# Self-organization of Wireless Sensor Networks for Wildfire Detection Using Shapley Values

Garrison Greenwood
Dept. of Electrical & Computer Engineering
Portland State University
Portland, OR 97201 USA

Wildfires are uncontrolled and unplanned fires that destroy vegetation (forests, bushland, etc.) and animal species.

In the United States about 8 million acres, on average, burned each year in wildfires between 2017 and 2021 with an annual expenditure of $2.5 billion (in 2020 dollars) on fire suppression activities.

Although wildfires do have positive effects on many ecosystems, their high economic costs and adverse human health effects can be staggering.

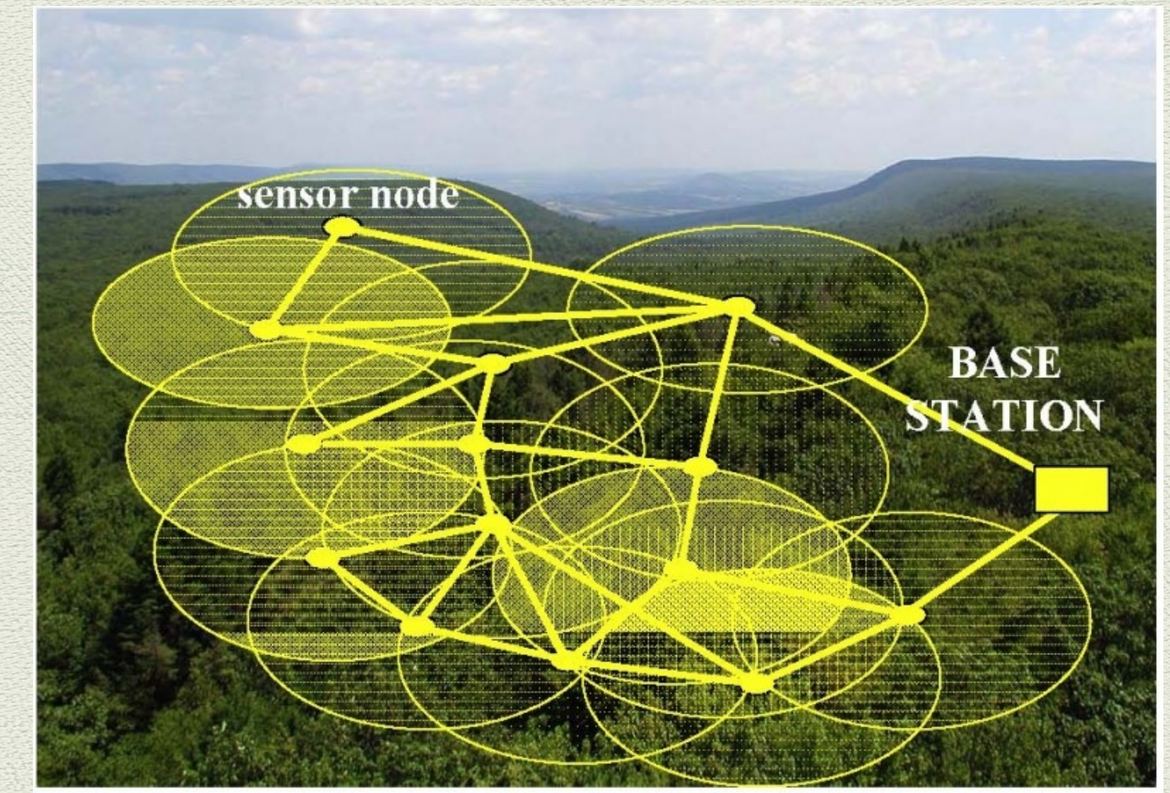
Early detection of wildfires can help minimize those negative effects.

Environmental monitoring should be effective, yet non-intrusive, non-toxic and as inexpensive as possible.

Unfortunately, monitoring in remote, limited-access areas is difficult…

***Wireless sensor networks*** (WSNs) can meet those requirements.

# Wireless Sensor Networks (WSNs)




Multiple sensors (100s or 1000s) cooperatively collect data about a physical environment.

Data is wirelessly sent to a base station.

The base station can locally use the data or serve as a gateway that sends the collected data to other networks (e.g., the internet)

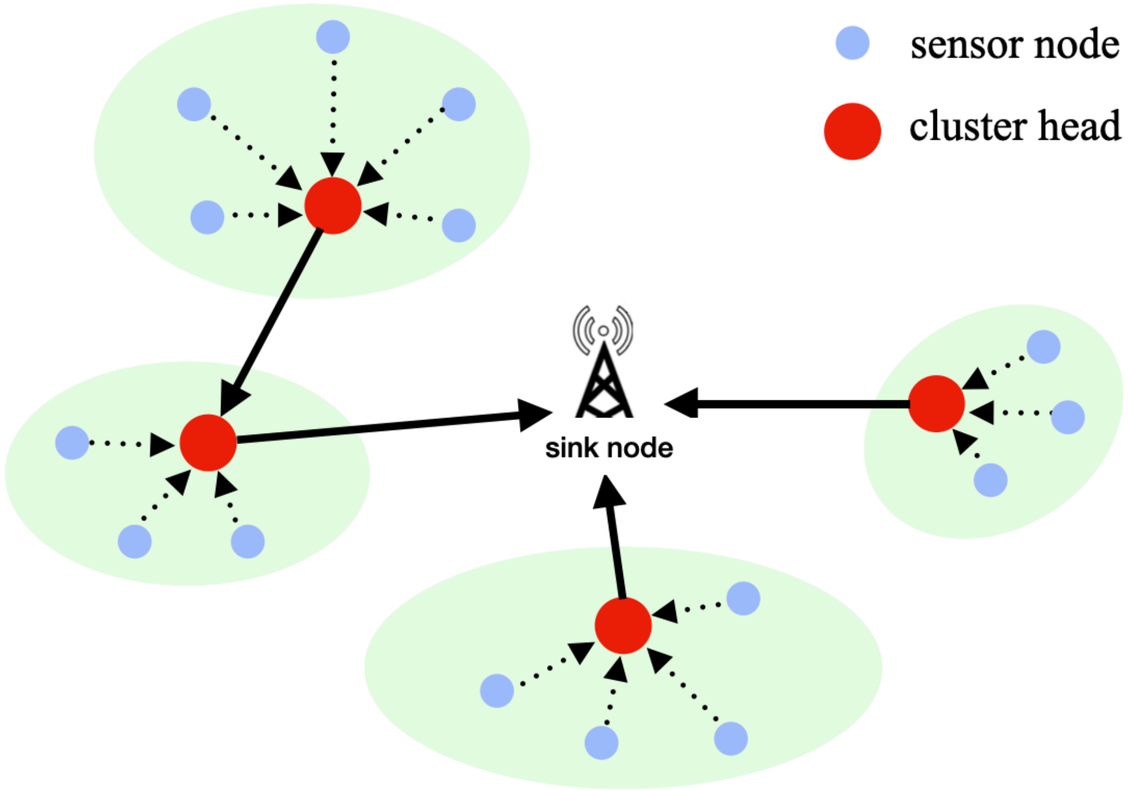
**Sensor nodes are randomly distributed (for example by air) in remote areas.**

# The network model

Sensor nodes are low cost by design and have a limited transmitter power output.

Consequently, most sensor nodes do not have a 1-hop communication with the sink node.

One solution is to organize nodes into clusters



The sink node is located at a known location and is not energy limited. It communicates with all nodes within $R_0$ meters.

For sensor nodes we assume

- sensor batteries have finite capacity and are not rechargeable.
- sensor locations are **not** known (randomly dispersed by air)
- sensors can communicate with neighbor nodes located within $R_1$ meters ($R_1 < R_0$).
- sensors can adjust their transmitter output power.
- all nodes are homogeneous so they can act as sensors or cluster heads.

After deployment, the sensors must self-organize, that is, organize itself into clusters autonomously.

Self-organization creates the WSN.

# Shapley's Problem

Lloyd Shapley* was interested in the following coalition problem:

**Problem Statement**

A coalition $C \subset N$ cooperates to complete some activity.

When the activity is finished, there is a profit to distribute among the $|C|$ coalition members.

What a fair distribution of the profit among the coalition members?

*2012 recipient of the Nobel prize in economics sciences

## What is a fair distribution?

Intuitively, a fair distribution would be an equal payoff to everyone.

**Example**

Three people want to build a house, sell it, and split the profit.

- **one person does all of the plumbing and internal wiring**
- **one person installs the doors and windows**
- **one person lays the foundation, puts up the walls and roof and connects all utilities (water, sewer, etc.)**

Question: How would you determine a fair distribution of the profit in this example?

# Shapley Values

Shapley believed a fair distribution must consider the marginal contribution of an individual—i.e., the value that individual adds to a coalition by joining it.

The marginal contribution of an individual joining a coalition $C$ can be positive, negative, or zero depending on whether the larger $C$ has more, less, or the same value.

A weighted sum of marginal contributions for an individual over all possible coalitions is called the Shapley value for that individual.

# Shapley Value (cont.)

The Shapley value for an individual is a weighted sum of the marginal contributions over all possible coalitions.

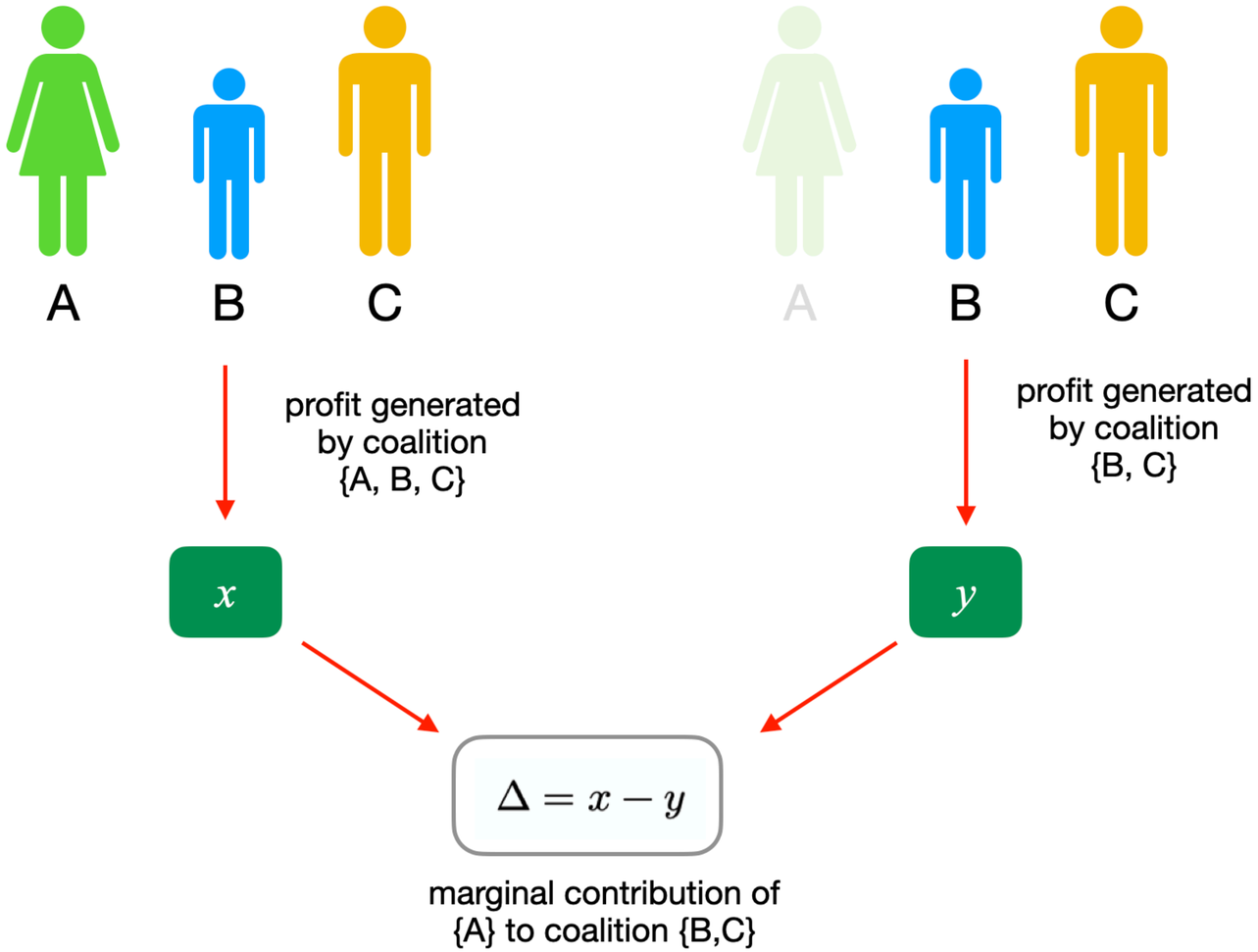
Let $C \subseteq N$ be a coalition with $n = |N|$ .

**Definition**

The Shapley value $\varphi_i$ of individual $i \in C$ is

$$\varphi_i = \sum_{C \subseteq N \setminus \{i\}} \underbrace{\frac{|C|! \times (n - |C| - 1)!}{n!}}_{\text{weight}} \underbrace{(v(C \cup \{i\}) - v(C))}_{\text{marginal contribution}}$$

$v(C)$ is a characteristic function which gives the value of the coalition $C$ (problem dependent).


A
B
C
A
B
C
profit generated
by coalition
{A, B, C}
profit generated
by coalition
{B, C}
$x$
$y$
$\Delta = x - y$
marginal contribution of
{A} to coalition {B,C}

1. Unmark all nodes

2. Sink node broadcasts alert message; all nodes within distance $d < R_0$ respond

3. Sink nodes selects subset of responding nodes as cluster heads (CHs)

4. CHs broadcasts alert message; unmarked all nodes within distance $d < R_1 < R_0$ respond

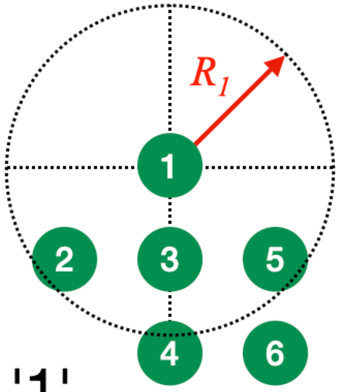
5. Nodes responding to CH($k$) are marked and join the cluster

6. Marked cluster nodes broadcast alert message; all marked nodes within distance $d <$ R1 respond. Nodes record ID numbers of responders.

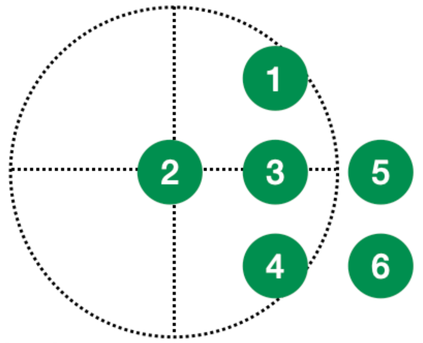
7. Shapley values (SVs) are computed for each node in the cluster

8. Node with the smallest SV re-designated as a CH that will form a new cluster

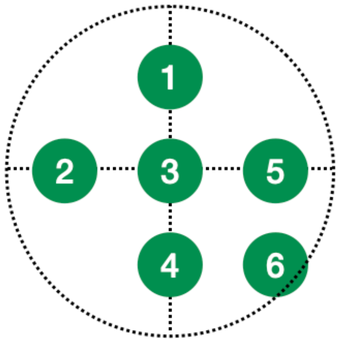
9. If not all nodes in a cluster, go to step 4.



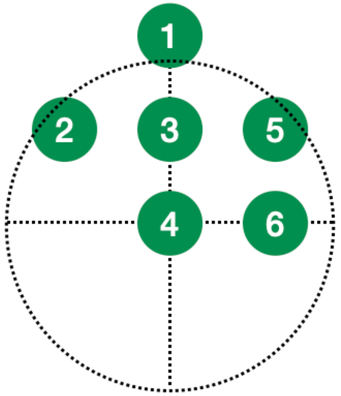

'1'



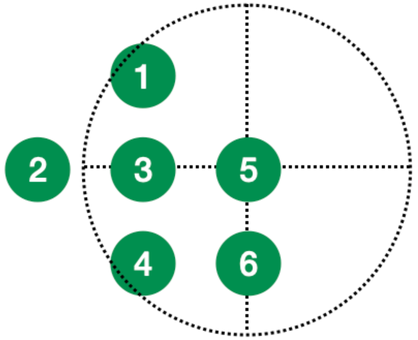

'2'



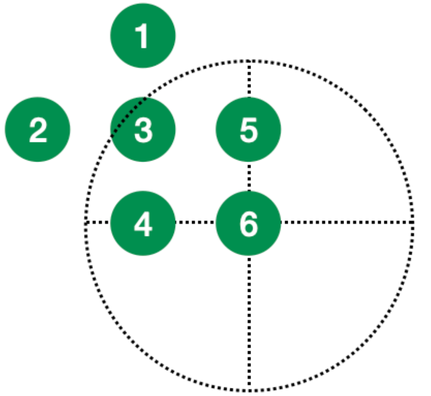

'3'




'4'




'5'

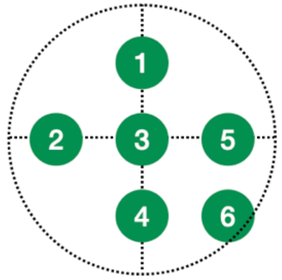



'6'

| Node ($i$) | Coalition set | Shapley value |
|---|---|---|
| 1 | $\{1,3\}$ | 0.70 |
| 2 | $\{2,3\}$ | 0.70 |
| 3 | $\{1,2,3,4,5\}$ | 1.87 |
| 4 | $\{3,4,6\}$ | 0.87 |
| 5 | $\{3,5,6\}$ | 0.87 |
| 6 | $\{4,5,6\}$ | 1.00 |

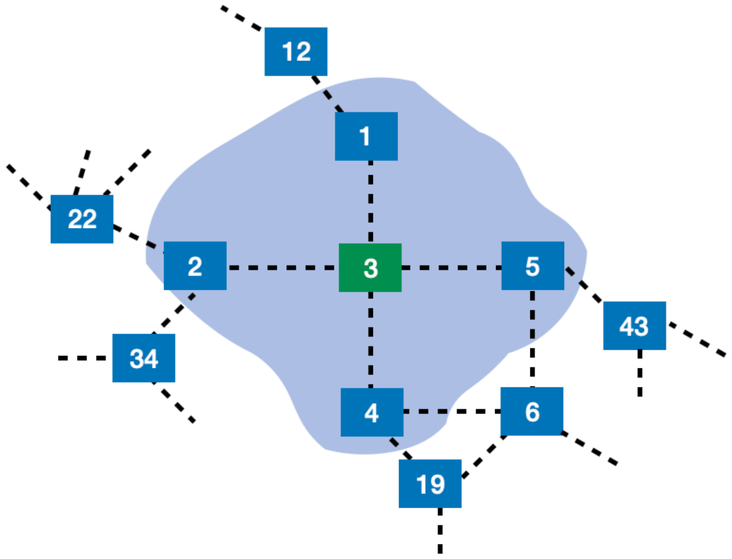
$v(\text{'2'})$ is the cardinality of its coalition set $= 2$

$v(\text{'2','5'})$ is the cardinality of union of the coalition sets $= 4$

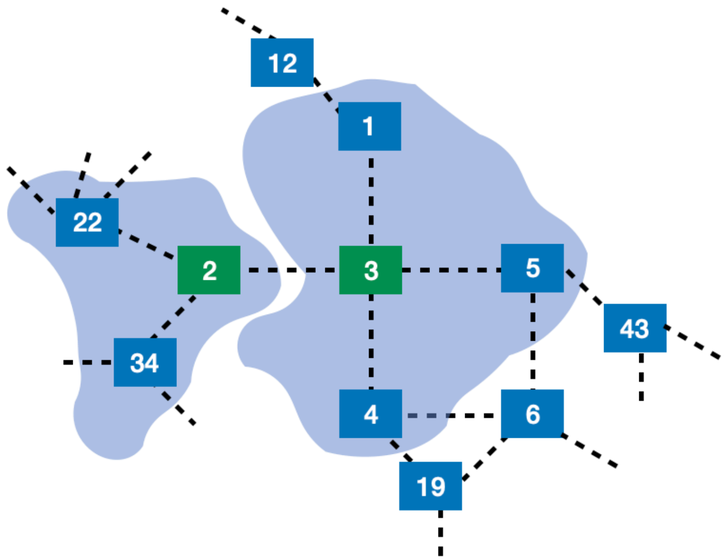



'3'

Nodes 1 and 2 had the same lowest Shapley values



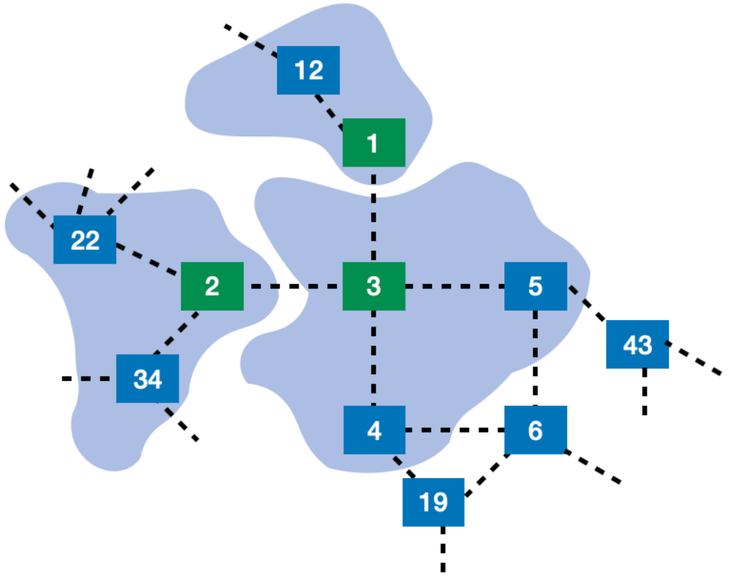

(a)



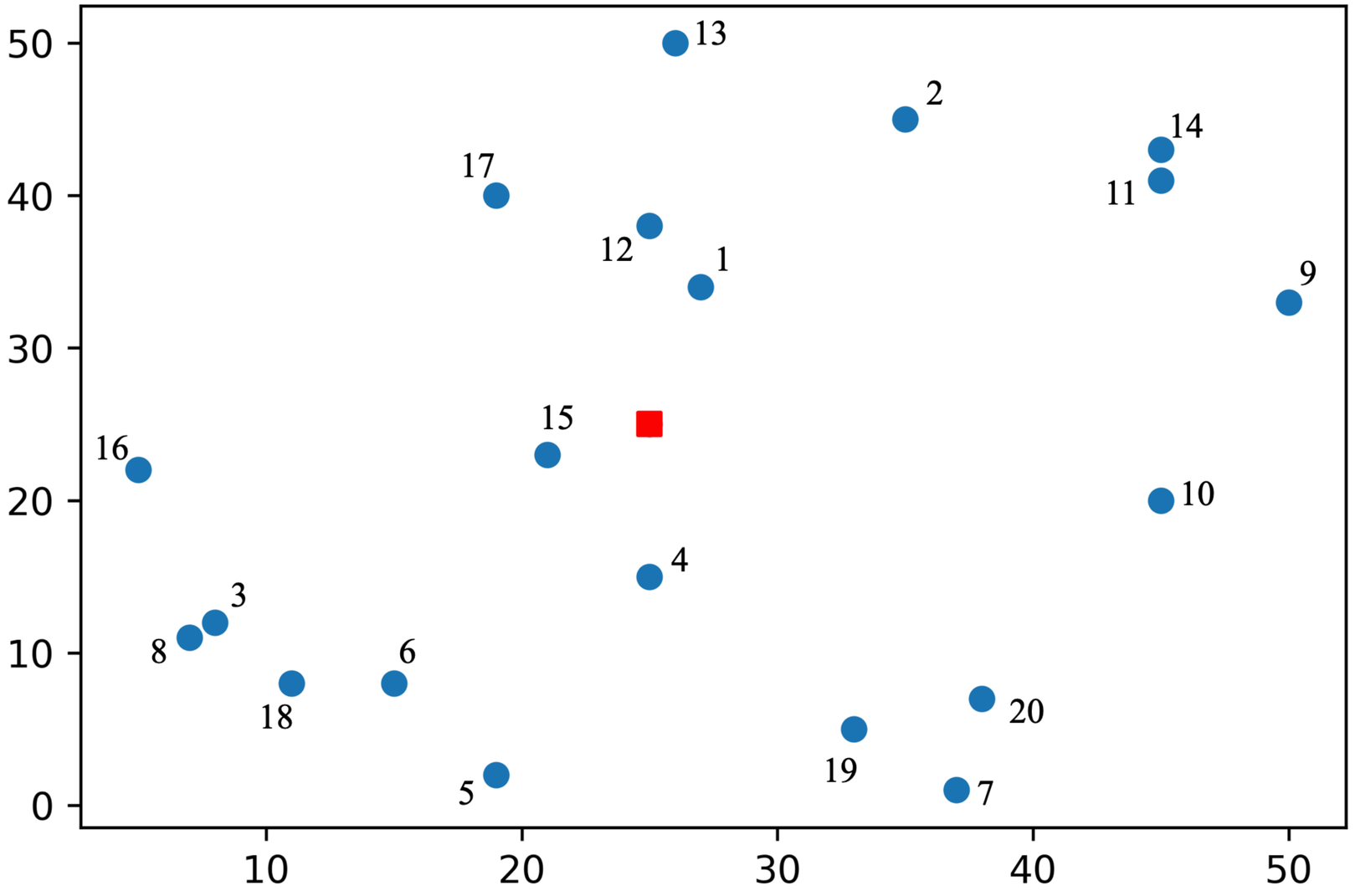

(b)

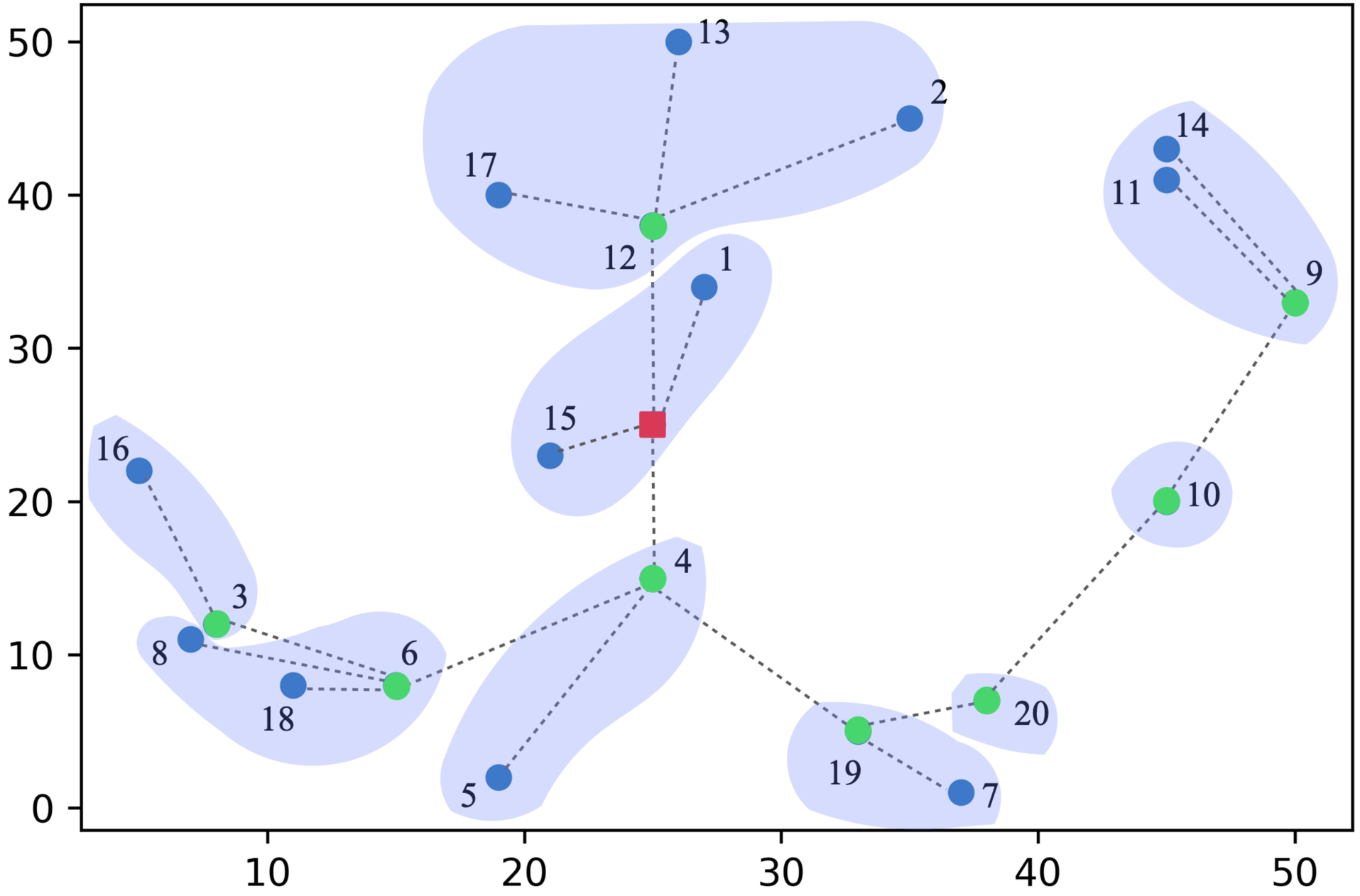
cluster head

sensor node




(c)


50
40
30
20
10
0
10
20
30
40
50
13
2
14
17
11
12
1
9
15
16
10
4
3
8
6
18
20
19
5
7




| Node | Shapley Value |
|---|---|
| 1 | 1.17 |
| 4 | 0.83 |
| 12 | 0.83 |
| 15 | 1.17 |

# Summary

- This paper presents a self-organization method for WSNs. Method is well suited wild-fire detection (or any other application) in remote, inaccessible areas.
- No sensor node localization is required; nodes determine neighbors by ability to communicate.
- All comunication between clusters is 1-hop
- Shapley values determine suitable cluster heads for forming new clusters
- Routing paths from clusters to the sink node are defined when the clusters are created.

# Questions