Research on Energy Control Policy in Low-Power Consumption Wireless Image Sensor Networks

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Abstract. With its low power consumption characteristics, a new type network named wireless sensor image networks (WISN) combined the traditional wireless sensor networks (WSN) and the latest image sensing technology have been attracting attention. This paper presents a kind of wireless image sensor networks energy optimization methodology which was based on the routing nodes buffer state schedule. According to the running mechanism of routing nodes in wireless sensor networks, when a sensor node transfers data to another node, the energy consumption will happen mainly during transit between the routing nodes, each routing node will analysis and storage the state transition in its buffer, this state transition was usually caused by sending and receiving operation. Also, the node can dynamically adjust their energy consumption count and service values compared to the other nodes, also these nodes can determine itself whether to be a critical path node or not. During the data transmission in the network, the nodes can be scheduled to be used as the routing node with regarding of each energy level, and finally the network can sustain longest.

Keywords: Wireless Image Sensor Networks · Low Power Consumption · Energy control strategy · Reliability · Performance analysis

1 Introduction

The low-power consumption WISN (Wireless Image Sensor networks) is a kind of particular WSN (Wireless Sensor networks), which consists of sensor nodes equipped with an image sensor or sensors [1, 2], using traditional low-power wireless sensor networks such as IEEE 802.15.4 protocol to communicate between nodes inside. Because the image sensor nodes usually need to be set up in remote areas or the harsh environment with lack of power supply, the energy consumption control method becomes particular serious to the WISN with high energy consumption image sensors. In addition to reduce the energy consumption of the every sensor node itself, it is more important to control that of the whole network, and the consumption during transit from the sensor node to sink node will be the key point [3].

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However, to the best of our knowledge, the theoretical analysis and research works regarding the problem of energy consumption in WISN are relatively lacking, Some research using the traditional WSN energy control strategy to improve the network life cycle in WISN always ignore the following observations:

1. Because of the high energy consumption of image sensor, so there exists function difference between the routing nodes in WISN and the same nodes in traditional WSN.
2. With the traditional energy consumption control method, when a large number of data packet from the same sensor node need to be transmitted, it will be easier to make effective path failure because the cluster head died for battery drain.
3. There may be exists data dependence between packet arrived in the sink node one after the other, the multiple packets from the same sensor node can be restored to the original image.

By self-configuration between the mobile routing nodes, [4–6] proposed a very clever sleep scheduling method based on mobile cloud computing to solve the energy balance problem inside cloud. However, the deployment of mobile nodes is limited and restricted by the environment in many cases.

Because of bandwidth limitations in WISN, an image data need to be divided into appropriate package which can be sent by consequent time slots, and the all or essential parts of divided data can be regrouped and restored to the original image in the sink node. Under the condition of a fixed image size and wireless transmission rate, the nodes will transmit the image packets as quickly as possible to reduce the energy consumption. When a packet from an image sensor node has arrived in a cluster or cloud, which was composed of routing nodes, the energy consumption mostly happened the transmission consumption between routing nodes. In WSN, the routing nodes can be configured into buffer mode and non-buffer mode [7]. According to one hop transmission, the buffer mode can hold more packet waiting to send, on the contrary, the non-buffer mode is easier to set up an end to end immediate transmission.

Even in the non-buffer mode, the source sensor nodes and sink nodes still need to work with buffer used to storage temp data. Because the buffer is so small that the intermediate routing node need to send the data to the next hop before the new image data arrive in [8], benefit from transmitting only small amounts of data packets, this kind of non-buffer structure is very effective in the traditional small data quantity, low-energy consumption, low latency WSN [9], however, there exist large number of correlative image packets in WISN, once interference in the link lead to the transmission failed, too much energy will be consumed in the data retransmission process, and it will be large number of packet data were congested or lost in one or some routing nodes, so, to the end, the sink node can only obtain parts of image data, and the final image from sensor node will not be assembled.

In the buffer mode, all nodes have to maintain their buffer, although the existence of the buffer unit increases the energy consumption of the single nodes, as far as higher energy consumption in data transmission is concerned, it is tolerable to set up some efficient buffer unit for holding packets to forward. At the same time, more forwarding data are transferred into the node buffer to queue, the block loss probability in the nodes is reduced, less retransmission improve the life cycle of the whole network.

As to routing nodes, the state change of buffer unit is responding to the process of data transmission. After validation, data into the node's buffer means some kind of packet from a sensor node or the other routing node has been received, on the other hand, data out from the node's buffer means a packet has been delivered successfully, in order to reduce the energy consumption in network transmission, we present a method base on buffer state change in the routing nodes with queue theory.

The remaining parts of the paper are organized as follows. The WISN network model base on routing cloud architecture and the definition of the state space are described in Sect. 2, according to the model discussed in Sects. 2 and 3 analyzes the energy optimization policy based on three buffer allocation ways and presents the energy formulation and constraint. Evaluation about energy consumption in these three buffer allocation ways are shown in Sects. 4 and 5 concludes this paper.

2 Network Model and State Space

For the sake of argument, we consider a single layer or multilayer area as a sensor routing cloud or cluster which is made up of large number routing nodes with buffer units, as shown in Fig. 1, generally, we could always separate this kind small cloud or cluster structure from a larger and more complex WISN. When an image packet from an image sensor node has been broadcasting into the sensor routing cloud, the transmission energy consumption is the key point to the whole cloud energy consumption [10], that is to say, the change in buffer state reflects its energy consumption in a single routing node inside the cloud, the whole changes in buffer state of all nodes reflect the energy consumption trend of the cloud.

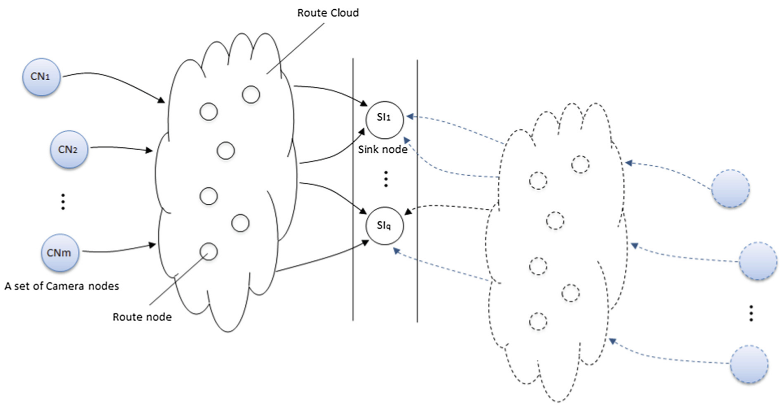


Fig. 1. A WISN system model based on sensor routing cloud

2.1 Network Model

Because of the higher energy consumption of image sensor, slightly different from homogeneous nodes in traditional WSN, there exist the function difference between the sensor nodes and routing nodes in WISN, when a node in WISN work as a routing node, we are just to say it act as a routing node, obviously, it may also work as a sensor node when it is equipped with image sensor. To discuss the state transition process, we present an abstract routing nodes cloud mode, at the same time, we consider a wireless image sensor networks consisting of m image sensor nodes, n routing nodes, and q sink nodes, as shown in Fig. 1, so we define some sets as: m image sensor nodes represented by set CN with CN = $\{cn_1, cn_2, \ldots, cn_m\}$, n routing nodes represented by set RN = $\{rn_1, rn_2, \ldots, rn_n\}$, and q sink nodes represented by set SI = $\{si_1, si_2, \ldots, si_q\}$.

After acquiring image data, CN split the image data into a series of packets, then push them one by one to the routing cloud RN from the side near to them, then the packets is transferred to SI in the other side. When all the packets from an image sensor node have been delivered to the sink node, the image data can be recombined.

When there are many packets from different image sensor nodes reach the same routing node, they have to queue in the buffer of the current routing node, and be delivered to the next hop according to their arrived order and priority. To achieve buffer occupancy for temporary data storage at the routing nodes, we develop a semi-Markov decision process (SMDP) based buffer allocation policy [11]. We have made the following assumptions base on SMDP theory, first of all, the process to deliver packet between routing nodes is independent, and follows Poisson distribution with mean arrival rate λ, with mean forwarding rate μ. Secondly, the time duration for all buffer state is identically distributed [12]. Thirdly, the mean holding time at different buffer states is small compared to data arrival time. The last the buffer is finite, and error sending and receiving communication protocol data do not cause the state transition in the buffer.

Without losing its generality, we define a set L with $L = \{l_{c1}, l_{c2}, \ldots, l_{cm}\}$, for the size of image data in *CN,* moreover, we consider *CN* work in periodic wake, and their buffer work as a FIFO *(First In and First Out)* with v segments, to each segment, there exist two states: full or empty, when a packet have been received successfully and pushed into the buffer, we can say a state changed, on the other hand, when a packet has been pulled out from the buffer and sent to the next node, the other state change occurs.

If we define a transition from a segment to a neighboring segment as a change, then the buffer size can be represent by a set B with B = $\{B_{r1}, B_{r2}, \ldots, B_{rn}\}$, the state space can be represent by a set S with S = $\{S_{r1}, S_{r2}, \ldots, S_{rn}\}$. Take the ith ($i \in \{1,2,\ldots,n\}$) node, for example, its buffer size can be defined a set B_{ri} with $B_{ri} = \{b_{i,1}, b_{i,2}, \ldots, b_{i,v}\}$, and its state space can be defined a set S_{ri} with $S_{ri} = \{s_{i,1}, s_{i,2}, \ldots, s_{i,v}\}$.

Among above: $s_{i,1}$ means the ith routing node buffer is empty, or the effective length of the packet is less than that of a segment, $s_{i,v}$ means the ith routing node buffer is full, at the moment, one more packet next received will be discarded or jump the queue on priority principle.

2.2 State Space

Definition: A transition from state s_j to state s_{j+1} (j < v−1) occurs with probability $p_{i,s_j \to s_{j+1}}$, when the data is stored into the buffer of rn_i node, while a state transition from state s_j to state s_k (k < j and j, k < v) occurs with probability $p_{i,s_j \to s_k}$, when the data is delivered to a next routing node in RN or a sink node in SI.

So whether data from a routing node is stored into the buffer or is loaded from the buffer for sending may be consider as two actions in an action space.

According to this, let A with A = $\{A_1, A_2,\ldots, A_n\}$ as an action set, and A_i with $A_i = \{0,1,\ldots,m\}(i \in \{0,1,\ldots,n\})$ is used to represent all possible transition states set in the buffer of the ith routing node.

Then an action $a_i \in A_i(s_j) \subseteq A_i \subseteq A$ can have following values:

$$a_i = j\,(\exists\,\text{packet has been stored into the buffer of } cn_i \text{ from } cn_i\, j \in \{0, 1, \ldots, m\}) \quad (1)$$

When the ith node has not received any data from any sensor node, we can describe the action with $a_i = 0(a_i \in A_i)$, however, if we have assumed half duplex communication between the nodes, an action $a_i = 0$ does not imply that the same buffer state is maintained due to equal number of data arrivals and departures.

Based on the assumptions above, the state transition probabiilities along with $\tau_{i,s_j}(a_i)$ which is the expected time in current state s_j when action a_i is taken in routing node r_i, describe the dynamics character of the system. The state transition probability can be given by:

$$p_{i,s_j\to s_k}(a_i) = \begin{cases} 1-\frac{1}{\lambda}-\frac{1}{\mu} & j=k, a_i=0,\ i\in\{1,2,\ldots,n\}, \\ & j\in\{1,\ldots,v-1\} \\ \frac{1}{\lambda} & k=j+1,\ a_i\in\{1,2,\ldots,m\}, \\ & i\in\{1,2,\ldots,n\};\, j\in\{0,2,\ldots,v-1\} \\ \frac{1}{\mu} & k=j-1, a_i\in\{1,2,\ldots,m\}, \\ & i\in\{1,2,\ldots,n\};\, j\in\{0,2,\ldots,v+1\} \\ 0 & other \end{cases}$$

$$= \begin{pmatrix} 1-p_{i,s_0\to s_1} & p_{i,s_0\to s_1} & 0 & 0 \\ p_{i,s_1\to s_1} & 1-p_{i,s_1\to s_0}-p_{i,s_1\to s_2} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{pmatrix}$$

$$= \begin{pmatrix} 1-\frac{1}{\lambda} & \frac{1}{\lambda} & 0 & 0 \\ \frac{1}{\mu} & 1-\frac{1}{\lambda}-\frac{1}{\mu} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{pmatrix}. \quad (2)$$

3 Energy Formulation and Constraints

RN working in the dormant state has extreme low energy consumption, so the key point to the energy consumption is data receiving, data holding and data sending, which can be showed by the state change in the buffer. When an action a_i ($a_i \in A_i$) is taken, incurs a mean consumption $\bar{E}_{i,s_j}(a_i)$ to the ith routing node changing its buffer state from state s_j to the other state.

$$\bar{E}_{i,s_j}(a_i) = \bar{E}_{\text{Hold}}(a_i) + \bar{E}_{\text{Trans}}(a_i) + \Delta\bar{E}_{\text{Trans}}(a_i). \tag{3}$$

In (3), $\overline{E}_{\text{Hold}}$ is the fixed energy consumption to hold the buffer state in the ith node, and $\bar{E}_{\text{Trans}}$ is the energy consumption of buffer state change caused by data sending or data receiving, and $\Delta\bar{E}_{\text{Trans}}$ is the energy consumption because of retransmission.

According to the Semi-Markov decision framework, so $\bar{E}_{i,s_j}(a_i)$ can be obtained as:

$$\bar{E}_{i,s_j}(a_i) = \sum_{s_k} p_{i,s_j \to s_k}(a_i)(\bar{E}_{s_j}(a_i) + (1+\delta)\bar{e}_{s_j \to s_k}(a_i)\tau_{i,s_j}(a_i))). \tag{4}$$

In (4), δ is the retransmission factor, $\bar{e}_{s_j \to s_k}$ is the energy consumption from state s_j to state s_k for action a_i in the ith routing node.

If $\varepsilon_{i,s_j}(a_i)$ is marked as the nonnegative decision variable, the optimal energy consumption problem in the whole RN networks is a NP problem, which can be formulated as the following linear program.

Minimize:

$$\sum_i \sum_{s_j \in S} \sum_{a_i \in A(s_j)} \bar{E}_{i,s_j}(a_i)\varepsilon_{i,s_j}(a_i). \tag{5}$$

Subject to:

$$\sum_i \sum_{s_j \in S} \sum_{a_i \in A(s_j)} \tau_{i,s_j}(a_i)\varepsilon_{i,s_j}(a_i) = 1 \ ,\text{且}\, \varepsilon_{i,s_j}(a_i) \geq 0 \ . \tag{6}$$

$$\sum_{a_i \in A(s_j)} \varepsilon_{i,s_j}(a_i) - \sum_{s_j \in S} \sum_{a_i \in A(s_j)} p_{i,s_j \to s_k}(a_i)\varepsilon_{i,s_j}(a_i) = 0 \quad (\forall i,\ s_k \in \text{S}). \tag{7}$$

$$\sum_x b_{i,x} \leq \max(L) \leq n \times \sum_x b_{i,x} \quad (\forall i,\ \exists a_x,\ x \in \{0, 1, \ldots, \text{m}\}). \tag{8}$$

The first constrain in (5) represents the balance equations, the second constrain in (6) is given to guarantees that the sum of the steady state probabilities is one. The last in (7) ensures that the individual contribution of a routing sensor in a buffer is limited by between maximum and minimum value of segment.

4 Performance Evaluation and Result

A. Parameter and Environment

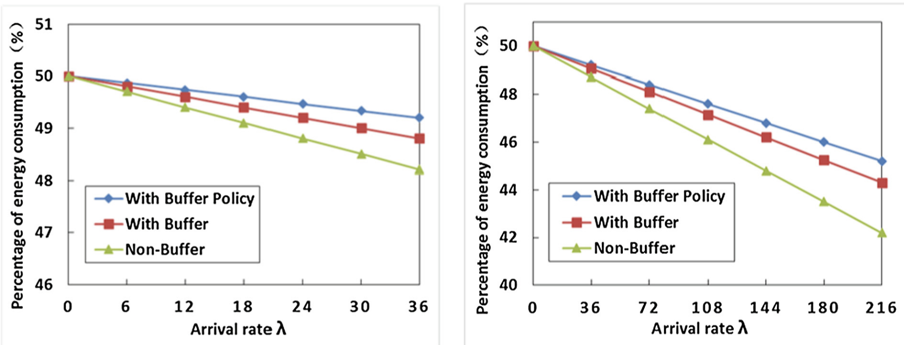
Referenced the specifications given in [2, 13] about the node composition and network topology in a typical WISN, we built a test environment base on IEEE 802.15.4 with 3 image sensor nodes, 6 routing nodes and 1 sink node. We can get images and their arrival time from 3 image nodes in the sink node per several minutes.

To test the difference in energy consumption under the condition of different packet workload, we set two kinds of typical node parameters in the image sensor nodes to compare, One is 320 × 240 resolution, JPEG image format, 3 KB image size, 80 Byte packet length, and 36 segments, the other is 640 × 480 resolution, JPEG image format, 17 KB image size, 80 Byte packet length, and 216 segments.

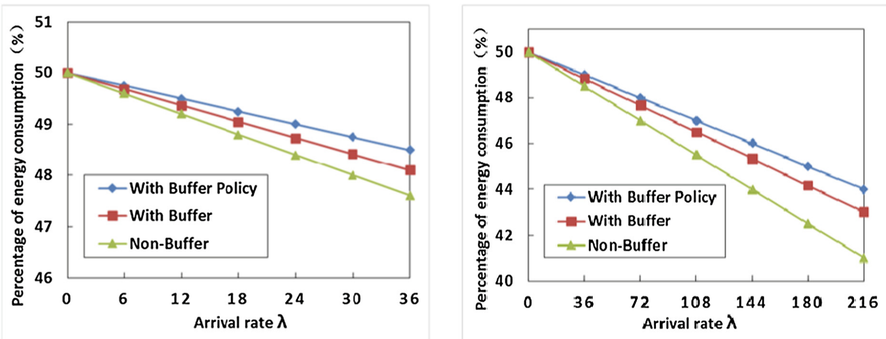
B. Result and Analysis

To transmit an image with same size, the energy consumption in the nodes of RN under the condition of using optimal energy optimization policy, non-buffered policy, and buffered node policy, respectively will shows difference.

In Fig. 2, the mean energy consumption of the routing nodes with three different node structure has been compared with different arrival rate λ and transmission rate μ, we can see clearly that the routing nodes with buffer policy presented in the paper shows the lowest energy consumption, which mean there will be a longer network lifetime to the RN when the energy optimal control method is considered, in addition, when data forwarding rate is lower than the data arrival rate, the energy consumption was increased to some extent.



A. The mean energy consumption comparison when μ=λ



B. The mean energy consumption comparison when μ=λ/2

Fig. 2. Comparison of energy consumption with three different buffer policies in routing nodes

Especially, if some interference lead to the decrease of channel transmission performance, the energy consumption of the routing nodes is increased, it will play a positive role in reduced the energy consumption of RN to improve the ability to receive data of the sink node.

5 Conclusion

With increasing service rate, more image packet are pushed into the routing cloud or cluster made up of sensor routing nodes in the unit time, compare to the traditional WISN without buffer or non-optimized buffer in the sensor nodes, it has better energy saving effect to increase the network life cycle by using the energy consumption control policy base on node buffer allocation. The paper is supported by the nature science of foundation of Liaoning province (L2013433).

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