# Modeling Malware Propagation in Wireless Sensor Networks Using Cell-DEVS

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A report for assignment 2 submitted to Professor Gabriel Wainer as part of the requirements for the course of

**SYSC 5104: Methodologies for Discrete Event Modeling and Simulation**

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## Motivation

Based on epidemic theory, the process of malware propagation in wireless sensor networks is modeled and analyzed in [1] using cellular automata. The model focuses on the stochastic properties of malware propagation and the intrinsic characteristic of wireless sensor networks.

## Conceptual Model Description

The model consists of a flat WSN which is composed of maximum N stationary and identical sensors. The sensors are randomly placed on rectangular 2-D grid composed of L*L cells. Each cell is occupied by at most one sensor node. Each sensor node can establish wireless links with only those nodes within a circle of radius $r$ due to the limited power of sensor nodes. All sensor nodes are equipped with omni-directional antennas that have a maximum transmission range $r$.

According to the corresponding transmission range $r$, the neighborhood of each sensor is shown in Fig. 1. Let the length of a cell of grid be 1. If $r = 1$, each node/cell can have no more than 4 nodes as neighbors, namely the neighborhood of Von Neumann, and if $r = 1.5$, each node/cell can have no more than 8 nodes as neighbors, namely the Moore neighborhood. It is obvious that a node should have more neighbors with the value of communication range $r$ increasing.

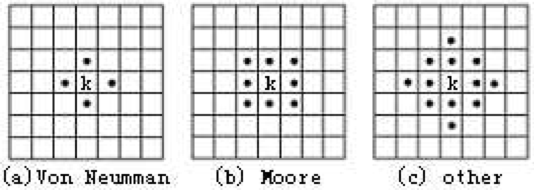


**Figure 1: Possible neighborhoods of a node [1]**

Borrowing the concept of epidemiology, the state of a sensor node can be one of following these states: susceptible, infected, recovering or dead. If $s_{i,j}(t)$ denotes the state variable of cell/node with coordinates $i$ and $j$ at time $t$, then

$$s_{i,j}(t) = \begin{cases} 0, cell(i,j) \text{ is susceptible at time } t \\ 3 \text{ or } 4, cell(i,j) \text{ is infected at time } t \\ 2, cell(i,j) \text{ is recovered at time } t \\ 1, cell(i,j) \text{ is dead at time } t \end{cases}$$

Infected nodes try to spread the malware to their neighbors at each time step. Susceptible sensor nodes become infected with a probability $\beta$ when they received a packet containing a copy of the malware from an infected neighbor. In addition, infected sensors get patch and recover from infected state with the probability *δ*. Considering restrained power of sensors and the consumptions during communications among sensor nodes, some sensor nodes can be dead nodes (nodes with no residual energy on their batteries) at a rate *γ*. A cell of the grid that does not contain any node is equivalent to a cell where there is a dead node. The transforming process of states is shown in Fig. 2. S(t), I(t), R(t) and D(t) denote the different states consisting of susceptible, infected, recovered and dead nodes, respectively.

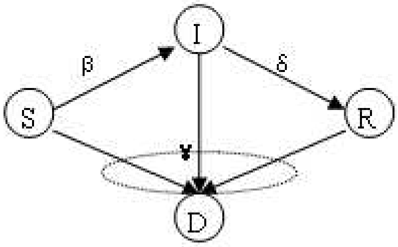


**Figure 2: State transformation process of sensor nodes [1]**

In general, packets routing in wireless sensor networks is by multi-hop broadcasts. Since the transmission power of a wireless radio is attenuated in a squared or even higher order with the distance, multi-hop routing will consume less energy than direct communication. The attackers take advantage of the broadcast mechanism to propagate malicious codes such that malware spreads quickly to the entire network. It is assumed that infected nodes adopt broadcasting strategy to spread malware to their neighbors.

## The Model

This work is based on the model simulated in [1] using Cellular Automata. However, I have used Cell-DEVS for simulating the model.

The model shows malware propagation over wireless sensor network. The malware propagation diffuses continuously from infected nodes toward outside. Initially, all the nodes in the sensor network are in the susceptible state which means that they can get infected by the malware. One of the nodes in the sensor network is assumed to be infected by the malware. Then, each node in the neighborhood (Moore neighborhood in this case) of the infected node can become infected with a probability *β*. From the infected state, a node can go to recovered state by running a patch with a probability *δ*. In any state (susceptible, infected, recovered), a node is assumed to consume energy and can go from that state to the dead state (meaning that the node has run out of energy). A node consumes energy at the highest rate in the infected state as it is assumed to be broadcasting the malware to other nodes in this state. A node consumes energy at the lowest rate in the susceptible state.

These assumptions give as the result the following CELL-DEVS coupled model for each sensor:

**WSensor = < Xlist$_A$, Ylist$_A$, I$_A$, X$_A$, Y$_A$, n, {t1,...,tn}, N$_A$, C$_A$, B$_A$, Z$_A$, select$_A$ >**
**WSensorstate = < Xlist$_A$, Ylist$_A$, I$_B$, X$_A$, Y$_A$, n, {t1,...,tn}, N$_A$, C$_A$, B$_A$, Z$_B$, select$_B$ >**

**Xlist$_A$** = { 0 }; **Ylist$_A$** = { 0 }; **n** = 20x20x2;

**Z$_B$:**

```
[malware-rule]
rule : 3 100 { (0,0,0) = 0 and stateCount(3) >= 1 and ( random <= 0.3 ) }
rule : 4 100 { (0,0,0) = 0 and stateCount(4) >= 1 and ( random <= 0.3 ) }
rule : 2 100 { (0,0,0) = 3 and ( random <= 0.01 ) and (0,0,1) > 1 }
rule : 2 100 { (0,0,0) = 4 and ( random <= 0.01 ) and (0,0,1) > 1 }
rule : 3 100 { (0,0,0) = 4 and (0,0,1) > 1 }
rule : 4 100 { (0,0,0) = 3 and (0,0,1) > 1 }
rule : 2 100 { (0,0,0) = 2 and (0,0,1) > 1 }
rule : 1 100 { (0,0,0) = 4 and (0,0,1) <= 1 }
rule : 1 100 { (0,0,0) = 3 and (0,0,1) <= 1 }
rule : 1 100 { (0,0,0) = 2 and (0,0,1) <= 1 }
rule : 1 100 { (0,0,0) = 1 }
rule : 0 100 { (0,0,0) = 0 }
rule : 0 100 { t }
```

**Z$_A$:**

```
[energy-reduction-rule]
rule : { (0,0,0)*.8 }   100   { (0,0,0)>1 and (0,0,-1)=3 }
rule : { (0,0,0)*.8 }   100   { (0,0,0)>1 and (0,0,-1)=4 }
rule : { (0,0,0)*.95 }  100   { (0,0,0)>1 and (0,0,-1)=2 }
rule : { (0,0,0)*.99 }      100   { (0,0,0)>1 and (0,0,-1)=0 }
rule : 0               100   { (0,0,0)<=1 }
```

**$N_A$:**

neighbors : malware(-1,-1,0) malware(-1,0,0) malware(-1,1,0)
neighbors : malware(0,-1,0) malware(0,0,0) malware(0,1,0)
neighbors : malware(1,-1,0) malware(1,0,0) malware(1,1,0)
neighbors : malware(0,0,1)
neighbors : malware(0,0,-1)

**$B_A$** = {nowrapped};

**$S_B$:**

| | |
|---|---|
| 0 | Susceptible State |
| 3 or 4 | Infected State |
| 2 | Recovered State |
| 1 | Dead State |

**B** = nowrapped

**d** = transport delay

**$\tau$:**

100 normal elapsed time
100 energy depletion step time

The coupled model represents a matrix of 20 by 20 by 2 cells, where the state change (susceptible, infected, recovered, dead) is represented by a plane and the energy status is represented by a different plane. It represents a 20 by 20 by 2 space that is nonwrapped on the edges.

```
[top]
components : malware

[malware]
type : cell
dim : (20,20,2)
delay : transport
defaultDelayTime : 100

border : nowrapped

neighbors : malware(-1,-1,0) malware(-1,0,0) malware(-1,1,0)
neighbors : malware(0,-1,0)  malware(0,0,0)  malware(0,1,0)
neighbors : malware(1,-1,0)  malware(1,0,0)  malware(1,1,0)
neighbors : malware(0,0,1)
neighbors : malware(0,0,-1)

localtransition : malware-rule
zone : energy-reduction-rule { (0,0,1)..(19,19,1) }

initialvalue : 0
initialCellsValue : sensor.val

[malware-rule]
rule : 3 100 { (0,0,0) = 0 and stateCount(3) >= 1 and ( random <= 0.3 ) }
rule : 4 100 { (0,0,0) = 0 and stateCount(4) >= 1 and ( random <= 0.3 ) }
rule : 2 100 { (0,0,0) = 3 and ( random <= 0.01 ) and (0,0,1) > 1 }
rule : 2 100 { (0,0,0) = 4 and ( random <= 0.01 ) and (0,0,1) > 1 }
rule : 3 100 { (0,0,0) = 4 and (0,0,1) > 1 }
rule : 4 100 { (0,0,0) = 3 and (0,0,1) > 1 }
rule : 2 100 { (0,0,0) = 2 and (0,0,1) > 1 }
rule : 1 100 { (0,0,0) = 4 and (0,0,1) <= 1 }
rule : 1 100 { (0,0,0) = 3 and (0,0,1) <= 1 }
rule : 1 100 { (0,0,0) = 2 and (0,0,1) <= 1 }
rule : 1 100 { (0,0,0) = 1 }
rule : 0 100 { (0,0,0) = 0 }
rule : 0 100 { t }

[energy-reduction-rule]
rule : { (0,0,0)*.8 }    100   { (0,0,0)>1 and (0,0,-1)=3 }
rule : { (0,0,0)*.8 }    100   { (0,0,0)>1 and (0,0,-1)=4 }
rule : { (0,0,0)*.95 }  100   { (0,0,0)>1 and (0,0,-1)=2 }
rule : { (0,0,0) *.99}  100   { (0,0,0)>1 and (0,0,-1)=0 }
rule : 0                       100   { (0,0,0)<=1 }
```

## An insight to the rules

### *Cell State plane rules* **[malware-rule]**

```
rule : 3 100 { (0,0,0) = 0 and stateCount(3) >= 1 and ( random <= 0.3 ) }
rule : 4 100 { (0,0,0) = 0 and stateCount(4) >= 1 and ( random <= 0.3 ) }
```

This rule changes the state of a cell (sensor node) from *susceptible* to *infected* with 30 % probability which means that $\beta=0.3$.

```
rule : 2 100 { (0,0,0) = 3 and ( random <= 0.01 ) and (0,0,1) > 1 }
rule : 2 100 { (0,0,0) = 4 and ( random <= 0.01 ) and (0,0,1) > 1 }
```

This rule changes the state of a cell (sensor node) from *infected* to *recovered* with 1% probability which means that $\delta$ =0.01 as long as its energy level is greater than 1.

```
rule : 3 100 { (0,0,0) = 4 and (0,0,1) > 1 }
rule : 4 100 { (0,0,0) = 3 and (0,0,1) > 1 }
```

This rule changes the state of a cell (sensor node) from an *infected* state (3) to another *infected* state (4) or vice versa as long as its energy level is greater than 1.

```
rule : 2 100 { (0,0,0) = 2 and (0,0,1) > 1 }
```

This rule keeps the cell (sensor node) in the *recovered* state as long as its energy level is greater than 1.

```
rule : 1 100 { (0,0,0) = 4 and (0,0,1) <= 1 }
rule : 1 100 { (0,0,0) = 3 and (0,0,1) <= 1 }
```

This rule changes the state of the cell (sensor node) from the infected state to the dead state if its energy level is less than or equal to 1.

```
rule : 1 100 { (0,0,0) = 2 and (0,0,1) <= 1 }
```

This rule changes the state of the cell (sensor node) from the *recovered* state to the *dead* state if its energy level is less than or equal to 1.

```
rule : 1 100 { (0,0,0) = 1 }
```

This rule keeps the cell (sensor node) in the *infected* state.

```
rule : 0 100 { (0,0,0) = 0 }
```

This rule keeps the cell (sensor node) in the *susceptible* state.

```
rule : 0 100 { t }
```

If none of the above rules is true, then this rule keeps the cell (sensor node) in the *susceptible* state.

### *Cell State plane rules* [energy-reduction-rule]

```
rule : { (0,0,0)*.8 }   100   { (0,0,0)>1 and (0,0,-1)=3 }
rule : { (0,0,0)*.8 }   100   { (0,0,0)>1 and (0,0,-1)=4 }
```

If the state of the cell (sensor node) is *infected*, then its energy is reduced to 80% of the original.

```
rule : { (0,0,0)*.95 }  100   { (0,0,0)>1 and (0,0,-1)=2 }
```

If the state of the cell (sensor node) is *recovered*, then its energy is reduced to 95% of the original.

```
rule : { (0,0,0) *.99}     100   { (0,0,0)>1 and (0,0,-1)=0 }
```

If the state of the cell (sensor node) is *susceptible*, then its energy is reduced to 99% of the original.

```
rule : 0              100   { (0,0,0)<=1 }
```

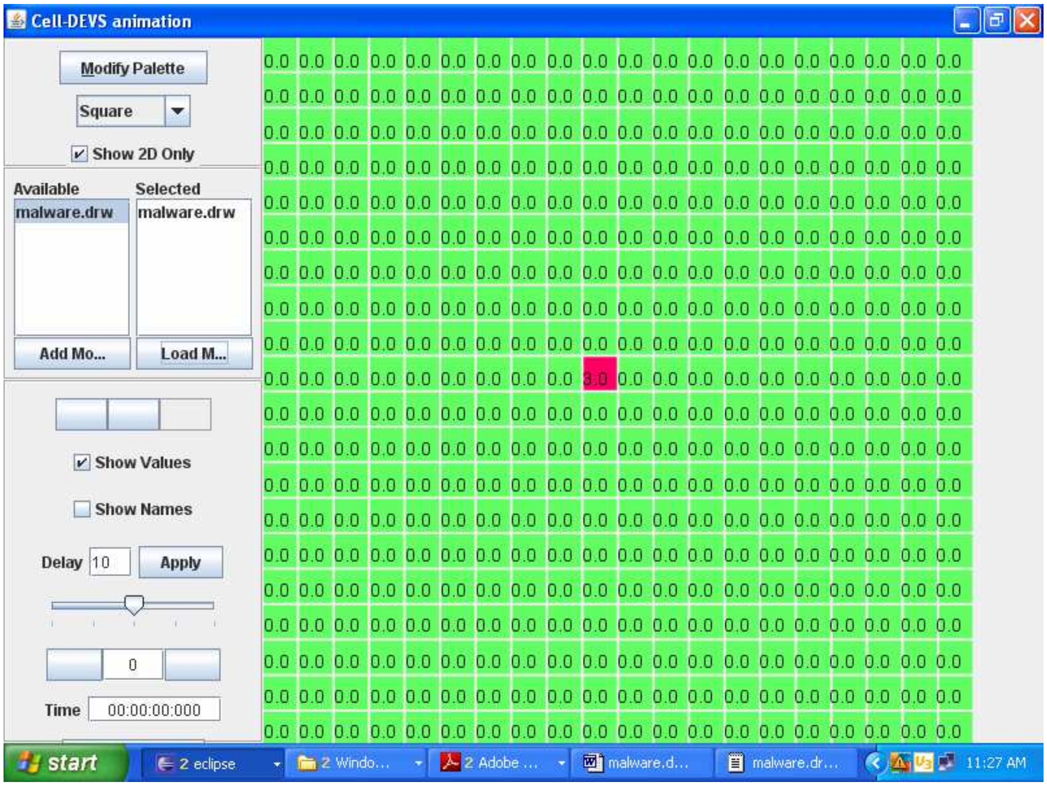
This rule forces the sensors to be *dead* if the energy level of a cell (sensor node) is in the [0,1] range.

## Simulation Results and Testing

The simulation scenario in [1] has used a sensor network of 100x100 nodes but this will present the results for a 20x20 network. However, the results can be extended up to an unlimited number of sensors as can be seen in the .drw files included with this report.

The initial state of the model is given in the *sensor.val* file. Initially all sensors starts the simulation with full power and one sensor is infected with malware, as shown below.

```
Line : 2011 - Time: 00:00:00:000
     01234567890123456789      01234567890123456789
    +--------------------+    +--------------------+
   0|                    |   0|100100100100100100100100100100100100100100100100100100100100|
   1|                    |   1|100100100100100100100100100100100100100100100100100100100100|
   2|                    |   2|100100100100100100100100100100100100100100100100100100100100|
   3|                    |   3|100100100100100100100100100100100100100100100100100100100100|
   4|                    |   4|100100100100100100100100100100100100100100100100100100100100|
   5|                    |   5|100100100100100100100100100100100100100100100100100100100100|
   6|                    |   6|100100100100100100100100100100100100100100100100100100100100|
   7|                    |   7|100100100100100100100100100100100100100100100100100100100100|
   8|                    |   8|100100100100100100100100100100100100100100100100100100100100|
   9|         3          |   9|100100100100100100100100100100100100100100100100100100100100|
  10|                    |  10|100100100100100100100100100100100100100100100100100100100100|
  11|                    |  11|100100100100100100100100100100100100100100100100100100100100|
  12|                    |  12|100100100100100100100100100100100100100100100100100100100100|
  13|                    |  13|100100100100100100100100100100100100100100100100100100100100|
  14|                    |  14|100100100100100100100100100100100100100100100100100100100100|
  15|                    |  15|100100100100100100100100100100100100100100100100100100100100|
  16|                    |  16|100100100100100100100100100100100100100100100100100100100100|
  17|                    |  17|100100100100100100100100100100100100100100100100100100100100|
  18|                    |  18|100100100100100100100100100100100100100100100100100100100100|
  19|                    |  19|100100100100100100100100100100100100100100100100100100100100|
    +--------------------+    +--------------------+
```



☑ Show 2D Only

☑ Show Values

☐ Show Names

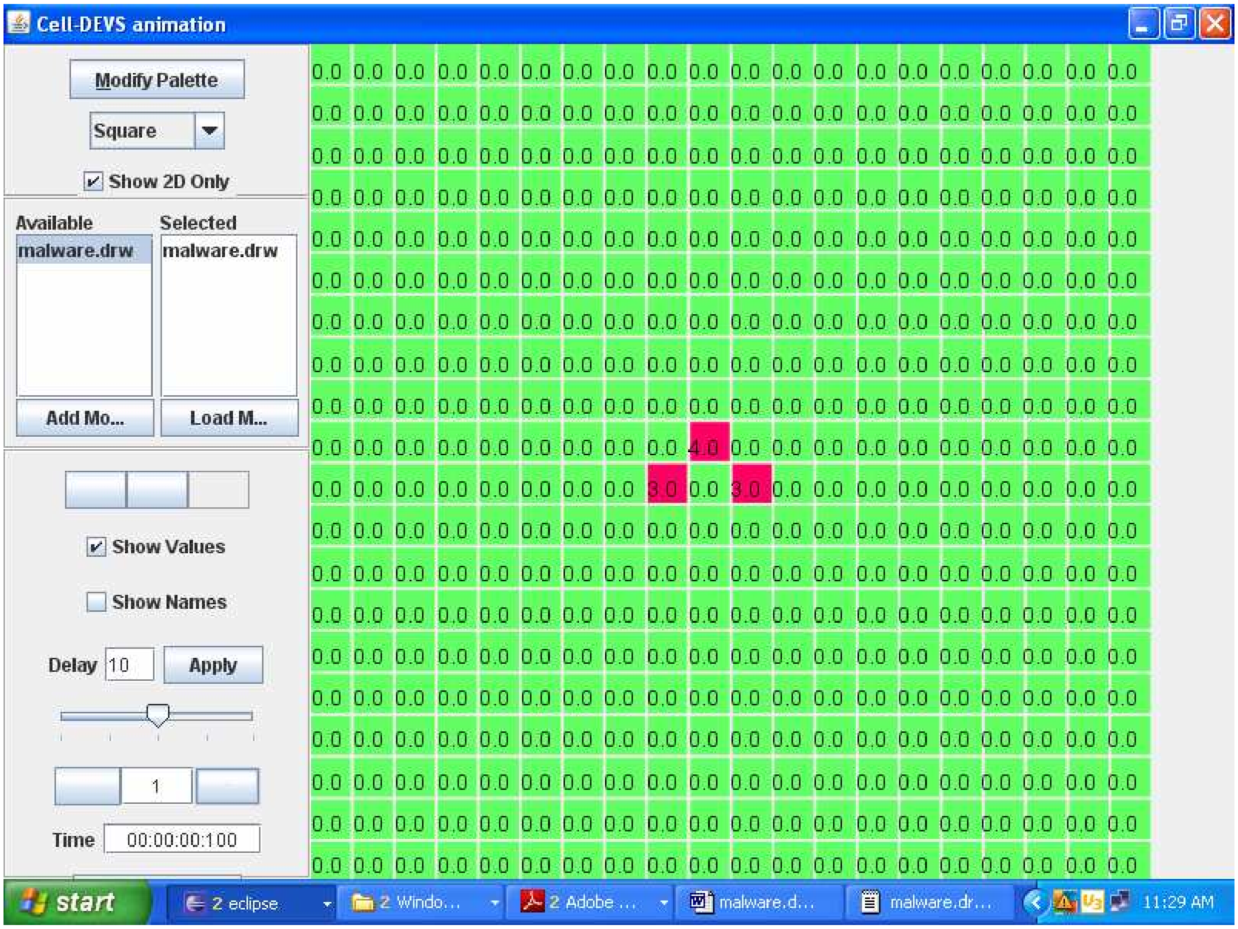
Delay 10

Time 00:00:00:000

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

In the next simulation step, the energy of the *infected* sensor decreases to 80. Also, the energy of the other sensors which are in the *susceptible* state decreases to 99. The malware speads and infects two more sensors as can be seen below.

```
Line : 4831 - Time: 00:00:00:100
     01234567890123456789      01234567890123456789
    +--------------------+    +--------------------+
  0|                    |   0|9999999999999999999999999999999999999999|
  1|                    |   1|9999999999999999999999999999999999999999|
  2|                    |   2|9999999999999999999999999999999999999999|
  3|                    |   3|9999999999999999999999999999999999999999|
  4|                    |   4|9999999999999999999999999999999999999999|
  5|                    |   5|9999999999999999999999999999999999999999|
  6|                    |   6|9999999999999999999999999999999999999999|
  7|                    |   7|9999999999999999999999999999999999999999|
  8|                    |   8|9999999999999999999999999999999999999999|
  9|         4          |   9|9999999999999999998099999999999999999999|
 10|        3 3         |  10|9999999999999999999999999999999999999999|
 11|                    |  11|9999999999999999999999999999999999999999|
 12|                    |  12|9999999999999999999999999999999999999999|
 13|                    |  13|9999999999999999999999999999999999999999|
 14|                    |  14|9999999999999999999999999999999999999999|
 15|                    |  15|9999999999999999999999999999999999999999|
 16|                    |  16|9999999999999999999999999999999999999999|
 17|                    |  17|9999999999999999999999999999999999999999|
 18|                    |  18|9999999999999999999999999999999999999999|
 19|                    |  19|9999999999999999999999999999999999999999|
    +--------------------+    +--------------------+
```



Available: malware.drw

Selected: malware.drw

Delay 10

1

Time 00:00:00:100

```
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
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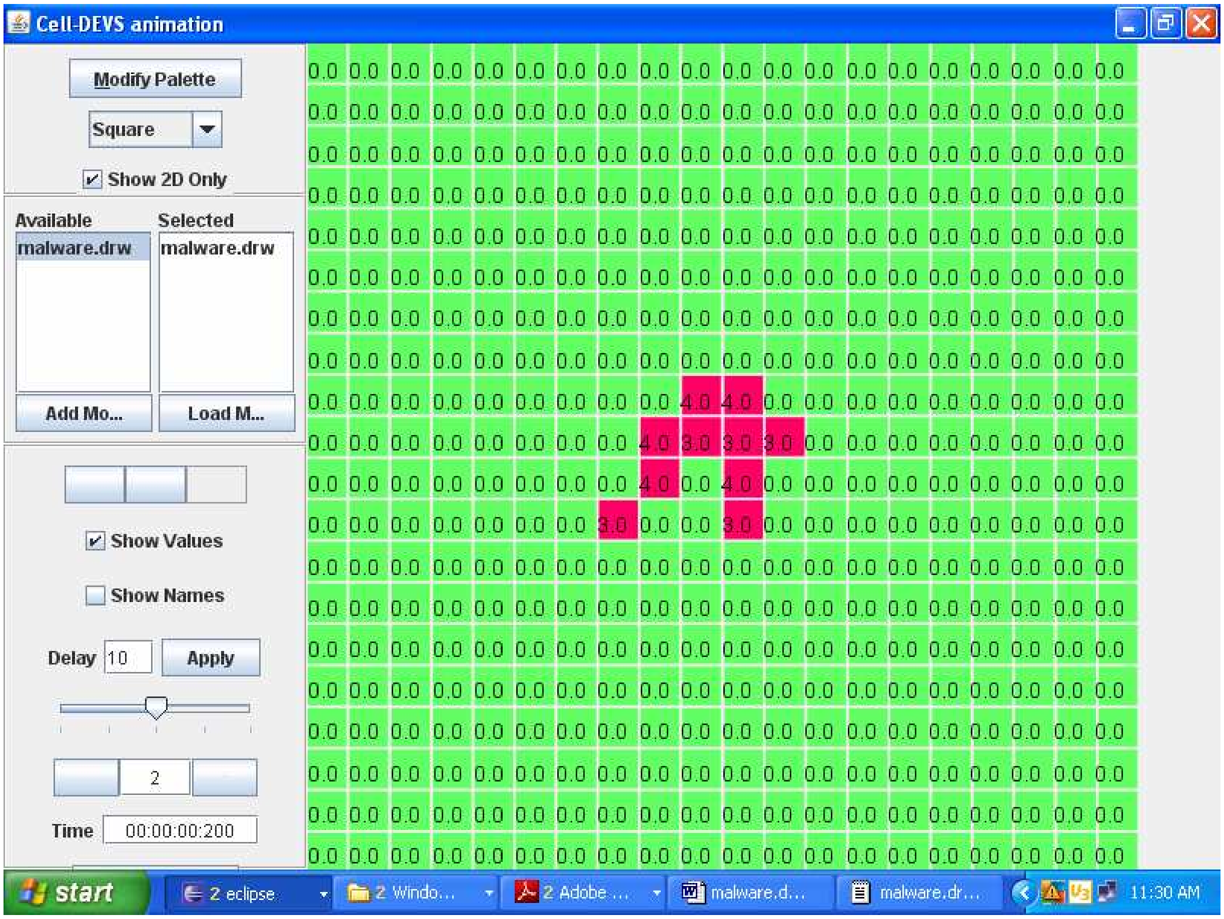
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
```

In each simulation step, the energy of the *infected* sensors is reduced to 80% of the previous value and the energy of the *susceptible* sensors is reduced to 99% of the previous value. The malware speads further and infects more sensors as can be seen below.

```
Line : 7672 - Time: 00:00:00:200
     01234567890123456789      01234567890123456789
    +--------------------+    +--------------------+
   0|                    |    0|9898989898989898989898989898989898989898|
   1|                    |    1|9898989898989898989898989898989898989898|
   2|                    |    2|9898989898989898989898989898989898989898|
   3|                    |    3|9898989898989898989898989898989898989898|
   4|                    |    4|9898989898989898989898989898989898989898|
   5|                    |    5|9898989898989898989898989898989898989898|
   6|                    |    6|9898989898989898989898989898989898989898|
   7|                    |    7|9898989898989898989898989898989898989898|
   8|         44         |    8|9898989898989898989898989898989898989898|
   9|        4333        |    9|9898989898989898986498989898989898989898|
  10|        4 4         |   10|9898989898989898799879989898989898989898|
  11|       3  3         |   11|9898989898989898989898989898989898989898|
  12|                    |   12|9898989898989898989898989898989898989898|
  13|                    |   13|9898989898989898989898989898989898989898|
  14|                    |   14|9898989898989898989898989898989898989898|
  15|                    |   15|9898989898989898989898989898989898989898|
  16|                    |   16|9898989898989898989898989898989898989898|
  17|                    |   17|9898989898989898989898989898989898989898|
  18|                    |   18|9898989898989898989898989898989898989898|
  19|                    |   19|9898989898989898989898989898989898989898|
    +--------------------+    +--------------------+
```

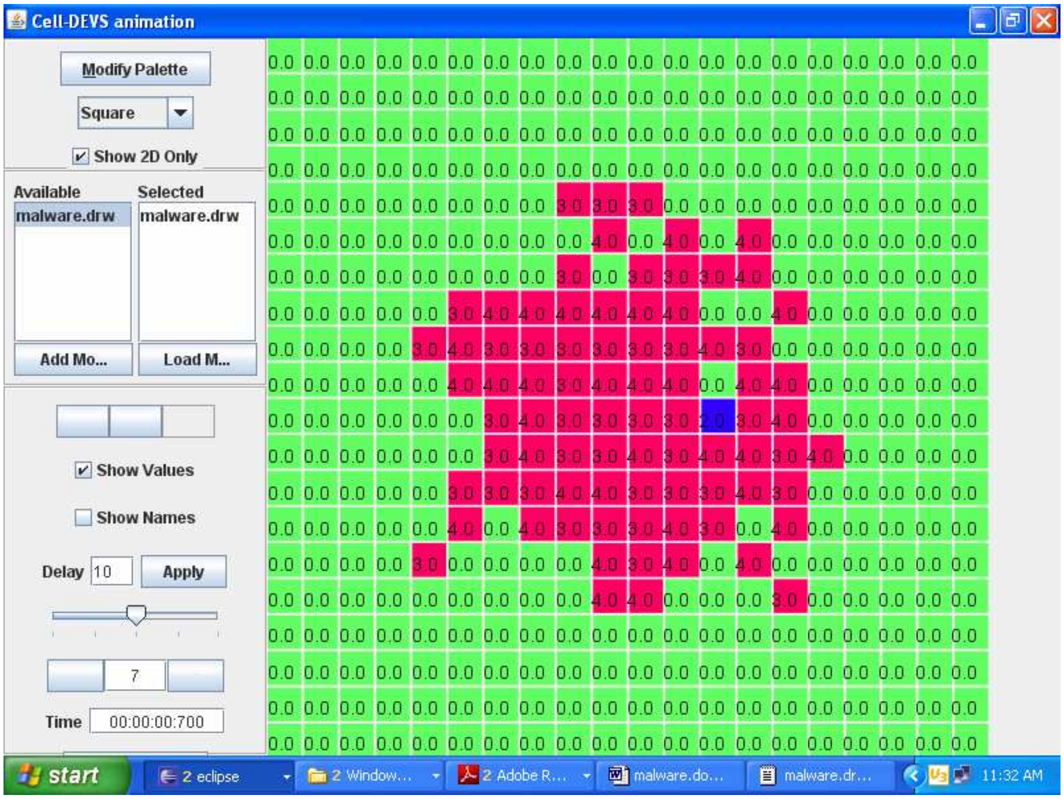


Square
☑ Show 2D Only
Available: malware.drw
Selected: malware.drw
☑ Show Values
☐ Show Names
Delay 10
2
Time 00:00:00:200

```
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 4.0 4.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 4.0 3.0 3.0 3.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 4.0 0.0 4.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 3.0 0.0 0.0 3.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
```

At the simulation time of 700 milliseconds, one of the *infected* sensors turns to recovered state as can be seen below. Note that the energy of the *infected* sensors is reduced to 80%, the energy of the *susceptible* sensors is reduced to 99% and the energy of the *recovered* sensors is reduced by 95% in each simulation step.

```
Line : 22485 - Time: 00:00:00:700
     01234567890123456789      01234567890123456789
    +--------------------+    +--------------------+
   0|                    |   0|9393939393939393939393939393939393939393|
   1|                    |   1|9393939393939393939393939393939393939393|
   2|                    |   2|9393939393939393939393939393939393939393|
   3|                    |   3|9393939393939393939393939393939393939393|
   4|        333         |   4|9393939393939393939393939393939393939393|
   5|         4 4 4      |   5|9393939393939393939375939393939393939393|
   6|        3 3334      |   6|9393939393939393939361756193939393939393|
   7|     3444444  4     |   7|9393939393939361496161409393939393939393|
   8|    3433333343      |   8|9393939393756161403232404975939393939393|
   9|     4443444 44     |   9|9393939393757549322132329393759393939393|
  10|      343333234     |  10|9393939393934049269326614061939393939393|
  11|      3433434434    |  11|9393939393934932614032494949759393939393|
  12|     3334433343     |  12|9393939393936161494961406175759393939393|
  13|     4 433343 4     |  13|9393939393759393939361496193939393939393|
  14|    3    434 4      |  14|9393939393939393937561759375939393939393|
  15|         44   3     |  15|9393939393939393937593939393939393939393|
  16|                    |  16|9393939393939393939393939393939393939393|
  17|                    |  17|9393939393939393939393939393939393939393|
  18|                    |  18|9393939393939393939393939393939393939393|
  19|                    |  19|9393939393939393939393939393939393939393|
    +--------------------+    +--------------------+
```



☑ Show 2D Only

☑ Show Values

☐ Show Names

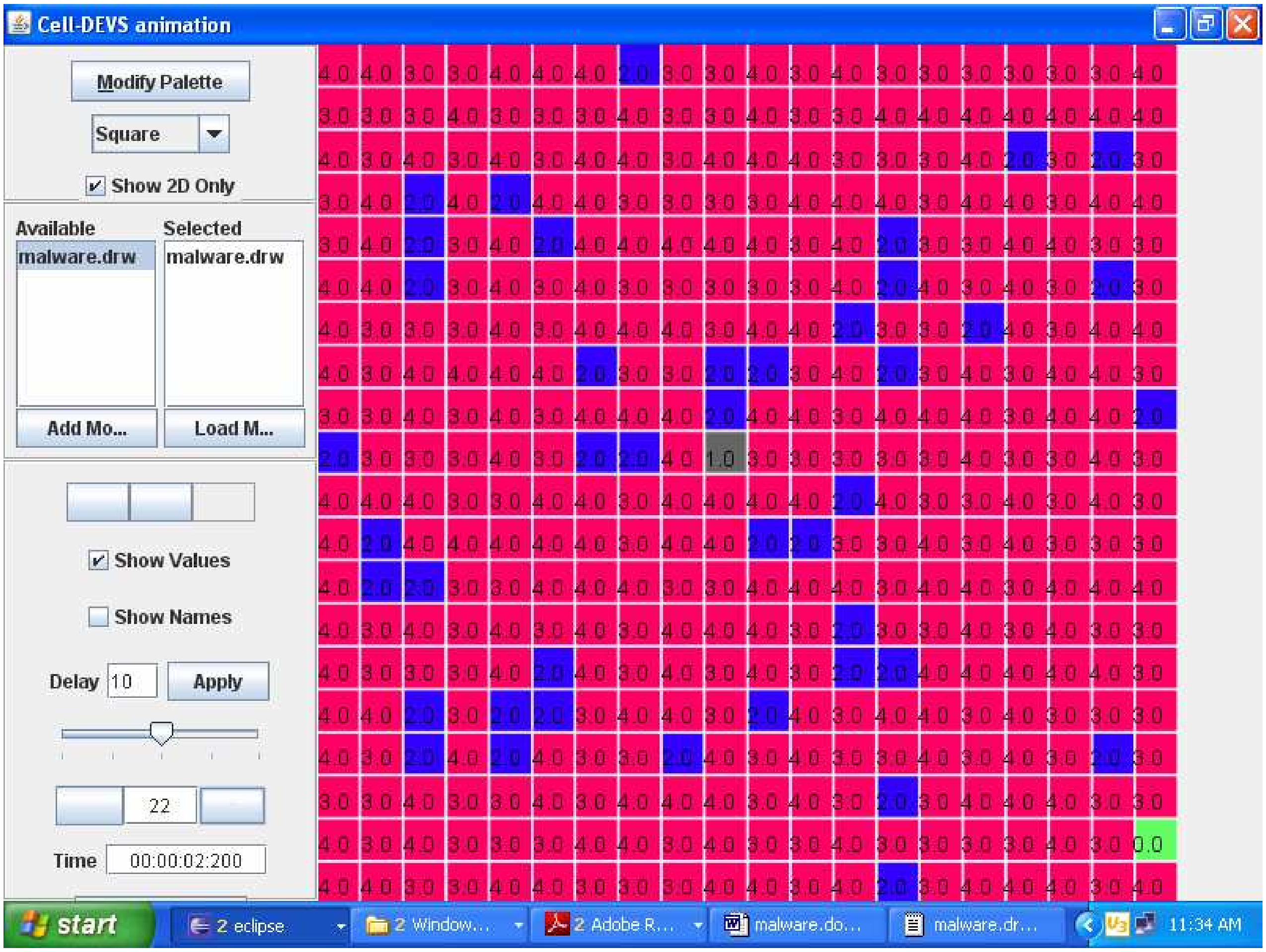
Delay 10

Time 00:00:00:700

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 3.0 | 3.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.0 | 0.0 | 4.0 | 0.0 | 4.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 0.0 | 3.0 | 3.0 | 3.0 | 4.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 0.0 | 0.0 | 4.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 4.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 4.0 | 3.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.0 | 4.0 | 4.0 | 3.0 | 4.0 | 4.0 | 4.0 | 0.0 | 4.0 | 4.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 4.0 | 3.0 | 3.0 | 3.0 | 3.0 | 2.0 | 3.0 | 4.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 4.0 | 3.0 | 3.0 | 4.0 | 3.0 | 4.0 | 4.0 | 3.0 | 4.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 3.0 | 3.0 | 4.0 | 4.0 | 3.0 | 3.0 | 3.0 | 4.0 | 3.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.0 | 0.0 | 4.0 | 3.0 | 3.0 | 3.0 | 4.0 | 3.0 | 0.0 | 4.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.0 | 3.0 | 4.0 | 0.0 | 4.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.0 | 4.0 | 0.0 | 0.0 | 0.0 | 3.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

At the simulation time of 2 seconds and 200 milliseconds, the first *infected* sensor turns to dead state after running out of energy as can be seen below.

```
Line : 77921 - Time: 00:00:02:200
     01234567890123456789      01234567890123456789
    +--------------------+    +--------------------+
   0|44334442334343333334|   0|524228182222121310158154215151518221852|
   1|33343333433433444444|   1|2222281518121581861268151265151815 22|
   2|43434344434443334232 3|   2|18121812221288656581015344912342 2|
   3|34242443333444344344|   3|1210191517151268641510815151018182 8|
   4|34234244444342334433|   4|18102210101710633310486610182222|
   5|44234343333342434323|   5|281241126884436342646101227 18|
   6|43333434443442332434 4|   6|12158564106342317355102215 18|
   7|43444423322342343443|   7|10885439221031483512183415|
   8|33434344424434443442|   8|15864332219112345615123 9|
   9|23334322413333343343|   9|3410844310101 114335581510|
  10|44433443444424334343|  10|12126105512131218234412810|
  11|42444443442233434333|  11|1219812662121422233561212|
  12|42233444334443443444|  12|181510815322222123345101015|
  13|43434343444323343433|  13|1212545353332234366612 12|
  14|43334243434322444443|  14|1886531554532319566881518|
  15|44232234432434434333|  15|101039410108105336484358151222|
  16|43242433243433434323|  16|151239643681232466548482234 22|
  17|33433434443432344433|  17|2218128121081515858628661028342 2|
  18|4343334434334333343 |  18|221812181212121012221015866810182880|
  19|44334433344342344434|  19|221815222242121512343412123618101012188 0|
    +--------------------+    +--------------------+
```



Square

☑ Show 2D Only

Available: malware.drw

Selected: malware.drw

☑ Show Values

☐ Show Names

Delay 10

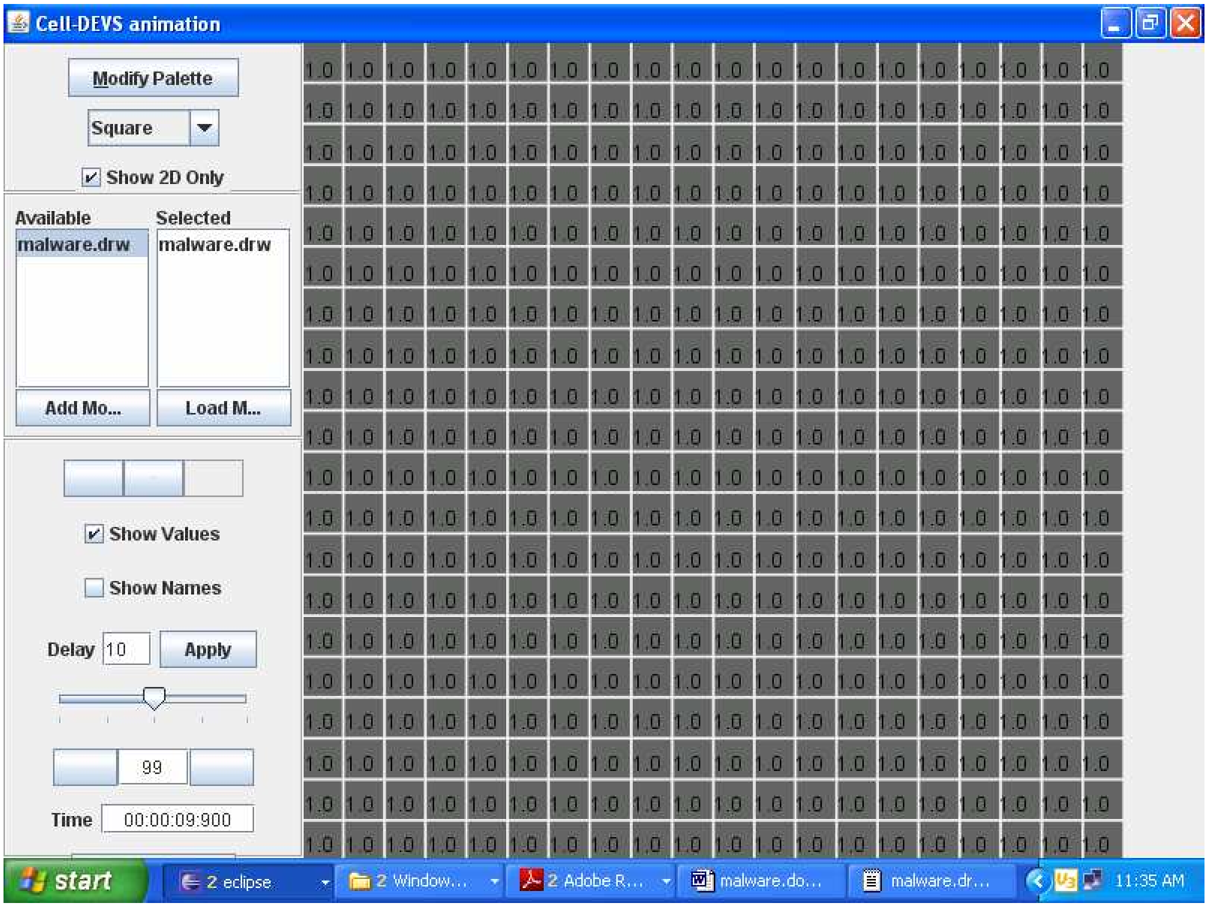
22

Time 00:00:02:200

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.0 | 4.0 | 3.0 | 3.0 | 4.0 | 4.0 | 4.0 | 2.0 | 3.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 4.0 |
| 3.0 | 3.0 | 3.0 | 4.0 | 3.0 | 3.0 | 3.0 | 4.0 | 3.0 | 3.0 | 4.0 | 3.0 | 3.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| 4.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 | 4.0 | 4.0 | 3.0 | 4.0 | 4.0 | 4.0 | 3.0 | 3.0 | 3.0 | 4.0 | 2.0 | 3.0 | 2.0 | 3.0 |
| 3.0 | 4.0 | 2.0 | 4.0 | 2.0 | 4.0 | 4.0 | 3.0 | 3.0 | 3.0 | 3.0 | 4.0 | 4.0 | 4.0 | 3.0 | 4.0 | 4.0 | 3.0 | 4.0 | 4.0 |
| 3.0 | 4.0 | 2.0 | 3.0 | 4.0 | 2.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.0 | 4.0 | 2.0 | 3.0 | 3.0 | 4.0 | 4.0 | 3.0 | 3.0 |
| 4.0 | 4.0 | 2.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 4.0 | 2.0 | 4.0 | 3.0 | 4.0 | 3.0 | 2.0 | 3.0 |
| 4.0 | 3.0 | 3.0 | 3.0 | 4.0 | 3.0 | 4.0 | 4.0 | 4.0 | 3.0 | 4.0 | 4.0 | 2.0 | 3.0 | 3.0 | 2.0 | 4.0 | 3.0 | 4.0 | 4.0 |
| 4.0 | 3.0 | 4.0 | 4.0 | 4.0 | 4.0 | 2.0 | 3.0 | 3.0 | 2.0 | 2.0 | 3.0 | 4.0 | 2.0 | 3.0 | 4.0 | 3.0 | 4.0 | 4.0 | 3.0 |
| 3.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 | 4.0 | 4.0 | 4.0 | 2.0 | 4.0 | 4.0 | 3.0 | 4.0 | 4.0 | 4.0 | 3.0 | 4.0 | 4.0 | 2.0 |
| 2.0 | 3.0 | 3.0 | 3.0 | 4.0 | 3.0 | 2.0 | 2.0 | 4.0 | 1.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 4.0 | 3.0 | 3.0 | 4.0 | 3.0 |
| 4.0 | 4.0 | 4.0 | 3.0 | 3.0 | 4.0 | 4.0 | 3.0 | 4.0 | 4.0 | 4.0 | 4.0 | 2.0 | 4.0 | 3.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 |
| 4.0 | 2.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.0 | 4.0 | 4.0 | 2.0 | 2.0 | 3.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 | 3.0 | 3.0 |
| 4.0 | 2.0 | 2.0 | 3.0 | 3.0 | 4.0 | 4.0 | 4.0 | 3.0 | 3.0 | 4.0 | 4.0 | 4.0 | 3.0 | 4.0 | 4.0 | 3.0 | 4.0 | 4.0 | 4.0 |
| 4.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 | 4.0 | 4.0 | 4.0 | 3.0 | 2.0 | 3.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 | 3.0 |
| 4.0 | 3.0 | 3.0 | 3.0 | 4.0 | 2.0 | 4.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 | 2.0 | 2.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.0 |
| 4.0 | 4.0 | 2.0 | 3.0 | 2.0 | 2.0 | 3.0 | 4.0 | 4.0 | 3.0 | 2.0 | 4.0 | 3.0 | 4.0 | 4.0 | 3.0 | 4.0 | 3.0 | 3.0 | 3.0 |
| 4.0 | 3.0 | 2.0 | 4.0 | 2.0 | 4.0 | 3.0 | 3.0 | 2.0 | 4.0 | 3.0 | 4.0 | 3.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 | 2.0 | 3.0 |
| 3.0 | 3.0 | 4.0 | 3.0 | 3.0 | 4.0 | 3.0 | 4.0 | 4.0 | 4.0 | 3.0 | 4.0 | 3.0 | 2.0 | 3.0 | 4.0 | 4.0 | 4.0 | 3.0 | 3.0 |
| 4.0 | 3.0 | 4.0 | 3.0 | 3.0 | 3.0 | 4.0 | 4.0 | 3.0 | 4.0 | 3.0 | 3.0 | 4.0 | 3.0 | 3.0 | 3.0 | 3.0 | 4.0 | 3.0 | 0.0 |
| 4.0 | 4.0 | 3.0 | 3.0 | 4.0 | 4.0 | 3.0 | 3.0 | 3.0 | 4.0 | 4.0 | 3.0 | 4.0 | 2.0 | 3.0 | 4.0 | 4.0 | 4.0 | 3.0 | 4.0 |

At the simulation time of 9 seconds and 900 milliseconds, the simulation ends when all of the sensor nodes have transitioned into the *dead* state (from either the *susceptible*, *infected* or *recovered* state) after running out of energy, as can be seen below.

```
Line : 160151 - Time: 00:00:09:900
     01234567890123456789     01234567890123456789
    +--------------------+   +--------------------+
   0|11111111111111111111|  0|                    |
   1|11111111111111111111|  1|                    |
   2|11111111111111111111|  2|                    |
   3|11111111111111111111|  3|                    |
   4|11111111111111111111|  4|                    |
   5|11111111111111111111|  5|                    |
   6|11111111111111111111|  6|                    |
   7|11111111111111111111|  7|                    |
   8|11111111111111111111|  8|                    |
   9|11111111111111111111|  9|                    |
  10|11111111111111111111| 10|                    |
  11|11111111111111111111| 11|                    |
  12|11111111111111111111| 12|                    |
  13|11111111111111111111| 13|                    |
  14|11111111111111111111| 14|                    |
  15|11111111111111111111| 15|                    |
  16|11111111111111111111| 16|                    |
  17|11111111111111111111| 17|                    |
  18|11111111111111111111| 18|                    |
  19|11111111111111111111| 19|                    |
    +--------------------+   +--------------------+
```



Delay 10

99

Time 00:00:09:900

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```

## CamStudio Screen-capturing Software

As part of this work, the CamStudio screen-capturing software was installed. Then, it was used to record the video of the Cell-DEVS animation. A file named *malware.avi* is being included with the assignment which contains the video of the simulation results shown by the Cell-DEVS animation.

## Conclusion

The simulation results presented in this work have checked the model on a step by step basis and have verified its accuracy. The spread of the infection depends on the parameter $\beta$ and a higher $\beta$ will lead to a quicker spread of the infection. The recovery from malware depends on the parameter $\delta$ and a higher $\delta$ will lead to a quicker recovery. The life of the sensor network also depends on the energy depletion rate in the *susceptible*, *infected* and *recovered* states.

## References:

[1] Song, Y., Jiang, G.-P., “Modeling malware propagation in wireless sensor networks using cellular automata,” In IEEE ICNNSP 2008, Zhenjiang, China, pp. 623-627, 2008.