Improving Energy Efficiency in Industrial Wireless Sensor Networks Using SDN and NFV

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***Abstract*—Industrial Wireless sensor networks (IWSNs) are emerging as a promising technique for industrial applications. With limited energy resources, prolonging the lifetime of IWSNs is a fundamental problem for industrial applications. At the same time, Software-Defined Networking (SDN) and Network Function Virtualization (NFV) are future network techniques which make the underlying networks and node functions programmable. SDN and NFV have inherent advantages to control topology and node mode in IWSNs. In this paper, we propose a mechanism improving energy efficiency in industrial wireless sensor networks using SDN and NFV named M-SEECH for industrial application. Firstly, we propose a new architecture based on traditional IWSNs and operation mechanism using SDN and NFV. In the architecture, the global view and central control properties of SDN are utilized to monitor IWSNs. Also, the programmability of SDN and instant deployment capability of NFV are utilized to control the topology of IWSNs and the modes of nodes in IWSNs. Thirdly, we propose advanced algorithms for controller in IWSNs taking the advantages of SDN and NFV. By this way, the average lifetimes of IWSNs are prolonged. Finally, the case study and evaluation show the advantages of the proposed energy efficient scheme comparing with traditional methods.**

Keywords- Industrial Applications, Wireless Sensor Networks, Energy Efficient, Software-Defined Networking, Network Function Virtualization

I. Introduction

Industrial wireless sensor networks (IWSNs) have obtained a great success for industrial applications such as machine condition monitoring and fault diagnosis [1] - [3]. Although IWSNs have the capability to be applied to industrial applications but there are some limitations associated to wireless sensor networks to be employed in harsh and inaccessible environments. One of the key challenges of IWSNs is the efficient use of limited energy resources in battery operated sensor nodes.

Energy efficiency in IWSNs has been extensively studied in literatures. Heinzelman et al. [4] presented a clustering algorithm named low-energy adaptive clustering hierarchy (LEACH) to aggregate the data from sensors. The purpose of LEACH is to randomly select sensor nodes as cluster heads, so the high energy dissipation in communicating with the base station is spread to all sensor nodes in the sensor network. Tarhani et al. proposes a new distributed algorithm named scalable energy efficient clustering hierarchy (SEECH), which selects cluster heads and relays separately and based on nodes eligibilities. Simulation results demonstrate that all these researches are effective in prolonging the network lifetime and supporting scalable data aggregation [5].

According to these researches, topology control is most mainstream and important technique used in IWSNs to promote energy efficiency [6]-[8]. Topology control aims to control the graph representing communication links between nodes, with the purpose of meeting a global property of the graph, while reducing energy consumption. But until now, most of them are self-organized topology method, and none of them give a central scheme.

At the same time, sleep mode based energy efficiency technique is already a mainstream method in future “green communications". According the researches, it is predicable that taking sleep mode based energy efficiency technique into wireless sensor networks will promote energy efficiency of the networks. But as aforementioned, the traditional energy efficiency methods for IWSNs do not exactly focus on sleep mode.

On the other hand, Software-Defined Networking (SDN) has emerged as a future communication network architecture which decouples network control and forwarding [9]. One of the inherent properties using SDN is feasible to control topology. Besides SDN, network function virtualization (NFV) is utilized as a promising technology to virtualize the network devices for more cost-efficiency [10]. It helps the realization of sleep mode.

As aforementioned, SDN and NFV help improve energy efficiency in IWSNs. This paper proposes a novel energy efficiency scheme using SDN and NFV. The remainder of the paper is organized as follows. The rest of the paper is organized as follows: Analysis of advantages of SDN and NFV for energy efficiency of IWSNs is described in Section II. Section III presents the novel network architecture and operation mechanism for IWSNs using SDN and NFV. Details of the clustering algorithm for the proposed scheme are discussed in Section IV. In Section V, a case study is illustrated. Finally, we conclude the paper in Section VI.

II. Analysis of Advantages of SDN and NFV for Energy Efficiency of IWSNs

We analyze the advantages of SDN and NFV for energy efficiency of IWSNs by providing four scenarios with or without SDN and NFV. At first, we provide typical wireless sensor network architecture as illustrated in Fig. 1.

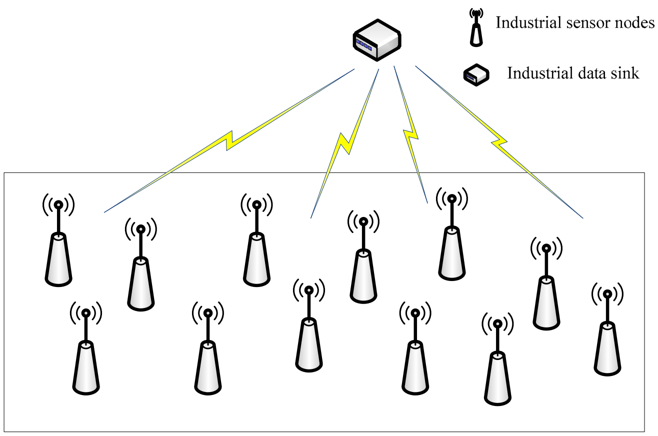


Fig. 1. Typical industrial wireless sensor network architecture

In the first scenario, all of the sensors are communicate with the data sink directly. They all have long transmission range and have to switch their radio to high power supply level. In the scenario, there must be one sensor node having the longest distance far away from the data sink, so it has to switch its radio power supply to highest level to increase its transmission range. Because all the transmission range of the sensors is wide, there exist collisions between the sensors. This leads this sensor node more energy consumption. In this scenario, this sensor node will die soon because of energy depletion.

In the second scenario, the sensors are self-organized. This is a traditional method to organize the sensors. The sensors exchange messages with their neighbors and decide to form a topology by the information exchanged with the neighbors. By this way, the network has a shorter average distance than the one in the first scenario. The main shortcoming in this scenario is that all the sensors do not have a global view about the network, so the topology is not global optimized.

In the third scenario, there exit a logic controller in the network as same as the SDN controller. At the startup phase, all the sensors broadcast their information to the logic controller, so the logic controller has a global view of the network. Then the logic controller computes a global optimized topology periodically according the situations of all the sensors. Compared with the traditional method discussed in the second scenario, the topology in the third scenario is more energy efficient.

In the fourth scenario, additional NFV is added into the third scenario. Using NFV, the functions of some nodes are replaceable. For example, sensor node A can take place of the function of sensor node B. In the other word, sensor B can take place of the function of sensor node A. Then sensor node A and sensor node B can be active alternatively. When sensor node A is active, sensor node B get into sleeping mode. This leads more energy efficient for both sensor node A and sensor node B. Also, because the functions of the two sensors are integrated into one sensor, it commonly leads data aggregation and compression. Data aggregation leads the communication throughput decreased, and then energy consumption decreases.

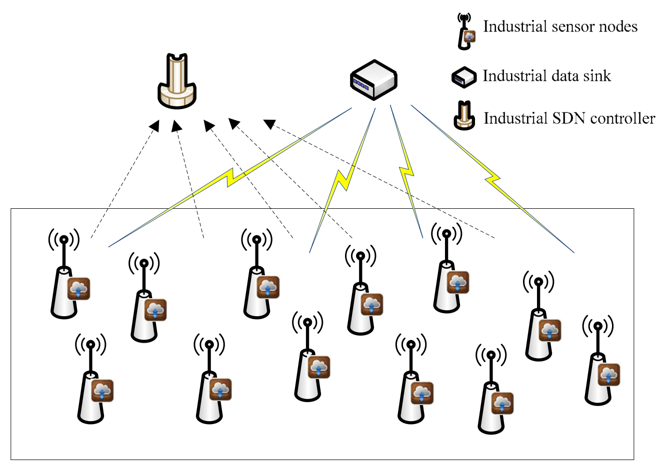
From the analysis of the energy consumptions in the four scenarios, we conclude that using SDN and NFV, a more optimized topology and sleep mode including data aggregation and compression are applied. This decreases more energy consumption of the network than traditional method. But a new architecture of IWSNs is needed.

III. PROPOSED NETWORK ARCHITECTURE FOR IWSNS USING SDN AND NFV

We call our scheme modified SEECH (M-SEECH) because the algorithms are based on SEECH [4].

A. Architecture of M-SEECH

We extend the architecture of typical IWSNs as shown in Fig. 2.



There are two main differences between the enhanced architecture and original architecture. The first one is that there exists a controller in the new architecture. The second one is that the sensor nodes have the ability to install virtual network function (VNF). More details about the controller and sensors are illustrated in Fig. 3.

Besides the common functions in SDN controller, the controller in proposed scheme also has information gathering, cluster decision, flow table, and virtual network functions (VNF). Sensor in our scheme has the four classic components including power unit, sensoring unit, processing unit and transceiver unit. Additionally, the transmission power is controlled by a radio controller in each sensor.

When the controller makes cluster decision using the proposed algorithms, the sensors enforce the decision utilizing the architecture. When a sensor node is selected as a sleeping node, it clears all of the VNF containers and only keeps an idle thread alive. Also, it adjusts the radio to sleeping mode to save energy. And the controller installs the VNF instances of the sleeping sensor into the peer of its replaceable pair. When a sensor node is selected as a cluster head, it adjusts its transmission power to cover all of its cluster members and table flows are installed. Similarly, when a sensor node is selected as a relay node, it adjusts its transmission power to cover its entire cluster heads and table flows are installed.

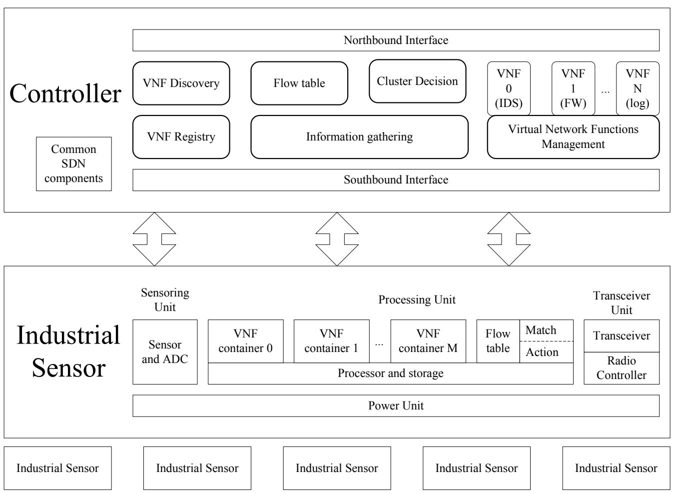


Fig. 3. Details of Industrial Controller and Sensors in M-SEECH

B. *Operation Mechanism of M-SEECH*

There are two mayor differences between M-SEECH and SEECH. The first one is that M-SEECH can appoint a sensor to take place of the function of another sensor using network function virtualziation. The second one is that M-SEECH is a central method opposite to SEECH's self organization method. The M-SEECH worflow is illustrated in Fig. 4.

The controller then pre-computes some parameters useful in following phase such as node degree.

The controller selects sleeping nodes which go into lowpower sleeping mode in this round. Sleeping nodes selection is based on "replaceable pair". Namely, when two nodes belong to a replaceable pair, one of the nodes can take place of the functions of the other one. For example, we can judge the two sensors belong to a replaceable pair when their distances between them are beyond a threshold value.

Excluding the sleeping nodes, the controller continues to select cluster heads. And the controller goes on to select relay nodes and formats the clusters.

At last, the controller distributes the decision to all the sensors until next round begins.

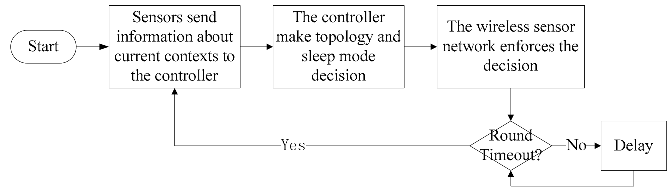


Fig. 4. Operation mechanism of M-SEECH

C. *Functions and Workflow of Controller*

The controller in the new architecture is the "brain" of the network. When a decision round begins, it decides the mode of each sensor node and the topology of the network. Also it decides how to distribute VNF instance into sensor nodes. The main functions and workflow of the controller is illustrated in Fig .5.

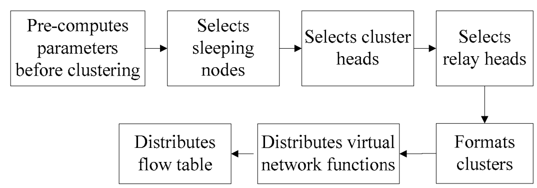


Fig. 5. Functions and workflow of controller in M-SEECH

Firstly, the controller pre-computes the parameters that will be used in the later phase. Secondly, it selects the sleeping nodes, cluster head nodes and relay head nodes in turn. Based on the selected nodes, the result clusters are format. At last, the controller distributes VNF instances to sensor nodes and distributes flow tables to sensor nodes to control topology.

IV. ALGORITHMS FOR CONTROLLER

The main algorithms of controller include pre-computing, sleeping nodes selection, cluster heads selection, and relay nodes selection and clusters formation.

A. *Pre-computing*

The controller derives the degree of each node according the number of its neighbors in a specific radius *RNG* as follows:

$$\deg_i = \frac{n_i}{\max\{n_1, n_2, \ldots, n_N\}} \tag{1}$$

where N denotes there are totally N nodes in the sensor network. And n_i denotes the number of its neighbors of the ith node. So, $\deg_i$ is the degree of the ith node.

B. *Sleeping Nodes Selection*

The controller judges some two nodes belong to a replaceable pair when their locations fit the following condition:

$$\sqrt{(x_i-x_j)^2+(y_i-y_j)^2}<d_{Threshold} \tag{2}$$

where (x_i,y_i) and (x_j,y_j) are the location coordinators of the ith node and the jth node separately. And $d_{Threshold}$ are the threshold of distance that make the two nodes are replaceable.

When $E_{res_i} < E_{res_j}$, the ith node is selected as sleeping node, and vice versa. E_{res_i} denotes residual energy of the ith node.

We define D_{com} to denote the data compression degree in data aggregation for replaceable sensor nodes as follows:

$$D_{com}=\frac{D_{total}}{D_i+D_j} \tag{3}$$

where D_{total} denotes the total output data amount after data aggregation. D_i denotes the output data amount of the ith node before data aggregation, and D_j denotes the output data amount of the jth node before data aggregation.

C. Cluster Heads Selection

The controller calculates the probability p_{c_i} which determines the ith node being a cluster head candidate as follows:

$$p_{c_i}=\begin{cases}\frac{E_{res_i}\times \deg_i}{p_{c\text{-}tot}}, & E_{res_i}\geq E_{av}\times(1-\lambda)\\ 0, & else\end{cases} \tag{4}$$

where E_{av} denotes the average residual energy of the nodes in the current round. λ is a number in(0, 1) and usually is set to be 0.9. By this factor, low energy nodes have no chance to be a cluster head candidate.And $p_{c\text{-}tot}$ is calculated as follows:

$$p_{c\text{-}tot}=\frac{E_{av}\times\sum_N \deg_i}{2K_{CHC}} \tag{5}$$

where K_{CHC} denotes the number of needed candidates.

When the controller obtains all the probabilities, it select the K_{CH} nodes with highest probabilities as cluster heads where $K_{CH} \leq K_{CHC}$.

D. Relay Nodes Selection

Excluding sleeping nodes and cluster heads, the controller calculates the probability p_{r_i} which determines the ith node being a relay node candidate as follows:

$$p_{r_i}=\begin{cases}\frac{E_{res_i}\times(1-\deg_i)}{p_{r\text{-}tot}}, & E_{res_i}\geq E_{av}\times(1-\lambda)\\ 0, & else\end{cases} \tag{6}$$

And $p_{r\text{-}tot}$ is calculated as follows:

$$p_{r\text{-}tot}=\frac{E_{av}\times\sum_N(1-\deg_i)}{2K_{RC}} \tag{7}$$

where K_{RC} denotes the number of relay nodes candidate.

When the controller obtains all the probabilities, it select the K_R nodes with highest probabilities as relay nodes where $K_R \leq K_{RC}$.

E. Clusters Formation

The controller assigns other nodes to join the closest cluster head and formats clusters ultimately.

V. Evaluation and Discussion

A. Simulation Setup

To evaluate the effect of M-SEECH, two well-known energy efficiency methods are adopted to be compared with M-SEECH. The two methods are LEACH and SEECH. The parameters of simulation setup are listed in Table I.

TABLE I
PARAMETERS OF SIMULATION SETUP

Parameter	Value	Parameter	Value
Area	(0, 0)~(200, 200)	Initial Energy	1J
Location of data sink	(100, 350)	E_{tx}	50nJ/bit
N	1000	E_{rx}	50nJ/bit
K_{CH}	3	ε_{fs}	10pJ/bit/m^2
K_{CHC}	8	ε_{tr}	0.0013pJ/bit/m^4
K_R	10	d_0	87m
K_{RC}	15	E_{da}	5nJ/bit/signal
RNG	55	Packet Size	4000bits

Also, we describe three scenarios with different number of replaceable sensors and data aggregation compression ratio. The three scenarios are listed in Table II.

TABLE II
PARAMETERS OF THREE SCENARIOS

Scenario	Number of replaceable sensors	Data aggregation compression ratio
1	400	1
2	500	0.9
3	500	0.8

B. Evaluation

We use the numbers of “alive nodes” during simulation time in terms of round to evaluate the effects of protocols. Alive node is a node whose battery is not completely depleted. The numbers of "alive nodes" are derived by average results obtained from 200 simulation test. In each simulation test, we distribute a new distributed set of sensor nodes in WSN.

Fig. 6 illustrates the results for three scenarios. And Fig. 7 illustrates the results for LEACH, SEECH and the third scenario of M-SEECH.

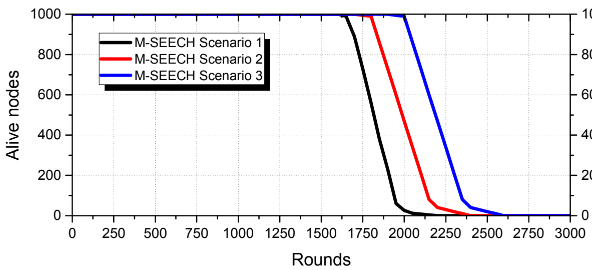


Fig. 6.The lifetime evaluation of M-SEECH for three scenarios

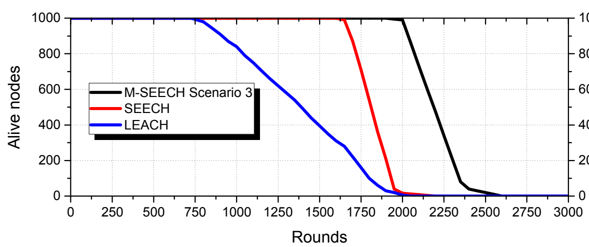


Fig. 7.The lifetime evaluation of M-SEECH, SEECH and LEACH

From Fig. 6, we can see that in scenario 3, M-SEECH is more efficient than the others. And the effect of M-SEECH in scenario 1 is almost as same as the effect in scenario 2. Intuitively, more replaceable sensors and higher data aggregation compression ratio makes less communications traffic and more sleeping nodes. It is beneficial to save radio energy consumption. From Fig. 7, we can see M-SEECH is greatly more efficient than LEACH. And in WSN with lots of replaceable sensors and high data aggregation compression ratio, M-SEECH has higher energy efficiency than SEECH. But in other WSN, M-SEECH is slightly less efficient than SEECH. This is because the switches of replaceable nodes and data aggregation consume some energy. But because of low data aggregation compression ratio, only a little communication traffic is saved. It leads a little energy saved.

VI. CONCLUSIONS

In this paper, we provide an effective energy efficiency scheme of IWSNs using SDN and NFV named M-SEECH for industrial applications. The typical IWSNs architecture is extended to an enhanced one that leverages the advantages of SDN and NFV. In the comprehensive architecture, topologies of IWSNs are controlled by logic controller that utilizes SDN technique and sensor functions are deployed dynamically into sensors in the network that utilizes NFV technique. By these means, topology control and sleep mode is introduced to realize energy efficiency. The algorithms for controller to make decision also are provided. The evaluation and discussion shows that our scheme is effective for energy efficiency in IWSNs

ACKNOWLEDGEMENT

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