Energy-Efficient Data Gathering in High-Voltage Transmission Line Monitoring System

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***Abstract*—It is important to protect power supply grid system against various damages for national economics. A high-voltage transmission line monitoring system is an effective way to protect the power supply system. This paper presents an energy-efficient data gathering mechanism for such a system. Our contributions are two-fold: (1) a detailed measurement of the energy consumption for wireless nodes, (2) the collaboration between backbone network nodes and subnets to implement the sleep-wakeup mechanism. To validate the proposed mechanism, we have established an indoor testbed consisting of 8 backbone network nodes. The energy consumption of each node with our mechanism is evaluated and compared to that without sleep. The results show that the energy consumption has decreased by 24% by our scheme.**

I. Introduction

High-voltage transmission is the most important way of supplying energy to major cities as well as other large residential areas, forming the backbone of a national electric power grid. However, high voltage transmission lines are vulnerable to terrorist attacks, vandalism and extreme natural factors including weather, fire and seismic activity. They can bring lines and towers down and disrupt the power service to wide areas in the country [1]. We have designed a high-voltage transmission line monitoring system based on two-tier heterogenous wireless sensor networks, which senses and identifies threats, then alerts power system operators to protect their valuable assets and take actions to damages [2] [3]. In the system, different types of sensors are installed at the towers or on the transmission lines according to the requirements, including image sensors and line temperature-and-sag sensors. Sensors around a tower form a subnet using Zigbee technology. The data sensed are collected by the sink node of the subnet and transmitted to the control center through a backbone network based on wireless ad hoc networks.

Sensors and the backbone network nodes installed at the tower have limited power supply. They have to use solar power because it is forbidden to drain power from the high-voltage line through the tower. The size of the solar panel and the weight of the battery are subject to the tower structure, which will affect the performance (for instance, wind-resistance) of the tower. Besides, the lead-acid battery is very heavy. Furthermore, light weight and small size devices are required for the installation. Therefore, energy-efficient data gathering is one of the key issues in the high-voltage transmission line monitoring system.

Fist, we need to know exactly how the energy is consumed by each part of the system, and then it is possible to design an energy efficient mechanism. We measured and analyzed the energy consumption of each type of network nodes in details, and found that: given the same transmission data, the smaller the packet length, the more the energy consumption; the higher the physical layer bit rate, the less the energy consumption.

Note that images are the major source of data in the network, which have large volume compared to the scalar data such as the temperature. In this context, a significant challenge is the following. The data needs to be gathered in such a way that keeps the transmission line being monitored in *real time*. But nodes also need to sleep to save energy. Furthermore, transmitting all the raw data to the control center will make the network congested. According to the characteristics of the data, we designed a smart data gathering strategy to balance these conflicting requirements as follows.

The data is uploaded to the control center in a low duty cycle under normal operation. When there is an emergency, the data is transmitted to the control center immediately. The low-power sensor nodes are in charge of detecting emergency events. There are two obvious benefits: (1) the total data volume to be gathered decreases a lot, which makes it feasible even operating in large scale networks, and (2) The periodic data gathering makes it possible to design a sleep-wakeup mechanism to save energy.

On the design of the sleep-wakeup mechanism, a cross-layer method dedicated to this application is adopted to inform each node when to sleep. Another critical problem is how to detect and transfer the emergency data to the control center during the sleep period. To this end, the sensor nodes with low energy consumption in the subnets act as a signaling channel to wake up the backbone network nodes. In addition, the awake duration is much shorter than the sleep duration in normal case, the time synchronization is needed in this context.

In comparison with prior work on energy-efficient data gathering in sensor networks [4], [5], [6], [7], our contributions are two-fold: (1) a detailed measurement of the energy consumption for wireless nodes, and (2) the collaboration between the backbone network nodes and the subnets to implement the sleep-wakeup mechanism.

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To validate our energy-efficient data gathering mechanism, we have established an indoor testbed consisting of 8 backbone network nodes. The energy consumption of each node by our mechanism is evaluated and compared to nodes that have no sleep interval. The results show that the energy consumption by our scheme has decreased by 24%.

The rest of the paper is organized as follows. Section III overviews the high-voltage transmission line monitoring system in brief. Section **IV** describes the energy-efficient data gathering mechanism in detail. Section**V** evaluates its performance. Section**VI** concludes the paper.

II. Related work

In sensor networks, there are a lot of techniques for reducing energy consumption at various levels of the communication protocol stack. From the bottom to the top, special hardware [8], MAC layer [9]. In-network aggregation [10] [11] and energy-efficient routing [12] [13] are efficient methods proposed for reducing energy consumption in sensor networks.

Due to the significant energy-saving when a node is sleeping, a widely used mechanism is to schedule the sensor nodes to sleep, thereby extending the lifetime of the sensor network. There are numerous related work such as GAF [14], SPAN [15] with determinedly sleeping schedule and [16] [17] with randomly sleeping mode. However, these schemes are designed for a system powered by a battery and cannot easily be implemented in WiFi networks where the transition from sleep to wake time has a delay of several seconds.

With the development of multi-interface smart mobile phone and other hand-held devices(HHDs), more and more work focuses on the reduction of energy consumption for these devices. One of the popular techniques is using multi-interface collaboration to turn some interfaces off [18].

Our energy-efficient data gathering has the same philosophy but has the following differences: (1) The existing schemes work based on the cooperation between the cellular interface and the WiFi interface. In our system, we make use of the Zigbee interface with low energy consumption to wake up the WiFi interface with high energy consumption. (2) The existing schemes designed for the HHDs have not considered the data forwarding demand. In our system, each node needs to forward the data from the downstream nodes. (3) Our energy-conservation solution adopts deep-sleep method instead of only shutdowning the driver.

III. The high-voltage transmission line monitoring system: a brief overview

We give a brief overview of the high-voltage transmission line monitoring system. For more details, please refer to [2] and [3]. Our design of energy-efficient data gathering mechanism is driven by the requirements in this system.

The framework of the high-voltage transmission line monitoring system is shown in Fig.1. The length of high-voltage transmission line between two substations is typically tens of Kilometers and the towers stand along the route almost linearly. The span of two adjacent towers is usually 300 - 500 meters. Sensors are installed at the towers or on the lines according to their functionalities. The sensor data is collected and sent to the control center via a two-tier heterogeneous wireless network. The network architecture is shown in Fig.2. The backbone network is composed of WiZiTJU nodes which are equipped with both IEEE 802.11 radios and IEEE 802.15.4 radios. The WiZiTJU nodes also act as the sink nodes of the subnets. The subnet consists of sensor nodes with IEEE 802.15.4 radios, supporting by the ZigBee protocol stack. It is worth to note that the backbone network topology is linear in nature because the sensors are installed along the high-voltage transmission line.

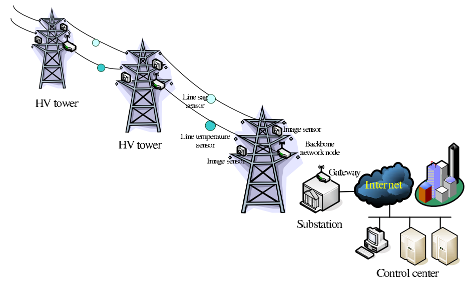

Fig. 1. System framework

The WiZiTJU, as a backbone network node, is a wireless router configured with 400MHz CPU, 128MB SDRAM and 256MB onboard Flash storage. The wireless card uses UBiquiti XR2 [19] with miniPCI interface. It is based on the Atheros chipsets, supporting 802.11b/g with maximum transmit power of 28dBm. Its transmission range can be over 50km in theory using high-gain directional antenna. We tested its 11b link performance in terms of TCP throughput over 1Km outdoor with 8dBi omnidirectional antenna. The achievable TCP throughput is over 5Mbps [3]. The backbone network nodes are installed at the tower with solar power supply.

There are two types of sensor nodes in the system, i.e. image sensor nodes and line temperature-and-sag sensor nodes. The image sensor is equipped with a low-power DSP with JPEG compression and simple image recognition functionalities. The image sensors are installed at the tower using a solar power supply. They monitor the vulnerable areas including areas under the line, the surface of the insulator and the tower base. The line temperature-and-sag sensor is hung on the line, sensing the line temperature and the sag length. It derives power from the electromagnetic field generated by the flow of current through the conductor.

All sensors are equipped with JN5139 module as their Zigbee radios. JN5139 integrates a 32-bit RISC processor, with a fully compliant 2.4GHz IEEE 802.15.4 transceiver [20]. Its maximum transmit power is 3dBm with the maximum transmission range of 1km in theory. We also verified its transmission range outdoor.

IV. Energy consumption measurements

Before designing an energy-efficient data gathering mechanism, we need to know exactly how the energy is consumed

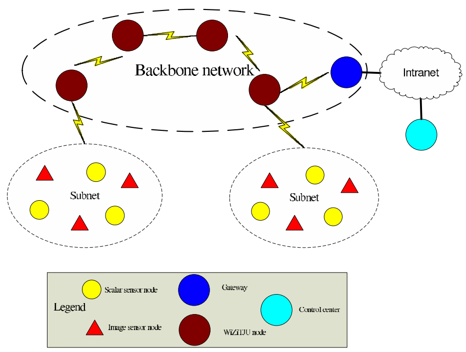

Fig. 2. Two-tier network topology

in the system. There are three types of nodes as described in Section III: the backbone network nodes (i.e. WiZiTJU), the image sensor nodes and the sag-and-temperature sensor nodes. The sag-and-temperature sensor nodes have sufficient power supply because they are hung on the line and are powered by the electromagnetic field generated by the current through the conductor. The image sensors and WiZiTJU nodes are installed at the tower using solar power supply, because it is forbidden to drain power from the power line at the tower.

The solar power supply is limited because the size and the weight of the solar power system is constraint to the power tower as well as its high price. The solar power system is mainly composed of the solar panel and the battery. The size of the solar panel and the capacity of the battery are the key issues to design a solar power system, which depends on the energy consumption of the devices per day and the number of days they need to work continuously without enough sunshine to recharge the battery. Currently the solar panel is inefficient on energy-transition, so the size is fairly big, for example, a 17V-75W solar panel is about $1176 \times 531 \times 28 (L \times W \times H, mm)$. The battery is heavy, as an instance, a 12V-120AH battery weighs about 30Kg. Therefore, the image sensors and WiZiTJU nodes need to work energy-efficiently.

The typical energy consumption of the image sensor is less than 3W, much smaller than that of WiZiTJU with maximum energy consumption of 10W. In addition, from the system design point of view, the sensor nodes are required to work all the time to detect the emergency events. Therefore, we focus on the energy consumption of the WiZiTJU nodes in the backbone network. IEEE 802.11b/g wireless card and ZigBee modules are the potential devices that can save energy. Their energy consumption performance are given by their datasheets listed in Table I [19] [20]. From the table, we can see that energy consumption is contributed mainly by the IEEE 802.11 module, the energy consumed by the ZigBee module can be ignored.

We further measured the energy consumption of WiZiTJU nodes in order to determine the most efficient way to save energy. In our experiments, we used two WiZiTJU nodes working in ad hoc demo mode with IEEE 802.11b, which is the same mode used in the monitoring system. The MAC

TABLE I
ENERGY CONSUMPTION OF WIFI MODULE AND ZIGBEE MODULE

Module	Status	operation Voltage (V)	Current
WiFi	Sending	3.3	1.3A
WiFi	receiving	3.3	300mA
Zigbee	Sending	2.2 to 3.6	39mA
Zigbee	receiving	2.2 to 3.6	39mA

ACK is disabled, and UDP traffic is adopted to test energy consumption. In this case, the data volume actually sent and received are accurate. Each experiment runs for 20 minutes, sending the same volume of data.

We firstly measured the energy consumption of WiZiTJU nodes working at different states including idle, receiving and sending. Undoubtedly, sending consumes the most energy, while the energy consumption in the idle and receiving states are comparable. In order to save more energy while sleeping, we tried three methods: shutdowning the wireless card driver; downloading the driver and turning off the PCI bus (the interface of the wireless card is miniPCI). We found that the third one is the most energy efficient, which we call deep sleep. The measurements results are shown in Fig. 3.

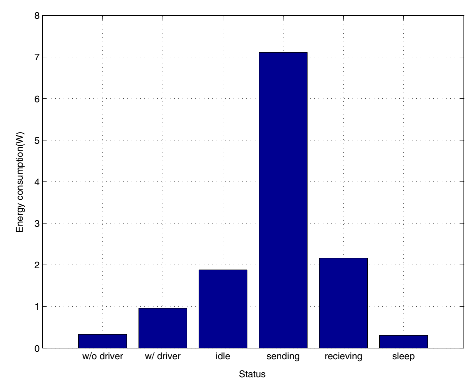

Fig. 3. Energy consumption of a WiFi node

In order to find a way to save energy in transmission, we further tested how energy consumption is affected by other factors, including the data length, the transmit power, the packet length and the transmission bit rate. The energy consumption increases with the data length and transmit power, which is not surprised and the results are omitted here for limited space. However, opposite to our instincts, given the data volume, the shorter the packet length, the more the energy consumption, while the lower the transmission bit rate, the more the energy consumption, as shown in Fig. 4 and Fig.5.

In Fig.4, the packet length varies from 100Bytes to 1000Bytes with the same total data volume of sending rate (kbps) $\times$ run time (1200s). The sending rates are 1000kbps, 800kbps and 500kbps respectively. The results show that sending the same volume of data at the same sending rate, the shorter the packet length, the more the energy consumption. It is because the shorter packet length the more packets that also get sent over the network, which further results in more MAC header and channel contention. In other words, more overhead will cause more energy consumption.

In Fig.5, the packet length is 1000Bytes, the sending rate and experiment time are the same, thus the same data volume. The results show that the larger the transmission rate, the less the energy consumption. This can be illustrated that the sending time seen from the MAC layer is shorter with the larger transmission rate sending the same data volume.

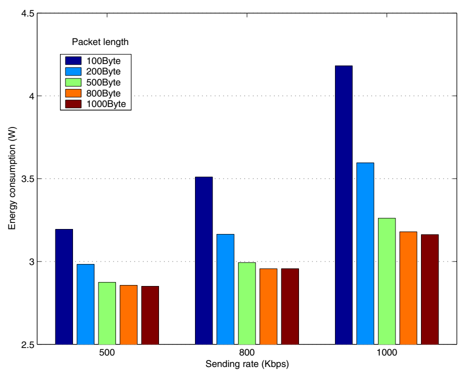

Fig. 4. Packet length

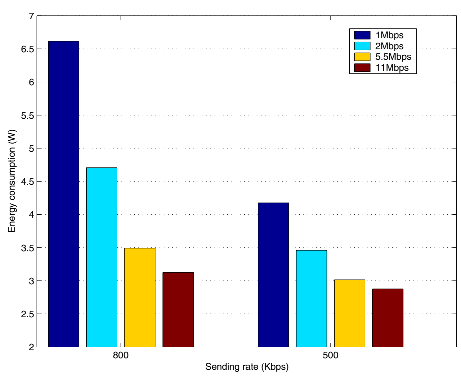

Fig. 5. Transmit bit rate

Therefore, we designed an energy-efficient data gathering mechanism making use of the coordination of Zigbee and WiFi. In addition, in order to save energy, we use long packet length of 1000 Bytes and the highest transmit bit rate of 11Mbps when a node has a transmission opportunity.

Now, we move on to the details of the energy-efficient data gathering mechanism.

V. Energy-efficient data gathering mechanism

We employ data preprocessing at the sensor node to solve the above problem, which enables data gathering in duty cycle. Periodic data gathering makes a sleep process a straightforward solution to save energy. We then developed an algorithm to coordinate between the sensor nodes and the backbone network nodes.

A. *Enabling data gathering in duty cycle*

We assume that the rate of change for events and phenomena of interest monitored varies slowly. For example, the surface of a powerline degrades slowly over time. It will take a long time for them to reach the dangerous point. However, there are sudden situations that should be captured in real-time. There could be something getting closer to the line suddenly which will cause flashover and even blackout. The fact is the same for other phenomena including line temperature.

Due to this fact, we gather data periodically in the normal case (i.e. when there is no emergency event). Only one image is uploaded in one duty cycle for each image sensor node. For the line sag-and-temperature sensors, all the data sampled during a duty cycle is transmitted to the control center. The duty cycle is 30 minutes currently in our project. In order to capture the emergency events, we sample the data in real time, then preprocess them to tell whether there is an emergency event. If it is an emergency, the data is transmitted to the control center immediately. This strategy has two benefits. One is that it reduces lot of data volume while meeting the real-time monitoring requirements. The other is that it makes it possible to design sleep mechanism to save energy.

Emergency event detection at the image sensor An image sensor recognizes the image contents after capturing one image. Each image sensor has its own recognition algorithm carefully in order to detect the emergency event accurately. Since the definition of the emergency event is different, the objects monitored are different from each other. The details of the recognition algorithms are omitted here, as we only focus on the data gathering collaborated between the Zigbee nodes in the subnets and the WiFi nodes in the backbone nodes. When the emergency event is recognized, the image and the following images captured in 3 seconds are compressed into JPEG format and sent to the control center.

Emergency event detection at the line temperature-and-sag sensor For the line sag-and-temperature sensors, it is easier to detect an emergency event. A safety threshold is set by the control center. If the data sampled is larger than the threshold, an emergency event can be detected.

B. *Sleep-wakeup mechanism*

Data gathering in duty cycle makes it possible to sleep. The sensor nodes in the subnet use Zigbee technology, whereas the WiZiTJU nodes in the backbone network use IEEE 802.11 radio. In this context, the important issues to design the sleep-wakeup mechanism are:

- When to make each node sleep in the normal case.
- How to wake up WiZiTJU nodes in the backbone network to transmit emergency data, if a sensor node in the subnet detects an emergency event during sleep period?

We deploy a cross-layer method to answer the first question, and make use of the collaboration of the heterogeneous wireless nodes to solve the second problem. The subnets are used as a signaling channel to wake up the WiZiTJU nodes to transmit the emergency image data during the sleep period.

Whereas the emergency scalar data is sent only using subnets without bothering the backbone network. We describe the details in this section.

1) Time to sleep in the normal case: In normal cases without emergency events, all the WiZiTJU nodes wake up at the beginning of a duty cycle, transmit the data collected from the sensor nodes to the control center. Recall that the network topology is linear, the node closer to the substation need to forward the data from the node farther away. Therefore, a node will go to sleep only when it has no data to transmit and all the other nodes behind it finish their transmission.

We noted that when the farthest node finishes transmitting, it goes to sleep, i.e. its wireless card is off. In this case, its neighbor cannot hear it, our routing algorithm then deletes the node's entrance in the neighbor's routing table. Therefore, if the node cannot find any nodes behind it in its routing table, it believes that all the nodes behind it have finished their transmissions.

2) Collaborative wake up when an emergency event happens during the sleep period: When an emergency event happens in the awake period, it is straightforward to send the emergency data via the backbone network as usual. However, if a sensor detects an emergency event during the sleep period, at that time the WiFi radios in the backbone network do not work, how to deliver the important information to the control center in time? Considering the emergency data volume and the performance of the network, we designed two strategies to deal with the image events and the scalar events, respectively.

Emergency image event If an image sensor node detects an emergency event, it tries to send the emergency data (the current image and the ones captured in the following 3 seconds) to the control center. If it finds that the WiZiTJU node is sleeping, then it generates a wake-up packet. On one hand, it sends the wake-up packet to its sink in the WiZiTJU node, telling the node to wake up its IEEE 802.11 wireless card to transmit data. On the other hand, it forwards the wake-up packet to other subnets along the route to the control center. Each subnet receiving such a packet wakes up its WiZiTJU node to work. That is to say, subnets are used here as a signaling channel to wake up all the WiZiTJU nodes along the route to the control center. Eventually, the emergency images are transmitted via the backbone network. After the WiZiTJU nodes finish forwarding the emergency data, they fall into sleep again until the end of this duty cycle if the sleep phase is not ended at that time.

Emergency scalar event If the emergency event is generated by a scalar sensor node, for instance, the line sag-and-temperature sensor, the emergency data is small enough that to be sent in one packet. Then the sensor node forwards the emergency packet to the neighbor subnet along the route closer to the control center. In other words, the subnets act as a backup route for the scalar emergency event, without bothering the backbone network. When this packet arrives at the gateway, it will be forwarded to the control center by the gateway.

3) Time synchronization protocol: Time synchronization is required to support the sleep-wakeup mechanism. In the normal case, the awake period (several seconds) is much shorter than that of the sleep period in one duty cycle (30 minutes). Furthermore, the emergency data can also be transmitted to the control center in a short time. Coarse granularity time synchronization is enough in this context. We designed a simple yet efficient time synchronization protocol. The control center will send its clock time to each backbone network node once per day. The backbone network node sets its clock to the time it receives, and sends the time to the sensor nodes in its subnet. When a node rejoins its network, it requests time synchronization to adjust its clock time. In such a way that all the network nodes have the same time with the control center.

The time drift depends on the number of nodes in the backbone network and the distance between the node and the gateway. The longer distance, the larger the time drift. Suppose there are n backbone network nodes in total, the largest time drift is approximately the end-to-end delay between the nth n-ode and the gateway. The packet length of the synchronization packet is no longer than 20 bytes. We measured the end-to-end delay in our test bed, when $n = 8$, the end-to-end throughput of the node 8 to the gateway is about 500kbps using TCP traffic. Therefore, the time drift is about $20 \times 8/500 = 0.32ms$. Usually the backbone network is no more than 20 nodes, thus the time accuracy is microseconds, which is enough for our sleep-wakeup mechanism.

VI. Performance Evaluation

We implemented the proposed data gathering mechanism in network backbone network nodes and the sensor nodes. To obtain the exact energy saved, and give some insight into the system design, we established an indoor testbed to evaluate its performance. In this section, we first introduce the experimental setup, and then give the experiment results and analysis.

A. Experiment setup

The indoor testbed is established simulating the field setup in order to make the results more realistic. The backbone network consists of 8 WiZiTJU nodes, which stand linearly. Each WiZiTJU node connects to a subnet including 3 image sensors and one line temperature-and-sag sensor. Please find the configuration of WiZiTJU nodes and the sensor nodes in Section III. Another WiZiTJU node acts as the gateway to our lab's Ethernet. There is a PC in our lab running the control center software.

To facilitate experimentation, we fixed the transmission power of each wireless card to its minimum value of 1dBm, the physical data rate was set to 11Mbps. However the transmission range is still over tens of meters with 3dBi omnidirectional antenna. We have to use only the feeder cable without an antenna. In this case, we obtained the transmission range of about 2 m using the same method in [21]. We set the distance between successive nodes to 1.5 m so that the link performance is stable for two adjacent nodes. For the sensor nodes, we also set the transmission power of its transceiver to its minimum value for a smaller transmission range.

We measured the power consumption of each backbone node with a fine-grained smart power meter [22]. The accuracy of the power meter is micro Watt and the power consumption can be read in a small period such as a second. Since the power meter is designed for the AC-powered appliance, we have to use an AC-DC adapter to convert AC to DC for WiZiTJU nodes. That is why we evaluate the energy efficiency of our mechanism in an indoor testbed where we can obtain AC power supply freely. However, the results obtained indoor can be used directly for the outdoor in the sense of energy consumption.

B. Experiment results

1) Energy efficiency in the normal case: The image sensor uploads only one image in one duty cycle in the normal case. With our sleep-wakeup mechanism, at the beginning of a duty cycle, each backbone network node wakes up and transmits the data collected from its subnet to the control center, then falls into deep sleep when finishing the transmission. The experiment ran for 8 duty cycles. The energy consumption of each backbone network node was recorded dynamically. The results were then compared with that of gathering data in the same duty cycle but without sleep. The duty cycle in our experiment is 30 minutes, which was selected by the power expert due to slow variation of the sensing data including line temperature and sag.

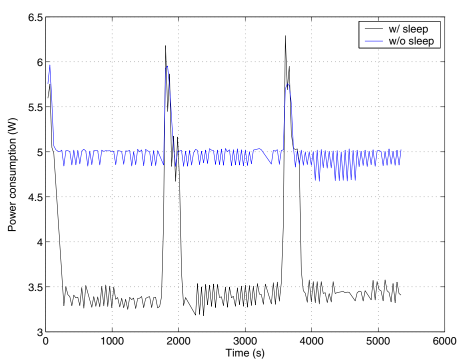

Fig. 6. Energy consumption of node 1 in the first 3 duty cycles

Figure 6 shows the dynamic energy consumption of node 1 with and without our mechanism in the first 3 duty cycle. To make it more clear, the energy consumption is averaged for 8 duty cycles. Fig.7 and Fig.8 show the average energy consumption for each node with and without the sleep-wakeup mechanism respectively. We can see from Fig.7 that All nodes consume more energy at the beginning of the duty cycle and then keep a lower level till the end of the cycle. The energy consumption of node 1 is the most and lasts the longest time. It says that our sleep-wakeup mechanism works well in the normal case. All the nodes wake up to transmit data at the beginning and then go to sleep. Node 1 has to forward all the data in the network so that it consumes the most

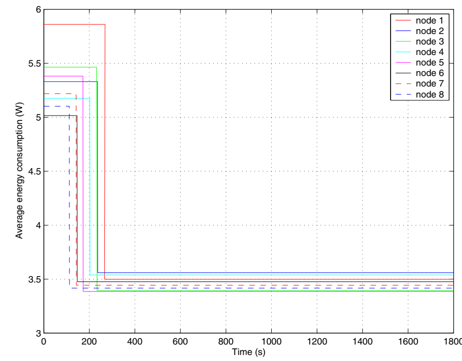

Fig. 7. Average energy consumption of each node with sleep-wakeup mechanism

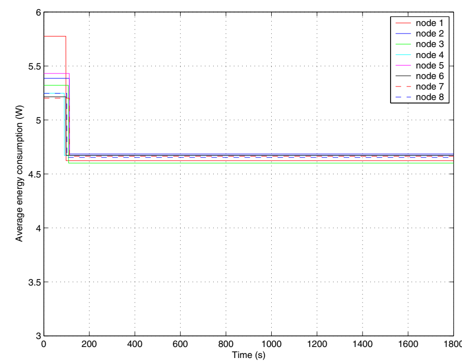

Fig. 8. Average energy consumption of each node without sleep-wakeup mechanism

energy and works for the longest time. Fig.8 presents the similar phenomena that nodes consume more energy at the beginning and then keep a lower level when finishing data transmission. However, the energy consumption while they are idle is much higher than that when nodes go to deep sleep with our mechanism. The total average energy consumption of all the nodes with sleep-wakeup mechanism has been saved by 24%. With the same network, If the duty cycle is longer, more energy will be saved.

2) Collaborative emergency data transmission during the sleep period : We also simulated the scenario that an image sensor in the 8th subnet detects an emergency event in the first duty cycle. From the energy consumption of node 1 in Fig.9, it is clear that the sensor nodes woke up the WiZiTJU nodes in the backbone network successfully when there was an emergency event. The energy consumption of other nodes are similar to this figure, and omitted here due to limited space.

VII. Conclusion

In this paper, we have designed an energy-efficient data gathering mechanism for the high-voltage transmission line monitoring system. To balance the conflicts between constrains of solar power and real-time monitoring, the data was gathered in a low duty cycle and the lower-power sensors take in charge of emergency event detection. Once there was an emergency

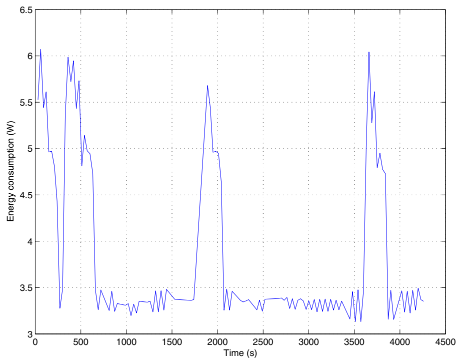

Fig. 9. Energy consumption of node 1 when there is an emergency event

event during sleep period, the subnets of sensors act as a signalling channel to wake up the backbone nodes along the routes to the control center, so that the emergency image data will be delivered in time. The emergency scalar data are transmitted via the subnets to save more energy. The functionalities and performance of the proposed mechanism were verified in an indoor testbed. The experiment results show that the subnets and the backbone network collaborate well to accomplish the mechanism, and the energy consumption has been saved by 24% with 8 backbone network nodes and 30 minute duty cycle.

Accurate image recognition in this mechanism is an import issue to detect an emergency image event. It will be studied further in the future work. We also plan to evaluate the proposed data gathering mechanism in our high-voltage transmission line monitoring system operating in the field.

Acknowledgment

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