Hop-based Energy Aware Routing Scheme for Wireless Sensor Networks

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Contents

Problem statement

❖ Transmission manner

- Small scale network: single hop transmission is preferred
- Large scale network: multi-hop transmission is preferred
- How to determine the transmission manner under diff. networks?

❖ Hot spot phenomenon

- Nodes close to BS die early using multi-hop transmission
- Nodes far from BS die early using single hop transmission
- How to alleviate this phenomenon under diff. transmission manner?

❖ Optimal hop number

- Commonly agreed that multi-hop trans. is more energy efficient.
- How to determine the optimal hop number and intermediate nodes?

❖ Up to now, the hop-based routing in WSNs is not well addressed

Motivations

- By using hop-based routing mechanism, the energy consumption can get reduced
- The network lifetime can get prolonged
- It can alleviate the hot spot phenomenon
- It should be energy balancing and efficient
- It is distributed, localized and easy to apply

Contributions

- We propose a Hop-based Energy Aware Routing (HEAR) algorithm for WSNs.
- By using our HEAR algorithm, the hot node phenomena in WSNs can get alleviated.
- We make extensive simulations to validate the performance of our hop-based energy aware routing algorithm.

Focus of this dissertation

- Objective:
  - prolong network lifetime
- Means:
  - reduce and balance energy consumption
- Research topic:
  - routing
- Uniqueness:
  - from hop number point of view

2. Related Work: Routing protocols for WSNs

Flat-based Routing

Representative ones:

Directed diffusion [36, 37]
SPIN [31, 38]
GRAB [42]
Others: [27-65]

Hierarchical-based Routing

Representative ones:

LEACH [32, 33]
PEGASIS [41]
HEED [48]
Others: [27-65]

.

Location-based Routing

Representative ones:

GAF [21, 22]
TTDD [39]
MECN [50]
Others: [27-65]

3. Related works

❖ Other hop-based routing algorithms

[43,44,45]	[32, 33]	[52, 53]	[30]
The authors study diff. energy models and optimal hop number. But: 1. They treat each node equally 2. More simulation is needed 3. Study under real sensor network is needed [2001]	The LEACH authors treat node differently. But: 1. They only use direct trans. by CH 2. No study of hop number 3. No study of the performance of hop-based routing [2002]	The authors study selection of trans. manner . But: 1. They only treat 2 hops routing as multi-hop routing 2. Further analysis and simulation is needed [2006/2007]	The author explain the influence of hop number on many network metrics. But: 1. Theoretical analysis of hop number is needed 2. More simulation is needed [2004]

3. Proposed Idea : HEAR

- How to determine ***the next hop node*** is one critical issue in routing

- **The next hop node selection criteria:**
  - Lowest ID
  - Max-degree
  - Shortest-path
  - Max. residual energy
  - Greedy routing
  - Probability based
  - Others…

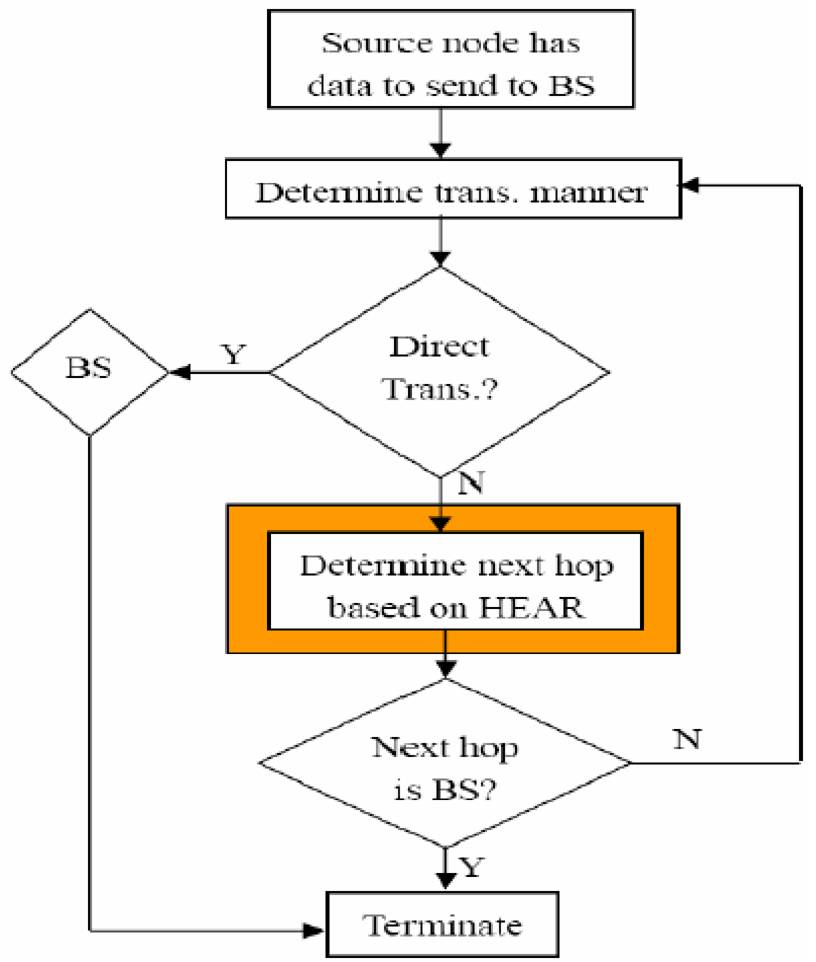
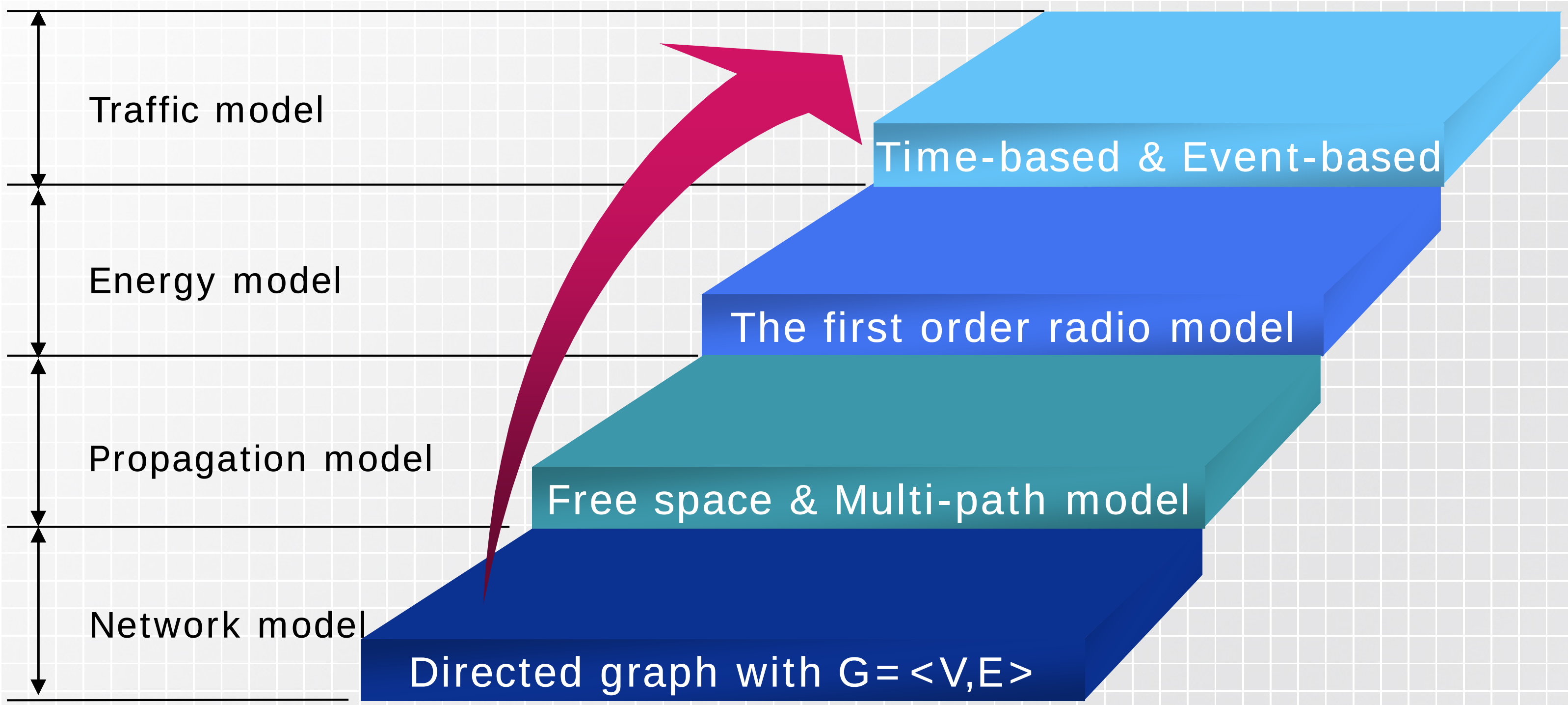


Fig. 11. Brief workflow of HEAR algorithm

4. HEAR algorithm for WSNs

❖ Relevant models



Network model

- **WSN can be regarded as a directed graph G=<V, E> where V represents the set of vertices and E represents the set of edges**

- **Assumptions about WSN**
  - Sensors are stationary
  - Sensors are homogeneous
  - Sensors are left unattended
  - Sensors are location aware
  - There is only one sink node
  - Comm. links are symmetric
  - There is no big obstacle

Table 3 Definition of network parameters

Parameter	Definition
A	Area of sensor network
N	Number of sensor nodes
R	Maximum transmission radius
l	Data length
BS	Position of Base Station
d	Distance between source and sink node

Propagation model

1. There exists a direct wireless link between u and v if $P_r \geq \beta$, where P_r is the power of received signal by v and β denotes the sensitivity threshold.
2. If the communication distance is less than a crossover distance ($d_{crossover}$), the Friss free space model is used (d^2 attenuation). If the distance is larger than $d_{crossover}$, multi-path model is used (d^4 attenuation).
3. The crossover distance is defined as

$$d_{crossover} = \frac{4\pi\sqrt{L}h_r h_t}{\lambda} \qquad (4.1)$$

where:

$L \geq 1$ is the system loss factor not related to propagation,

h_r is the height of receiving antenna above ground,

h_t is the height of transmitting antenna above ground,

λ is the wavelength of the carrier signal.

Free space model

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2 L} \qquad (4.2)$$

where:

$P_r(d)$ is the receive power given a transmitter-receiver distance d,

P_t is the transmit power,

G_t is the gain of the transmitting antenna,

G_r is the gain of the receiving antenna,

λ is the wavelength of the carrier signal,

d is the distance between transmitter and receiver,

$L \geq 1$ is the system loss factor not related to propagation.

Multi-path model

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4} \qquad (4.3)$$

where:

$P_r(d)$ is the receive power given a transmitter-receiver distance d,

P_t is the transmit power,

G_t is the gain of the transmitting antenna,

G_r is the gain of the receiving antenna,

h_r is the height of receiving antenna above ground,

h_t is the height of transmitting antenna above ground,

d is the distance between transmitter and receiver.

Energy model

The energy consumption model we use in this thesis is called the first order radio model [32, 33]. Each sensor node will consume the following E_{Tx} amount of energy to transmit a l-bits message over distance d:

$$E_{Tx}(l,d)=\begin{cases} l\cdot E_{elec}+l\cdot\varepsilon_{fs}\cdot d^2, & if\, d<d_0 \\ l\cdot E_{elec}+l\cdot\varepsilon_{mp}\cdot d^4, & if\, d\geq d_0, \end{cases} \quad (4.5)$$

E_{Rx} amount of energy to receive this message:

$$E_{Rx}(l)=l\cdot E_{elec}, \quad (4.6)$$

and E_{Fx} amount of energy to forward this message:

$$E_{Fx}(l,d)=E_{Tx}(l,d)+E_{Rx}(l)=\begin{cases} 2l\cdot E_{elec}+l\cdot\varepsilon_{fs}\cdot d^2, & if\, d<d_0 \\ 2l\cdot E_{elec}+l\cdot\varepsilon_{mp}\cdot d^4, & if\, d\geq d_0. \end{cases} \quad (4.7)$$

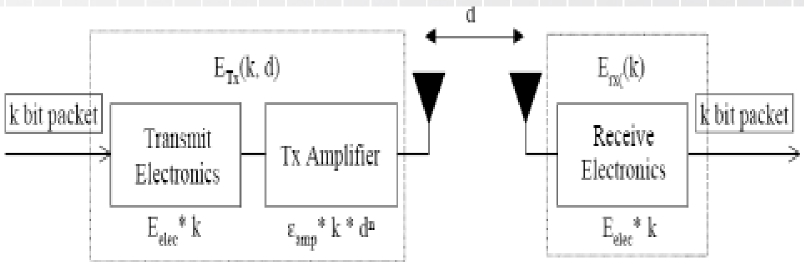


Fig. 12. Radio energy dissipation model

Table 4 Definition of hardware parameters

Parameter	Definition	Unit
E_{elec}	Energy dissipation	50 nJ/bit
ε_{fs}	Free space model of	10 pJ/bit/m^2
ε_{mp}	Multi-path model of	0.0013 pJ/bit/m^4
l	Data length	2000 bits
d_0	Distance threshold	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ m

Traffic model

- **There are four types of traffic models for WSNs, namely time-based, event-based, query-based and hybrid traffic models.**
  - Time-based traffic model is used in applications like seismic and temperature monitoring, video surveillance etc.
  - Event-based traffic model is used in applications like target tracking, intrusion/event detection etc.
  - Query-based traffic model is used in applications where the remote control center sends a query for certain information at some area.
  - Hybrid traffic means more than one traffic mode above are used simultaneously. For example, during time-based traffic monitoring period, remote center can also send query for info.
- **In this thesis, we mainly use time-based and event-based traffic models.**

Problem formulation

Fig. 13 shows a one dimensional linear sensor network model where each sensor node is placed along a line with individual distance r_i. The distance between source and sink node is d and the energy model is called the first order radio model.

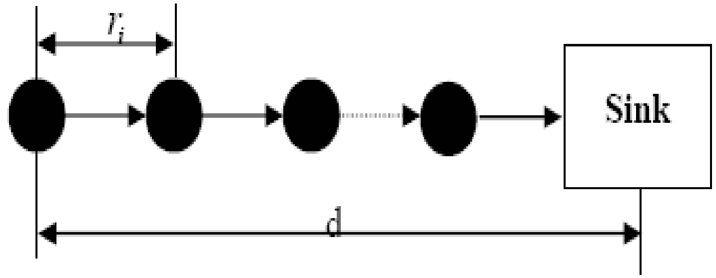


Fig. 13. One dimensional linear sensor network model

To transmit a one cbit message over n-hop route in Fig. 13 will consume a total $E(n)$ amount of energy as follows:

$$E(n) = (E_{elec} + \varepsilon_{amp} \cdot r_1^{\alpha}) + \sum_{i=2}^{n-1} (2 \cdot E_{elec} + \varepsilon_{amp} \cdot r_i^{\alpha})$$
$$= (2n-1) \cdot E_{elec} + \sum_{i=1}^{n} \varepsilon_{amp} \cdot r_i^{\alpha}. \quad (4.13)$$

here, $\sum_{i=1}^{n} r_i = d$, $\varepsilon_{amp} = \varepsilon_{fs}$ when $\alpha = 2$ and $\varepsilon_{amp} = \varepsilon_{mp}$ when $\alpha = 4$.

Our objective is to find the minimal value of $E(n)$ with optimal hop number n and r_i under constraint conditions like $\sum_{i=1}^{n} r_i = d$ and hardware parameters listed in Table 4.

Determination of the optimal hop number

For a given source to sink node distance $d\ (d=\sum_{i=1} r_i)$, the latter pat in Eq. (4.13) $\sum_{i=1}^{n} r_i^{\alpha}$ has a minimal value when $r_1=r_2=\ldots=r_n=d/n$. Finally, the total energy consumption $E(n)$ is equal to:

$$E(n)=(2n-1)\cdot E_{elec}+\varepsilon_{amp}\cdot n\cdot(d/n)^{\alpha}, \qquad (4.16)$$

Eq. (4.16) has the minimum when $E'(n)=0$ or:

$$2E_{elec}+\varepsilon_{amp}\cdot(1-\alpha)\cdot(d/n)^{\alpha}=0,$$

Finally, we can get the optimal theoretical hop number as:

$$n^{*}_{opt}=d\cdot(\varepsilon_{amp}\cdot(\alpha-1)/2E_{elec})^{1/\alpha}. \qquad (4.17)$$

and the corresponding optimal individual distance as:

$$r^{*}_{i}=d/n^{*}_{opt}=\sqrt[\alpha]{\frac{2E_{elec}}{(\alpha-1)\cdot\varepsilon_{amp}}} \qquad (4.18)$$

- **Unfortunately, the optimal hop number can not be used directly for 3 reasons:**
  - Hop number should be an integer value rather than a decimal one
  - Constraint conditions like d>d0 (d<d0) should be met under different radio parameters
  - It is impossible to find such optimal intermediate nodes under practical sensor network
- **Therefore, we have to find the sub-optimal hop number and proper intermediate nodes under practical sensor network**

Determination of the transmission manner

When the source to sink node distance $d < d_0$, it is easy to prove that $E(n)$ in Eq. (4.13) is a monotonously increasing function for hop number n. So, direct transmission ($n = 1$) is always more energy efficient than multi-hop transmission ($n \geq 2$).

When $d \in (d_0, 2d_0)$, we can either use direct transmission or 2-hop transmission manner.

Let:

$$f(d) = E_{Direct} - E_{Multi-hop}(2) \geq 0$$

so:

$$\begin{aligned} f(d) &= (E_{elec} + \varepsilon_{mp} \cdot d^4) - (3E_{elec} + \varepsilon_{fs} \cdot d^2 / 2) \\ &= \varepsilon_{mp} \cdot d^4 - \varepsilon_{fs} \cdot d^2 / 2 - 2E_{elec} \geq 0. \end{aligned} \tag{4.14}$$

Eq. (4.14) will always hold true when:

$$d \geq d_c = \sqrt{\frac{\varepsilon_{fs}/2 + \sqrt{\varepsilon_{fs}^2/4 + 8\varepsilon_{mp} \cdot E_{elec}}}{2 \cdot \varepsilon_{mp}}}, \tag{4.15}$$

and the critical distance $d_c \approx 104$ here.

Thus, if the distance $d_0 < d \leq d_c$, we will still choose direct transmission with multi-path model. If $d > d_c$, we will choose multi-hop transmission. Table 6 lists the determination of transmission manner under different source to sink node distance d.

Table 6 Determination of transmission manner

d	Direct Transmission	Multi-hop Transmission
$d < d_0$	√	
$d_0 \leq d \leq d_c$	√	
$d_c < d$		√

Determination of the sub-optimal hop number

- We can not use the optimal hop number for 3 reasons.
- We propose an empirical selection criterion of the sub-optimal hop number.

Table 9 Selection criterion of the sub-optimal hop number

d	r_i	Hop Number
$(0,d_c)$	$r_1 < d_c$	1
$[d_c,2d_0)$	$r_1,r_2 < d_0$	2
$\vdots$	$\vdots$	$\vdots$
$[(n-1)d_0,nd_0)$	$r_1,\cdots,r_n < d_0$	n

Selection criteria of the next hop node:

1. Each intermediate distance $r_i \geq d / n_{opt}$ with similar distance.

2. A node should choose its next hop node which is closer to sink node than itself.

3. Intermediate should be as close to the direct line from source to sink node as possible.

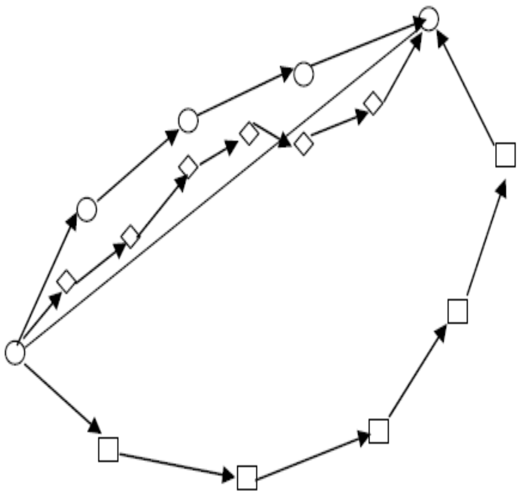


Fig. 16 Illustration of the next hop node selection criteria

HEAR algorithm

- HEAR is a distributed and localized algorithm which combines the general routing mechanism with hop-based nature during routing process.
- Each sensor node has two tables. One is the routing table and another is neighboring table.
- Each node can make intelligent decision of the next hop locally and it is easy to implement for practical engineering applications.
- HEAR algorithm consists of two phases which are route setup and route maintenance phase.

HEAR workflow and features

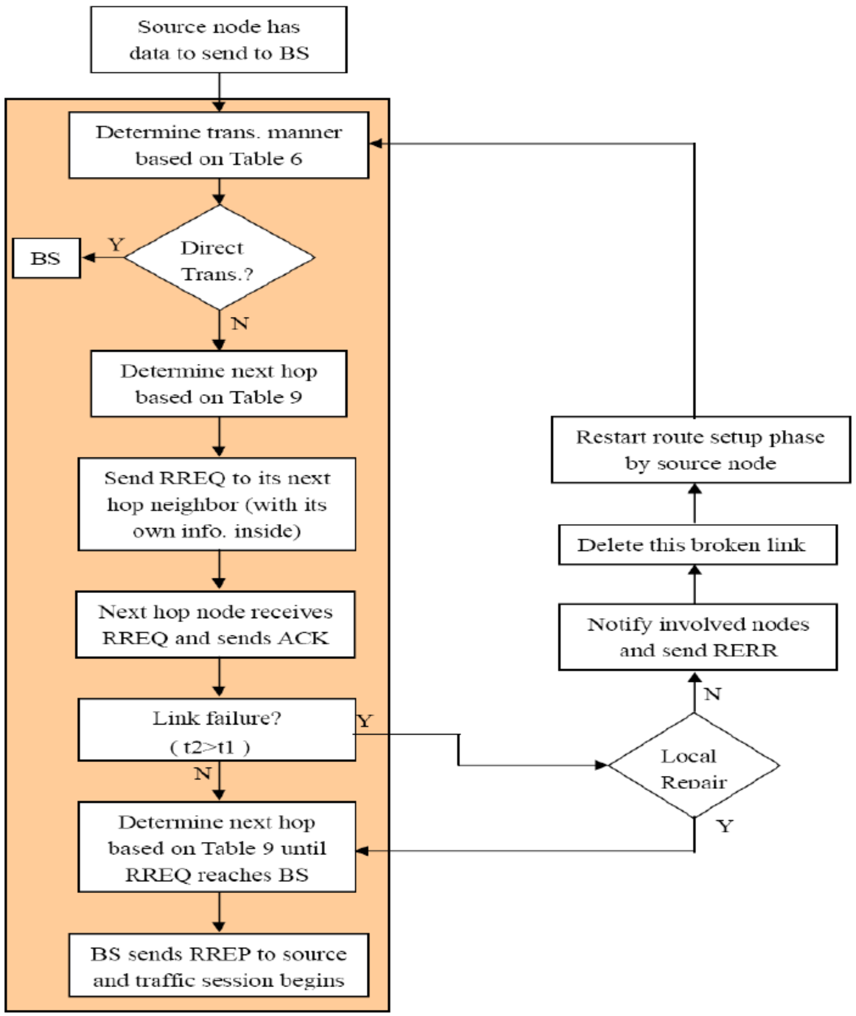
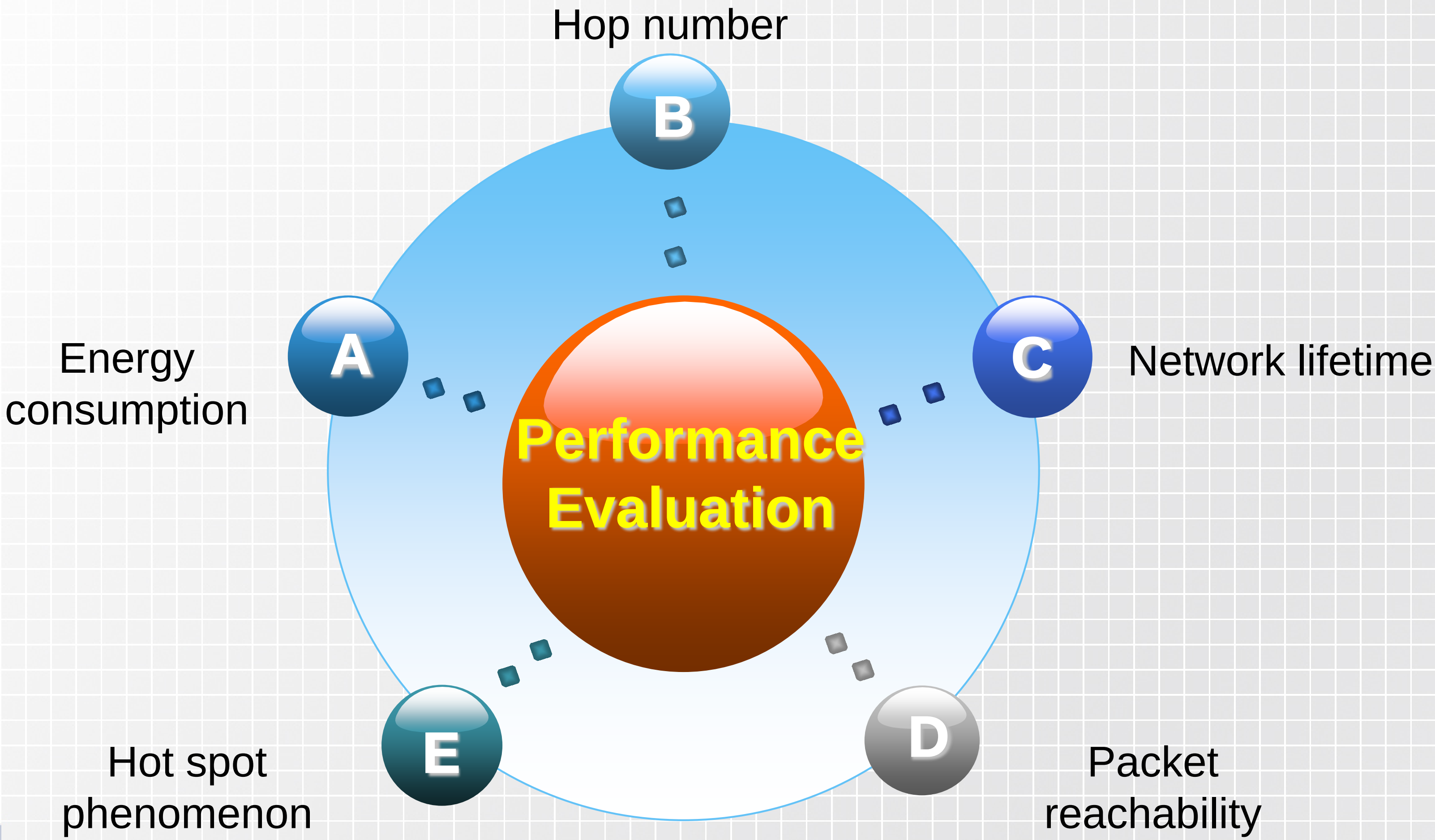


Fig. 17. HEAR algorithm workflow

❖ HEAR features

- Random and dynamic network
- Distributed and localized
- Hop-based
- Energy efficient
- Energy balancing
- Alleviate hop spot phenomenon
- Easy to implement

5. Performance evaluation



Simulation environment

Table 12 Simulation environment

Parameter	Value
Network size	$[100\times100,\ 800\times800]\ m^2$
Node number	[80, 500]
Trans. radius	$[80, 300]\ m$
Sink node location	Inside or outside
Data length	2000 bits
Initial energy	2 J
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
d_0	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}} \approx 87.7m$

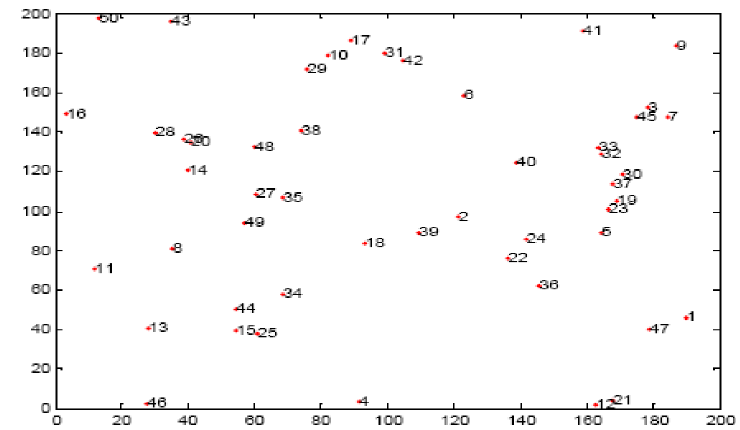


Fig. 18. Sensor network simulation environment

5.2 Algorithms to compare

We compare our HEAR algorithm with the following algorithms

A) **Direct transmission algorithm**

B) **Greedy algorithm** [47]

C) **Maximal remaining energy (MRE) algorithm** [59]

D) **LEACH algorithm** [32, 33]

E) **HEED algorithm** [48]

Energy consumption under diff. R

Simulation environment:

N=300; [X, Y]=[300,300], BS(150,150), k=2000 bits;

$R \in [50,140]$, $d_c = 120$ and $\Delta = 20$.

❖ Observations

- HEAR>Greedy>MRE> Direct transmission
- When R is small, more energy is consumed
- $R \in [90,120]$ can ensure good performance for greedy and MRE algo.

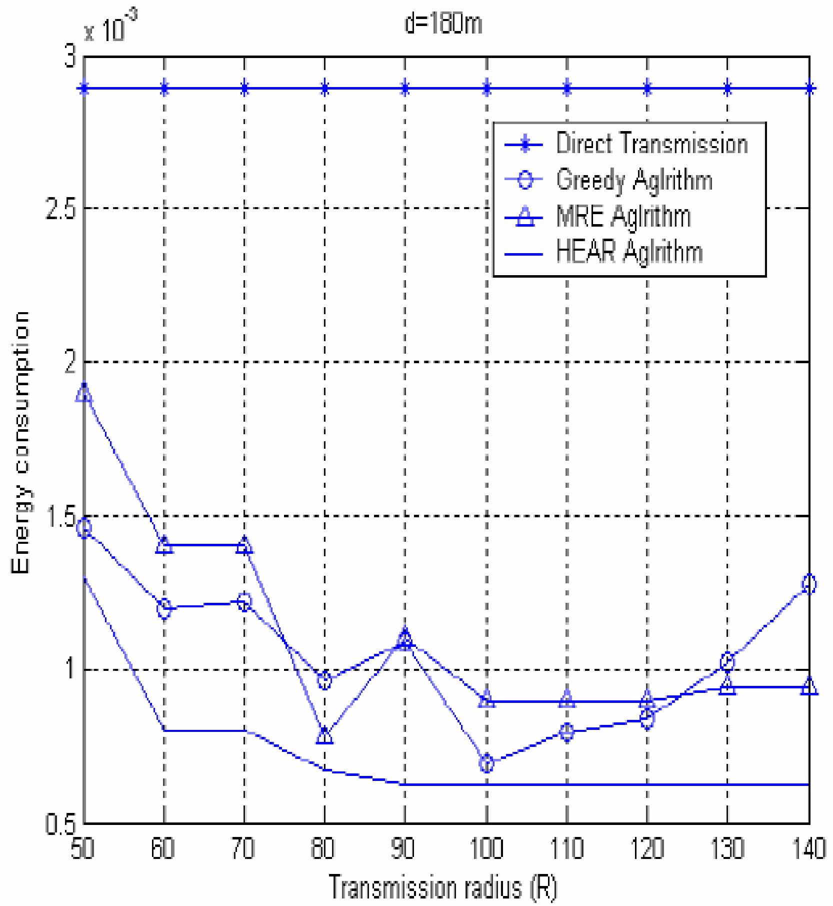


Fig. 19. Energy consumption under different R

Energy consumption under diff. d

Simulation environment:

N=300; [X, Y]=[300,300], BS(150,150), k=2000 bits;

$d \in [90,200]$, $R = 110$, $d_c = 120$ and $\Delta = 20$.

Observations

- HEAR>Greedy>MRE> Direct transmission
- Energy consumption increases with d
- Similar performance for 4 algorithms when d is small

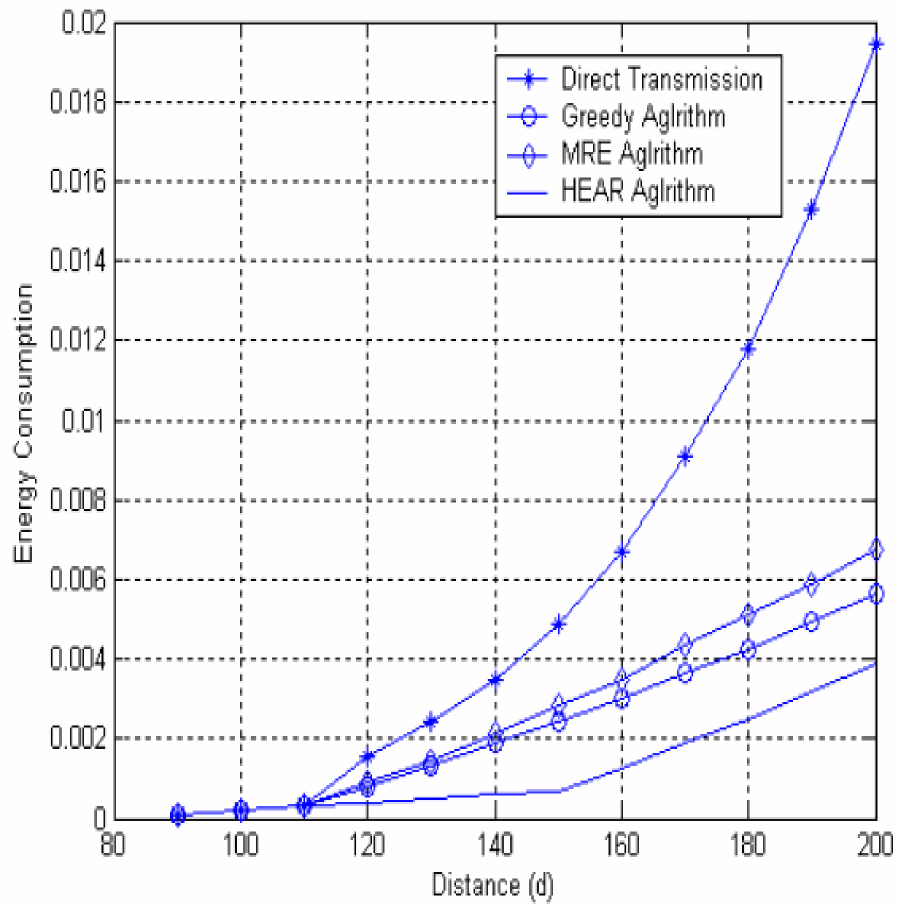


Fig. 20. Energy consumption under different d

Energy consumption under diff. N

Simulation environment:

$N \in [100,300]$; [X, Y]=[300,300], BS(150,150), k=2000 bits;

$R = 110$, $d_c = 120$ and $\Delta = 20$.

❖ Observations

- HEAR>Greedy>MRE>Direct transmission
- When N is small, the value changes a lot due to random topology
- The fluctuation becomes smaller as N increases

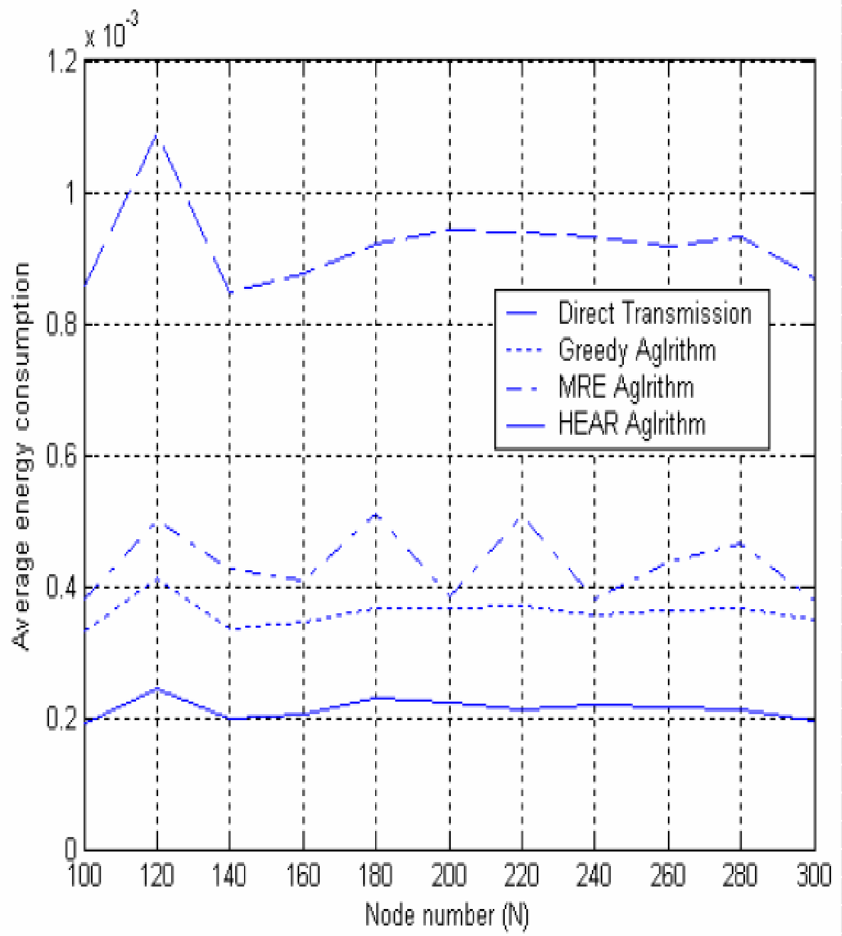


Fig. 21. Energy consumption under different N

Energy consumption under diff. BS location

Simulation environment:

$N \in [100,300]$; [X, Y]=[300,300], k=2000 bits;

$R = 110$, $d_c = 120$ and $\Delta = 20$.

BS moves along diagonal line from (0,0) to (300,300)

❖ Observations

- HEAR>Greedy>MRE
- It is symmetric based on line x=150
- The energy consumption increases as BS moves from (150,150) until outside

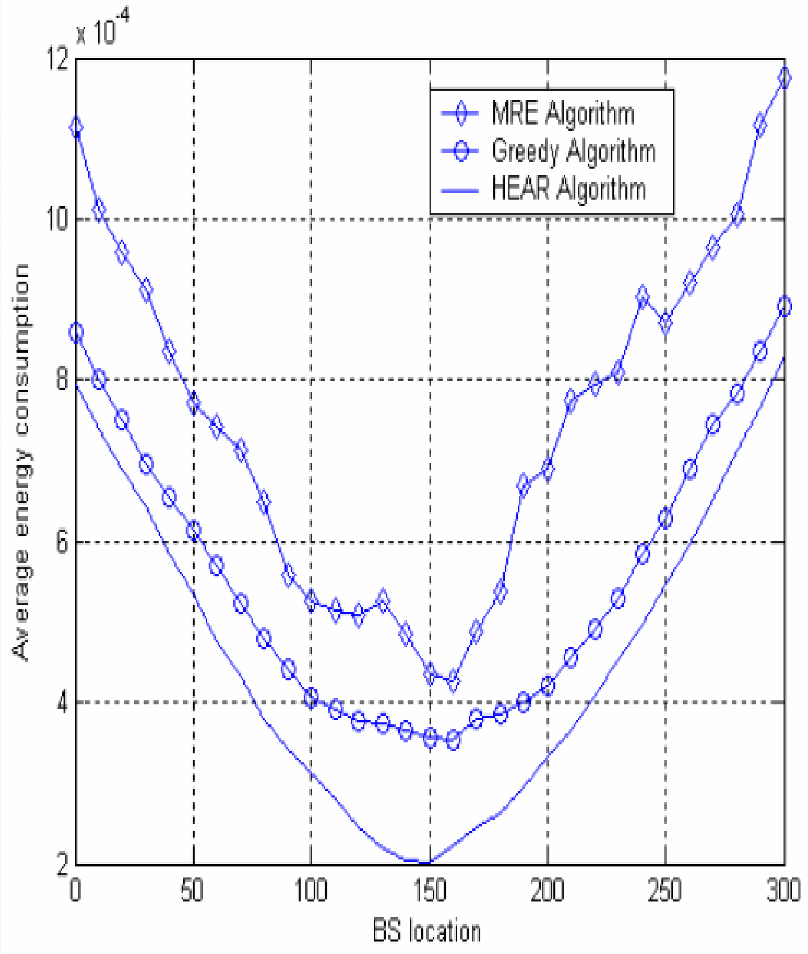


Fig. 22. Energy consumption under different BS location

Energy consumption under diff. net. scale

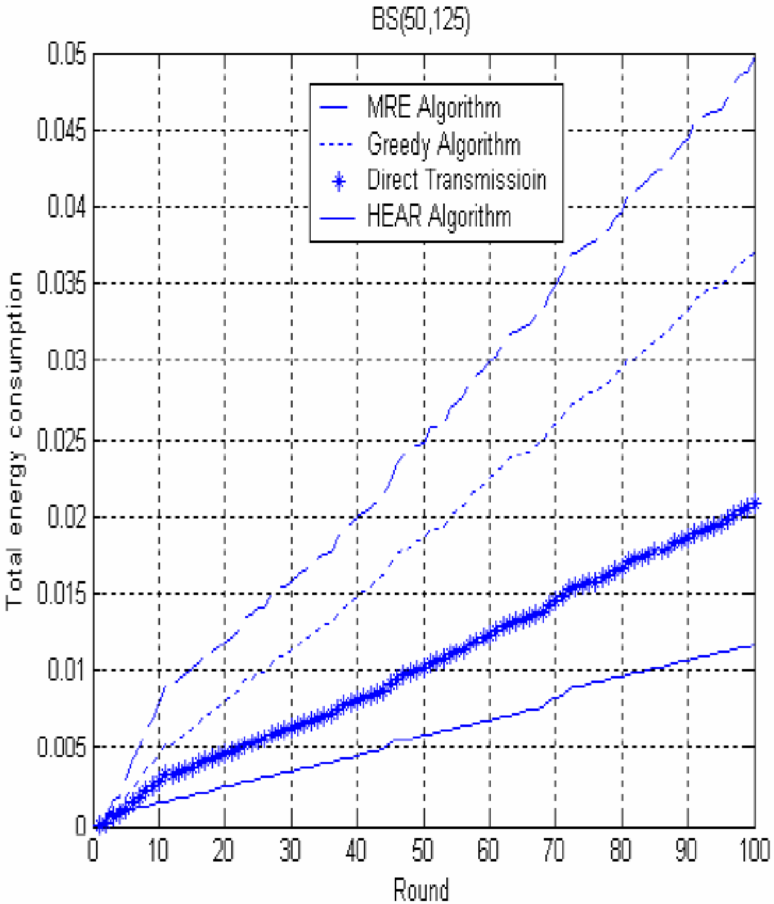
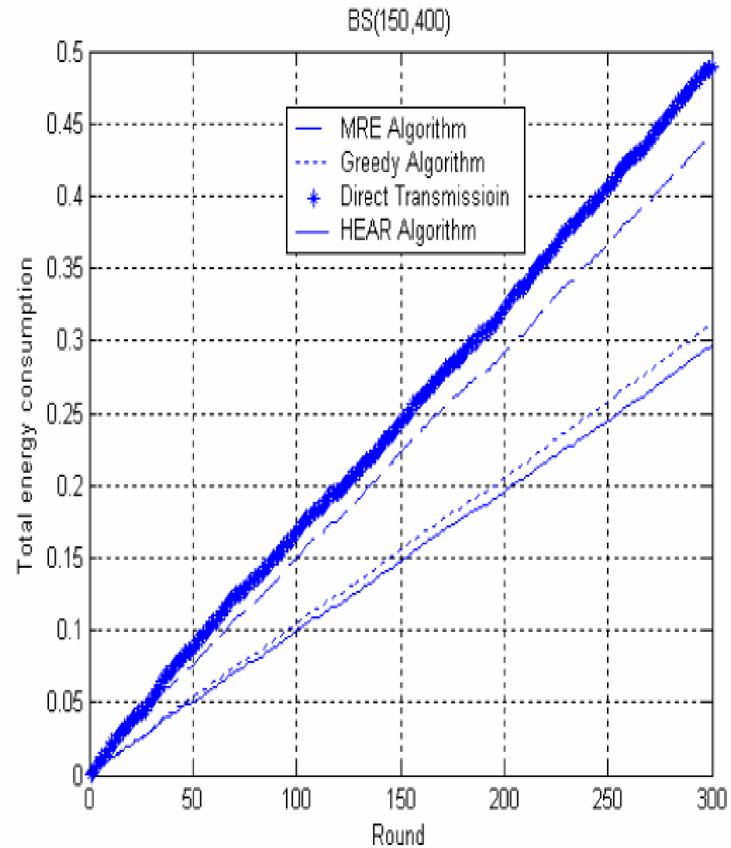


Fig. 23. Total energy consumption under small scale network



(b) BS placed outside

Fig. 24. Total energy consumption under large scale network

Energy consumption under diff. traffic model

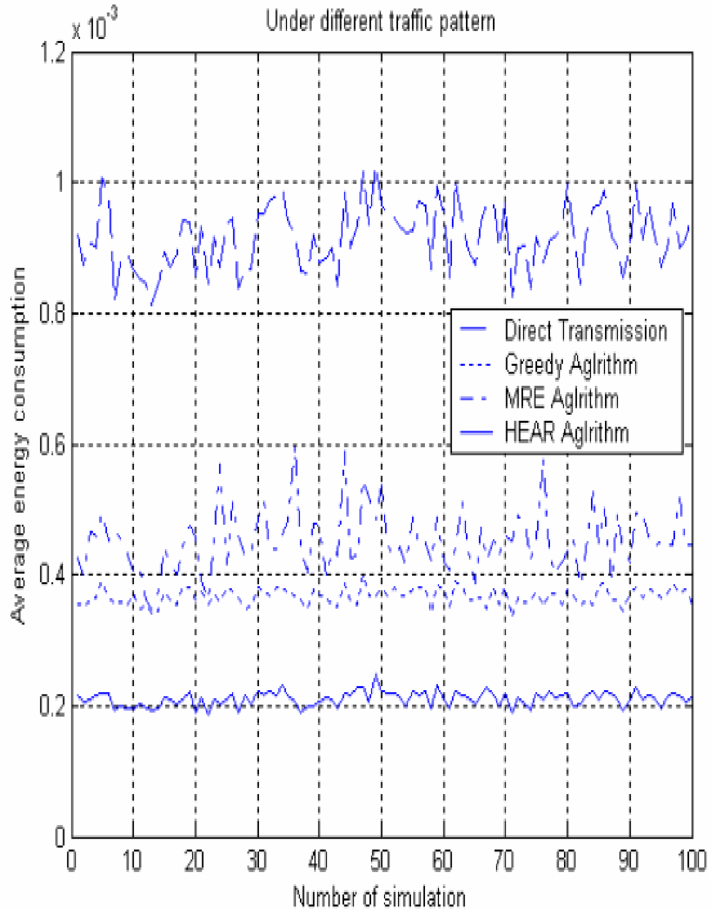


Fig. 25. Average energy consumption under different traffic pattern

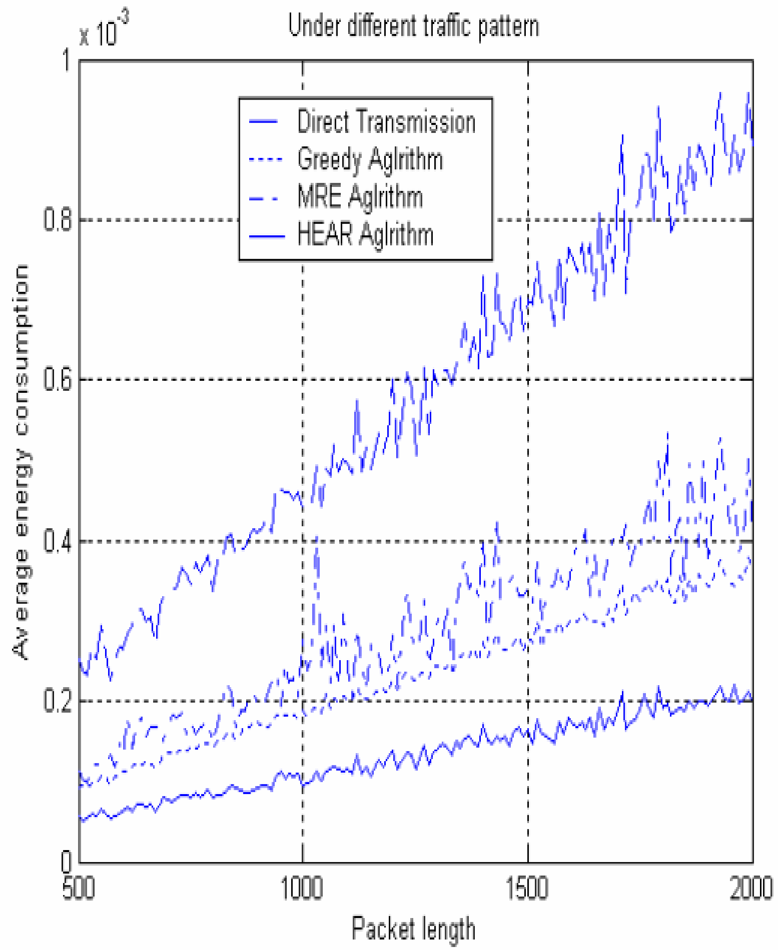


Fig. 26. Average energy consumption under different packet length

Hop number under diff. network topology

Simulation environment:

$N = 300$; [X, Y]=[300,300], BS(150,150), k=2000 bits;

$R = 110$, $d_c = 130$ and $\Delta = 20$.

Observations

- Direct transmission> HEAR>Greedy>MRE
- HEAR and greedy have stable performance
- MRE performance varies very much under different network topology

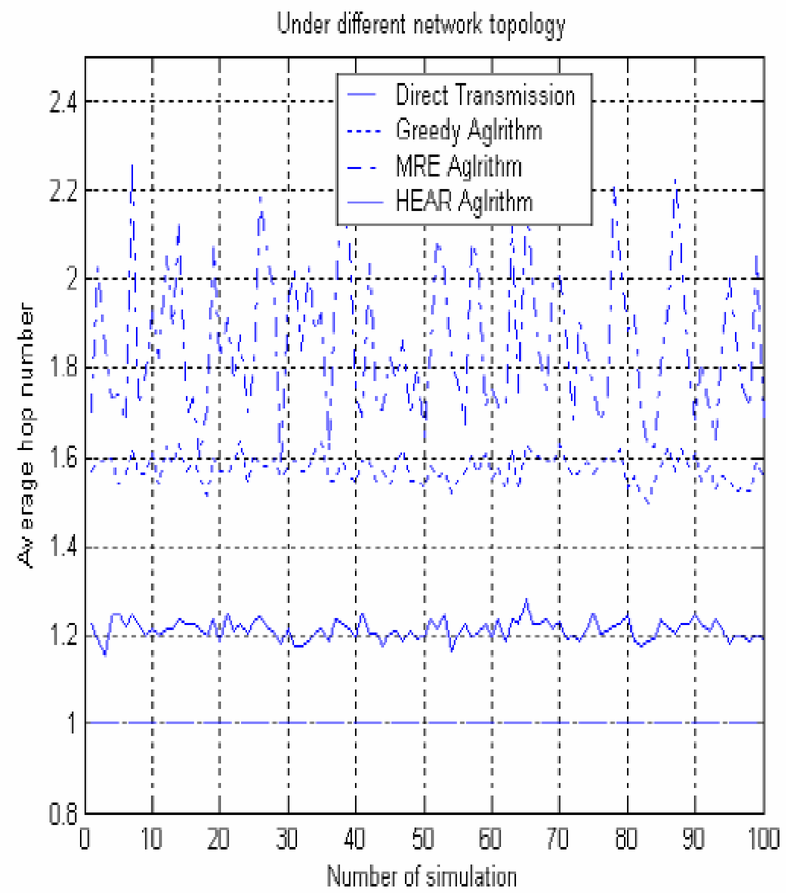


Fig. 27. Hop number under different network topology

Hop number under diff. R

Simulation environment:

$N = 300$; [X, Y]=[300,300], BS(150,150), k=2000 bits;

$R \in [50,140]$, $d_c = 130$ and $\Delta = 40$.

Observations

- Direct transmission> HEAR>Greedy>MRE
- Performance decreases with R on average
- When R<110, HEAR and greedy algorithms have similar performance

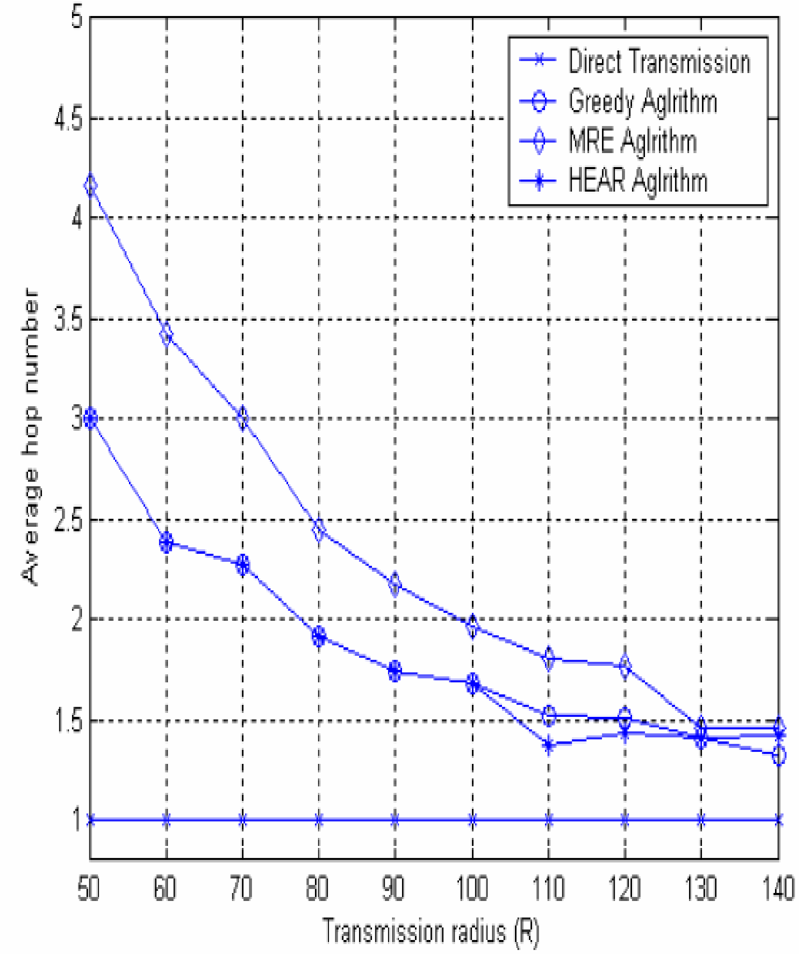


Fig. 28. Hop number under different transmission radius

Hop number under diff. BS location

Simulation environment:

$N = 300$; [X, Y]=[300,300], k=2000 bits;

$R = 110$, $d_c = 130$ and $\Delta = 40$. BS moves along

line x=150 from (150,0) to (150,390)with step size 30

Observations

- Direct transmission> HEAR>Greedy>MRE
- It is nearly symmetric based on line x=150
- The hop number increases as BS moves from (150,150) until outside

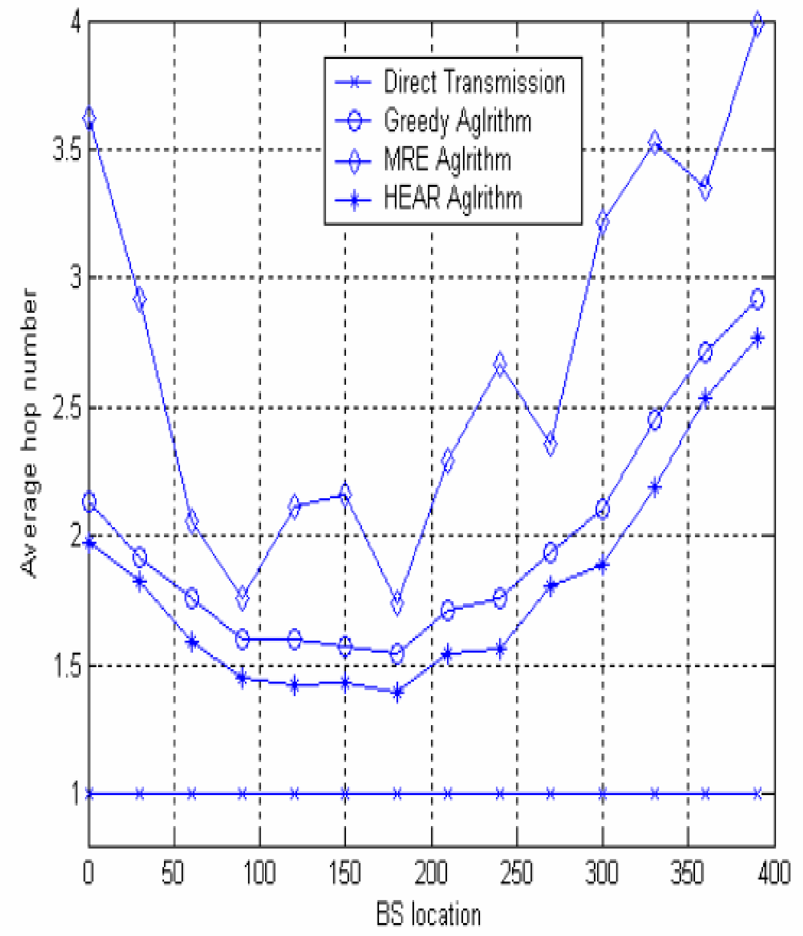


Fig. 29. Hop number under different transmission radius

Network lifetime under diff. network topology

Simulation environment:

$N = 300$, [X, Y]=[300,300], BS(150,150), k=2000 bits;

$R = 110$, $d_c = 130$, $\Delta = 20$ and $E_{ini} = 2$ Joule.

- **Observations**
  - HEAR>Greedy>MRE> Direct transmission
  - Performance of HEAR changes under diff. network topology
  - HEAR has a factor of 2 to 4 times longer network lifetime than the other 3 algorithms

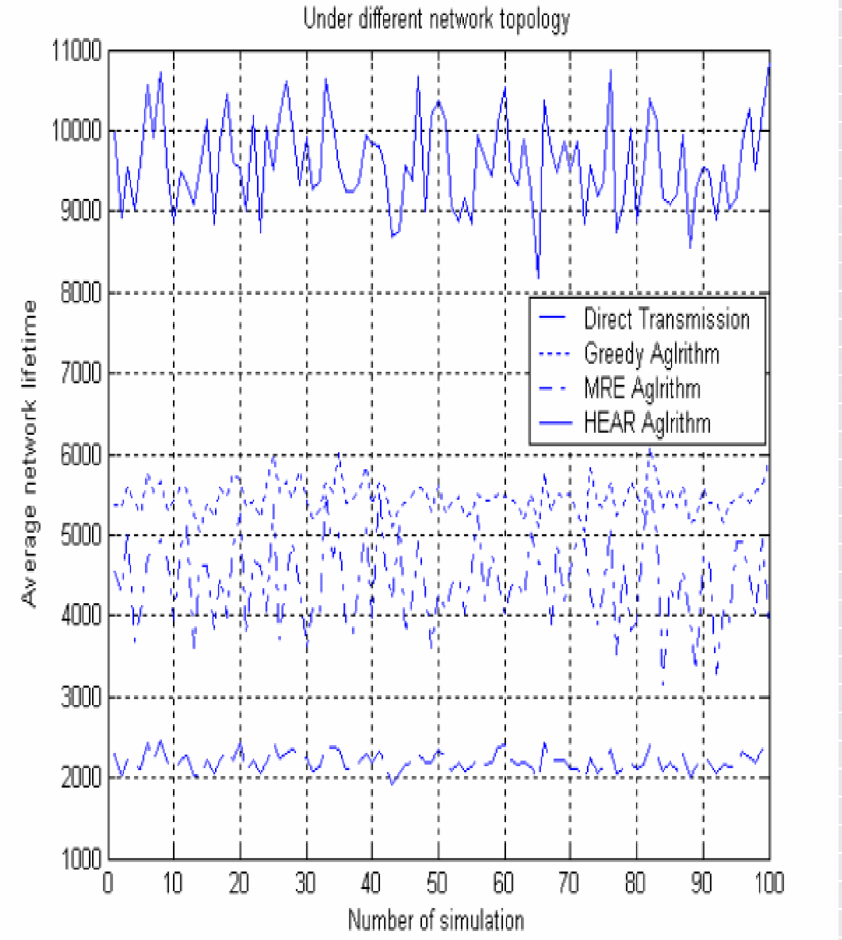


Fig. 30. Network lifetime under different network topology

Network lifetime under diff. BS location

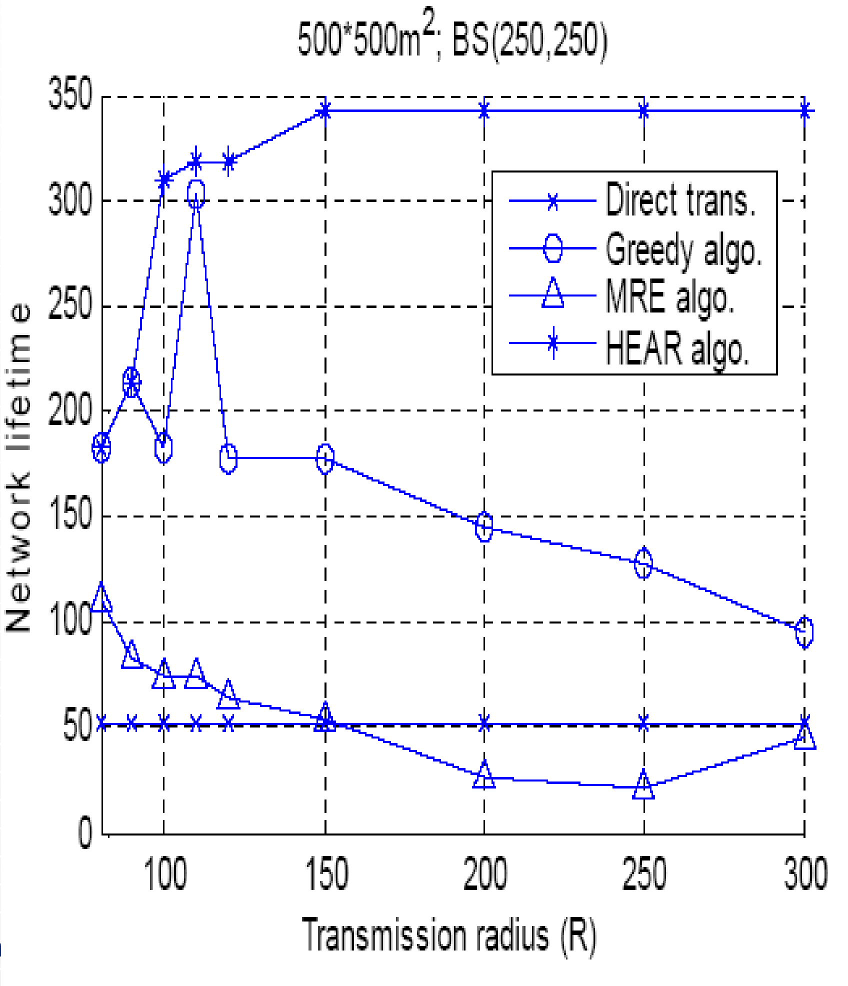


Fig. 31. Network lifetime with BS placed inside

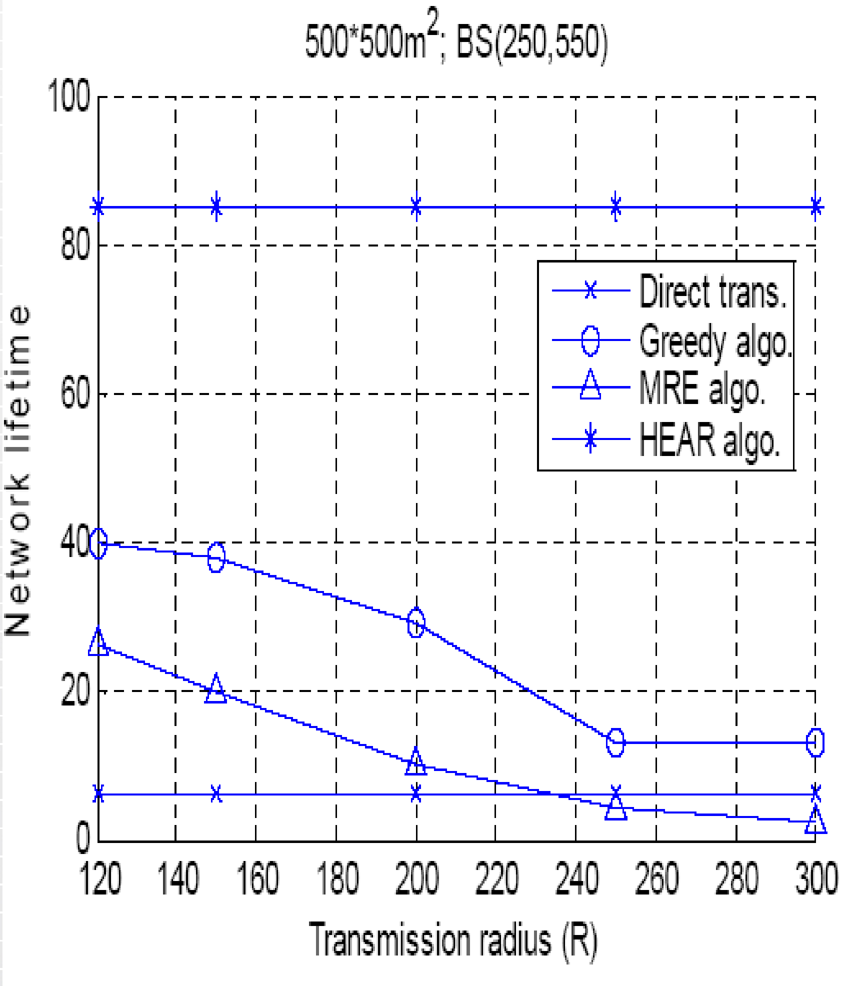


Fig. 32. Network lifetime with BS placed outside

Packet reachability

Simulation environment:

$N = [50,100]$, [X, Y]=[800,800], BS(400,400), k=2000 bits;

$R = [110,140]$, $d_c = 130$, and $\Delta = 20$.

❖ Observations

- Ideal (Flooding)>HEAR
- Performance increases with N (network density)
- Performance is 100% in the environment above
- Low packet reachability is caused by void nodes and void area.

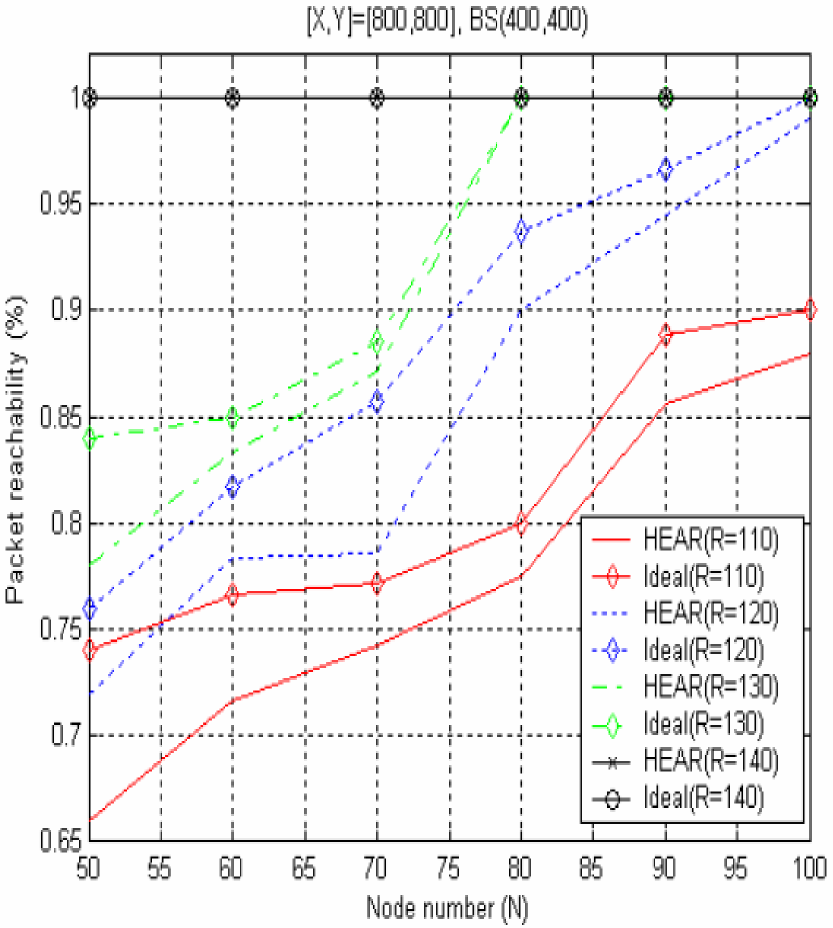


Fig. 33. Packet reachability

Comparison with LEACH and HEED

We consider the following 4 scenarios:

- **Scenario 1**: In a $200 \times 200\,m^2$ network, there are 100 sensor nodes with sink node at (100, 200).
- **Scenario 2**: In a $500 \times 500\,m^2$ network, there are 300 sensor nodes with sink node at (250, 250).
- **Scenario 3**: In a $500 \times 500\,m^2$ network, there are 300 sensor nodes with sink node at (250, 550).
- **Scenario 4**: In a $800 \times 800\,m^2$ network, there are 500 sensor nodes with sink node at (400, 800).

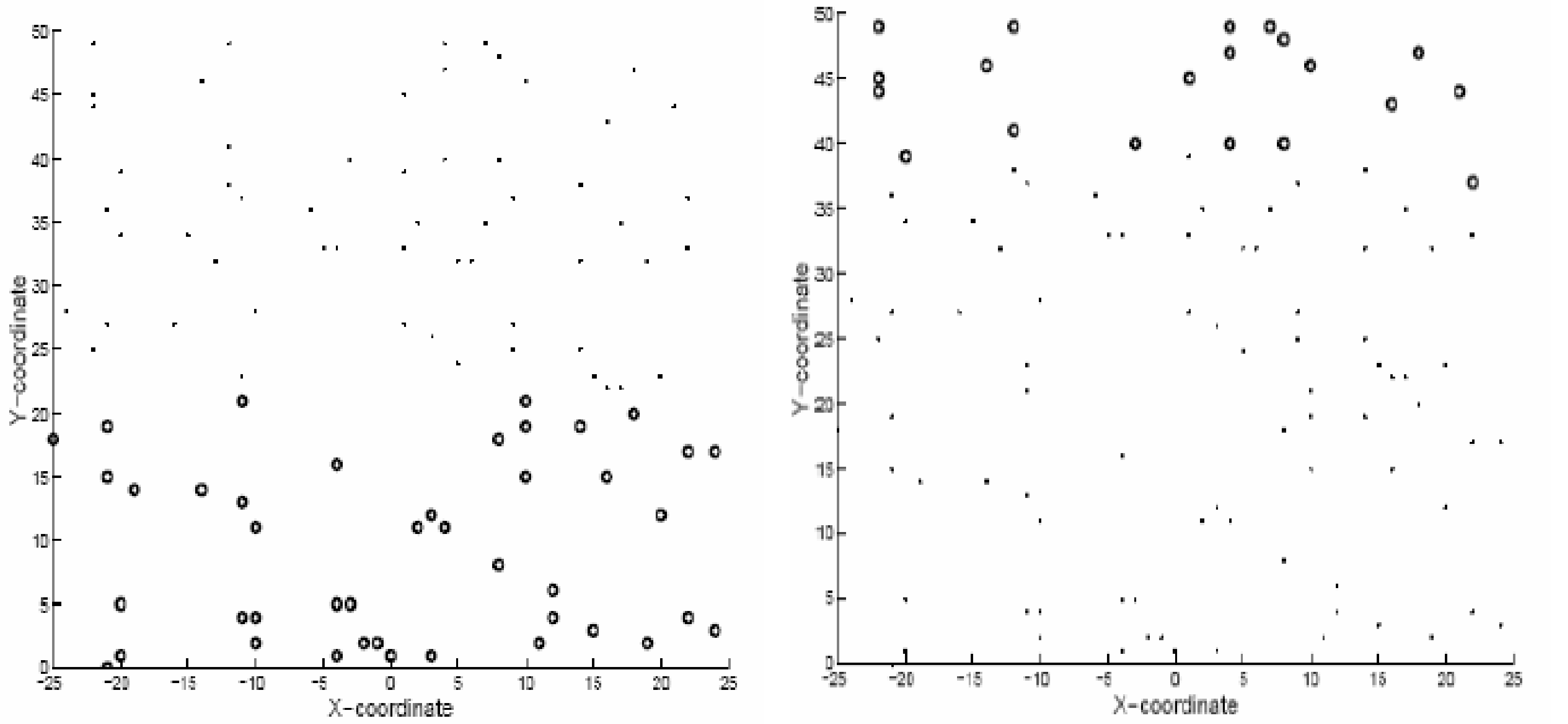
Table 14 Average energy consumption (J) under 4 scenarios

Algorithm \ Scenario	1	2	3	4
LEACH	0.0013	0.0060	0.0676	0.2664
HEED	0.0010	0.0027	0.0272	0.0847
HEAR	0.0004	0.0007	0.0020	0.0029

Table 15 Average network lifetime under 4 scenarios

Algorithm \ Scenario	1	2	3	4
LEACH	476	256	23	7
HEED	537	458	93	11
HEAR	769	667	294	17

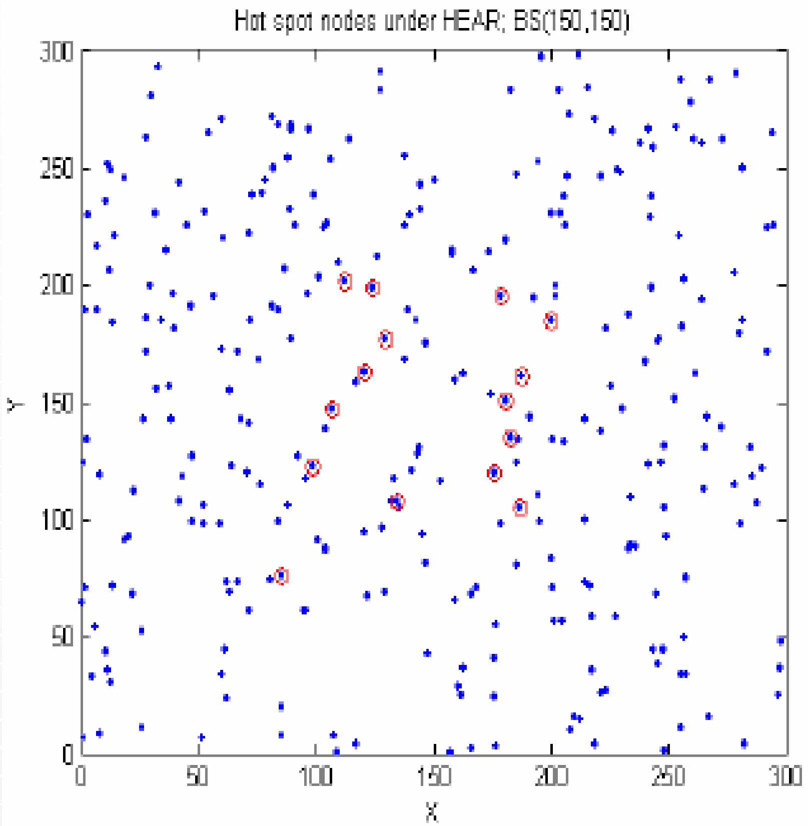
Hop spot phenomenon under LEACH



(a) hot spot nodes under direct trans. (b) hot spot nodes under multi-hop trans.

Fig. 34. Hop spot phenomenon

Hop spot phenomenon under HEAR



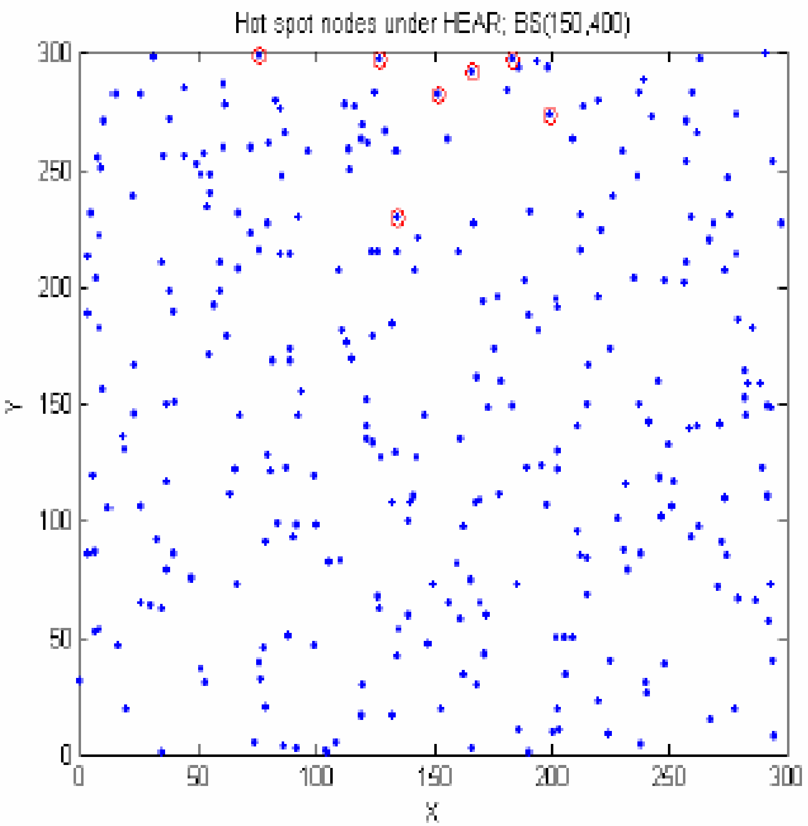


Fig. 35. Hop spot nodes under HEAR algorithm

Discussion

- Different set of hardware parameters may have various performance, but the **hop-based routing methodology is the same**
- The hop spot phenomenon can be further alleviated by **considering residual energy**
- The network lifetime can be further prolonged by **optimizing each individual distances**
- Shortcoming of HEAR is to know the relative distance between each node and BS. Besides, proper next hop is not available under very low density network or under big obstacles.

6. Conclusions and future work

- **Propose hop-based routing for WSNs from hop-based aspect and deduce:**
  - Transmission manner
  - Optimal and sub-optimal hop number
- **Propose HEAR algorithm**
  - Energy consumption can get reduced
  - Network lifetime can get prolonged
  - Hot spot phenomenon can get allievated

6. Conclusions and future work

- **Future work can be done in the following aspects:**
  - HEAR with concern about residual energy
  - HEAR combines with clustering mechanism
  - HEAR-I to use different distance so that each node consumes the same amount of energy (further prolong network lifetime)
  - HEAR combines with probability mechanism
  - Study other network metrics related with hop number

Thank You !