# A Synchronous Network for Brown Planthopper Surveillance Based on Hexagonal Cellular Automata

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**Abstract.** The paper proposes a new approach to model the Brown Planthopper surveillance as a synchronous network, network consists of components running simultaneously, based on hexagonal cellular automata. In the surveillance network, working space of hoppers is divided as a hexagonal cell system of which cell is a node of a graph G and two neighborhood cells compose an edge of the graph. Sensor nodes are deployed at some cells to measure surrounding conditions as well as hopper density. Simulation results of the hopper surveillance network model with data collection in Cantho, Mekong Delta may provide some useful information in managing pest insects as well as in sensing and collecting data from observation wireless sensor network.

**Keywords:** Synchronous network · Hexagonal cellular automata · Brown Planthopper · BPHSYN

## 1 Introduction

Light trap network is considered as an useful tool in pest management. For instance, in Britain, Rothamsted light trap networks [1] have been established since the early 1960 s in order to understand the population change when pest insects occur and to measure as well as analyze biodiversity [2]. In addition, to confront with Brown Planthopper (BPH) invasion, a light trap network [7] with more than 340 traps have been constructed in Mekong Delta since 2006 so that people can know situations of their fields better and make decision if possible.

The Wireless Sensor Network approach applied to a light trap network (as proposed solutions in [3,4]), may help calculating Brown Planthopper (BPH) densities and measure environmental factors automatically. This kind of solution uses sensors, new automatic light traps, to measure environments and hopper behaviors. These sensed values from sensors will be sent via a wireless network to

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a data center periodically. Next, a back-end system will manipulate these values and propose solutions relating to situations of collected data. Such application is called BPH surveillance network.

Factors influencing BPH behaviors occur continuously and concurrently. Continuous occurrence means these factors compose an unbroken whole, without interruption. Concurrency implies that they can happen at the same time. For example, some factors such as temperature, wind causing hoppers invasion from one place to another. These conditions are continual. Besides, they are concurrent because the motivation to propagate from a source to a destination comes from surrounding conditions of the source and its neighbors. These conditions from such different places must be simultaneous executions.

In this paper, we propose a new approach to model BPH surveillance network as a synchronous network [13] to illustrate the concurrency and continuousness of these influencing conditions. Topology of the synchronous network is based on hexagonal cellular automata [22], a parallel structure.

The structure of this paper is as follows. Section 2 depicts some previous work relating to wireless sensor network as well as insect surveillance modeling. Definition of synchronous network is depicted in the next section. This section also depicts the synchronous BPH surveillance network based on hexagonal cellular automata. Implementations of the above model is described in Sect. 4. Next section illustrates some simulation results of BPH surveillance network with data collection in Cantho, Mekong Delta. The last section is our conclusion and future plans.

## 2 Related Work

Light trap method is one of solutions to prevent high densities of spruce budworm in Canadian forests [8,9]. This method allows people to participate insect trapping by giving light traps to them and track their traps from June to end of August every year. Periodically, people only report estimated densities of insects via a website, an application or even with a paper and a pen. Finally, trap samples are collected and counted in a lab environment. Applications of data collections from these light traps are variant, for example, thanks to wing wear and body size measurements of adult spruce budworms captured at light traps in some previous years, some useful inference on seasonal patterns related to reproduction can be archived [10]. However, these light traps seem not to compose a network, instead, they create a combination of traps to collect data for post processing. Therefore, there are few information about the model of the light trap network.

An insect surveillance network is modeled based on Unit Disk Graph [7]. In this model, a sensing device is a node where an edge between two nodes is established if the distance between them is at most the disk radius r. The weight of that edge is the ability insects move from the start node to the end node. This weight is calculated based on historical and current data at these nodes.

A BPH surveillance network is considered as a graph $\mathbf{G} = (V, E)$ [3,4] where each sensing device is modeled as a node and an edge is created between 2 nodes based on the communication ranges them. Some basic algorithms of WSN such as diameter, routing table are implemented using the data collection in provincial level in the Mekong Delta. Nevertheless, factors influencing hopper behaviors are not examined in these work.

There are not many investigations of synchronous network in modeling insects surveillance, especially synchronous network based on hexagonal cellular automata.

## 3 Brownplant Hopper Synchronous Network

### 3.1 Synchronous Network

Synchronous network [13] is a network describing synchronized rounds of message exchange and computation. It consists of pieces of processes which may send and receive messages simultaneously.

Mathematically, a synchronous network can be considered as a graph G where processes are located at the nodes and they communicate together via the edges using message sending.

Each node in a synchronous network is termed as a process which consists of the following components:

- $states_i$: a collection of states at process i.
- $msgs_i$: a message-generation function specifies that the process i sends to the indicated neighbor, starting from the given state.
- $trans_i$: a state-transition function specifies the new state to which the process i moves from the current state and messages from incomming neighbors.

In practice, both message-generation and state-transition functions can be shortly called as “transition rules”, rules allowing the process i to send messages to neighbors in order to compose its new state.

### 3.2 Wireless Sensor Network

A Wireless Sensor Network (WSN) [16] consists of n wireless sensor nodes distributed in a two dimensional planes (Fig. 1). As in this figure, data collected from sensor nodes of the physical world is transmitted to a gateway which these pieces of data are manipulated by an application to make decisions.

Figure 1 shows the star topology [24] of WSN where sensor nodes use single-hop to communicate with the gateway. In the star topology, if a sensor node fails, it does not effect the whole network, except that the gateway does.

Gateway plays an important role as a data center to collect sensed data from sensor nodes. Commonly, it is connected to Internet and/or to an application for post processing.

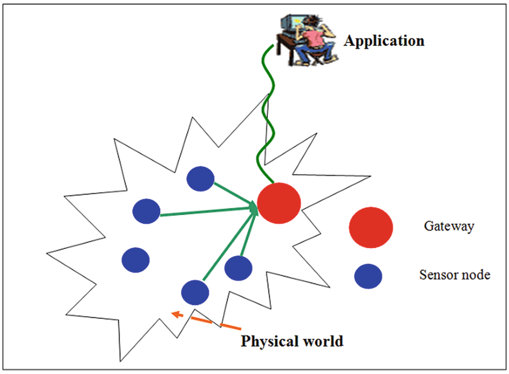


**Fig. 1.** Sensor nodes in WSN.

### 3.3 Brownplant Hopper Surveillance Network

A Brownplant hopper (BPH) surveillance network is a network to monitor BPH behaviors due to environmental factors based on WSN approach [3,4,7]. In this network, working space or working environment of hoppers such as rice fields and meteoric conditions, is divided as a grid of hexagonal cells (a hexagonal cellular automaton) (Fig. 2). Some cells of the grid contain automatic light trap sensor nodes to sampling measure surrounding conditions and hopper densities. These sensor nodes compose a WSN which has a star topology for minimizing communications.

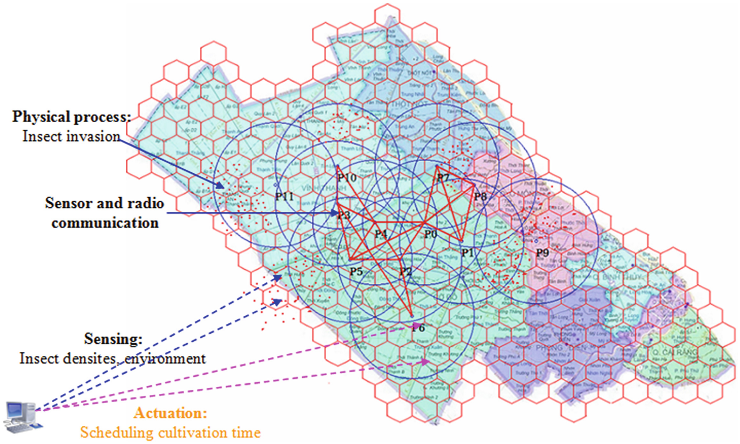
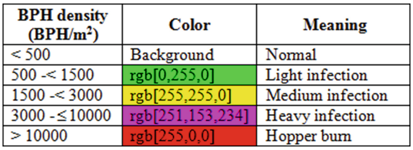


**Fig. 2.** The hexagonal automaton of the BPH surveillance network. It is composed by dividing the map into hexagonal cells, next some sensor nodes (centers of circles) are distributed to these cells.

The above grid of hexagonal cells represents a hexagonal cellular automaton which is depicted by a triple $(S, n, f)$ where:

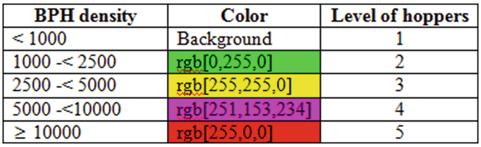
1. A finite state set S. A state of a cell describes the hopper status of that cell. This status is calculated thanks to the density of hoppers at that cell. In practice, people use following table [5] (Fig. 3) to depict hopper statuses in their fields:



| BPH density (BPH/m²) | Color | Meaning |
|---|---|---|
| < 500 | Background | Normal |
| 500 -< 1500 | rgb[0,255,0] | Light infection |
| 1500 -< 3000 | rgb[255,255,0] | Medium infection |
| 3000 -≤ 10000 | rgb[251,153,234] | Heavy infection |
| > 10000 | rgb[255,0,0] | Hopper burn |

**Fig. 3.** Ascending levels of infested BPHs in rice fields.

Therefore, at the time t, a cell in the hexagonal CA can be valued as an element of the set $\{\boldsymbol{N}\mathit{ormal}, \boldsymbol{Light}, \boldsymbol{M}\mathit{edium}, \boldsymbol{H}\mathit{eavy}, \boldsymbol{B}\mathrm{urn}\}$.
In addition, a cell may locate an automatic light trap sensor node. This trap can catch hoppers and the density of hoppers in the trap may indicate the real infected situation at that cell. The following table [27] (Fig. 4) is used for describing hopper statuses in a sensor node:



| BPH density | Color | Level of hoppers |
|---|---|---|
| < 1000 | Background | 1 |
| 1000 -< 2500 | rgb[0,255,0] | 2 |
| 2500 -< 5000 | rgb[255,255,0] | 3 |
| 5000 -<10000 | rgb[251,153,234] | 4 |
| ≥ 10000 | rgb[255,0,0] | 5 |

**Fig. 4.** Ascending levels of infested BPHs in light traps.

2. Distance $n$ identifying neighbor cells, *normally n=1.* When *n=1*, a cell has at most 6 surrounding cells.
3. Transition rule f: $S^n \rightarrow S$ depict the change of a cell's state at a specific time based on the current state of the cell and its neighbors. For example, if the center cell and its neighbors have the state **N**ormal at the time t, then the state of that cell at the time t+1 is **N**ormal: f(NNN**N**NNN) = N.
   At the time t, the state of a cell depends on the state at time t–1 of its neighbors. The cell itself can be integrated in its neighborhoods. Updating cells are done by a transition rule. All cells have the same transition rule and the transition rule is applied to all cells at the same time. Whenever the rule are applied to the entire system, they could change the entire system synchronously.

In fact, the transition rule f is a function depending on some variables such as: density of hoppers in a cell as well as its neighbors, rice age, wind, hopper velocity and other environmental factors.

- Rice age: The young rice is a very good food for hoppers, therefore, they tend to locate at the young rice fields [5,6,14]. On the other hands, hoppers can not suck ripe rice so they will propagate to other fields due to wind if their rice in their current fields become mature or ripe. In addition, young rice is the first condition for hoppers landing. The green color of young rices mapped into the water is a very attractive color source for hoppers, therefore, they tend to take landing to the young ones. On the other hands, ripe rice color does not attract hoppers because they are not sensitive with this color.
- Wind: the wind velocity, calculated in cells/time step. It illustrates the maximum distance that adult hoppers can propagate in a time step. For example, 5 cells/t means that hoppers can propagate to another cell with the distance 5 from the current cell under the wind direction. To be simple, in this model, there are 6 wind directions according to 6 neighbor directions. If there is no wind, hopper can transmit to 6 neighbor cells. Only a part of adult one can propagate to other fields. In this paper, it is an predetermined constant.
- Hopper velocity. Without wind, hoppers can propagate to near rice fields by this their velocities, approximate 0.4 m/s [15].
- Hopper age. Totally, the life circle of BPHs is 26–30 days [14] depending on environmental factors and it spreads in 3 phases: eggs, nymphs and adults. The growth time lapse of each phase is as followed: eggs 6–8 days, nymph 12–15 days, adults 19 days. Some experiments show that a female adult BPH can lay 100–300 eggs during its life circle [14].
- Density of hoppers in a cell and its surroundings. The relation between the density of a cell and its state depicted in Fig. 3.

Mathematically, the above hexagonal cellular automaton is a topology of **a synchronous network** which is modeled as a directed graph $\mathbf{G} = (V, E)$ where V is the collection of nodes and E is the set of edges.

*Nodes.* Each hexagon in Fig. 2 represents a node in the graph $\mathbf{G} = (V, E)$. By the time passing, each node (or process) $i$ composes a collection of states $states_i$ of which a state holds values of rice age, wind, and BPH density at the time t.

Each node may consist a sensor node to sense above factors of a state. When the sensor node senses environment, it transmits the collected data to a gateway for storing and post processing.

*Edges.* Edges in the graph G are composed by links between a hexagon node and its neighbors (6 neighbors). Because G is a directed graph, there are 2 edges between the node and a neighbor of it (2 directions).

*Example.* Figure 5 is an example of a graph of the BPH surveillance network in Phongdien district, Cantho, Vietnam. In this example, the map of this district is divided as cells, each cell is almost a commune of the district. For example, if Phongdien and Nhonai communes are considered as a hexagonal center (**Center cell** in the figure), following communes such as Truonglong, Tanthoi, Giaixuan, Mykhanh, Nhannghia (hexagons 1, 2, 3, 4, 5) become neighbors of the hexagonal center approximately. The hexagon 0 is another neighbor of the center, however, it seems to occupy few area of Phongdien district.

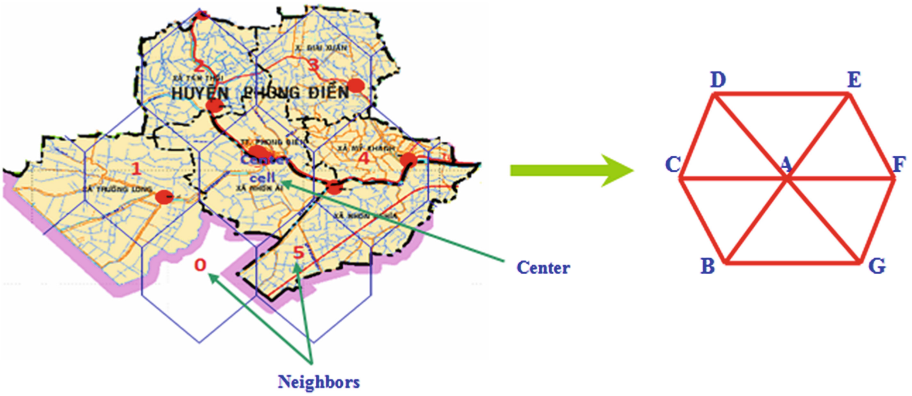


**Fig. 5.** The graph of Phong Dien district, Cantho when it is divided as hexagonal cells.

The graph of the BPH surveillance network of this district is illustrated in the right of Fig. 5. In this graph, each hexagonal cell becomes a node and 2 cells in a neighborhood compose an edge. The **Center cell** is illustrated as a node A which has 6 neighbors named B, C, D, E, G, F (corresponding to cells 0, 1, 2, 3, 4, 5 respectively). However, each of B, C, D, E, G, F only has 3 neighbors.

*Behaviors.* Behaviors at node $i$ are expressed by transition rules of states $transitions_i$. Normally, these rules are functions mapping a collection of states at a cell and its neighbors at the time t to create the new state of that cell at the time t+1. These transition rules are applied simultaneously at every cell.

The following pseudo code depicts the transition rule of a node n:

```
Calculate the insect density at node n using reproduction model
Update current state of n
if (node n has BPH density >= THRESHOLD or rice IS NOT young){
  if (no wind)
    for (j in neighbors of n){
      Calculate the number of adult BPHs migrating to j
      Update the state of j
      Update current state of n
```

```
    }
    else
      for (j in neighbors of n)
        if (j is in leeward of n){
          Calculate the number of adult BPHs migrating to j
             according to the wind velocity
          Update the state of j
          Update current state of n
        }
    }
 }
}
```

Let node $n$ is a source cell which is able to propagate $d$ *adult hoppers* under the wind velocity $v$ *(m cells/t)*. Thus, the wind velocity causes adult hoppers distribute to *at most m cells* in a period of time $t$. In this case, the number of hoppers propagating to a cell $n_k$ which has *distance* $k$ from the *source cell* $n$ under the wind direction, is estimated as $\frac{d}{2^k}$ (Fig. 6).

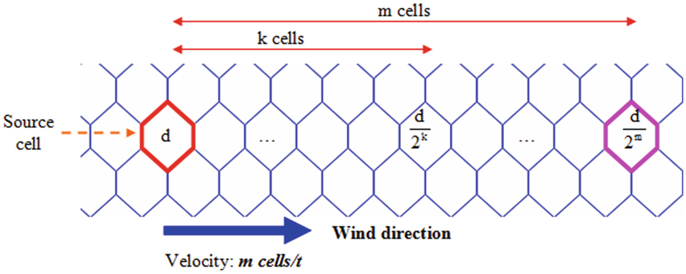


**Fig. 6.** Estimation of propagated adult hoppers due to wind

*Wireless Sensor Network.* WSN is applied by distributing sensors in some cells to sampling measure environmental factors and hopper density. Data collections from the WSN can be considered as indications for the operating of the whole BPH surveillance network as well as for post processing. To be simple, in this paper the WSN is supposed to have the star topology to transmit data.

### 3.4 BPHSYN

The above synchronous network for BPH surveillance based on hexagonal CA can be shortly called the BPH Surveillance sYnchronous Network (BPHSYN).

## 4 BPHSYN Implementation

### 4.1 Workflow

The implementation of a surveillance model contains 3 important parts: data structure, states and behaviors. Firstly, data structure (cells in Fig. 2) is generated from geographic data. Next, states and behaviors are implemented in CUDA [18] to illustrate the synchronous characteristic in the model.

CUDA is chosen for implementing BPHSYN since the parallel programming paradigm of CUDA is well-suited for the synchronous network model's concurrency.

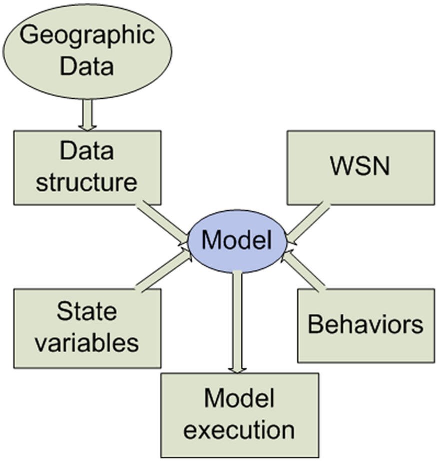


**Fig. 7.** Work flow for modeling insect physical and WSN system.

### 4.2 The Hexagonal CA Based Synchronous Network

**Graph.** The following CUDA code is the definition of the graph described in Sect. 3.3:

```
typedef struct{
    int x, y;
}Point2D;
typedef struct{
    int xPos, yPos; //offset coordinates
    Point2D Corners [6]; // 6 corners
    int Neighbors [6]; // 6 neighbors numbered from 0 to 5
}Hexagon;
typedef Hexagrid Hexagon[N]; // Honeycomb structure
```

**State.** Each node in the graph represents a process in a synchronous network. This process maintains a structure to store its states by the time passing. The following code is the definition of a state in the case study BPH surveillance network:

```
typedef struct{
  int xPos, yPos; //position
  float     riceAges;   // rice ages
  InsectDensity densityBPH;
  float     windVelocity;
  Direction     windDirection;
}State;
```

**WSN.** Sensor nodes are distributed in some cells of the graph. The following code describes the definition of the WSN:

```
typedef struct{
    int node;
    float distance;
}Neighbor;
typedef struct{
    int xPos, yPos; //offset coordinates of the hexa cell
    Neighbor Neighbors[MAXFLOW]; // neighbors of sensor node
}Channel;
typedef Network Channel[N]; // WSN
```

**Behaviors.** Because behaviors express the concurrency of the model, they are implemented as device codes run in GPU [19]. The skeleton of the behaviors code is as followed:

```
extern __global__ void compute(State *now, int node_number){
 int idx=threadIdx.x+blockIdx.x*blockDim.x;
 if (idx < node_number){
   Calculate behaviors of node idx
 }
}
```

# 5 Experiment

## 5.1 Data Used

The simulation of the BPH synchronous network uses data collections in Cantho city (Fig. 2), a typical rice city in the Mekong Delta. Current light traps (8 traps till 2015) are considered as sensor nodes in the simulation (circles in Fig. 2). The area of Cantho is divided as hexagonal cells with approximately 0.18 $\text{km}^2$ each.

## 5.2 Tools Used

HexGen, a tool written in C++ is used to generate the synchronous network code in Cuda. Besides, the map of Cantho city is processed by the tool PickCell in the framework NetGen [17]. Behaviors of the BPHSYN are implemented in CUDA to run the simulation on the NVIDIA card GeForce GTX 680 1.15 GHz with 1536 CUDA Cores (8 Multiprocessors × 192 CUDA Cores/MP).

### 5.3 Scenario 1: Observing Hoppers at a Location

This scenario allows observing the reproduction phase of hoppers at a location. In this scenario, some communes in Cantho suffer lightly from hoppers (light infection color of rice fields and warning level of sensor nodes in Fig. 8) while the rest do not cultivate yet. The wind direction is 2 (the direction from the **Center cell** to **cell 5** in Fig. 5 with the velocity is 5 km/h (approximately 10 hexagonal cells/h). That means BPHs can transmit to the cell distance 10 from the source cell in one hour.

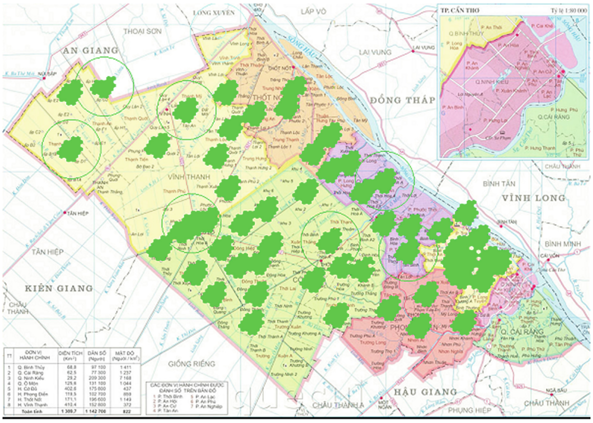


**Fig. 8.** Light infections at some communes in Cantho city.

Figure 9 describes the hoppers infection in Cantho city at the day 3, 4, 5, 7. At the day 3, most of the experimental communes suffer from heavy infection of BPHs. Hoppers density reaches the peak point at the day 4 and starts decreasing a few days later. At the day 7, normal infections appear in some communes although other are still light, medium or even heavy (warning level of sensor nodes in Fig. 10). However until the day 9, hoppers seem not to appear in Cantho city.

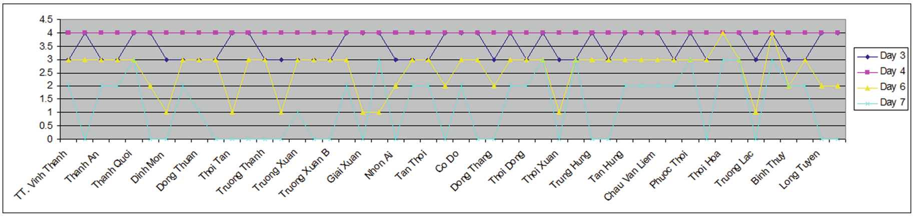


**Fig. 9.** Hoppers infection in Cantho city at the day 3, 4, 6, 7.

This scenario depicts the reproduction of hoppers in Cantho city. Initially, experimental communes are infested lightly due to hoppers. By the time passing, hoppers are growing and become adults. At adult phase, hoppers can propagate to other places due to wind, however, these places do not contain rice, therefore, propagated hoppers die because of lack of food. Densities of hoppers at experimental communes decline gradually and return normal infestation after the peak day of hoppers 6 to 7 days.

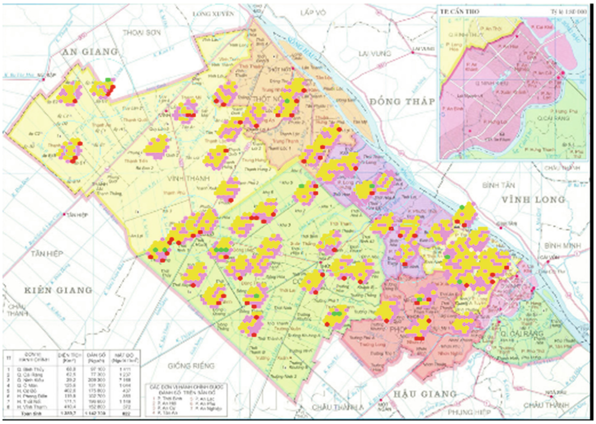


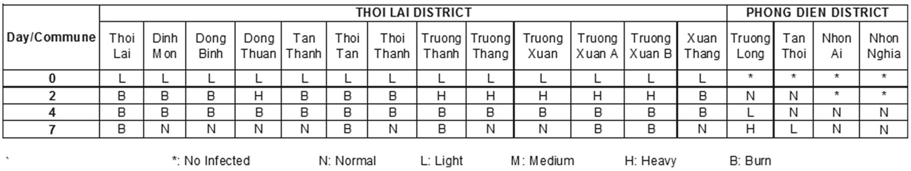
**Fig. 10.** Hoppers infection in Cantho city at the day 7.

The scenario illustrates the 'Escape Strategy' or 'Chien Luoc Ne Ray' in Vietnamese to confront with hoppers [23]. This strategy can be done by monitoring the historical light traps data through several years to recognize the trend of hoppers migrations. Next, crops are sown after the peak season of BPHs. If crops are sown after that peak day very soon, when the next generation of hoppers comes (around 28 days later), the rice is strong enough to resist with hoppers. In this case the WSN can help to sense the surrounding conditions data and maintain these pieces of data so that the peak point of hoppers can be identified later.

### 5.4 Scenario 2: Hoppers Propagation Due to Wind

This scenario assumes that the Thoi Lai district is an infection source with lightly infestation in almost its communes (Fig. 11). A current unique sensor at Dinh Mon, Thoi Lai provides following meteorological data: wind velocity: 5 km/h (10 cells/h), wind direction: 2 (from Dinh Mon toward Phong Dien and also indicates the light infection at the rice field in this commune.

Due to wind, hoppers can propagate to leeward fields. At the day 3, the whole Thoi Lai is burned by BPHs and a part of Phong Dien is lightly infected (Figs. 11, 12). At the day 7, the light trap at Dinh Mon sensor node still gives burn warning although other communes in this district become normal.



| Day/Commune | THOI LAI DISTRICT | | | | | | | | | | | | | PHONG DIEN DISTRICT | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Thoi Lai | Dinh Mon | Dong Binh | Dong Thuan | Tan Thanh | Thoi Tan | Thoi Thanh | Truong Thanh | Truong Thang | Truong Xuan | Truong Xuan A | Truong Xuan B | Xuan Thang | Truong Long | Tan Thoi | Nhon Ai | Nhon Nghia |
| 0 | L | L | L | L | L | L | L | L | L | L | L | L | L | * | * | * | * |
| 2 | B | B | B | H | B | B | B | H | H | H | H | H | B | N | N | * | * |
| 4 | B | B | B | B | B | B | B | B | B | B | B | B | B | L | N | N | N |
| 7 | B | N | N | N | N | B | N | B | N | N | B | B | N | H | L | N | N |

*: No Infected N: Normal L: Light M: Medium H: Heavy B: Burn

**Fig. 11.** Hoppers infestation in Thoi Lai and Phong Dien in 7 days.

However, the area of infestation in Phong Dien district is broaden from Truong Long, Tan Thoi, to Nhon Ai, Nhan Nghia. BPHs spread over these communes from heavy infection in Truong Long to light ones (almost normal) in Nhon Ai, Nhon Nghia (Fig. 13). Indeed, under the wind direction 2, the commune Truong Long, Phong Dien is the leeward of the commune Truong Thanh, Thoi Lai. Similarly, the commune Tan Thoi, Phong Dien is the leeward of the commune Dinh Mon, Thoi Lai. Inside the district Phong Dien itself, the commune Nhon Ai is the leeward of Tan Thoi and is the windward of Nhon Nghia. Therefore, due to wind, hoppers can transmit to Nhon Nghia as well.

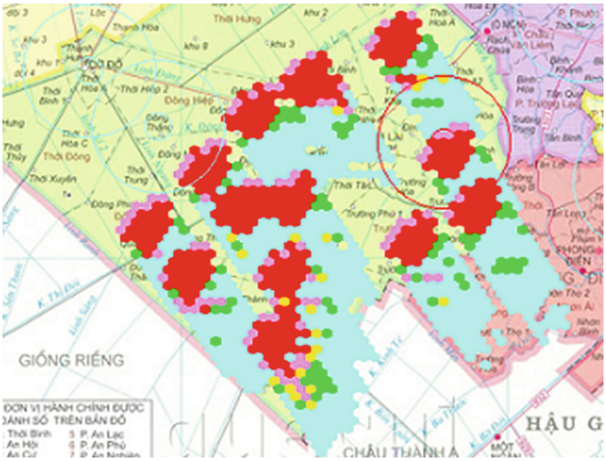


**Fig. 12.** Hoppers infection in Thoi Lai and Phong Dien at the day 3.

In this scenario, the sensor node at Dinh Mon plays as the indication for the hoppers infestation and the hoppers propagate according to the transition rules mentioned in the Sect. 4.2. However, this only one sensor node in Thoi Lai (with 20,345.16 ha rice field[1]) may not provide enough information relating to hoppers and the surrounding environment. Indeed, although the wind direction collected at Dinh Mon is toward the direction 2 of this hexagon, the wind direction at

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[1] http://cantho.gov.vn/wps/portal/thoilai.

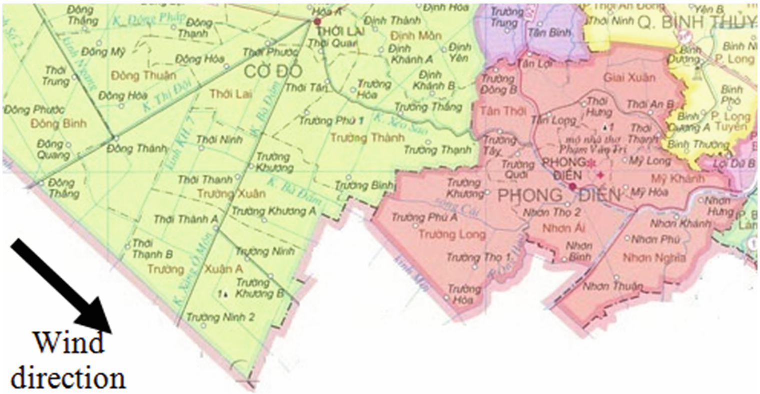

**Fig. 13.** Leeward communes in Phong Dien district.

other communes in Thoi Lai may be different. It could be better if each commune has a sensor node to sense surrounding conditions more details because these conditions can provide useful information for the direction of propagation of hoppers.

## 6 Conclusion

We have described the BPH surveillance network BPHSYN as a synchronous network. In our work, the BPHSYN consists of a physical insect process modeled as a synchronous network and a WSN as indications for the BPHSYN. The environment where hoppers behave is divided as a hexagonal cellular system of which each is a node and the cell as well as its neighbors compose edges of the synchronous network. The behaviors of the network is depicted by the transition rules of the hexagonal cellular automata.

Data collection is in Cantho, Vietnam is used to simulate for the BPHSYN. The simulation shows the importance of the 'Escape Strategy' to confront with hoppers in Mekong. The WSN provides environmental factors input for the simulation and from these pieces of data, the infected situation of hoppers could be predicted and could provide some beneficial information for pest management.

The simulation also figures out that it is necessary to have more sensor node to sense environmental factors in order to better provide these values as inputs for the model execution. An alternative could be to use external data sources to provide meteoric data for the model so that the these pieces of data can be embedded to the BPHSYN as well.

The topology of the WSN system in the surveillance network could be mesh network to have a better communications (instead of star topology in the paper). In this case, the distance between 2 sensor nodes is quite far, therefore, LORA [25] technology could be considered as an alternative to transmit data to a distant destination.

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