

# UAV based SDN system for wireless sensor networks

## ABSTRACT

[illegible]

## 1. INTRODUCTION

Software defined network (SDN) [4, 30] and artificial intelligence (AI) [24, ?] are two popular topics in recent research field, both of which greatly improve the performance of traditional networks.

On the one hand, SDN enables flexible programmability on traditional network system by using programmable data plane and centralized network controller [37]. It shows remarkable advantages in good management of network control, less operating costs and easy deployment for new applications [10]. On the other hand, AI technology promises a smarter and more effective network system due to its high performance in predicting and optimizing network capacity, e.g. network throughput, energy consumption, etc.

In this paper, we study integrating these two elegant techniques into the wireless sensor networks (WSN) [8, 32]. Our fundamental observation is that conducting AI methods in WSN requires the support of SDN. This is due to two major reasons. First, traditional sensor device has limited processing capability and cannot deal with complex computations [31, 15]. Second, the sensor

device is also lack of storage space to support complicated operations. With the help of SDN, the central controller can conduct complex computations and store huge data information instead.

Unfortunately, implementing a real SDN in sensor system is still an open problem. The existing work [21, 7, 20, 9, 11] all design framework of SDN for WSN and validate them by simulations. Even worse, these simulational SDN works construct the central controller of SDN in their database station. The controller transmits control instructions with sensor nodes by multi-hop communications [22]. This causes a great deal of energy consumption [35], which makes it a paradox since sensor network ought to be an energy-efficient network.

Our insight is that, since it is impractical to deploy SDN for sensor system by multi-hop control, we refer to various equipments and techniques to support one-hop communication, and finally find the unmanned aerial vehicle (UAV) [5, 26, 6] perfect to serve as the SDN controller. The flexibility of UAV can promise one-hop communication between controller and nodes [29]. Furthermore, the advantage of utilizing UAV compared to terrestrial mobile controller is that, the air-ground communication range is almost 10 times than that of ground-ground communication under ZigBee protocol, which are around 145 meters and 15 meters respectively tested by our practical experiments. This is due to the air-ground communication suffers from less interference of the terrestrial WSN.

In this paper, we present Malak<sup>1</sup>, a real UAV based SDN sensor system. In Malak, UAV plays the role of the central controller to monitor the sensor system. We implemented five fundamental applications: routing, network diagnosis, AI energy prediction, AI node selection and multi-task, and provide users with easy-to-use interfaces. Routing application allows users to update the flow table of nodes. Network diagnosis is used to find the fault source when network exception is detected. Multi-task application enables sensor to perform multiple tasks simultaneously. All the applications are within

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<sup>1</sup>In the Bible, Malak is a word used to denote a messenger from God.

a ecosystem and can be combined to achieve synergistic effect. For example, users can execute the AI node selection application to choose the node set for the multi-task application.

We implemented Malak with DJI M100 UAVs and CC2560 Sensor tags in real experiments, and we conducted extensive experiments for a large-scale sensor network. We deploy 130 sensors .....

The main contribution of this paper is the first practically implemented SDN for sensor system, Malak. We adopt AI tools in Malak and realize five applications with easy-to-use interfaces. We then conduct practical experiments and the evaluations validate the high performance of Malak.

The paper is organized as follows. We introduce related works in the next section. Design of Malak is presented in Section 3, and we implement five fundamental applications: routing, network diagnosis, AI prediction, AI node selection and multi-task in Section 4. Section 5 gives the implement setup. The evaluation results are provided in Section 6 and we conclude the paper in Section 7.

## 2. RELATED WORK

### 2.1 Software Defined Wireless Sensor Networks

There are several existing SDN approaches for sensor system, namely flow sensor [21], SDWN [7], sensor openflow [20], TinySDN [9], SDN-WISE [11]. However, they are all implemented and evaluated by simulations.

**Flow Sensor.** The previous idea presented in paper [21] addresses reliability in the sensor networks through exploiting the OpenFlow technology. Coming up with the concept of flow-sensor instead of typical sensor [19], they have successfully made it possible to communicate between controller, gateway and sensors. Besides that, they proved flow sensor more reliable since data packets, control packets and the sensor nodes themselves can be easily monitored, regulated and routed whenever required. Therefore, a robust routing and uninterruptable messages flow of sensors are achieved. The results described in this paper shows flow-sensor is able to display much better performance even for large networks.

**SDWN.** The solution of supporting the SDN approach in LR-WPANS is first presented in [7]. Given the gap that advantages of SDN and the proper ways to expand that to wireless network were not clear enough, the group analyzes the opportunities of SDN-related wireless network and illustrates the requirements should be considered to utilize SDN solution for wireless network. They made a good attempt to develop the SDWN protocol stack.

**Sensor OpenFlow.** In the paper [20], the group took a radical, yet backward and peer compatible, approach to tackle the problems existing in WSN such as

resource underutilization, counterproductive, rigidity to policy change and manage difficulty. They propose SD-WSN with a separation between data plane performing flow-based packet forwarding and control plane performing network control. The core part designed is Sensor OpenFlow(SOF), which gives a standard protocol for the communication between data and control part. Based on the whole architecture they gave, the underlying network becomes programmable by using SOF.

**Tiny SDN.** TinySDN [9] is a TinyOS-based SDN framework aims to address the problem that only single controller can be coupled to the sink. Besides, TinySDN is a hardware independent framework that comprises two parts: SDN-enable sensor node and SDN-controller node. In order to test the reliability of this framework, the authors done some experiments on COOJA. Through analyzing results concerning delay and memory footprint, they found it is feasible in communication provided by SDN paradigm.

**SDN-WISE.** One solution for wireless sensor network is introduced in the paper [11], and the authors implement the prototype of this idea. Compared to other SDN solutions for wireless network, this solution successfully reduces the messages exchange needed between sensor node and controller. Besides, flexible APIs are provided by the authors, thus making the network much easier to program. Also, they done some experimental testbed, found that in a power limit hardware, the response delay is still very small, SDN-WISE shows its good performance in different operation conditions.

### 2.2 Applications for Wireless Sensor Networks

To design a ecosystem for sensor network, we are to implement several applications. We make a survey of the traditional sensor networks and find some typical applications: routing, network diagnosis, AI sensor, sensor selection and multi-tasks.

**Routing** Low-power and lossy network consist of devices whose processing, memory and energy are both constrained [33]. Hence, traditional protocols can't be used there. However, RPL is one of the standards for ipv6 routing in LLN. It builds the topology like a tree, performing DAO, DIO, ACK to generate a directed acyclic graph from one or more root to the leaf nodes. The experiments done in the paper [Low-Power Wireless IPv6 Routing with ContikiRPL] [34] shows that Ipv6 routing with ContikiRPL is both lightweight and power-efficient.

**Network Diagnosis** Previous diagnosis algorithms share the same drawback that their process of gathering information is static and the reports sent to be analysis is not intermediate enough [27, 16]. Directional Diagnosis [13] is an online diagnosis approach to dynamically recognize the most useful information according to an engine designed in the approach. Besides, the diagnosis

process only focuses on the problematic area, so that it can produce a more accuracy prediction [25]. To be specify, the whole approach consist of four main parts: Node Tracing, Trace Collection, Inference Model and Incremental Probing. The node tracing algorithms dynamically reconstruct topical topology and derive inner dependencies. Based on the data information collected, inference model can guide the next probe by Incremental Probing applying Belief network. The experiments done show the diagnosis result is efficient and in real time.

**AI sensor** The application of sensors often relays on the filed like sensor select, data prediction combining with AI algorithms. In order to select the subset of nodes to be active, related study give a way to dynamically response to the change of sensor network based on the historical information [23], the new sensor node has a different time factor from the old node when construct the predict network. Besides, the position of nodes may be highly used to reduce the weight of nearby nodes in a predict network [17]. As for data prediction, on the one hand, the energy consuming information can be collected. Previous work on diagnosis, for example, only performs diagnosis when sensor almost run out of energy. On the other hand, the original data about temperature, humidity, light intensity is a reliable resources for prediction in time series[28].

Sensor Select Redundant sensor network always contains nodes that generating data stream with some over-leap parts [2]. Collected information can be useful to determine which sensors are active. The algorithms come up with in paper[18] are called Spatially Regularized Streaming Sensor Selection(SRSSS). The authors not only consider the spatial information but also the historical obversion of the sensor network. They apply higher weights to nearby sensors and introduce a time-forgetting factor [3] so that their approach can predict more accuracy and response much faster than others.

**Multitask** One single sensor node may shoulder several tasks. To achieve power saving, when a task performed, we need to choose which sensor to be active and which to be inactive [12]. Nowadays, work aims to design an energy-efficient sensor management strategy tends to develop their method in three ways: choose the proper subset of nodes to be active [1], which sensors to assign the task and the sampling rate on one node when performing task. Related study has found an efficient online algorithm considering sensor activation and task mapping to deal with dynamic events during runtimes of SDSNS [36].

### 3. ARCHITECTURE

The architecture of Malak is shown in Fig. 1. The system is divided into three layers: data plane, control plane and management plane respectively.

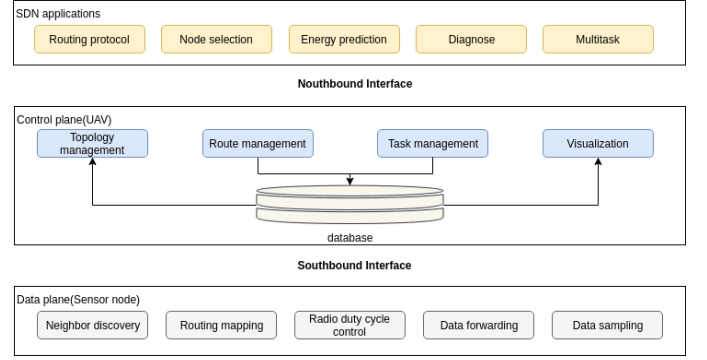


Figure 1: Architecture of the system.

To build software defined network system in WSN and achieve low energy consumption and high performance, the SDN controller ought to configure data plane within as less hops as possible. In Malak, we choose UAV as a mobile SDN controller, which communicates with sensor nodes by on-hop communication. It significantly reduces the energy consumption of nodes in Malak. To achieve high performance, the UAV controller carries a powerful airborne computer which has ability to run some intelligent applications in real-time.

The data plane runs on sensor nodes while the control plane and management plane run on UAV controller. And the interface between data plane and control plane is defined as southbound interface, while the interface between control plane and management plane is defined as southbound interface.

In the control plane, in order to make our system easy to use, we implement a database on the UAV and design interfaces for data plane and SDN applications. The control plane connected data plane and management plane. The database maintain the topology gathered from the data plane, route table inputed form applications, and sensor task schedule table form management application.

On management plane, user can run tons of applications base on our well-defined southbound APIs, such as routing algorithms, network diagnose, sensor task scheduler, tec.

Different from wired network, the data plane of WSN not only runs data forwarding function, but also executes data sampling function. For example, sensor nodes execute neighbor discovery process for getting topology, data sampling process for getting data from environment and data forwarding process for data gathering. In

Malak is a easy-to-use system that we design and implement a lot of interfaces for users.

The Table 1 shows our southbound interface for user write applications.

The List. 1 demonstrate a deployed routing algorithm based on our southbound APIs. And the List. 2

**Table 1: System API**

Structure && Function	Description
<b>Sensor Control Interface</b>	
struct node	Sensor node structure
struct nodeset	A set of sensor nodes
struct neighbor_list	Neighbor infomation
struct energy_item	Energy statistic information
struct flow_table	Flow table
struct duty_cycle_table	Duty cycle control table
struct sensor_enable_table	All the nodes's states. Node state: {on,off}
switch_node(node,state)	Turn on or turn off the node
get_node_info(node)	Get node's information, including node's position, duty cycle, power, etc.
set_node_attr(node,attrTag,value)	Set node attribute, including duty cycle, radio strength, etc.
get_neighborlist(node)	Get the neighbor list of a node
<b>UAV Application Interface</b>	
<b>Routing</b>	
get_topology()	Get the topology of the network
get_flow_table(node)	Get the flow table of a node
set_flow(flow,node)	Set the flow of a node
<b>AI Node selection</b>	
nodeset simple_selection(nodeset)	Select sensor set by location information
nodeset SRSSS_selection(dataset)	Select sensor set by AI algorithm based on sensing data
<b>AI Energy Prediction</b>	
model_selset(modeltype)	Select an AI model
model.train(dataset,ratio)	Train an AI model with learning ratio on the data set
model.test(dataset)	Test the AI model on the data set
model.predict(node)	Do the energy prediction for a node
<b>Multi-tasks</b>	
create_scheduler()	Create a task scheduler
scheduler.create_buffer()	Create a task buffer
scheduler.task_buffer_add(task,nodeset)	Add a new task to task buffer
scheduler.task_buffer_remove(task)	Remove a new task to task buffer
scheduler.task_buffer_update(task,nodeset)	Update a task to task buffer with a new nodeset
scheduler.task_update()	Schedule the added or removed tasks in the buffer
<b>Diagnosis</b>	
detect()	Detect problematic region with probes
get_topical_topology(nodeset)	Construct topical topology
diagnose_network(topology,nodeset)	Diagnose the failure nodes or lossy links

demonstrate a AI selection and Multi-tasks application.

**Listing 1: An example of deploy routing algorithm**

```

topology = get_topology();
//calculate flowtable for each node
//based on topology
for(node in nodeset){
    node.flowtable =
        calculate_flowtable(topology);
}
//set flowtable for each node
for(node in nodeset){
    UAV fly to node;
    for(flow in node.flowtable)
        set_route(flow);
}

```

**Listing 2: An example of AI selection and Multi-tasks**

```

AI_Multitasks(taskset){
    create_scheduler();
    scheduler.create_buffer();

    for(task in taskset)
        scheduler.task_buffer_add(
            task,
            defaultset);

    scheduler.task_update();
    ...
    ...
    for(task in scheduler.task_buffer){
        data = get_collected_data();
        nodeset =
            SRSSS_selection(dataset);
        scheduler.task_buffer_update(
            task,
            nodeset);
    }
    scheduler.task_update();
}

```

Configure data structure

Routing table

Time slot	T1	T2	...	Tn
Role	(H/M)	(H/M)	...	(H/M)
Next hop	Next hop Ip	Next hop Ip	...	Next hop Ip

⋮

Sample frequency control:

Time slot	T1	T1	T3	T4	T5	T6	T7
Sample frequency							

Sensor enable map

Sensor	S1	S2	S3	S4	S5	S6	S7	S8
On/Off								

Feedback data structure

Neighbor information

Neighbor list			
IP	RSSI	Connectivity rate	Traffic statistic
IP	RSSI	Connectivity rate	Traffic statistic

⋮

Energy statistic information

Items	Radio	Sensor	CPU	Others
Cost	Er	Es	Ec	Eo

**Figure 2: Southbound data structure**

## 4. APPLICATIONS

### 4.1 Overview

Traditional applications can not achieve complicated and efficient goals due to the limited processing power and memory space of sensors.

In Malak, applications for wireless sensor networks are inspired by greater potential with the UAV based SDN controller. The central controller helps sensors execute complex calculations such as AI model training,

as well as store global information. Besides, UAVs have flexible features and can deploy tasks to sensors by one-hop communication directly. Thus it enables the sensor network to achieve much more intelligent applications.

In Malak, applications can be found for a variety of purposes, including routing, network diagnosis, AI energy prediction, AI node selection and multi-task. We design all these applications and provide easy-to-use interfaces to users as in Table 1.

## 4.2 Routing

### 4.2.1 Motivation

Routing is a fundamental application of SDN system. There are lots of studies on SDN in wired network, but only few researches on wireless sensor networks since implementation of SDN routing in WSN have following challenges. First, the wireless communication is unstable, the poor reliability of connection between controller and sensor nodes make SDN system performance worse, especially the controller connect with nodes through multi-hop wireless approach. Second, the sensor network is energy sensitive, the deployment of SDN downward stream energy cost need be ignore compare with the normal network data communication, and the frequency of routing update should low. Last but not least, the robust of SDN routing mechanism in WSN is difficult to achieve, since the controller and nodes not may be disconnected, if some nodes radio failure, it may cause all network connection crash.

To address above challenges, we use mobile controller which communicate with nodes via one-hop to improve the reliability of nodes and controller connection. Meanwhile, we design cluster-base SDN routing protocol and local repair mechanism to achieve both energy efficiency and robustness.

### 4.2.2 Design

In WSNs, cluster routing method is a kind of protocol, which nodes choose a header periodically, the other node around cluster header send it's data to cluster header, and the cluster header forward it to anther header, until root node receive the data. Through cluster method will reduce the energy hole problems, but the routing protocol between is running on sensor nodes locally, because sensor nodes only have local information of network and limited computing ability, it can not achieve global optimal routing, and it is difficult to modify protocol according users requirements.

We improve cluster method by using our SDN controller to update the routing protocol between cluster headers. At first, UAV fly around sensor field and get topology data from nodes, and then calculate the cluster header schedule do decide which node should be cluster header at specific time phase to balance energy con-

sumption between nodes, and calculate the routing result between current header's topology through Open Shortest Path First (OSPF) protocol base on gathered topology information, In WSN, every node only need send its data to root node, so the OSPF destination internet protocol (IP) has be set as root IP. Through OSPF, UAV get the routing table between cluster header. When UAV fly near the nodes, it send routing table to nodes, including the node role and next hop IP in every time phase.

Considering the economic and energy limitation, UAV can not keep fly above the sensing field. It only fly to sensing field to gather topology after node deployed and update nodes routing on demand. So after the routing has been deployed, the system routing repair mechanism should make sure some nodes failure don't make the network routing crashed.

By designing local routing repair mechanism, our system achieves robustness to radio failure. When a node in cluster member failure, it didn't influences the whole routing between the routing we deployed routing. On other case, when the cluster header failure, if the network don't have local repair mechanism, the whole routing between cluster headers will crash and make the network partial. So we design the local repair mechanism through local header switching.

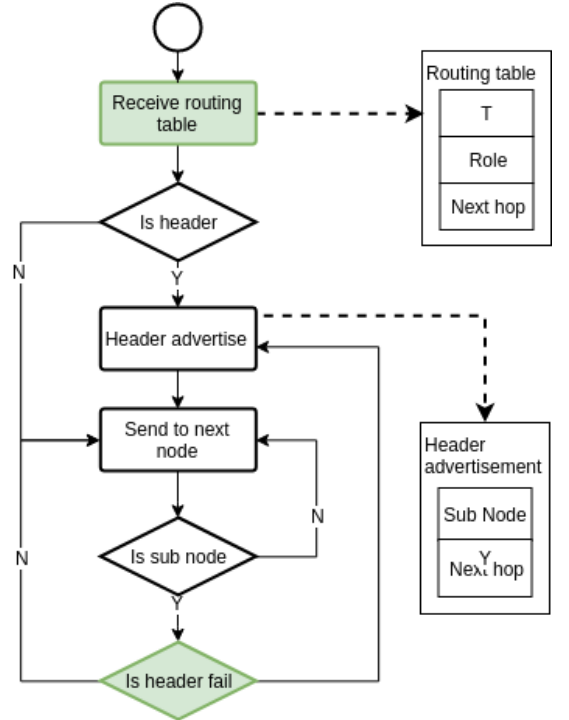


Figure 3: Routing local reparation

As shown in Fig. 3, after the node get routing table for UAV, it set it's next hop IP following received table, and also using neighbor's RSSI information find the nearest node as its substitute node, then node broadcast

its next hop IP and substitute node IP. After the substitute node received the broadcast packet, it save the source's next hop IP and keep monitoring the source status. The substitute node will became new header when it detected the current header failed.

We implement our software defined routing and local reparation, the routing in our system achieve both energy efficiency and robustness.

### 4.3 Network Diagnosis

#### 4.3.1 Motivation

Sensor nodes are provisioned with low-capacity batteries and will run out of energy in the end. Besides, uncertain environmental factors will lead to the failure of communications. Upon these two factors, there occurs network faults such as failure nodes and lossy links from time to time.

Network fault diagnosis is then designed to help network administrators monitor the network operational status and maintain a sensor network system. The key idea of the existing works on fault diagnosis is to collect running information from nodes and deduce root causes of network exceptions. The running information is collected by a mechanism of probing.

We implement the network diagnosis process as an application in our Malak system. Since in Malak we have our mobile UAV as a controller, a more flexible way is to infer the suspicious nodes of the network fault in traditional way first and then set the UAV to check out the fault sources.

#### 4.3.2 Design

We first introduce a state-of-the-art algorithm named DID [13], which is a directional diagnosis approach. We utilize the node tracing module and the tracing collection module of DID to infer the suspicious nodes in our network diagnosis application, and then set our UAV controller to confirm the network elements being faulty.

The node tracing module is conducted in each sensor node. Every time a packet arrives at a node, it counts the source of the packet. The tracing collection module is set in the UAV controller. When network exception is detected, it gathers the tracing information in the tracing module of the relevant nodes and infers a suspicious node set. Next we set the UAV to fly through the node set and check each node first to diagnose the failed nodes. Then UAV collects the neighbor lists of all the nodes in the suspicious node set. With the collected neighbor lists, the UAV controller reconstructs the topical topology and compares it with the default topology to find the failed links.

Compared to DID, the diagnosis application in Malak releases the complicated inference computations and can achieve accurate diagnosis since the UAV can fly to the

sensors to confirm the network faults. Malak can realize the four types of fault sources the same as DID:

- Node failure. This network failure is caused by the node itself.
- Link failure. This network failure is caused by the communication links between nodes, mainly relating to traffic flow in networks.
- Temporary failure. This network failure is caused by complex interior or exterior interferences and quick self-recovery
- Multiple failures. This network failure is caused by multiple failures above.

### 4.4 AI Energy Prediction

#### 4.4.1 Motivation

Traditional wireless sensor networks (WSN) generally carry out data collection by multi-hop transmission, and due to limited computation capability and storage capacity, sensors are incapable to perform deep learning methods for data mining. Hence, intelligent self energy consumption optimization for a sensor is hard to achieve.

The sensor next to the data center always has the most frequent routing tasks, which leads to the heaviest workload and the shortest battery life. Worse more, after the first sensor runs out of energy, a new sensor will be selected to take the place of it with more workload. As a result, its lifetime becomes shorter and the whole sensor network will soon run out of energy. We call this energy exhausted problem.

An ideal solution to the energy exhausted problem is to find a self-adjusted routing schedule which makes adjustments according to the energy status of each sensor. Actually, this is a kind of dynamic programming problem and the optimization target is to achieve the longest lifetime of the whole network under complex constrains. We modify linear and simple MLP[14] deep learning model to simulate and simplify this constrains. Challenges occurs in traditional WSN because of lack of global energy information.

In Malak, the UAV controller. all these factors makes it possible to execute this optimization. Besides, the The AI prediction application can contribute to the network diagnosis application This kind of cooperation and mutual assistance makes Malak an effective ecosystem.

#### 4.4.2 Design

In our Malak system, we implement a prediction application for energy storage of sensors. The architecture of the AI energy prediction can be seen in Fig. 4. The special system architecture enables us to analyze the sensor data in real time. After the information collected

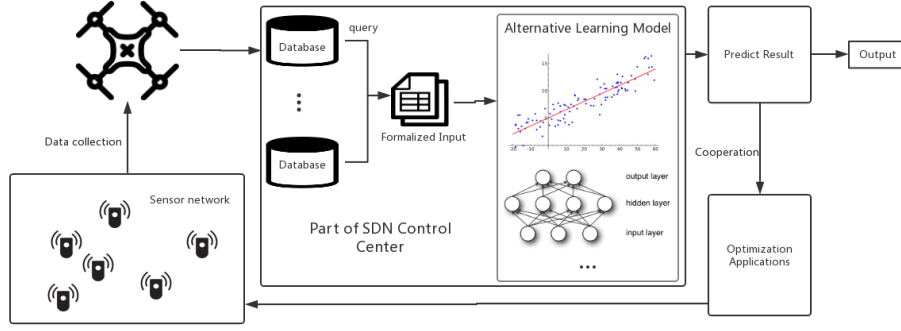


Figure 4: AI prediction

by the sensor is transmitted to database, it is used as the input of the incremental learning model, which outputs the life expectancy of each sensor. These predicted information contributes to other application.

A sample input of energy information contains at least four components: sensors' duty cycle, packet-sending time, data receiving time and other energy consumption. Data collection module records these information with time stamp, as well as routing information. We use the database to maintain our experimental data, and use the sql query to manage training data. In this way, we can easily get each sensor's routing task and energy consumption at any time as input. A forgetting factor is used to avoid overfitting. Then the model will output the prediction of a energy consumption list in time sequences. The sensor which is most likely to run out of energy will rank in the first place of the list. Combined with our diagnosis application, we can make use of our prediction result to prolong the network lifetime.

## 4.5 AI Node Selection

### 4.5.1 Motivation

It is inevitable that there will be a part of redundant sensors when deploying a practical wireless sensor network. These redundant nodes have overlaps of observation regions, and what makes the matter worse is that redundant nodes may cause great communication interference. Therefore it is significant to select proper sensors to avoid data redundancy and save the sensor network energy consumption.

In Malak, we provide the node selection application to users. The SDN controller executes the selecting algorithm and send the control instructions to activate the selected nodes.

### 4.5.2 Design

Our Malak system provide two main node selecting methods: greedy selection algorithm and SRSSS algorithm. This application will be extended to more ele-

gant algorithms in our future work.

**Greedy selection algorithm.** We first provide a simple method to select the redundant nodes by a greedy selection algorithm, as described in Alg. 1. The key idea is to select nodes as less as possible to coverage the whole area based on the location and sensing range.

We implement the greedy selection algorithm in Malak. The evaluations in section 6 wshow it greatly saves the sensors' energy and thus prolongs the network lifetime.

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#### Algorithm 1 Greedy Selection Algorithm

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- 1: Input: Sensor set  $N$ , Selected set  $M$ , Target area  $\Omega$ , Covering area  $\Phi$ ;
  - 2: Initialize :  $M = \emptyset, \Phi = \emptyset$
  - 3: **while**  $M \neq N$  **do**
  - 4:   **if**  $\Phi = \Omega$  **then**
  - 5:     break;  $\backslash \backslash$  Selected set has been found
  - 6:   **end if**
  - 7:   **if**  $\forall n_i \in (N - M) : range(n_i) \subset \Phi$  **then**
  - 8:     break;  $\backslash \backslash$  Cannot cover the target area;
  - 9:   **end if**
  - 10:   Find  $n_i : argmax(\Phi \cap range(n_i)), n_i \in (N - M)$ ;
  - 11:    $\Phi = \Phi \cup n_i$
  - 12: **end while**
  - 13: Output:  $M$ ;
- 

**Spatially regularized streaming sensor selection (SRSSS).** To realize more intelligent and effective sensor selection, we introduce a state-of-the-art AI algorithm named spatially regularized streaming sensor selection (SRSSS) [18].

Different from the greedy selection algorithm, SRSSS is a multi-variate interpolation framework and focuses on selecting a subset of sensors in a streaming scenario to minimize collected information redundancy.

Traditional wireless sensor network is not suitable to implement an AI selection approach due to the limited computational capability of sensors. Some work use the database to collect data and make decisions by multi-hop communications. However, in this way the network



will use up a great deal of energy. In our Malak, the UAV fly through the nodes to pick up the collected data and executes the computations. Then it sends the control instructions to the nodes by one-hop communication and greatly saves the network energy.

The aim of SRSSS is to optimize its objective function which is an equation given certain constraints of collected information, location and energy consumption. The objective function is formulated as:

$$\begin{aligned}
& (W_{k+1}, z_{k+1}) \\
& = \arg \min_{W, z} \sum_{i=1}^k \mu^{k-i} \|X_k^i D_z W (I - D_z) - X_k^i (I - D_z)\|_2^2 \\
& + \alpha \sum_{i,j=1}^n \|y_i - y_j\|_2 |W_{i,j}| - \beta \sum_{i,j=1}^n \|y_i - y_j\|_2 z_i z_j \\
& + \lambda \|W\|_F^2 \\
& s.t. z = [z_1, \dots, z_n] \in \{0, 1\}^n, c^T z \leq P
\end{aligned} \tag{1}$$

The first term in (1) is to minimize the prediction error of the collected data and the following two terms incorporate spatial information. The last term constrains the complexity of the learned matrix  $W$ . The energy constraint is controlled by the inequality in (1). Because of the limitation of length, we leave out all the details. The meaning of the parameters and the mechanism of SRSSS can be seen in [18].

With the AI sensor selection process, Malak becomes a smarter and adaptive sensor systems.

## 4.6 Multi-task

### 4.6.1 Motivation

Wireless sensor networks (WSN) generally comprise of a group of spatially dispersed sensors. In a wireless sensor network, sensor nodes are equipped with various types of sensors monitoring and recording environmental conditions like temperature, sound, sunlight, humidity, etc.

A given sensing task involves multiple sensors to achieve a certain quality-of-sensing. Generally, an efficient task scheduling for the nodes is that nodes are able to perform multiple tasks simultaneously. For example, sensors deployed in a grove are assigned tasks to collect sunlight, temperature and humidity data and these tasks require different number of nodes with respective sensing range, rate and duration. However, traditional sensor networks are not suitable to conduct this multi-task due to the limitations of computation complexity for task arrangement of each node.

In our Malak system, we implement the multi-task application with the help of the central controller. The SDN controller maintains programmable task scheduling and management modules while sensor nodes are

loaded with interfaces to receive task control instructions.

### 4.6.2 Design

A deployed wireless sensor networks are usually assigned with different data collection requirement. In Malak, we design and implement multi-task application and provide easy-to-use interfaces to users.

When a user assign a task to Malak, the UAV controller will first check out the energy and storage constraints of the required sensor set, as described in Alg. ?? . If the task requirement exceeds the capacity of the sensor set, it will be sent to a task queue; Otherwise it will be put into the task buffer to conduct.

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#### Algorithm 2 Sensor Constraint Detection

---

```

1: Input: Sensor set  $N$ , Task  $T$ ;
2: Input: Remaining Energy for each node
   :  $Energy(u_i)$ ;
3: Input: Remaining Storage for each node
   :  $Storage(u_i)$ ;
4: Initialize: Energy capacity  $\eta$ , Storage capacity  $\xi$ ;
5: Calculate the energy cost of  $T$  for each sensor as :
    $\phi$ ;
6: Calculate the storage cost of  $T$  for each sensor as
   :  $\varphi$ ;
7: for Each node  $u_i$  in  $N$  do
8:   if  $Energy(u_i) + \phi \geq \eta$  or  $Storage(u_i) + \varphi \geq \xi$  then
9:     Set  $T$  to task queue;
10:  end if
11: end for
12: Set  $T$  to task buffer;

```

---

A sensor node may have different sensing ranges for different tasks.

There are several practical requirements.

Different tasks have different requirements, including time, sensing range, sensing ratio, etc.

For example tasks like sunlight collection only need to be carried out during the daytime.

Our system provide a task scheduling to

Sensors are usually assigned multi-task.

Sensors are assigned tasks to monitor a specific area.

Different tasks have different requirements, i.e.

- **Node set.** Users can assign tasks to
- **Sensing rate.**
- **Sensing range.** The maximum distance that a node can detect.
- **Sensing duration.** The sensing time from start to end. There is no need to collect sunlight data at night.

Task scheduler do the arrangement.

**Table 2: Task Buffer**

Task ID	Node set	Sensing rate	Sensing range	Sensing duration
Task ID	Node set	Sensing rate	Sensing range	Sensing duration
...	...	...	...	...
Task ID	Node set	Sensing rate	Sensing range	Sensing duration
...	...	...	...	...

Task buffer.  
Task queue.  
Scheduling table.  
...

## 5. IMPLEMENTATION

We run modified contiki-ng, a system for next generation IOT (Internet of things), on data plane. we modified the network layer of contiki-ng, and abstract data plane interface to separate network control functions from data plane.

Neighbor discovery, After deployment, nodes start IPv6 neighbor discovery protocol to find the nodes which communicate with it within one hop, and save neighbor information to neighbor table and wait for UAV arrive and gather the topology information. Every neighbor's information include the neighbor's IP and RSSI.

Packet forwarding, the nodes get routing table from UAV through northbound interface, when it receive a data packet from other nodes, it just send it to the next hop node according the routing table.

Data sampling, node read task table received from UAV to decide when to wake up sensors to make sure node cost minimal energy to get same quality data.

On UAV, we run our UAV flight controller on ROS and use MySQL as our SDN database, UAV gathered topology data from every node and save in database, so user can easily read the whole network data from database, For the same reasoning, after user get routing algorithm result and save it to database via northbound interface, our middleware will automatically divide the whole network routing result to individual node routing table, and then send it to specific node.

## 6. EVALUATION

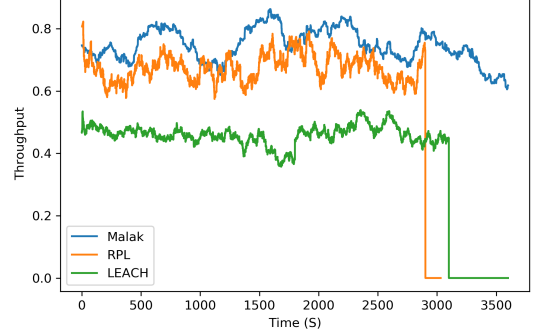
In this section, we describe our performance evaluation in real-scene experiments. We distribute 130 TI SensorTag sensors in an about  $250 \times 250$  square meters area, with contiki-ng as its operating system. We use different metrics for various applications and compare our works with other state-of-the-art works.

### 6.1 Routing

#### Energy efficiency

We estimate sensor energy cost by multiplying different coefficients on CPU running time and radio listening and transmitting time and summing them up. The

coefficients are proportional to the working current described in sensor's DataSheet.



**Figure 5: Routing throughput.** The figure shows throughput corresponding to three kinds of Routing algorithms. Throughput can drop to zero when some key nodes are dead in the network.

**Fault-tolerance**  
**Scalability**

### 6.2 Network Diagnosis

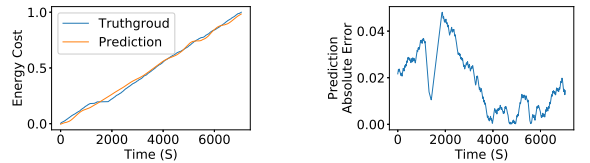
**Robustness**

### 6.3 AI Node Selection

**Scalability**

### 6.4 AI Energy Prediction

**Prediction accuracy**

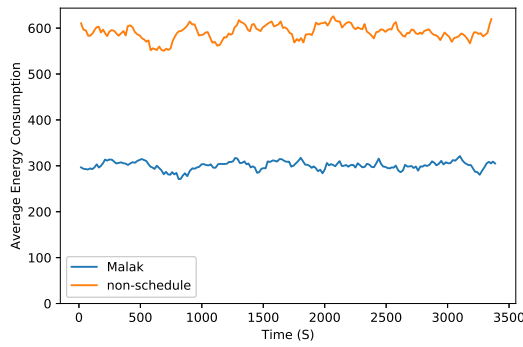


(a) Energy prediction (b) Energy prediction error

**Figure 6: Energy prediction** We use regression method to predict energy consumption and the prediction result is consistent with the truthground. The absolute error of energy prediction never exceeds 0.05 with normalized energy (i.e. the maximum energy of a sensor is 1).

### 6.5 Multi-tasks

**Energy Performance Scalability**



**Figure 7: Average energy consumption with and without multitask schedule** When with multitask schedule, sensor consumes half of the energy comparing to when without multitask schedule.

## 7. CONCLUSION

Conclusion goes here.

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