Distributed Sensor Networks with Collective Computation

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Outline

- Theoretical evaluation of sensor networks.
- DSN-CC fundamentals.
- Example problem using DSN-CC.
- Simulating a DSN-CC.
- Modeling results.
- Hardware overview.

Introduction

- **Classical sensor networks:**

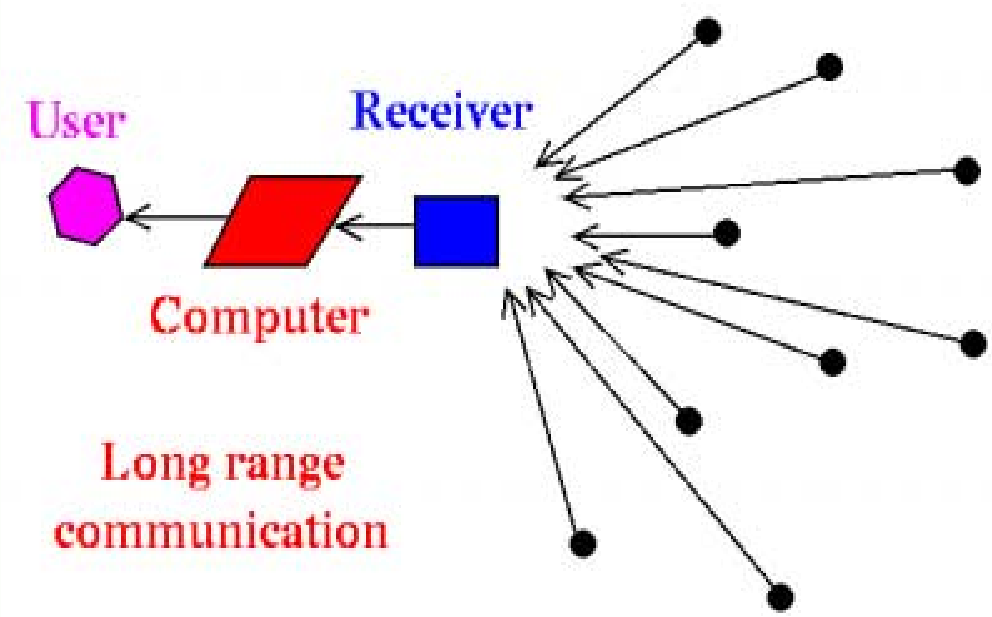
  Traditional networks are built using the star topology. Sensor measurements are sent to a central collection point (the hub of the star), where data is processed and presented to the end user.

- **Problem:**

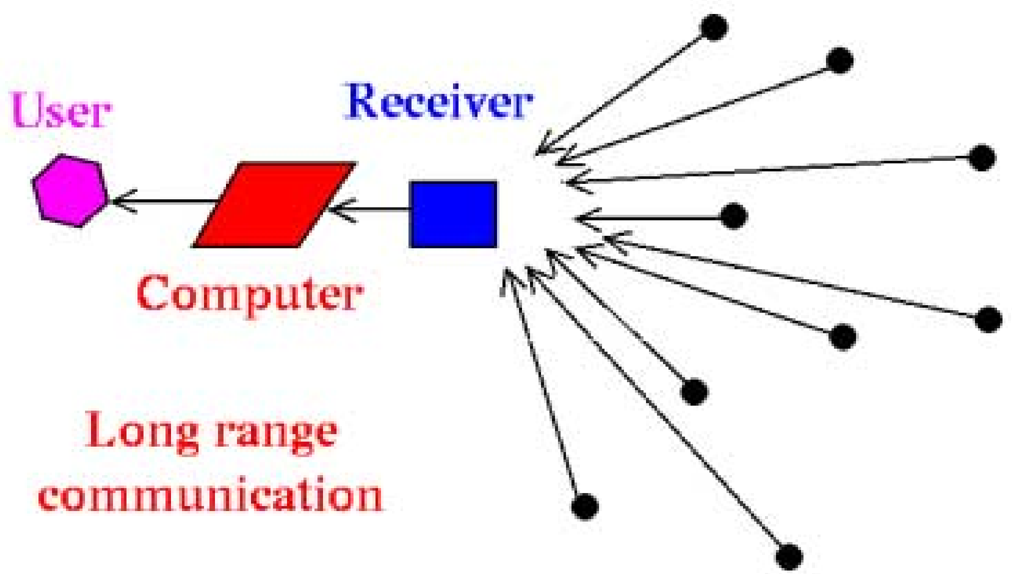
  Because transmitter power drops as r^{-2} it is very costly, in terms of energy consumption, to transmit long distances.

- **Solution:**

  If a message is routed through a relay, or a series of intermediate transmitters, then energy consumption can be reduced.



Resource Scaling



Classical Sensor Network

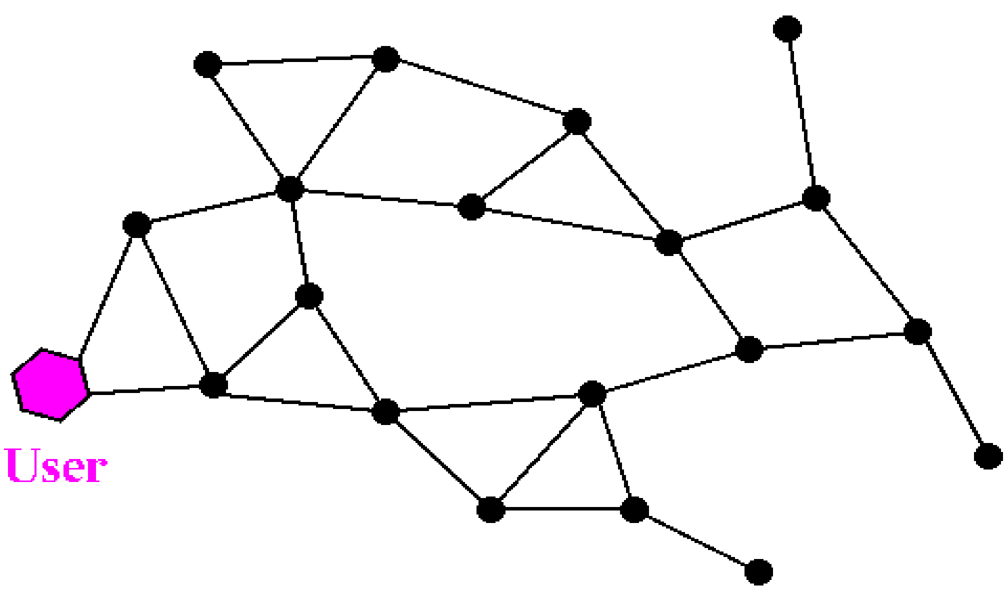
$$\text{Exfiltration Time} \propto N$$

$$\text{Transmission Energy} \propto d^2$$

$$\text{Transmission Distance} \propto \sqrt{N}$$

$$\Rightarrow \text{Sensor Energy} \propto (\sqrt{N})^2 = N$$

$$\Rightarrow \text{Exfilration Energy} \propto N^2$$



DSN-CC

$$\text{Transmission Hops} \propto \sqrt{N}$$

$$\text{Transmission Distance} \propto C$$

$$\Rightarrow \text{Exfiltration Time} \propto \sqrt{N}$$

$$\Rightarrow \text{Sensor Energy} \propto C$$

$$\Rightarrow \text{Exfilration Energy} \propto N$$

Collective Behavior

- **Collective behavior:**

  What the network does as a whole that no single node can do on it's own. Node interaction results in a solution that no single sensor can provide.

- **Goal:**

  Program individual nodes in a DSN-CC to achieve the desired collective behavior.

- **Desired collective behavior includes:**

  - Fastest possible sensing and data reduction.
  - Robustness to failure.
  - Minimum energy usage.

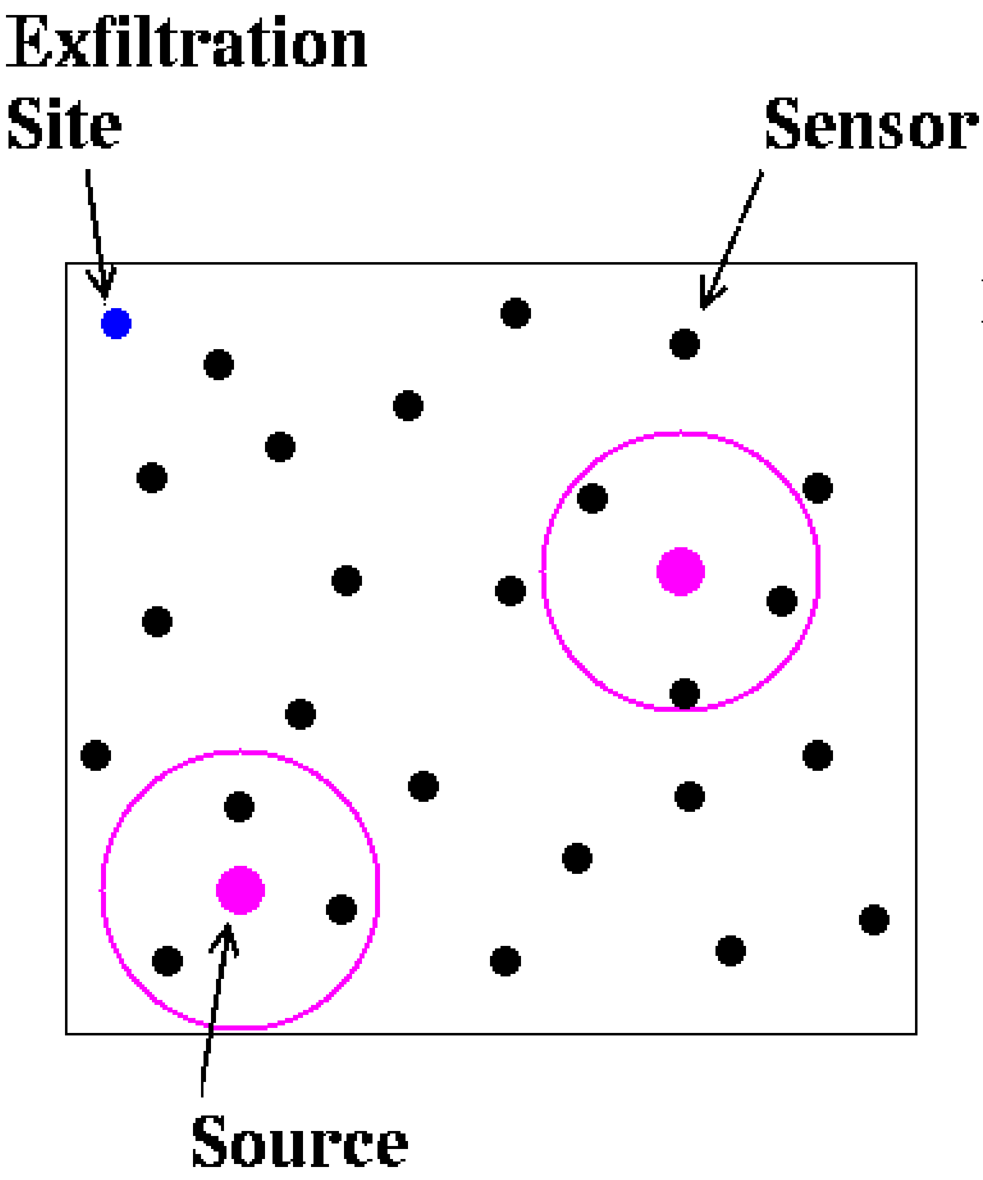
- **Problem:**

  No theory exists for direct inversion.

- **Practical solution:**

  Next best thing is to use forward modeling to develop empirical rules for the behavior of DSN-CC.

Simulation Picture



Exfiltration Site

- Information sink
- Extraction site

Could be a node or a network user

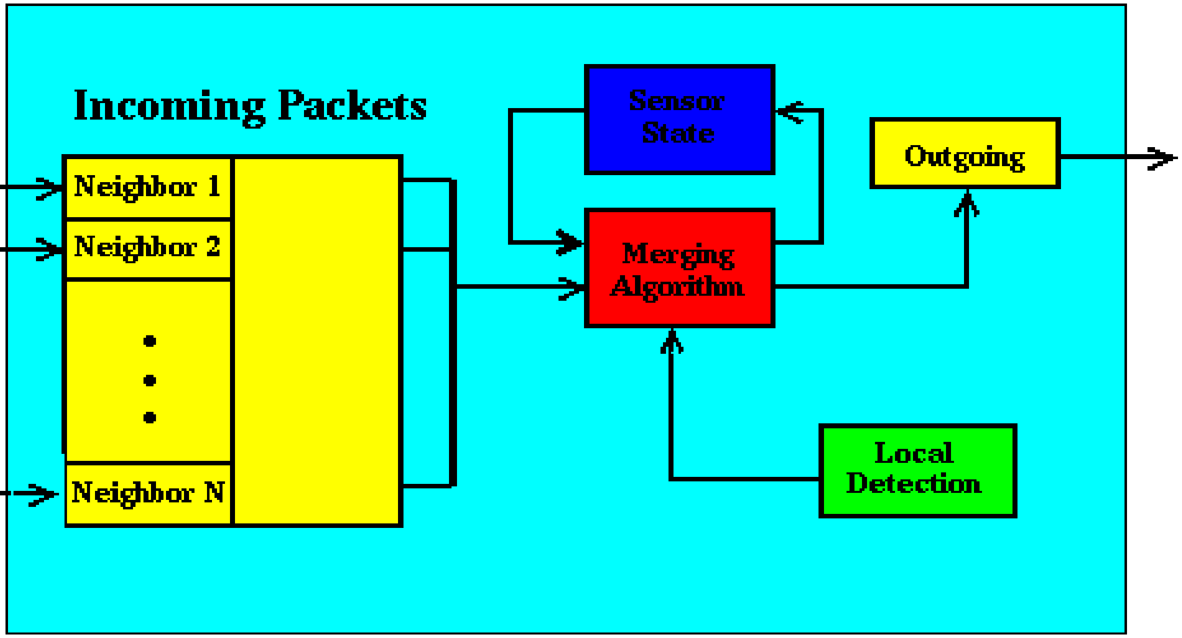
Sensor Overview

Hardware simulation

```
void send_packet(void *);
void *receive_packet();
int carrier_detect();
int sensor_detect(float *);
```

Sensor simulations

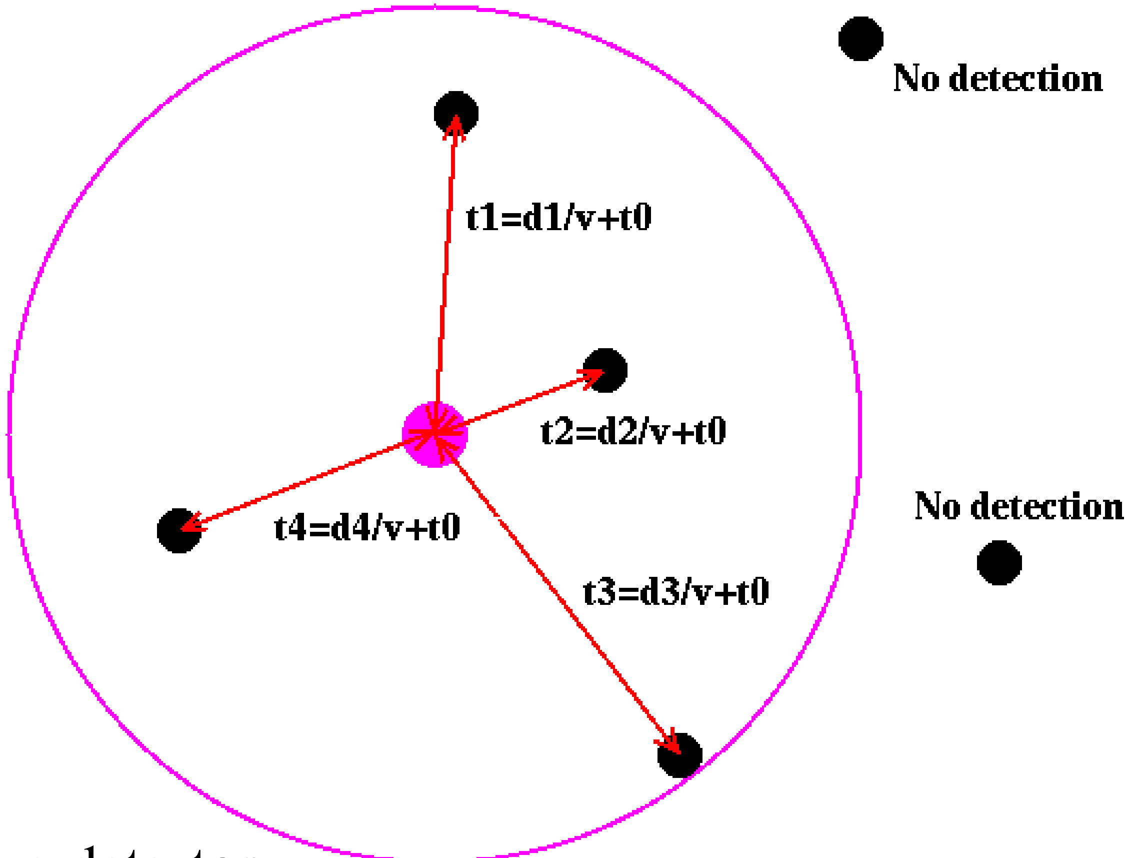
```
p=receive_packet();
t=sensor_detect();
//  merge information
o=merge_packets(p,r,d);
if(new(o)&&carrier_detect()==0)
   send_packet(o);
```



DSN-CC Example: TDOA

- **General problem:**
  Locate a source given the times of arrival of the signal at several nodes.

- **Specific problem:**
  Locate a sound source.



- **Applications:**
  - Lightning strikes
  - Emergency response
  - Firearm discharges
  - Ionizing radiation source detector
  - (Global positioning system)

TDOA Solution

- **Equations:**

$$\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} - \sqrt{(x_2 - x_0)^2 + (y_2 - y_0)^2} = v_s(t_1 - t_2)$$
$$\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} - \sqrt{(x_3 - x_0)^2 + (y_3 - y_0)^2} = v_s(t_1 - t_3)$$
$$\sqrt{(x_2 - x_0)^2 + (y_2 - y_0)^2} - \sqrt{(x_4 - x_0)^2 + (y_4 - y_0)^2} = v_s(t_2 - t_4)$$

- **Givens:**

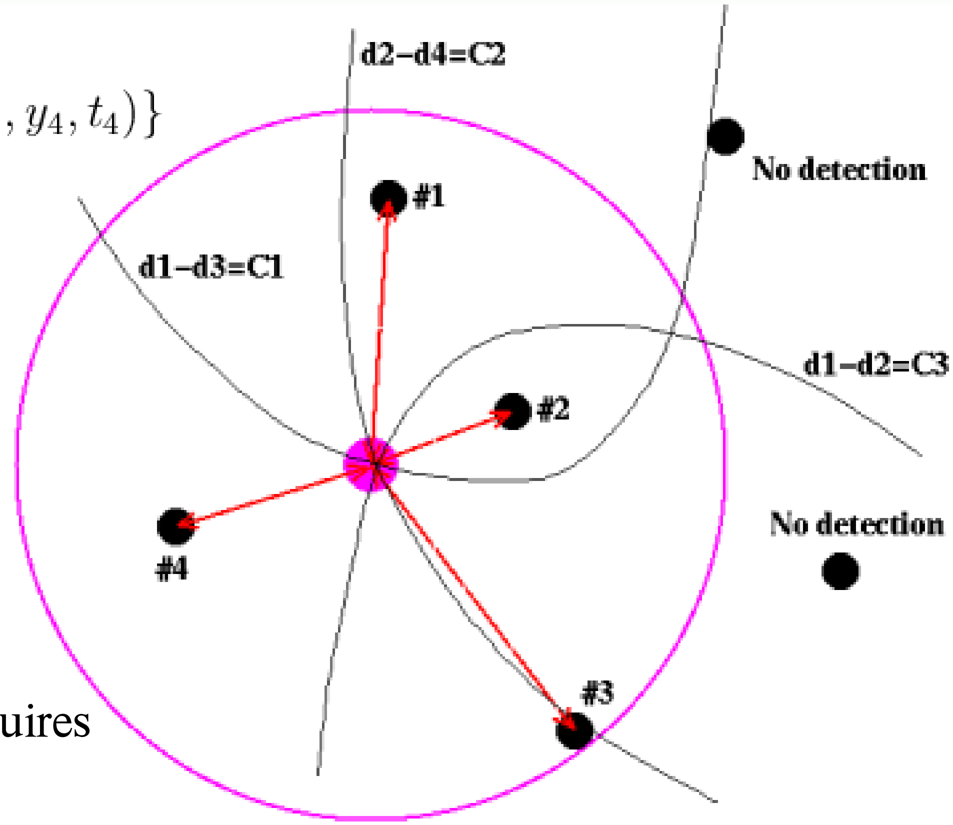
$$\{v_s, (x_1, y_1, t_1), (x_2, y_2, t_2), (x_3, y_3, t_3), (x_4, y_4, t_4)\}$$

- **Unknowns:**

$$(x_0, y_0, t_0)$$

- **Observation:**
  Each pair of measurements expresses a hyperbola.

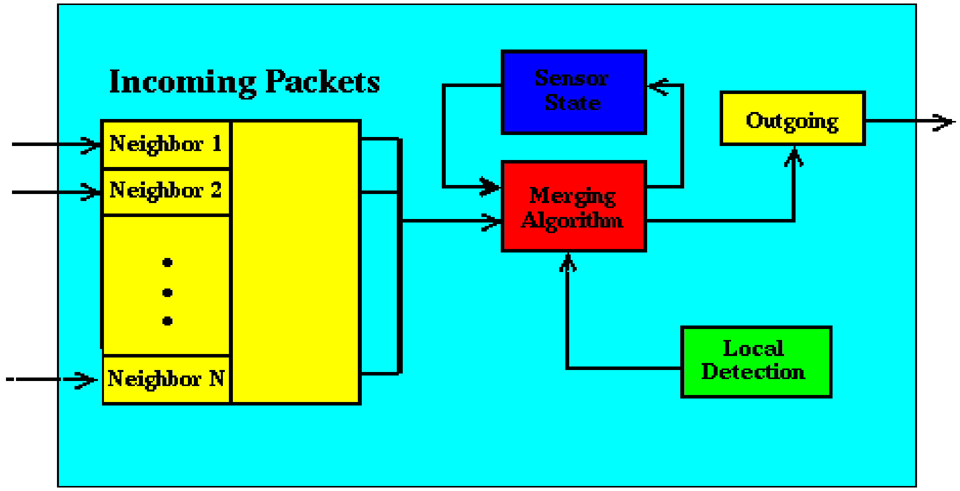
- **Conclusion:**
  Exact solution of the TDOA problem requires four independent measurements.



Data Reduction

- **Packet structure**:
  64 bytes

  Sensor ID (4)
  Number of conclusions (1)
    x-position (2)
    y-position (2)
    time of detection (TOA) (4)
  Number of TOA measurements (1)
    x-position (2)
    y-position (2)
    time of event (4)



- **Data reduction scheme:**

  - **Receive packet.**
    Compare new measurements and conclusions to previous knowledge, adding new information to memory.

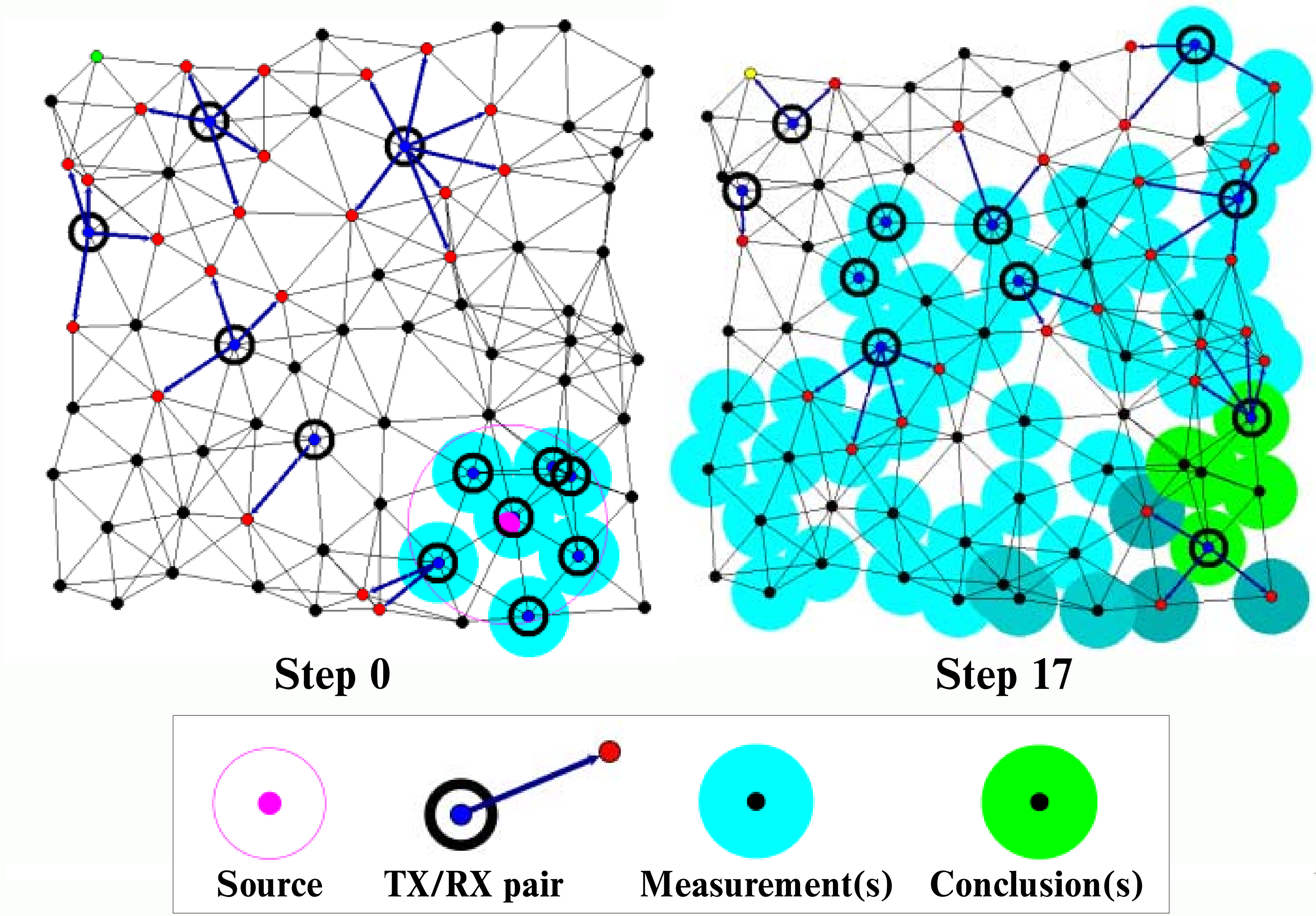
  - **Detect events.**
    Append new measurements to memory.

  - **Form conclusions (merge information).**
    If new measurements have been introduced and more than four TOAs are available, then try to solve for event location.

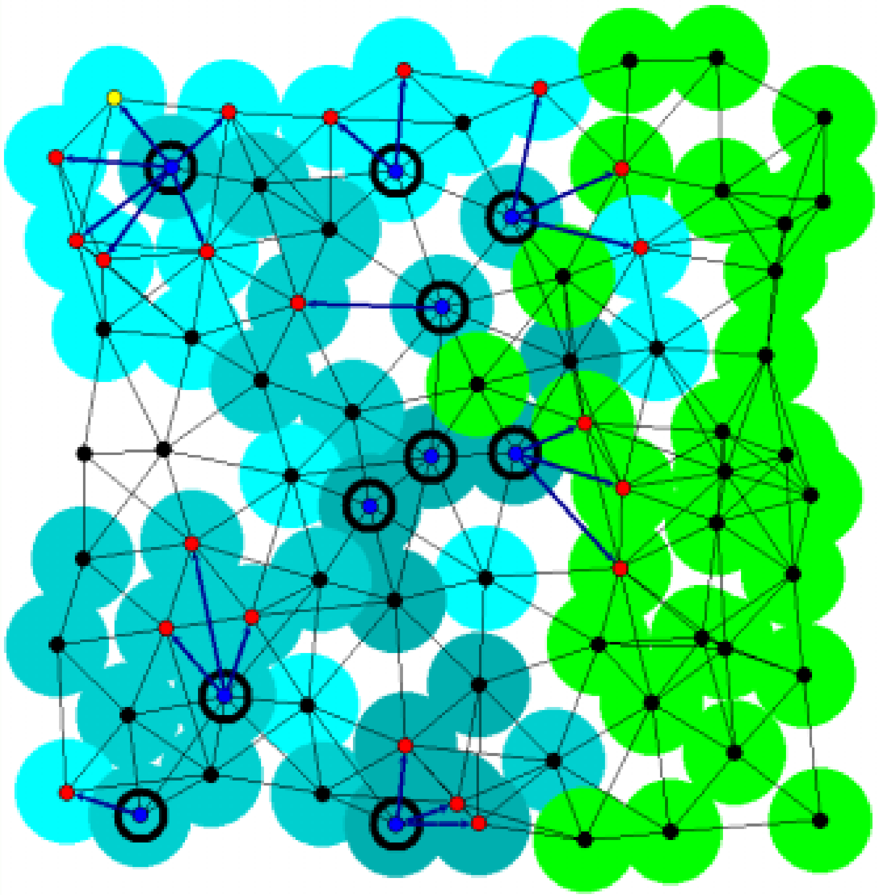
    If a new conclusion is formed, remove all consistent measurements.

  - **Transmit packet if necessary.**
    If internal memory has changed, then send new knowledge to neighbors, else wait to receive again.

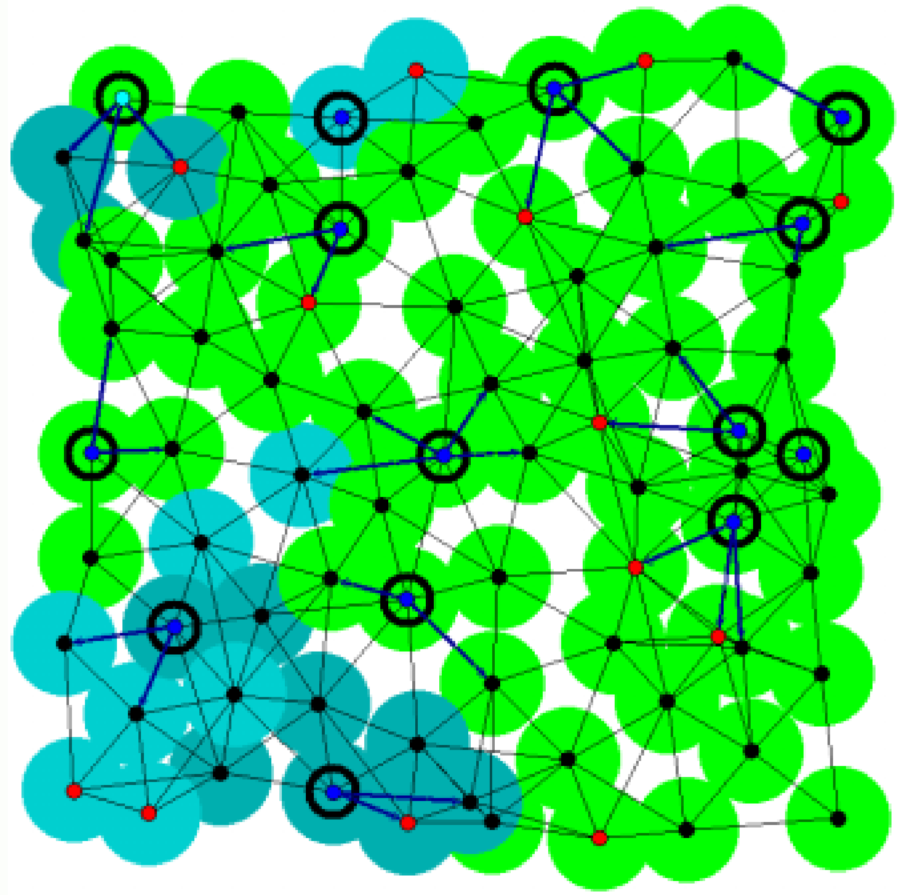
Simulation (1)



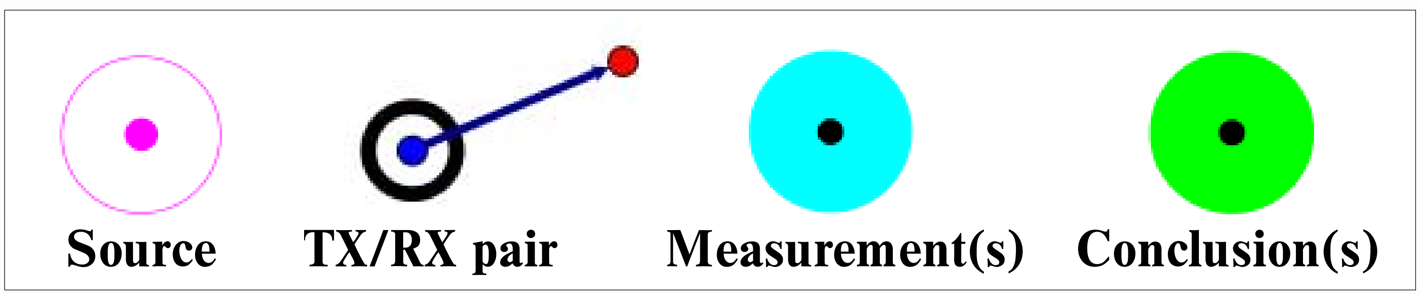
Simulation (2)



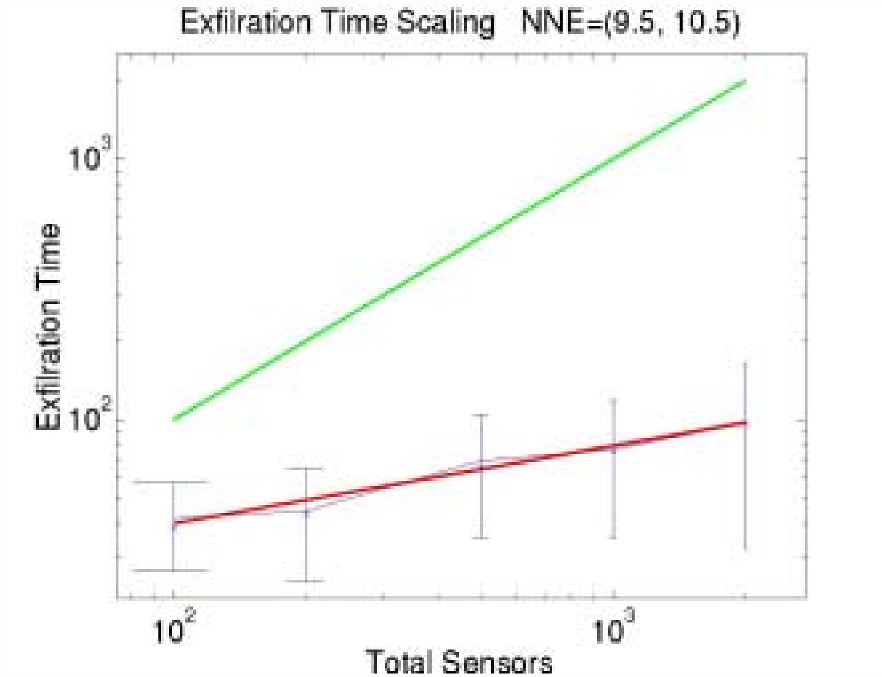
Step 28

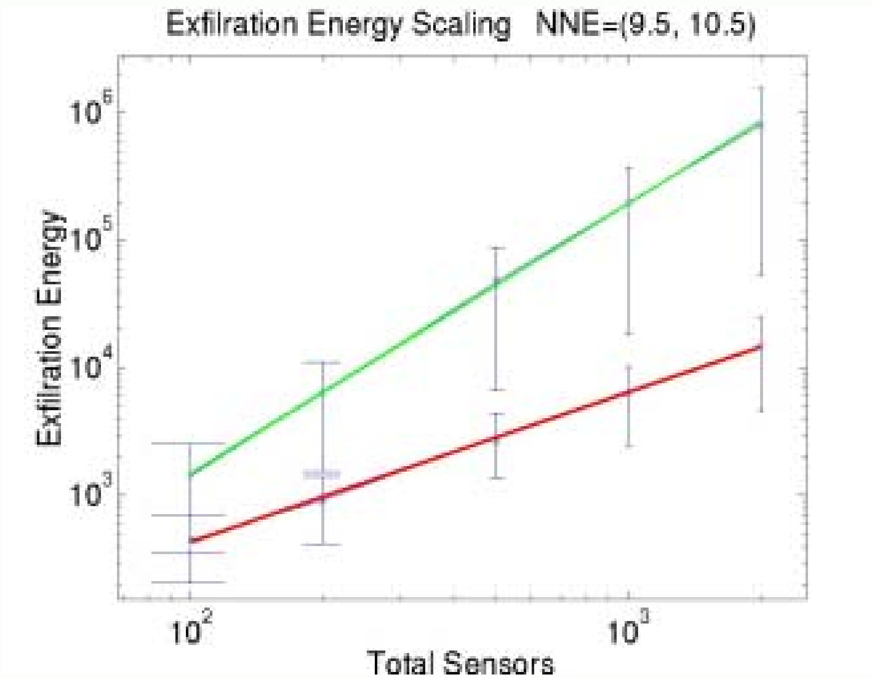


Step 41



Simulation Results





Experimental results:

$$\mathbf{t}_{\mathbf{CLASSIC}} \propto N$$

$$\mathbf{t}_{\mathbf{DSN}} \propto N^{0.30}, \ R^2 = 0.9660$$

$$\mathbf{E}_{\mathbf{CLASSIC}} \propto N^{2.12}, \ R^2 = 0.9997$$

$$\mathbf{E}_{\mathbf{DSN}} \propto N^{1.17}, \ R^2 = 0.9990$$

Theoretical predictions:

$$\mathbf{t}_{\mathbf{CLASSIC}} \propto N$$

$$\mathbf{t}_{\mathbf{DSN}} \propto \sqrt{N}$$

$$\mathbf{E}_{\mathbf{CLASSIC}} \propto N^2$$

$$\mathbf{E}_{\mathbf{DSN}} \propto N$$

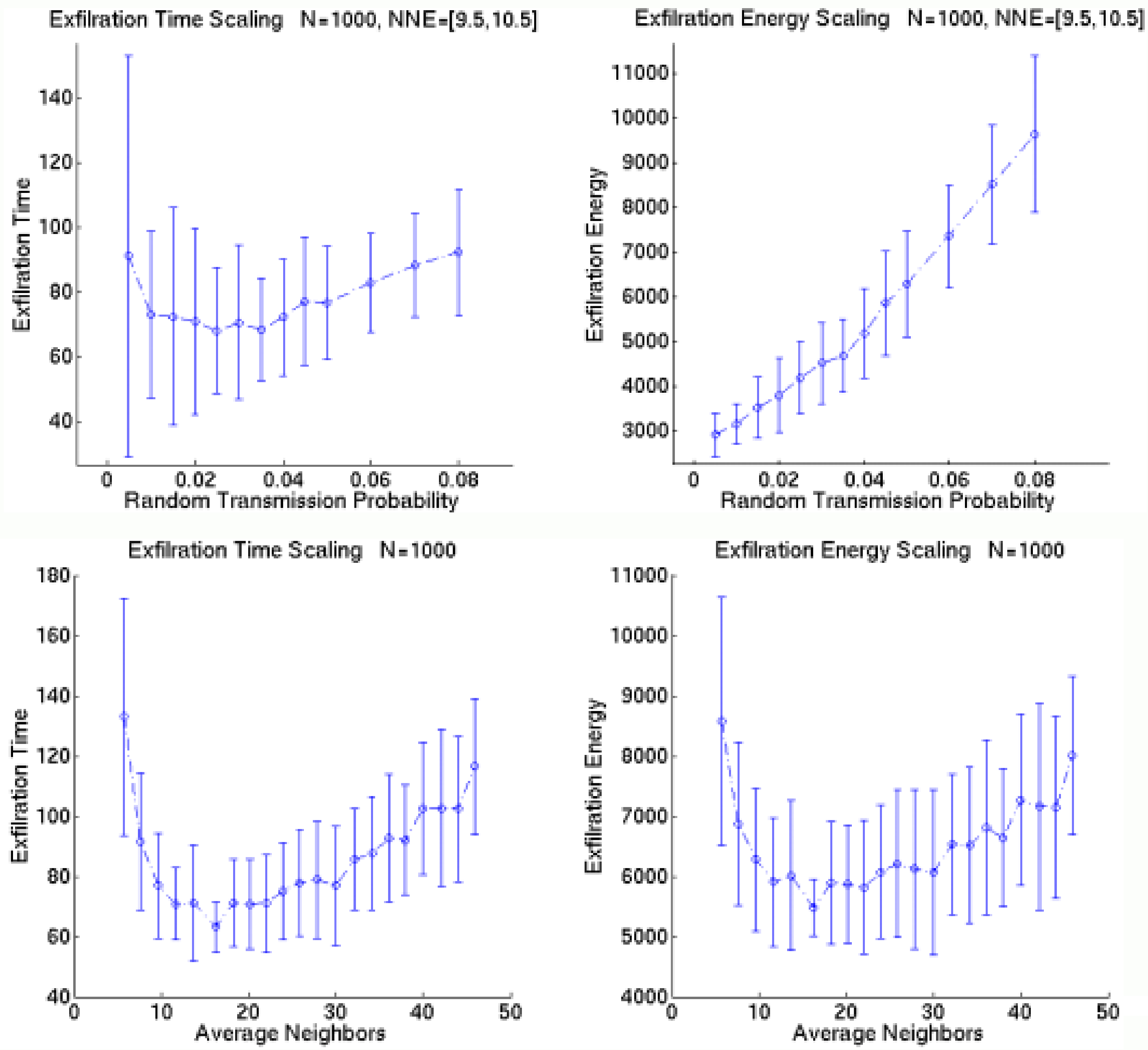
Forward Modeling: Free Parameters

- **Recall:**
  No general theory exists for direct inversion of free sensor parameters.

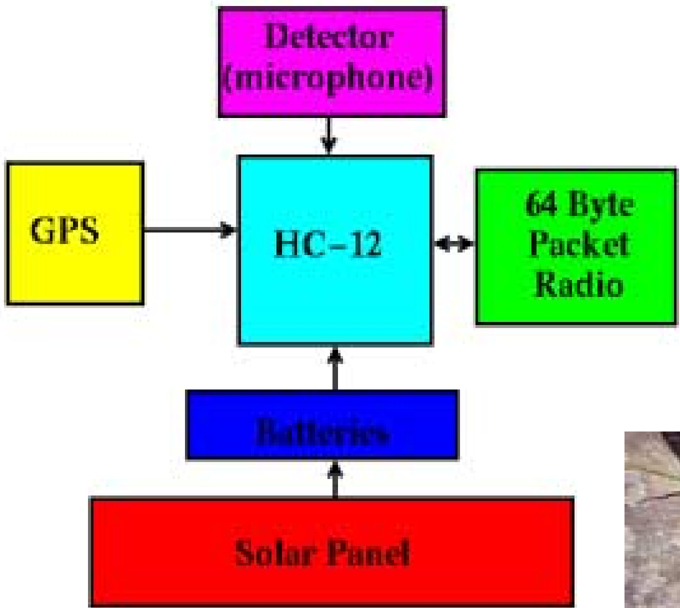
- **Free parameters:**
  - **Random transmission probability (psend)**
    If psend=0, then collisions could stop the flow of information.
    If psend>>0, then too many collision occur and exfiltration time increases.
  - **Number of neighbors (nne)**
    If nne>>0, then too many collisions will occur.
    If nne≈0, then network will be disconnected.

- **Simulations are required to explore free parameters.**
  - Develop empirical rules.
  - Support development of general theory.

Parameter Modeling Results



Hardware Platform



- Weather proof
- 100 mA @ 5V
- 10x5x2 inches

Conclusions | Future Work

Conclusions:

- **DSN-CCs exfiltrate faster and expend less energy.**
  - Scales for energy and exfiltration time.
  - Constant peak energy.
- **Robustness.**
  - Messages propagate around obstacles.
  - Message loss does not cause failure.
- **Local algorithms result in apparent global coordination.**

Future Work:

- **Parameter studies**
  - Do further simulations of sensor algorithms.
  - Develop theory or empirical rule set.
- **Further hardware.**
  - Extend hardware deployment and conduct new experiments.
- **Sensor specialization.**
  - Self-organization and sensor specialization.
  - Repair/defense.
- **Role of actuators.**
  - Mobile sensors (possibly capable of modifying the environment).
- **Detecting and reacting on sensor failures.**
  - Benchmark robustness.