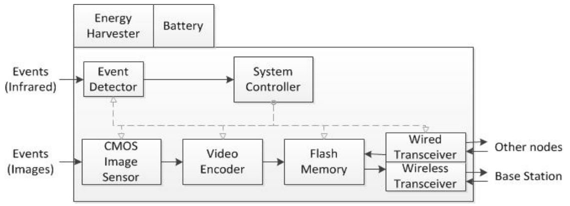

Fig 2. Our WVSN node architecture

The Energy demand for time slot i (E^i_{dmd}) is linearly proportional to the sampling rate. We define event occurrence rate (R^i_{ev}) as event occurrence time ratio with respect to the length of a time slot. E_{ed},E_{cis},E_{ctr}, and E_{enc} are maximum energy consumption of event detector, CMOS image sensor, system controller, and video encoder in a time slot (L), respectively. R_{enc} denotes the bitrate (the number of bits per second, *bpp*) of video encoder. $E_{fla,r}$, and $E_{fla,w}$ expresses energy consumption of flash memory when reading and writing one bit of data. E_{tx} denotes energy consumption of wireless transmission to base station for a bit.

C. Cluster Architecture

We assume that the WVSN are formed with a set of clusters each of which consists of four sensor nodes. The sensor nodes in a cluster are connected via wired links as well as wireless links. The wired links are used for energy transmission to balance the energy supply and demand of nodes in a cluster. In addition, data can be also transferred to other nodes in the same cluster via wired links in energy-deficiency situations. Fig. 3 shows the overview of our proposed WVSN which consists of clusters.

There are two advantages of wired node clustering architecture as follows. First, it can solve energy imbalance problem in a cluster by sharing the energy supply and demand in energy-deficiency situation. Second, a cluster can provide more reliable operation of WVSN than the independent operation of each node because wired and wireless channels are both available in case of one of communication links damage.

For the cooperation among nodes in a cluster toward energy resource sharing, each node can set up its modes for video capturing, energy transfer, and data transfer:

- Energy mode: *receiving, transmitting, no sharing*.
- Data mode: *receiving, transmitting, no sharing*
- Video Capturing mode: *enable, disable*

D. Control Parameters for Energy Management

Due to the solar energy supply fluctuation and event occurrence rate changes, the energy consumption rate for video data capturing should be controlled to maximize the operation time of WVSN. We manage the energy consumption by two knobs as follows:

- *video sampling rates* by changing frame sampling rate and resolution of each node, and
- *Operation mode* of data, energy, and video capturing of each node to prolong the network operation time.

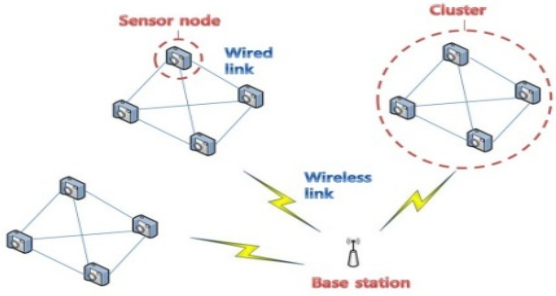

Fig 3. Our WVSN cluster structure with wired links

In case energy supply enough for all the node in a cluster, there is surplus energy. In that case it would be better to increase the sampling rates to maximize the data quality. On the other hand, in case that energy supply is not sufficient, the sampling rate should be lowered for longer operation time.

In winter season with quite less radiation for long time, node operation may be interrupted even with the minimal sampling rates. In such severe shortages of solar radiation, a node with less energy than minimum level should be in *energy receiving* mode and the neighboring node with sufficient energy level should be in *energy transmitting* mode. Or, a node with minimum energy can be in *data transmitting* mode and another node with enough energy can be *in data receiving* mode. Captured video data at the nodes of *data transmitting* mode are transferred to the nodes of *data receiving* mode via wired link. The data will be transmitted to base station eventually.

Problem Definition

Given solar radiation energy supply and energy demand statistics over time slots for each sensor node, we should find the proper energy use assignment and energy and/or data transferring mode of each node in a cluster at each time slot. The design objectives are two: (1) maximizing the operation time of WVSN and (2) maximizing the sampling data quality. The objective (1) has higher priority than objective (2). The network operation time (T_{act}) is defined as the sum of time duration in which all of nodes in a cluster have enough energy to work normally for video capturing and transmitting. The sampling data quality of time slot i can be controlled by sampling data rate of node j ($\psi^{i,j}$). The transmission of energy and data between nodes are defined by the amount of transmitted energy and data from node j to k for time slot i($E^{i,j\to k}_{tx}$,$D^{i,j\to k}_{tx}$).

Our Energy Management Scheme

A. Energy Supply and Demand Prediction Method

We assume that a sensor node receives accurate weather forecast information from the weather center including cloud amounts in the sky. We assume to use the cloud cover radiation model (CRM) described in [10] to predict the values of solar radiation energy. The error of the method in [10] is about 28% and we simulated the same accuracy level in our experiments to reflect the correctness of the prediction.

For energy demand prediction of each node, we use the event occurrence prediction based on the past event occurrence statistics because our sensor node consumes energy only when events occur. We utilize the modified moving average (MMA) algorithm [9]. MMA predicts event occurrence rates calculated by weighted average of the event occurrence rates from previous time slots in several hours and days.

B. Overall Scheme of our WVSN

For every node and time slot, (1) single node operation or (2) cluster operation is selected. The decision is based on the available energy supply and demand prediction. When energy is sufficient single node operation is performed by algorithm 1 while cluster operation is performed by algorithm 2 and 3 when energy level is low.

C. Single Node Operation

Algorithm 1 shows how to assign sampling rate for each node in energy-sufficient condition. If the energy is not sufficient algorithm 2 and algorithm 3 should be used instead. The algorithm 1 does not assign the available energy to a node, but assigns proper amount of energy for the next time slot based on the energy supply and demand prediction in terms of long(L1), middle(L2), and short(L3) time range. Starting with the longest range (L1) with highest sampling rate, algorithm 1 assigns usable energy to each range hierarchically to prevent the early exhaustion of energy. For each node and time slot, the algorithm 1 selects the smaller energy between predicted demand and predicted supply for L1 range as usable energy and assigns L2 range the amount of usable energy proportional to the ratio of L1 and L2 length. For L2 and L3, the similar computations are repeated in sequence and finally get the energy assignment in terms of sampling rates for next time slot. This algorithm helps nodes to utilize energy supply for best video quality while preventing node operation interruption.

D. Cluster Operation

In energy-insufficient conditions, cluster co-operation algorithm is applied using minimum sampling rate. First, we decide capturing enable modes for each node. If the sum of energy demands with minimum sampling rate is greater than sum of predicted energy supply in a cluster-level, we select some of nodes in a cluster to be in disabled mode. The disabled nodes are powered down and act as an energy harvester to other nodes until the situation is recovered back to energy-sufficient condition.

Algorithm 2 shows the decision flows for the data sharing mode and the amount of transmission data. Note that wireless transmission to the base station accounts for the dominant energy consumption of our sensor node. To balance the remaining battery energy level among the nodes in a cluster, the amounts of wireless transmission should be distributed using the wired data transmission in a cluster. Note that the wired transmission incurs the energy overhead for memory read at sender and write operations at receiver.

Algorithm 3 shows the decision flow for the energy sharing mode and the amount of energy transmission of each node. We set the default energy modes of all the nodes as no sharing. Since the capturing disabled node acts as energy harvesters to other nodes in a cluster, we set the energy mode of these nodes as *energy transmitting*. Then, amounts of insufficient energy use of other nodes are calculated based on the comparison of current battery energy level plus predicted energy supply and the predicted energy minimum consumption at nodes.

Algorithm 1. Sampling Rate Decision by Energy Prediction

```
1:if $\widetilde{E_{dmd}^{L1,j}}(\psi^{max}) < \widetilde{E_{spp}^{L1,j}}$ then$E_{use}^{L2,j} \leftarrow \frac{L2}{L1} \cdot \widetilde{E_{dmd}^{L1,j}}(\psi^{max})$
    else then $E_{use}^{L2,j} \leftarrow \frac{L2}{L1} \cdot \widetilde{E_{spp}^{L1,j}}$ end if
2: if $E_{use}^{L2,j} < \widetilde{E_{spp}^{L2,j}}$ then $E_{use}^{L3,j} \leftarrow \frac{L3}{L2} \cdot E_{use}^{L2,j}$
    else then $E_{use}^{L3,j} \leftarrow \frac{L3}{L2} \cdot \widetilde{E_{spp}^{L2,j}}$ end if
3 :if $E_{use}^{L3,j} < \widetilde{E_{spp}^{L3,j}}$ then $E_{use}^{i,j} \leftarrow \frac{1}{L3} \cdot E_{use}^{L3,j}$
    else then $E_{use}^{i,j} \leftarrow \frac{1}{L3} \cdot \widetilde{E_{spp}^{L3,j}}$ end if
4: Find $\psi^{i,j}$ having the smallest $\left| E_{use}^{i,j} - \widetilde{E_{dmd}^{i,j}}(\psi^{i,j}) \right|$
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(In the above equations, $\widetilde{E_{dmd}^{Li,j}}$ and $\widetilde{E_{spp}^{Li,j}}$ is the predicted energy demand and supply for Li period for node j respectively. $E_{use}^{Li,j}$ is assigned energy to node j for Li period.)

Algorithm 2. Data Mode Decision for nodes in each cluster

```
1:Calculate amount of data that can be transferred via wireless link to the
    base station ($D_{tx}^{i,j}$) considering the available energy for each node j
    at the time slot i.
2:foreach node j in a cluster at time slot i loop
    if node capturing mode = enabled then
        if $D_{cap}^{i,j} > D_{tx}^{i,j}$ then Set data transmitting mode.
        else if $D_{cap}^{i,j} < D_{tx}^{i,j}$ then Set data receiving mode.
        else then Set no data sharing mode. end if
    else Set no data sharing mode. end if
  end loop
3:Find the amount of data transmission $D_{tx}^{i,j \to k}$ for each node j to its
neighboring node k at time slot i.
```

(In the above equations, $D_{cap}^{i,j}$ is the data volume to be captured in time i at node j and $D_{tx}^{i,j}$ is the data volume that can be transmitted via wireless.)

Algorithm 3. Energy Mode Decision for nodes in each cluster

```
1:Set the energy mode of all nodes with no sharing
2:Set energy mode of capturing disabled nodes as transmitting.
3: foreach node j in a cluster at time slot i loop
        if $E_{bat}^{i,j} + \widetilde{E_{spp}^{i,j}} < E_{use}^{i,j}$ then Set energy mode of node i as
        receiving. end if
    end loop
4:Calculate the sum of $E_{tx}$ from capturing disabled nodes
5:Calculate the sum of $E_{rx}$ for all nodes with $E_{bat}^{i,j} + \widetilde{E_{spp}^{i,j}} < E_{use}^{i,j}$
6:if $E_{tx} < E_{rx}$ then Set energy mode as transmitting for all nodes
except the capturing disabled nodes. end if
7:Find the amount of transmitted energy $E_{tx}^{i,j \to k}$ for each node j and its
neighboring node k for time slot i.
```

(In the above equations, $E_{bat}^{i,j}$ is remaining battery energy of node j at time i, E_{tx} is transmitted energy and E_{rx} is received energy)

Experimental Results

In our simulation, we utilize real measured solar harvesting energy for four seasons from [12], solar harvester efficiency from [11], and event occurrence from KAIST video sequence. We set parameters related to the energy consumption for

WVSN according to the data from published works.

We define 10 levels of sampling rates to control the energy demand level at each node. The levels ranges from QCIF@3fps to CIF@30fps. We set the duration of a time slot is 30 minutes. We set L1, L2, and L3 time length for energy management algorithm as 5 days, 1 day, and 5 hours, respectively.

Fig. 5 shows the status of single node when a node operates independently each other. Fig 5 (a) shows the remaining battery energy level of a node in fall season. Our proposed single node operation with sampling rate control leads to stable remaining battery energy while operations with high and low sampling rate reach to energy waste and interrupted operation. The sampling rates change in a node is shown in Fig. 5(b). Fig. 6 shows the remaining battery energy level of nodes in a cluster with cluster co-operation situation in winter season. Some of nodes in a cluster have stopped their operations when independent single node operation is applied as shown in Fig 6 (a). However, our proposed cluster operation leads to a longer system operation time as shown in Fig 6 (b). As shown in Fig 7, the simulation results with different scenarios show that our clustered WVSN that collaborate each other in each cluster has extended the operation time by up to 33.14% (26.66% on average) compared to the independent node operation.

Conclusion

In this paper, we propose an efficient energy management algorithm which prolongs network operation time and maximizes data quality for solar-powered WVSNs. We utilized the wired connections in a cluster to share energy supply and data transmission burden among nodes in a cluster. The simulation results with real video surveillances show that the proposed method achieves longer WVSN operation time by 26.66% on average (up to 33.14%) compared to the greedy energy distribution approach.

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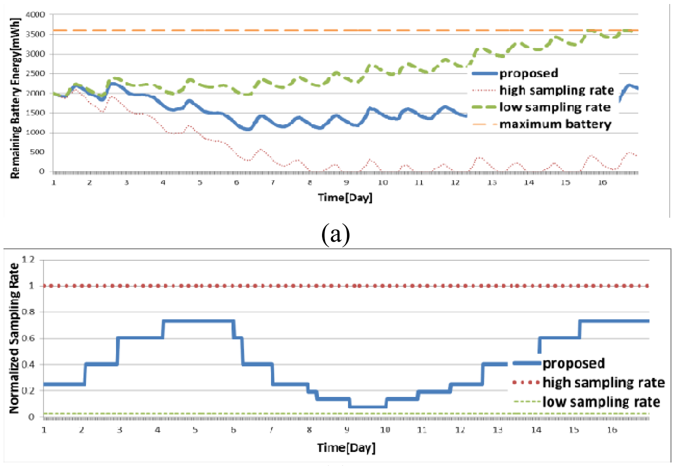
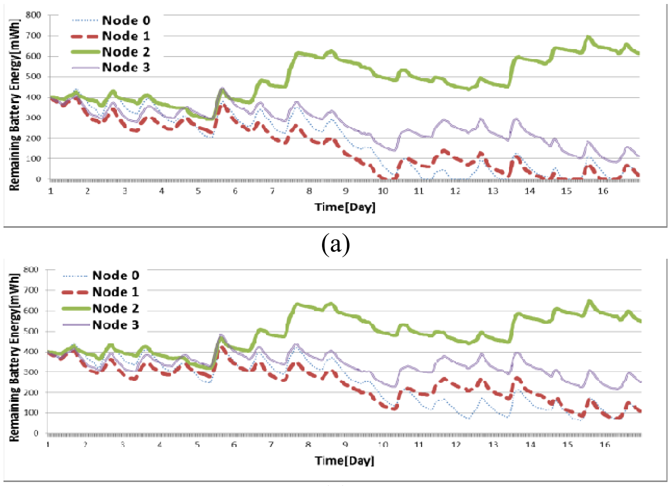


(a)

(b)

Fig 5. Simulation Results: (a) the remaining battery energy of a single node in spring and (b) its sampling rate change



(a)

(b)

Fig 6. The remaining battery energy of each node in a cluster (a) when independent node operation is applied and (b) when the collaboration among nodes in cluster is applied.

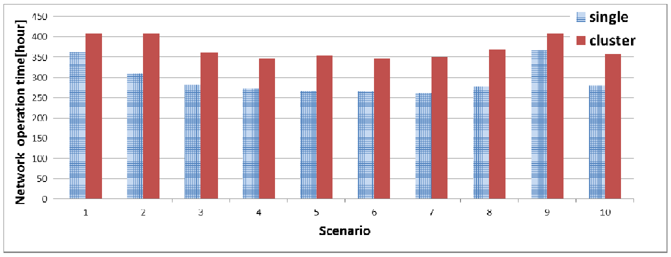


Fig 7. WVSN operation time comparison for ten real scenario