Enhancing Lifetime in Wireless Sensor Networks Using Muliple Base Stations And Cooperative Diversity

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Outline

- Introduction
- Single vs Multiple Base Stations
- Network Lifetime Enhancement using Multiple BSs
  - Bounds on Network Lifetime
- Optimum Base Stations Placement Algorithms
  - Top-$\{K_{max}\}$ Algorithm
  - Max-Min-RE Algorithm
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- Cooperative Diversity
- Conclusions

Introduction

- Wireless sensor networks
  - sensor nodes typically distributed in remote/hostile sensing areas
  - nodes powered by finite energy batteries
  - batteries not easily replaced/recharged
  - depletion of battery energy can result in
    * a change in NW topology or
    * end of NW life itself
- Key issues in wireless sensor networks
  - Network lifetime
  - amount of useful data successfully transferred during NW lifetime
- Enhancing NW lifetime is crucial

Data Transport Model

- A base station (BS) is typically located at the boundary of or beyond the field/area in which sensors are distributed
- BS collects data from the sensor nodes
- Sensor nodes act as
  - source nodes that generate data to be passed on to the BS
  - intermediate relay nodes to relay data from other nodes towards the BS on a multihop basis
- Consequence of sensor nodes acting as relays
  - energy spent by nodes may not contribute to end-to-end delivery always (e.g., packets may still have more hops to reach the BS)
  - this results in reduced NW lifetime and efficiency in terms of total amount of data delivered to BS per joule of energy
  - affects more when number of hops between sensor node(s) to BS gets larger

Multiple Base Stations

- NW lifetime can be enhanced by the use of *multiple BSs*
  - deploy multiple BSs along the periphery/boundary of the sensing field/area
  - allow each BS to act as a data sink, i.e.,
    - each sensor node can send its data to any one of these BSs (may be to the BS towards which the cost is minimum)
  - BSs can communicate among themselves to collate the data collected
    - energy is not a major concern in the communication between BSs
- Deploying multiple BSs *essentially can reduce the average number of hops between the source-sink pairs*
  - can result in enhanced lifetime / amount of data delivered

I. Limits on NW Lifetime?

- Several works have reported bounds on the NW lifetime for single BS scenario
  - *Bhardwaj et al.,* **IEEE ICC'2001**
  - *Bhardwaj and Chandrakasan,* **IEEE INFOCOM'2002**
  - *Zhang and Hou,* **ACM Mobihoc'2004**
  - *Blough and Santi,* **Mobicom'2002**
  - *Arnon S.,* **IEEE Commun. Letters***, Feb'2005*
  - *Gandham, Dawande, Prakash and Venkateshan,* **Globecom '2003**
- Our contribution
  - derive upper bounds on NW life time *when multiple BSs* are deployed
  - obtain optimum locations of the BSs that maximize these lifetime bounds

System Model

- Network
  - # sensor nodes: N, # base stations: K

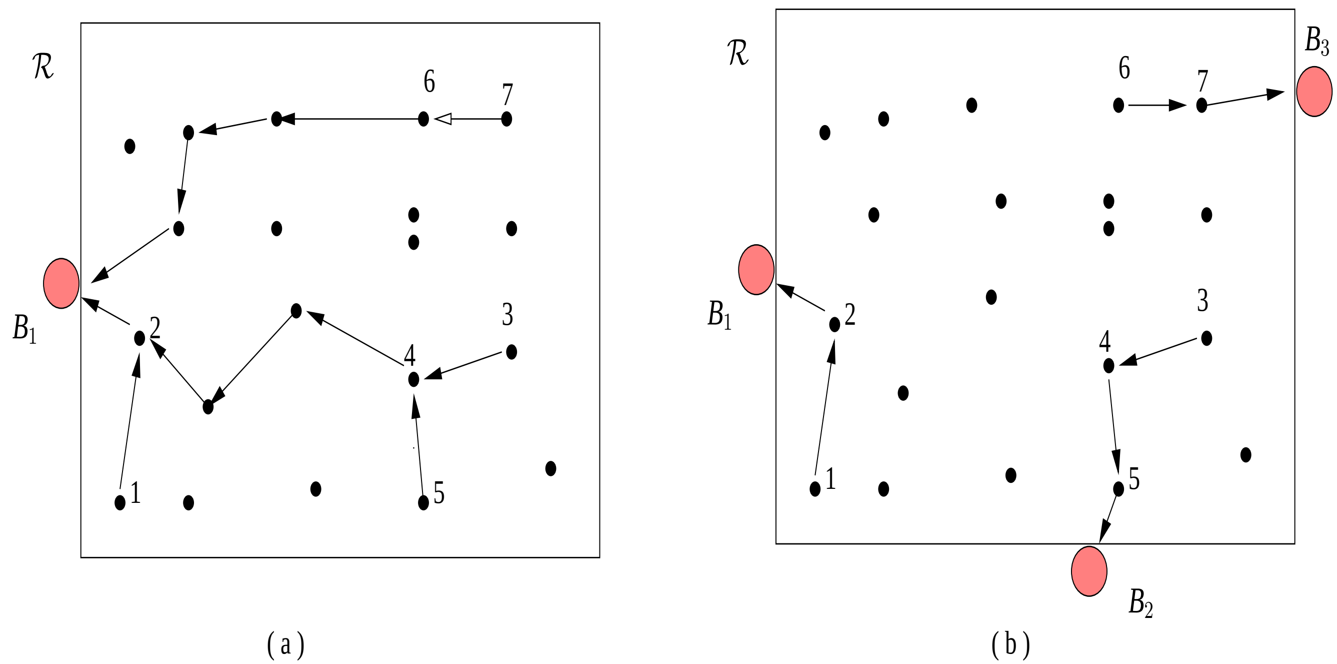


Figure 1: *A sensor network over a rectangular region of observation $\mathcal{R}$ with three base stations B_1, B_2, B_3. Node 1 sends its data to base station B_1 via node 2. Node 3 sends its data to B_2 via nodes 4 and 5. Node 6 sends its data to B_3 via node 7. However in Single base station case data has to travel more no. of hops.*

System Model

- Node Energy Behaviour
  - key energy parameters are energies needed to
    - ∗ sense a bit (E_{sense}), receive a bit (E_{rx})
    - ∗ transmit a bit over a distance d, (E_{tx})
- Assuming a d^η path loss model,

$$E_{tx} = \alpha_{11} + \alpha_2 d^\eta, \quad E_{rx} = \alpha_{12}, \quad E_{sense} = \alpha_3,$$

  - α_{11}, α_{12}: energy/bit consumed by the Tx, Rx electronics
  - α_2: accounts for energy/bit dissipated in the Tx amplifi er, α_3: energy cost of sensing a bit
  - Typically, $E_{sense} << E_{tx}, E_{rx}$.
- Energy/bit consumed by a relay node is

$$E_{\text{relay}}(d) = \alpha_{11} + \alpha_2 d^\eta + \alpha_{12} = \alpha_1 + \alpha_2 d^\eta$$

where $\alpha_1 = \alpha_{11} + \alpha_{12}$

System Model

- Node energy behaviour
  - If r is the # bits relayed per sec, the energy consumed per sec (i.e., power) is

$$P_{\text{relay}}(d) = r \cdot E_{\text{relay}}(d)$$

- The following energy parameters are used [*Bhardwaj et al, ICC'2001*],[*Heinzelman Ph.D Thesis, MIT, 2000*]:
  - $\alpha_1 = 180$ nJ/bit
  - $\alpha_2 = 10$ pJ/bit/m^2 (for $\eta = 2$) or 0.001 pJ/bit/m^4 (for $\eta = 4$).

Battery / Network Lifetime

- E_{battery} Joules: Battery energy available in each sensor node at the initial deployment
- A sensor node ceases to operate if its battery is drained below a certain usable energy threshold
- Network lifetime definitions, e.g.,
  - time taken till the first node to die - we use this definition in the derivation of NW lifetime upper bound
  - time taken till a percentage of nodes to die
- Given $\mathcal{R}$, N, E_{battery}, $(\alpha_1, \alpha_2, \alpha_3)$ and η, we are interested in
  - deriving bounds on the network lifetime when K, $K \geq 1$ base stations are deployed as data sinks along the periphery of the observation region $\mathcal{R}$
  - obtaining optimal locations of the base stations

Minimum Energy Relay

- Bounding NW lifetime involves the problem of establishing a data link of certain rate r between a sender (A) and destination (B) separated by distance D meters
- Two ways of doing this
  - direct transmission from A to B (in a single hop), or
  - using several intermediate nodes acting as relays (multihop)
- A scheme that transports data between two nodes such that the overall rate of energy dissipation is minimized is called a *minimum energy relay*
- If $M-1$ relays are introduced between A and B, i.e., M links between A and B (see Fig.), the overall rate of dissipation is

$$P_{\text{link}}(D) = \sum_{i=1}^{M} P_{\text{relay}}(d_i) - \alpha_{12},$$

where d_i is the inter-node distance of the ith link.

Minimum Energy Relay

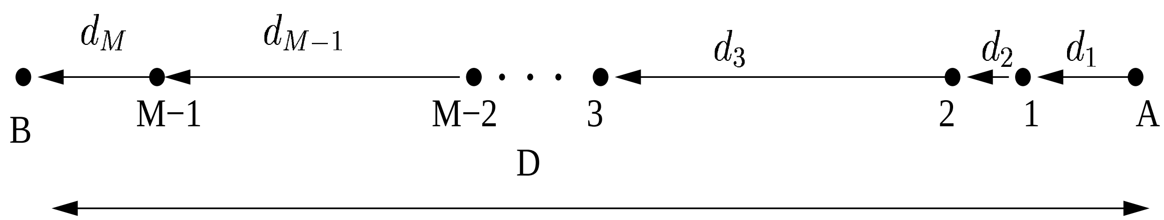


Figure2: $M-1$ *relay nodes between points* A *and* B

- *Theorem:* Given D and the number of intermediate relays ($M-1$), $P_{link}(D)$ is minimized when all hop distances (i.e., d_i's) are made equal to D/M.
- So, optimum number of hops (links) is the one that minimizes $MP_{\text{relay}}(D/M)$, and is given by

$$M_{opt} = \left\lfloor \frac{D}{d_{\text{char}}} \right\rfloor \quad \text{or} \quad \left\lceil \frac{D}{d_{\text{char}}} \right\rceil,$$

where

$$d_{\text{char}} = \sqrt[\eta]{\frac{\alpha_1}{\alpha_2(\eta-1)}}$$

Minimum Energy Relay

- Energy dissipation rate of relaying a bit over distance D can be bounded as

$$P_{\text{link}}(D) \geq \left(\alpha_1 \frac{\eta}{\eta - 1} \frac{D}{d_{\text{char}}} - \alpha_{12}\right) r$$

  with equality iff D is an integral multiple of d_{char}

- Power dissipated in the network is always larger than or equal to the sum of this $P_{\text{link}}(D)$ and the power for sensing, i.e.,

$$P_{\text{nw}} \geq P_{\text{link}}(D) + P_{sense} \geq \left(\alpha_1 \frac{\eta}{\eta - 1} \frac{D}{d_{\text{char}}} - \alpha_{12}\right) r + \alpha_3 r$$

- As an approximation, sensing power can be ignored since the power for relaying data dominates.

Bound on NW Lifetime - One BS

- Single BS: (BS can be located on any one of the four sides of $\mathcal{R}$)

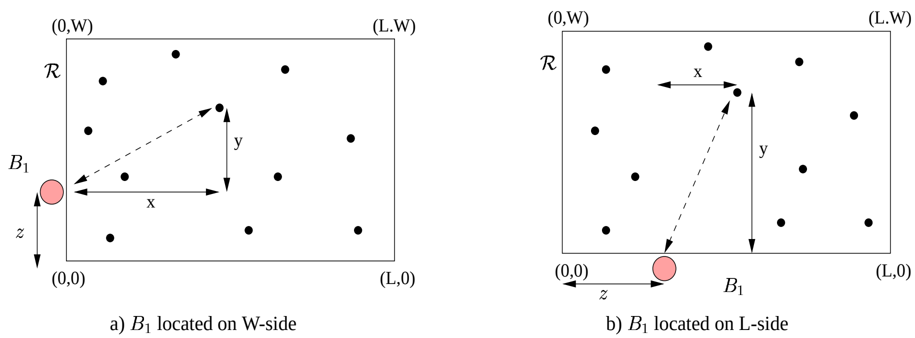


Figure3: *Single base station placements. a) B_1 located on W-side. b) B_1 located on L-side*

- Let $P_{\text{NW}}^{(z)}$ denote the energy dissipation in the entire NW for a given BS z
- Assuming uniform distribution of N nodes

$$P_{\text{NW}}^{(z)} = N \int\int_{\mathcal{R}} P_{\text{nw}}(x,y)\,\frac{1}{WL}\,dx\,dy.$$

- By minimum energy relay argument, $P_{\text{nw}}(x,y) \geq P_{\text{link}}\left(\sqrt{x^2+y^2}\right)$, and hence

$$\begin{aligned} P_{\text{NW}}^{(z)} &\geq \frac{N}{WL}\int_{-z}^{W-z}\int_{0}^{L} P_{\text{link}}\left(\sqrt{x^2+y^2}\right)\,dx\,dy \\ &\geq r\alpha_1\,\frac{\eta}{\eta-1}\,\frac{N}{WL}\int_{-z}^{W-z}\int_{0}^{L}\frac{\sqrt{x^2+y^2}}{d_{\text{char}}}\,dx\,dy \end{aligned}$$

Bound on NW Lifetime - One BS

- Achieving NW lifetime demands that energy consumed in the NW to be no greater than NE_{battery}
- Denoting $\mathcal{T}^{(z)}_{\text{one-BS}}$ as the NW lifetime with one BS at a given location z, we have

$$P^{(z)}_{\text{NW}} \, \mathcal{T}^{(z)}_{\text{one-BS}} \leq NE_{\text{battery}}$$

- An upper bound on the NW lifetime for a given BS location z is then given by

$$\mathcal{T}^{(z)}_{\text{one-BS}} \leq \frac{NE_{\text{battery}}}{P^{(z)}_{\text{NW}}}$$

- Optimal placement of the BS on the W-side can be obtained by choosing the z that maximizes the lifetime bound in the above, i.e.,

$$z^{(W)}_{\text{opt}} = \underset{z \in (0,W)}{\text{argmax}} \; \mathcal{T}^{(z)}_{\text{one-BS}}.$$

- Performing the above maximization, the optimal BS location is obtained as

$$z^{(W)}_{opt} = W/2,$$

Bound on NW Lifetime - One BS

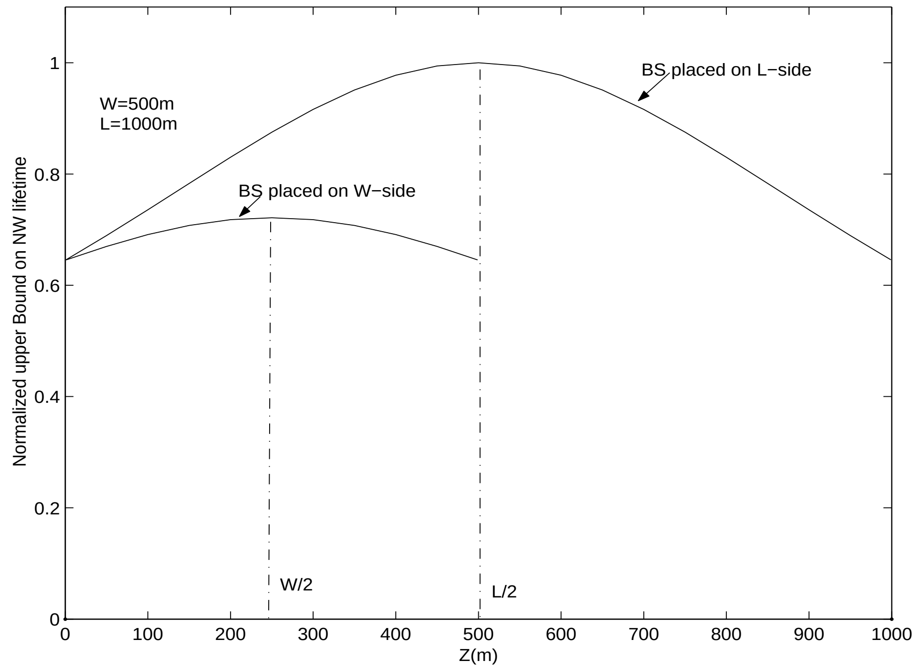


Figure 4: *Normalized upper bound on network life time as a function of base station location for* $L = 1000$ *m and* $W = 500$ *m*

- Optimum BS location is midpoint of L-side if $L > W$ (midpoint of W-side if $L \leq W$)

Bound on NW Lifetime - Two BSs

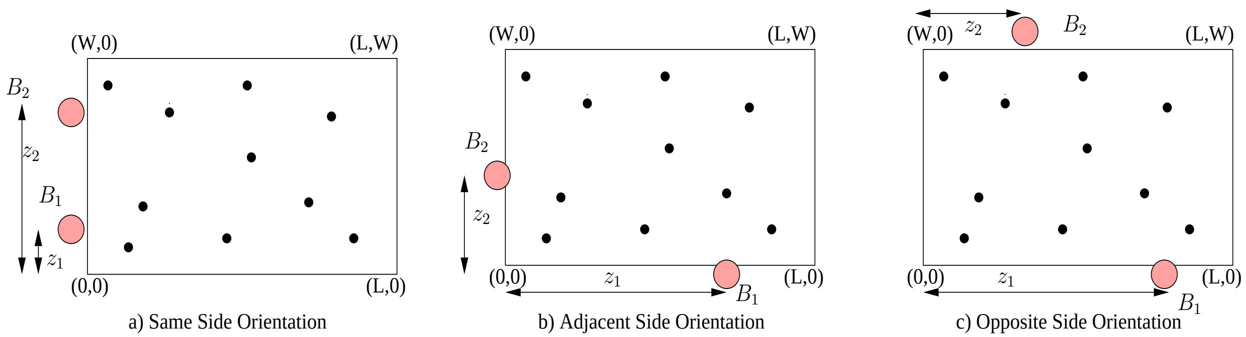


Figure5: *Placements of two base stations. a) Same side orientation, b) adjacent side orientation, and c) opposite side orientation*

- Each node in the NW must be associated with any one BS
  - can choose the BS towards which energy spent for delivering data is minimum (by min. energy relay argument, it could be the nearest BS)
- This results in the region $\mathcal{R}$ to be partitioned into two sub-regions $\mathcal{R}_1$ and $\mathcal{R}_2$
  - This partitioning will occur along the perpendicular bisector of the line joining B_1 and B_2

Two BSs - Adjacent Side Orientation

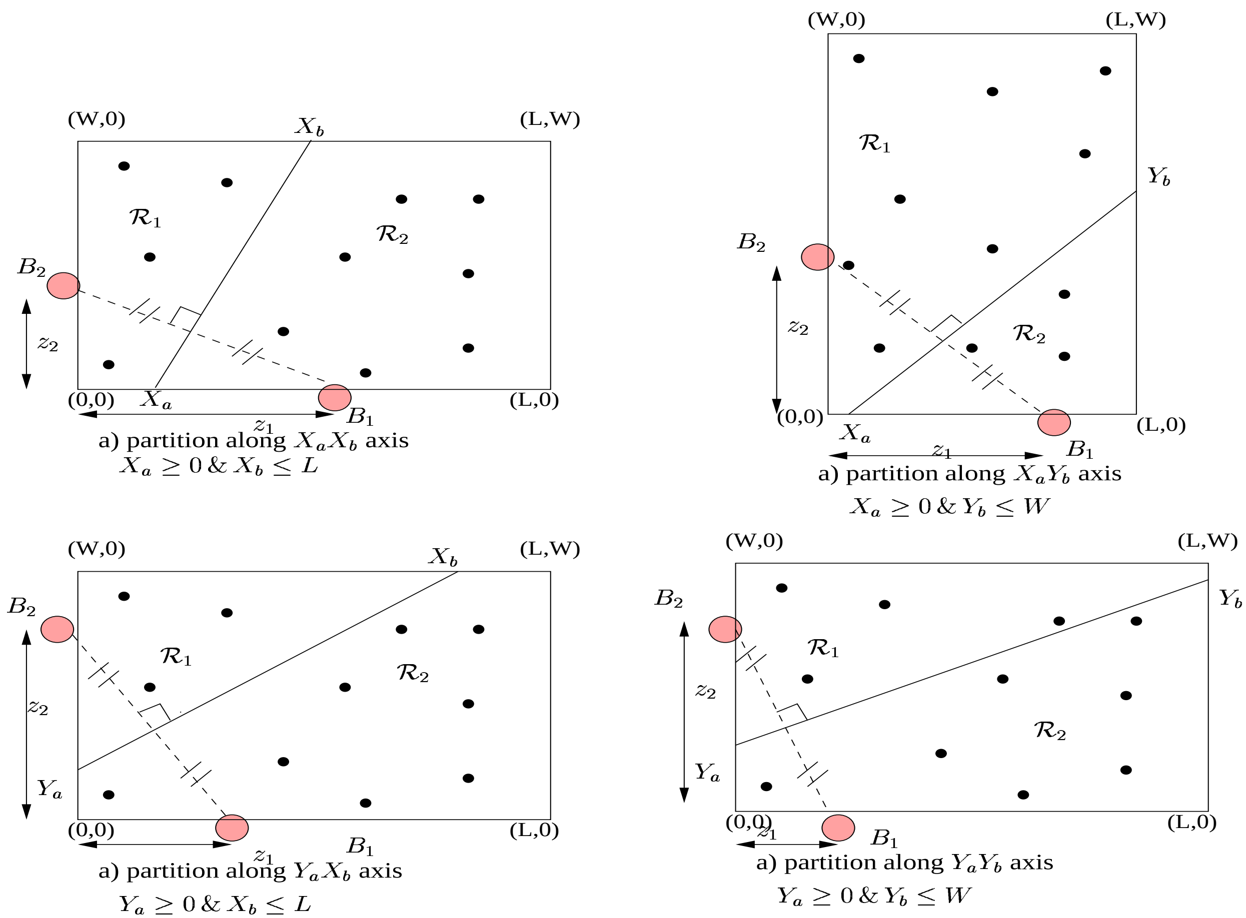


Figure6: *Adjacent side orientation of two base stations.* $\mathcal{R}_1$, $\mathcal{R}_2$ *partition can occur along a)* X_aX_b *axis, b)* X_aY_b *axis, c)* Y_aX_b *axis, and d)* Y_aY_b *axis.*

Two BSs - Adjacent Side Orientation

- The axis partitioning $\mathcal{R}_1$ and $\mathcal{R}_2$ is represented by the straight line

$$Y = mX + c, \qquad m = \frac{z_1}{z_2} \text{ and } c = \frac{z_2^2 - z_1^2}{2z_2}$$

$$X_a = X|_{Y=0} \implies X_a = -\frac{c}{m} = \frac{z_1^2 - z_2^2}{2z_1}, \quad X_b = X|_{Y=W} \Rightarrow X_b = \frac{W-c}{m} = \frac{Wz_2}{z_1} - \frac{z_2^2 - z_1^2}{2z_1}$$

$$Y_a = Y|_{X=0} \implies Y_a = c = \frac{z_2^2 - z_1^2}{2z_2}, \quad Y_b = Y|_{X=L} \Rightarrow Y_b = mL + c = \frac{Lz_1}{z_2} + \frac{z_2^2 - z_1^2}{2z_2}$$

- Partition axis type is

  $i)$ X_aX_b if $X_a \geq 0$ and $X_b \leq L$ (Fig. (a)),

  $ii)$ X_aY_b if $X_a \geq 0$ and $Y_b \leq W$ (Fig. (b)),

  $iii)$ Y_aX_b if $Y_a \geq 0$ and $X_b \leq L$ (Fig. (c)), and

  $iv)$ Y_aY_b if $Y_a \geq 0$ and $Y_b \leq W$ (Fig. (d))

Two BSs - Adjacent Side Orientation

- Energy dissipation in the entire NW with BS locations z_1 and z_2 for ASO case

$$P_{\text{NW,aso}}^{(z_1,z_2)} = N\left(\int\int_{\mathcal{R}_1} P_{\text{nw}}(x,y)\,\frac{1}{WL}\,dx\,dy + \int\int_{\mathcal{R}_2} P_{\text{nw}}(x,y)\,\frac{1}{WL}\,dx\,dy\right)$$

- By minimum energy argument, $P_{\text{nw}}(x,y) \geq P_{\text{link}}\left(\sqrt{x^2+y^2}\right)$, and hence

$$P_{\text{NW,aso}}^{(z_1,z_2)} \geq \frac{r\alpha_1}{d_{\text{char}}}\,\frac{\eta}{\eta-1}\,\frac{N}{WL}\left(d_{\text{2-BS,aso}}^{\mathcal{R}_1}(z_1,z_2) + d_{\text{2-BS,aso}}^{\mathcal{R}_2}(z_1,z_2)\right)$$

where

$$d_{\text{2-BS,aso}}^{\mathcal{R}_1}(z_1,z_2) = \int_{y_1}^{y_2}\int_{x_1}^{x_2}\sqrt{x^2+y^2}\,dx\,dy + \int_{y_3}^{y_4}\int_{x_3}^{x_4}\sqrt{x^2+y^2}\,dx\,dy$$

$$d_{\text{2-BS,aso}}^{\mathcal{R}_2}(z_1,z_2) = \int_{x_5}^{x_6}\int_{y_5}^{y_6}\sqrt{x^2+y^2}\,dy\,dx + \int_{x_7}^{x_8}\int_{y_7}^{y_8}\sqrt{x^2+y^2}\,dy\,dx$$

Limits	For X_aX_b axis Fig.(a)	For X_aY_b axis Fig.(b)	For Y_aX_b axis Fig.(c)	For Y_aY_b axis Fig.(d)
(x_1, x_2)	$(0, X_{z_2})$	$(0, X_{z_2})$	$(0, X_{z_2})$	$(0, X_{z_2})$
(y_1, y_2)	$(-z_2, W - z_2)$	$(-z_2, Y_b - z_2)$	$(Y_a - z_2, Y_b - z_2)$	$(Y_a - z_2, W - z_2)$
(x_3, x_4)	$(0, 0)$	$(0, L)$	$(0, L)$	$(0, 0)$
(y_3, y_4)	$(0, 0)$	$(Y_b - z_2, W - z_2)$	$(Y_b - z_2, W - z_2)$	$(0, 0)$
(x_5, x_6)	$(X_a - z_1, X_b - z_1)$	$(X_a - z_1, L - z_1)$	$(-z_1, L - z_1)$	$(-z_1, X_b - z_1)$
(y_5, y_6)	$(0, Y_{z_1})$	$(0, Y_{z_1})$	$(0, Y_{z_1})$	$(0, Y_{z_1})$
(x_7, x_8)	$(X_b - z_1, L - z_1)$	$(0, 0)$	$(0, 0)$	$(X_b - z_1, L - z_1)$
(y_7, y_8)	$(0, W)$	$(0, 0)$	$(0, 0)$	$(0, W)$

Table I: Values of limits $y_1, y_2, \cdots, y_8$ and $x_1, x_2, \cdots, x_8$ for various partition axis types in Figs. (a), (b), (c), (d)

Two BSs - Bound on NW Lifetime

- An upper bound on lifetime for a given z_1, z_2 and ASO can be obtained as

$$\mathcal{T}_{\text{2-BS,aso}}^{(z_1,z_2)} \leq \frac{N E_{\text{battery}}}{\frac{r\alpha_1}{d_{char}} \frac{\eta}{\eta-1} \frac{N}{WL} \left(d_{\text{2-BS,aso}}^{\mathcal{R}_1}(z_1, z_2) + d_{\text{2-BS,aso}}^{\mathcal{R}_2}(z_1, z_2) \right)}$$

- Optimum locations of BSs for ASO is then given by

$$\left(z_{1,\text{opt}}, z_{2,\text{opt}} \right)_{\text{aso}} = \underset{\substack{z_1 \in (0,L), \\ z_2 \in (0,W)}}{\text{argmax}} \; \mathcal{T}_{\text{2-BS,aso}}^{(z_1,z_2)}$$

- Lifetime bounds for SSO and OSO are derived likewise

- Finally, optimum locations of the BSs are chosen from the best locations of ASO, SSO, and OSO cases, as

$$\left(z_{1,\text{opt}}, z_{2,\text{opt}} \right) = \underset{\substack{z_1 \in (0,L), \\ z_2 \in (0,W) \\ \text{orient} \in \{\text{aso,sso,oso}\}}}{\text{argmax}} \; \mathcal{T}_{\text{2-BS,orient}}^{(z_1,z_2)}$$

Two BSs - Numerical Results

- We obtained NW lifetime bound and optimum BS locations through optimization using genetic algorithm

Two Base Stations (Jointly Optimum)			
Orientation		NW life time Upper Bound (# rounds)	Optimal locations of B_1, B_2
SSO	W side	18.28	$(0, 121.3), (0, 381.5)$
	L side	31.36	$(133.7, 0), (761.4, 0)$
ASO		32.60	$(693.2, 0), (0, 263.6)$
OSO	W side	31.41	$(0, 249.4), (1000, 251.2)$
	L side	32.99	$(716.6, 0), (282.6, 500)$

Table II: Upper bounds on network lifetime and optimal base station locations. Two base stations. Joint optimization. $L = 1000$m, $W = 500$m.

Two BS - Jointly vs Individually Optimum

- The locations of B_1 and B_2 were jointly optimized
  - optimization complexity is high
  - becomes prohibitively complex for more number of base stations
- An alternate and relatively less complex approach is to individually optimize locations of B_1 and B_2, i.e.,
  - fix B_1 at its optimal location obtained from the solution of one BS problem
  - then optimize the location of B_2

Two BSs - Jointly vs Individually Optimum

Two Base Stations (Individually Optimum)		
Location of B_1 fixed at $(L/2, 0) = (500, 0)$		
Orientation	NW life time Upper Bound (# rounds)	Optimal location of B_2
SSO	28.36	$(164.9, 0)$
ASO	30.22	$(0, 496.2)$
OSO	31.41	$(502.5, 500)$

Table III: Upper bounds on network lifetime and optimum base station locations for two base stations. B_1 fixed at optimum location obtained from solving single BS problem. $L = 1000$m, $W = 500$m.

- Both jointly as well as individually optimum solutions results in OSO (opposite side orientation) deployments

Bound on NW Lifetime - Three BS

- Take the individually optimum approach (since less complex)
  - once locations of B_1 and B_2 are fixed, problem gets simplified to optimizing only over location of B_3

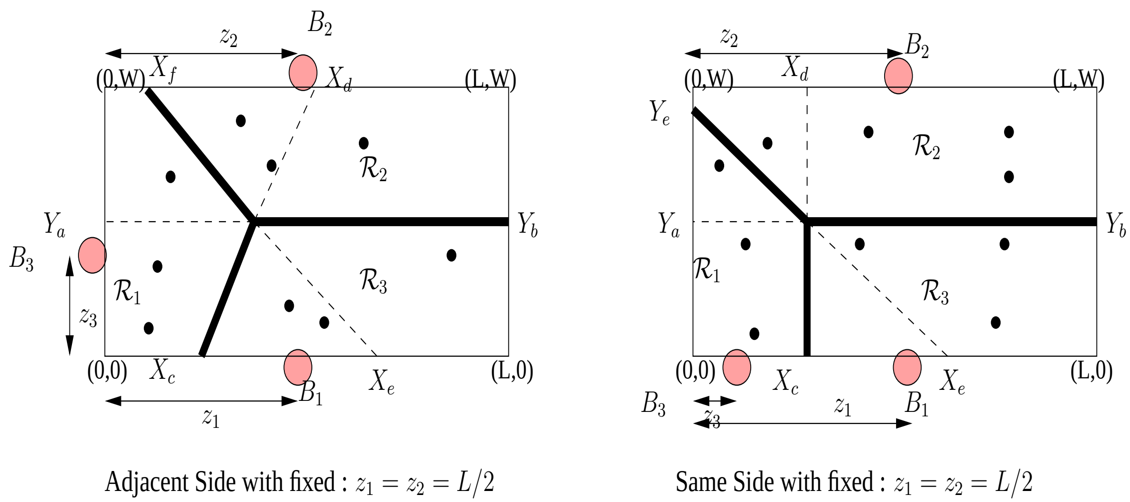


Figure7: *Placement of three base stations. B_1 and B_2 are placed at optimal locations obtained by solving the two base station problem. Location of B_3 is then optimized. a)B_3 on adjacent side of B_1. b) B_3 on same side as B_1.*

Three BSs - Numerical Results

Three Base Stations (Individually Optimum)		
Location of B_1 fixed at (500,0) Location of B_2 fixed at (500,500)		
Orientation	NW life time Upper Bound (# rounds)	Optimum location of B_3
SSO	36.44	$(152.6, 0)$
ASO	38.38	$(0, 249.8)$

Table IV: Upper bounds on network lifetime and optimum base station locations for three base stations. B_1 and B_2 fi xed at optimum locations obtained from solving two base stations problem. L=1000m. W=500m.

Performance Comparison of One, Two, Three BSs

No. of BS	NW life time Upper Bound (# rounds)	Optimum BS Locations
One BS	24.34	$B_1 : (489.9, 0)$
Two BS (Jointly opt)	32.99	$B_1 : (716.6, 0)$, $B_2 : (500, 282.6)$
Two BS (Indiv. opt)	31.41	$B_1 : (500, 0)$, $B_2 : (502.5, 500)$
Three BS (Indiv. opt)	38.38	$B_1 : (500, 0)$, $B_2 : (500, 500)$ $B_3 : (0, 249.8)$

TABLE V: Comparison of the upper bounds on network lifetime for one, two, and three base stations. $L = 1000$ m, $W = 500$ m.

Simulation Results

- Simulated NW lifetime over several NW realizations at different BS locations were obtained
- Simulation parameters:
  - $N = 50$, $L = 1000$ m, $W = 500$ m, $E_{battery} = 0.5J$
  - Routing: A modified version of Minimum Cost Forwarding (MCF) protocol
  - MAC: Contention-free 'Self-organizing MAC for Sensor NW (SMACS)' protocol
  - Data packets are of equal length (each packet has 200 bits)
  - Time axis is divided into rounds; each round consists of 300 time frames
  - Each node generates 1 packet every 30 frames; i.e., 10 packets per round
  - NW lifetime: time until first node dies
  - Lifetime averaged over several realizations of the NW with 95% confidence for different number and locations of BSs

Simulation Results - One BS

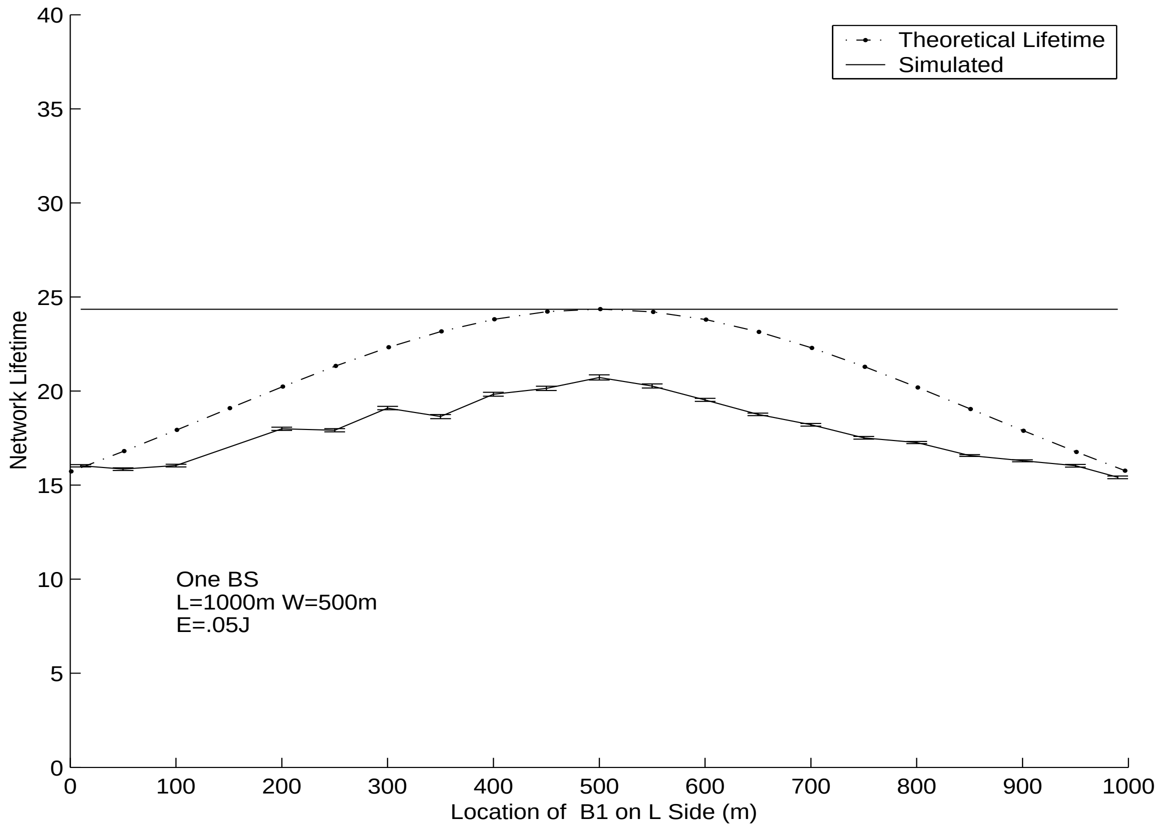


Figure 8: *Comparison of simulated network life time with theoretical upper bound for single base station case.* $L = 1000$ *m,* $W = 500$ *m,* $E_{battery} = 0.05$ *J. Location of* B_1 *varied from (0,0) to (1000,0)*

Simulation Results - Two BSs

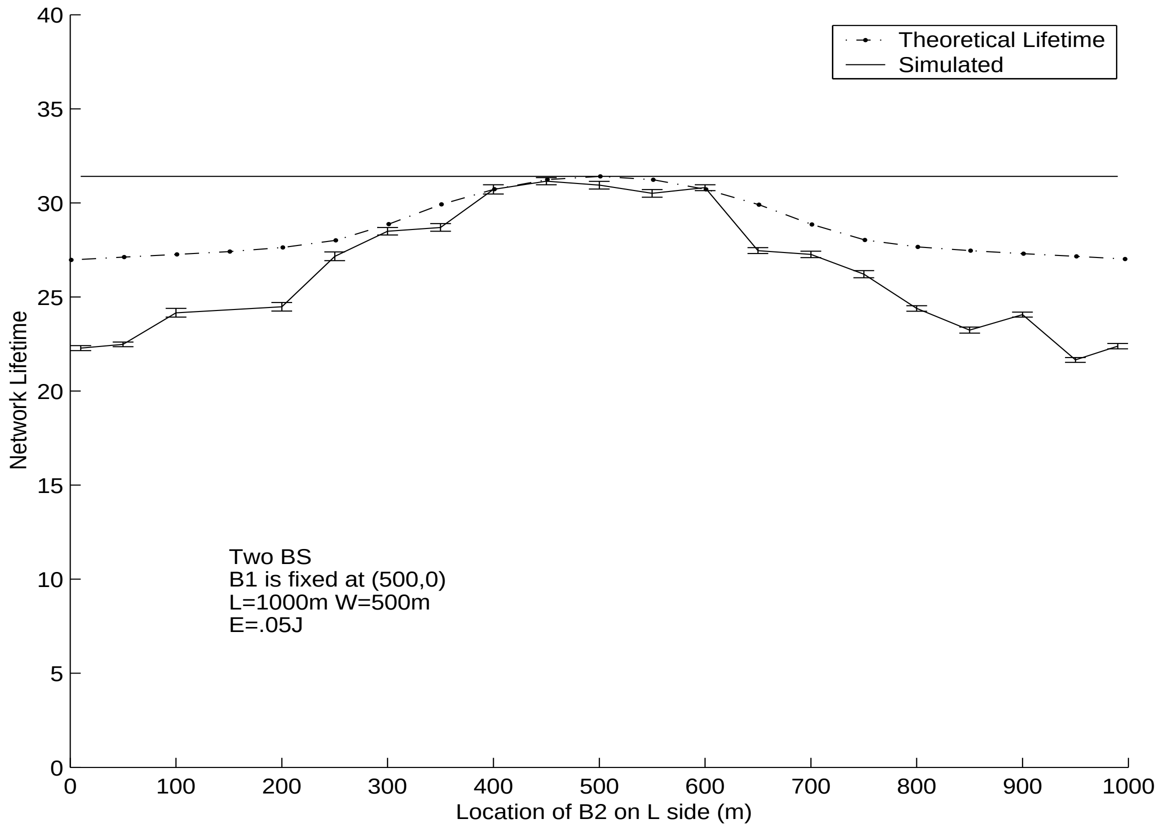


Figure 9: *Comparison of simulated network lifetime with theoretical upper bound for two base stations.* $L = 1000$ *m,* $W = 500$*,* $E_{battery} = 0.05$ *J.* B_1 *fixed at (500,0). Location of* B_2 *varied from (0,500) to (1000,500)*

Simulation Results - Three BSs

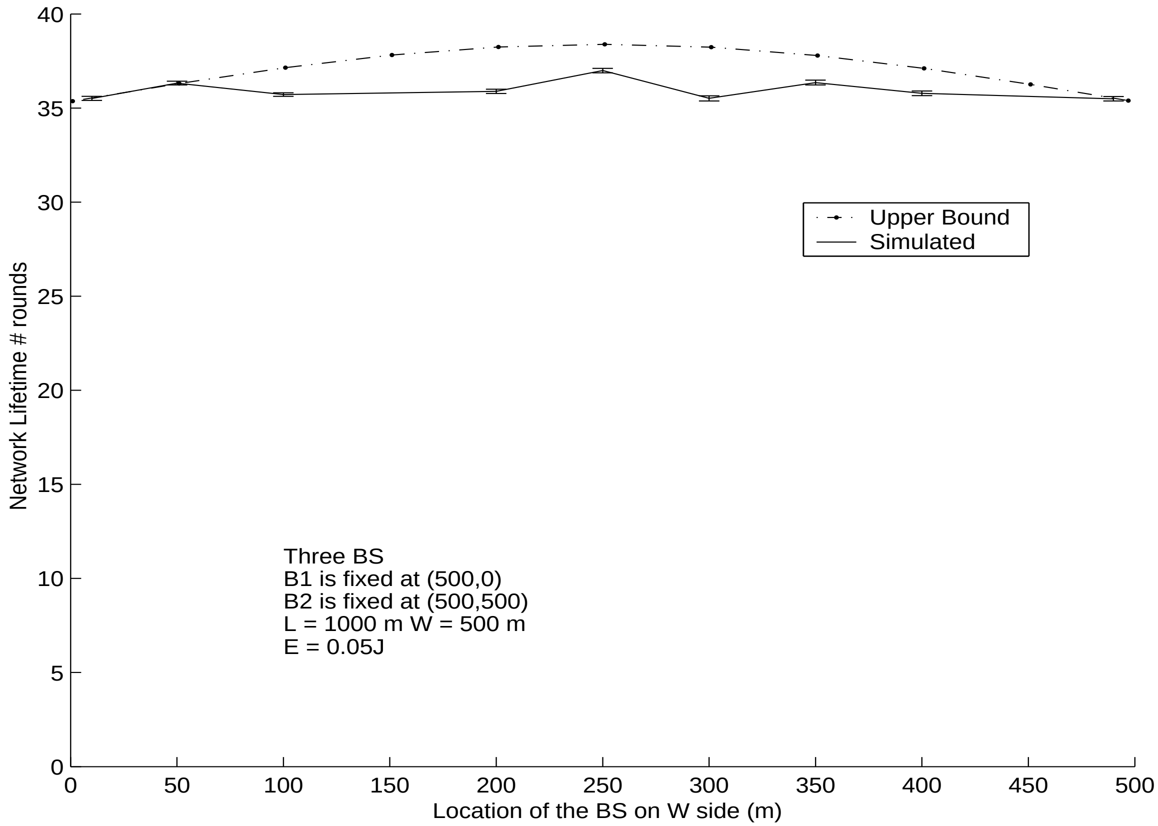


Figure 10: *Comparison of simulated network lifetime with theoretical upper bound for two base stations.* $L = 1000$ *m,* $W = 500$*,* $E_{battery} = 0.05$ *J.* B_1 *fixed at (500,0).* B_2 *fixed at (500, 500). Location of* B_3 *varied from (0,0) to (0,500)*

II. Energy Efficient BS Placement Algorithms

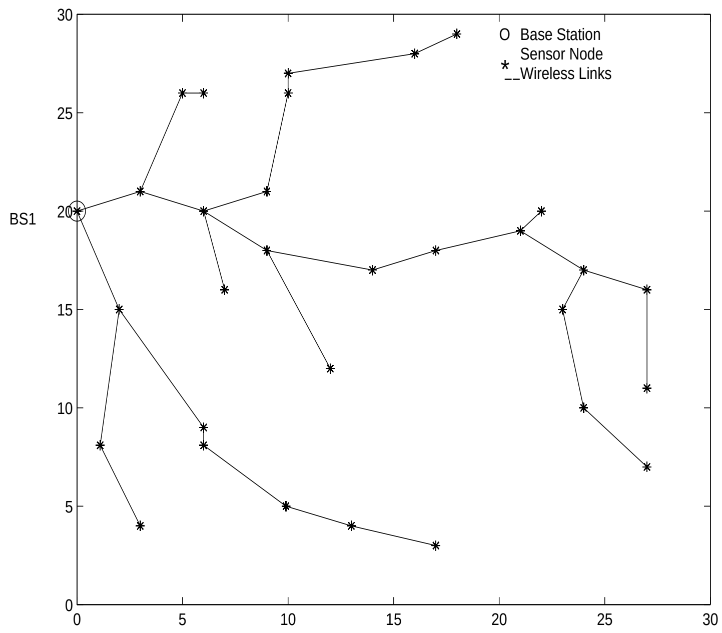
- Given
  - $K, K \geq 1$ BSs
  - a set of *feasible* BS locations (sites) on the boundary of the sensor field
- Problem to solve
  - Choose the optimum locations for these K BSs from the set of feasible sites
- Approach
  - Divide the time axis into *rounds* of equal period
  - Placement of BSs is carried out at the beginning of each round and held for the entire duration of the round
  - A new placement is carried out in the beginning of the next round, and so on, till the end of network life
- We propose three energy efficient algorithms to determine the BS locations

System Model

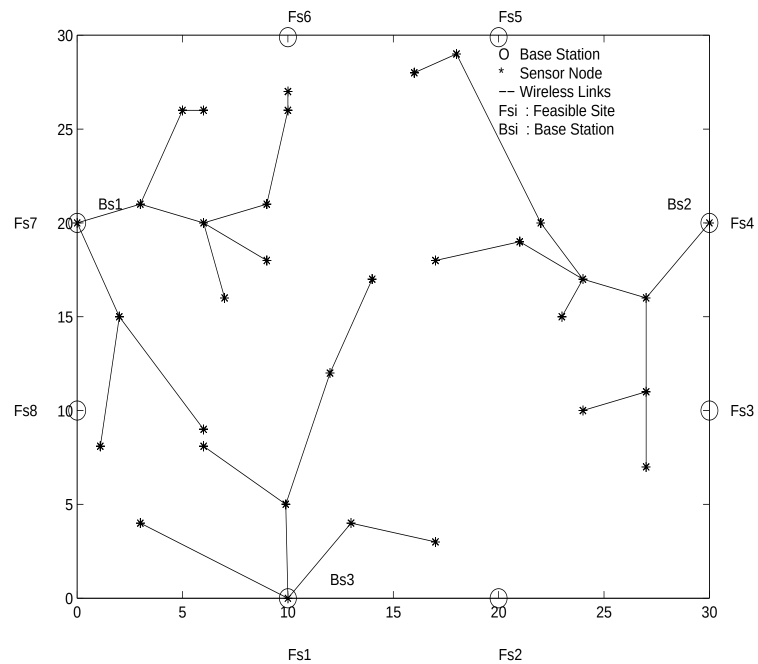
- Assumptions
  - A set of sensor nodes V_s are uniformly distributed over a square sensor field
  - A set of feasible sites V_f (i.e., feasible BS locations) along the periphery of the sensor field is assumed
  - The graph $G(V, E)$ denotes the sensor network where $V = V_s \cup V_f$ and $E \subseteq V \times V$ represents the set of wireless links
  - Wireless links between sensor nodes and a feasible site refer to the links that would exist if a base station is located at that particular site
  - Transmission range of all sensor nodes is same and fixed. $\eta = 2$
  - MAC protocol: SMACS; Routing protocol: MCF routing
  - E_t, E_r: energy consumed for a packet to be Tx and Rx, respectively
  - NW lifetime: time till all nodes die or all live nodes are disconnected from all the feasible sites

MCF Routing

* MCF routing with one BS



* MCF routing with three BSs



BS Placement Algorithms

- Let
  - s_i denote the location of sensor node i, $i \in V_s$
  - f_i denote the location of feasible site i, $i \in V_f$
  - r denote the transmission range of each sensor node
  - RE_i denote the residual battery energy in sensor node i at the beginning of a round when the base station locations are computed.
- Three algorithms
  - Top-K_{max} algorithm
  - Maximizing the minimum residual energy (Max-Min-RE) algorithm
  - Minimizing the residual energy difference (Min-Diff-RE) algorithm

Top-K_{max} Algorithm

- Select those feasible sites (maximum K sites) whose nearest neighbour nodes have the highest residual energies
- Essentially a greedy algorithm. Advantage: Simplicity and less complexity
- *Algorithm:*
  1. For each feasible site $i \in V_f$, find the nearest sensor node n_i within the connectivity range r, i.e., for each $i \in V_f$ choose node $n_i \in V_s$ such that

     $$|f_i - s_{n_i}| \leq |f_i - s_j|, \forall j \in V_s, j \neq n_i$$

     and

     $$|f_i - s_{n_i}| \leq r$$

  2. Order these nearest neighbour nodes $\{n_i, i \in V_f\}$ in descending order of their residual energies, RE_{n_i}.
  3. Select a maximum of K nodes from the top in this ordered list, and declare their corresponding nearest feasible sites as the solution.

Max-Min-RE Algorithm

- Top-K_{max} algorithm gives preference to nearest neighbours
  - likely that the nodes nearer to feasible sites are heavily loaded
- Max-Min-RE algorithm
  - attempts to distribute the load more evenly to different loads
  - # solutions possible are $P = \binom{N}{K}$.
  - Let this solution set be S.
  - Let the jth solution in the solution set S be T_j
  - choose the solution in which the 'heavily loaded node' has the maximum residual energy among all possible solutions
    - ∗ 'heavily loaded node' in a solution: identified by the minimum residual energy among various nodes in a given solution (instead of 'minimum distance' as done in Top-K_{max} algorithm)

Max-Min-RE Algorithm

- *Algorithm:*

1. Determine set $S_c \subseteq S$ such that $S_c = \{T_j : \forall i \in V_s$ there exists $p \in V_s$ such that $|s_i - s_p| \leq r$ or $q \in V_f$ such that $|s_i - f_q| \leq r\}$.
2. For a given solution $T_j \in S_c$, determine the routes from all the sensor nodes to their respective base stations using MCF routing.
3. For each node $i \in V_s$ compute the energy consumed at all nodes in the path in delivering a data packet from node i to its corresponding base station, and determine the resulting residual energies in all nodes.
4. Find the minimum residual energy among all nodes in the jth solution

$$M_j = \min_{i \in V_s} \{RE_i\}$$

5. Choose the solution as

$$T_{Max-Min-RE} = \max_j \{M_j : T_j \in S_c\}$$

Min-Diff-RE Algorithm

- Also attempts to evenly drain the nodes
- *Algorithm:*

1. Perform steps 1) to 3) of the Max-Min-RE algorithm.
2. Compute the metric

$$M_j = \max_{i \in V_s} \{RE_i\} - \min_{i \in V_s} \{RE_i\}$$

3. Choose the solution as

$$T_{MinDiff-RE} = \min_j \{M_j : T_j \in S_c\}$$

Simulation Parameters

- A square sensor field of area 30 m $\times$ 30 m
- Sensor nodes uniformly distributed in the sensing area
- Number of sensor nodes = 30
- Number of feasible sites = 8
  - coordinates of the feasible sites: $\{(0,10),(0,20),(10,30),(20,30),$ $(30,20),(30,10),(20,0),(10,0)\}$
- Number of BSs = 3
- $E_{battery} = 0.05J$, $r = 10$ m, $E_t = 0.1$ nJ/bit-m^2, $E_r = 50$ nJ/bit
- Packet length = 200 bits, 1 round = 300 time frames
- Each node generates 1 packet every 30 frames (10 packets per round)

Simulation Results

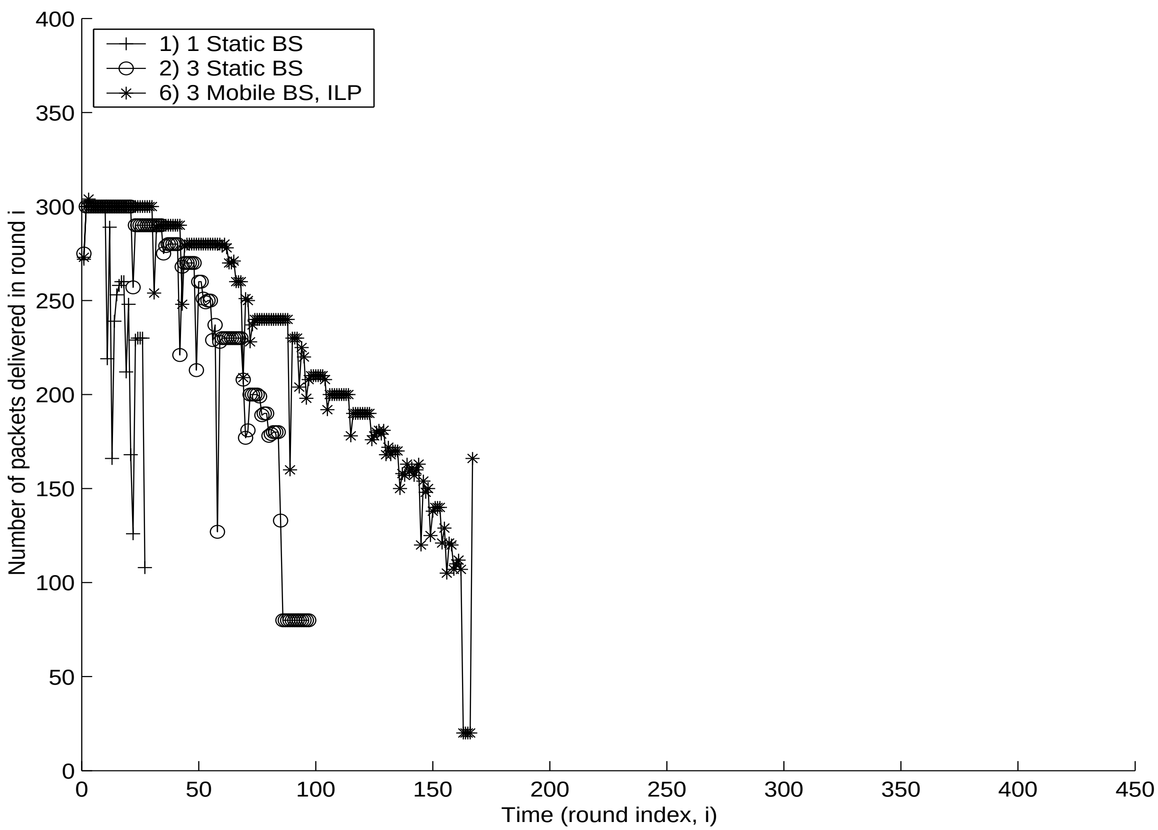


Figure 11: *Traces of number of packets delivered per round as a function of time for schemes 1), 2), and 6). MCF routing. Initial energy at each node,* $E_{battery} = 0.05$ *J. One packet = 200 bits. Range of each node,* $r = 10$ *m.*

Simulation Results

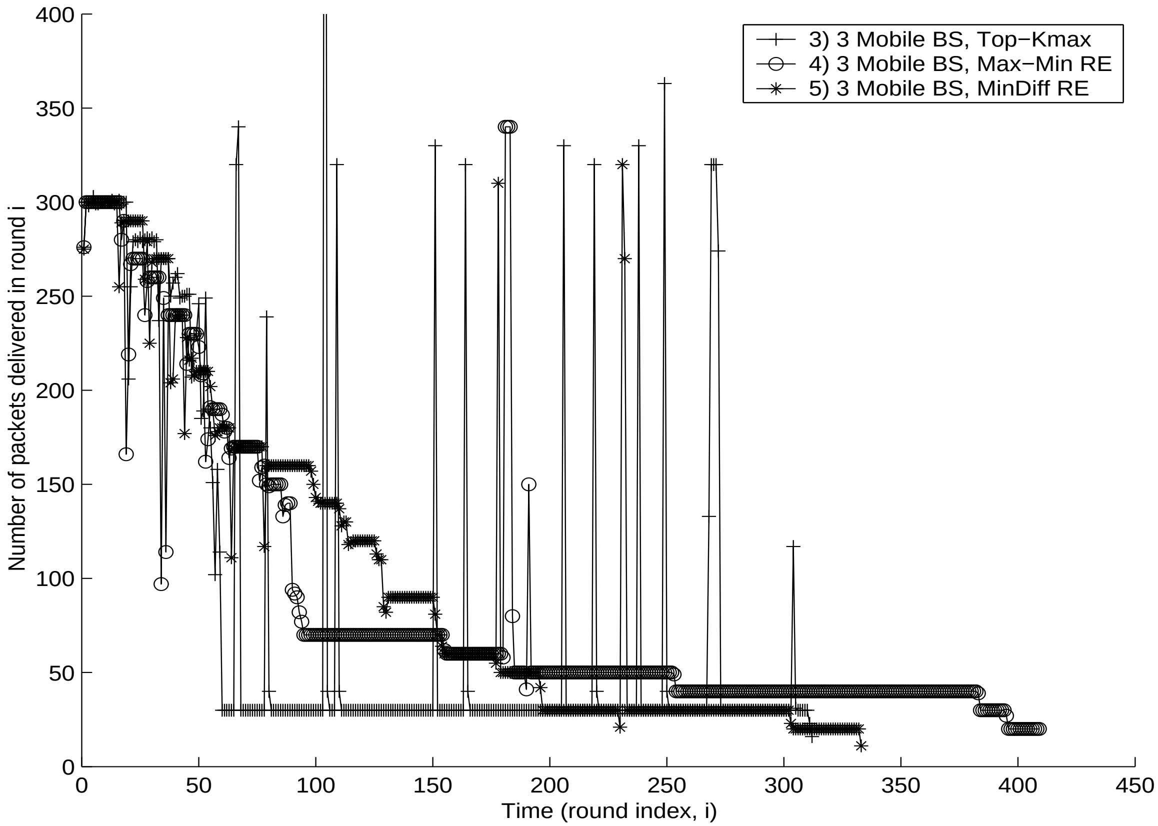


Figure 12: *Traces of number of packets delivered per round as a function of time for the proposed schemes 3), 4), and 5). MCF routing. Initial energy at each node,* $E_{battery} = 0.05$ *J. One packet = 200 bits. Range of each node,* $r = 10$ *m.*

Simulation Results

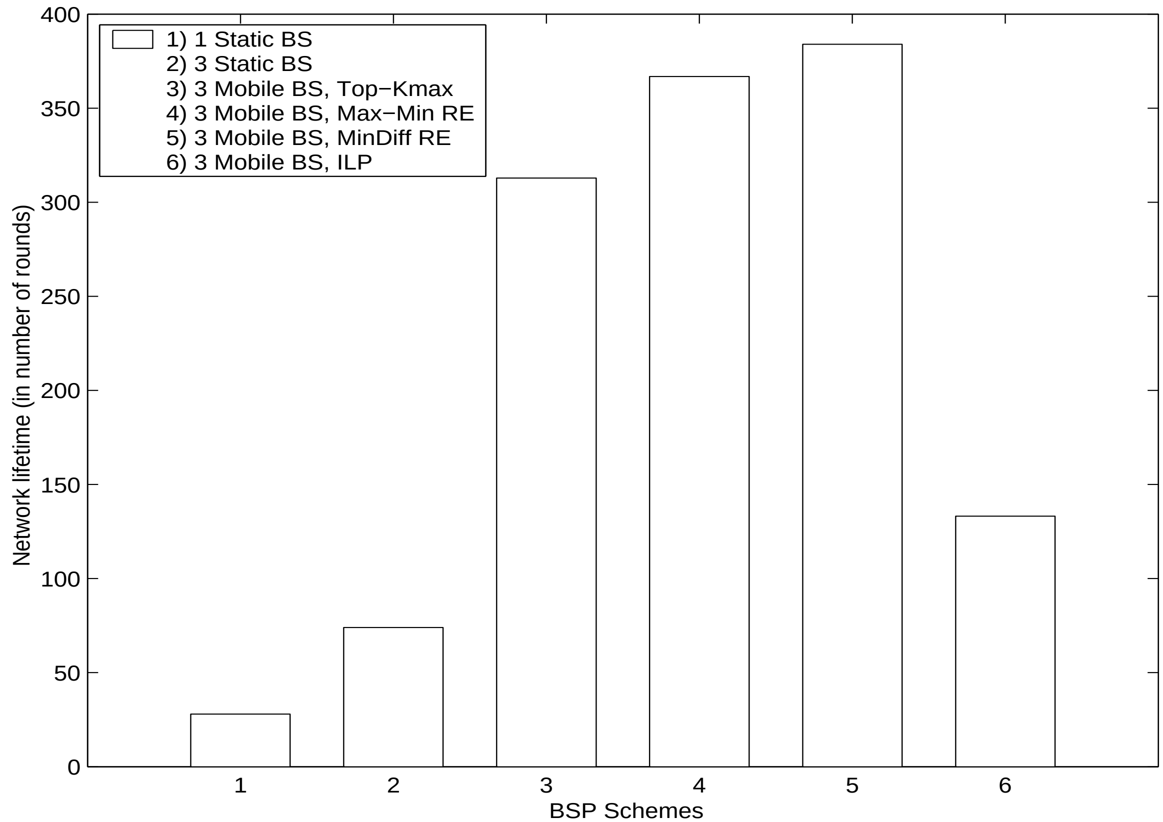


Figure 13: *Network lifetime in number of rounds for different BSP algorithms. MCF routing. Initial energy at each node,* $E_{battery} = 0.05$ *J. One packet = 200 bits. Range of each node,* $r = 10$ *m.*

Simulation Results

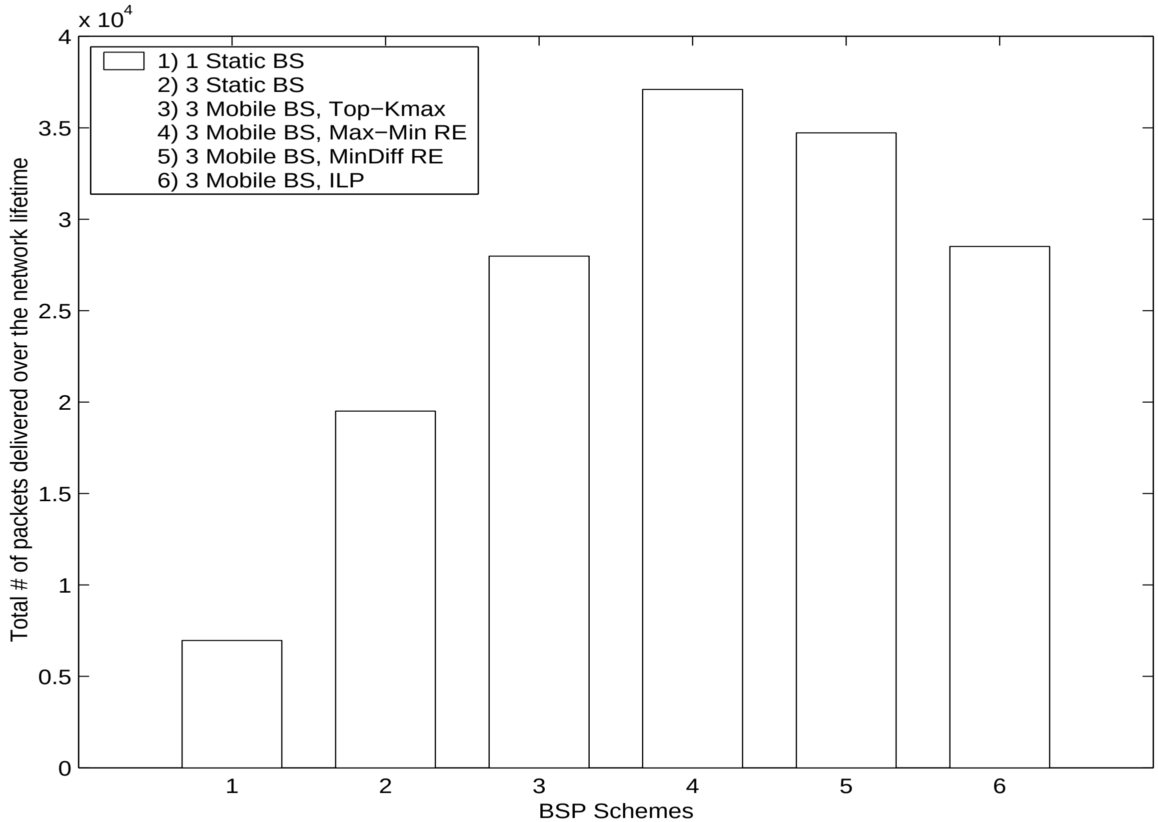


Figure14: *Amount of packets delivered during network lifetime for different BSP algorithms. MCF routing. Initial energy at each node,* $E_{battery} = 0.05$ *J. One packet = 200 bits. Range of each node,* $r = 10$ *m.*

Simulation Results

BSP Algorithm	NW lifetime in # rounds (95% confidence)	Data delivered in # packets (95% confidence)
1 BS	28 ± 0.009	$0.7 \times 10^4 \pm 0.34$
3 BS, static	74 ± 0.25	$1.9 \times 10^4 \pm 14.8$
3 BS, Top-K_{max}	312 ± 0.17	$2.8 \times 10^4 \pm 1.42$
3 BS, Max-Min-RE	365 ± 0.87	$3.7 \times 10^4 \pm 42.9$
3 BS, MinDiff-RE	380 ± 1.11	$3.5 \times 10^4 \pm 45.2$
3 BS, ILP	130 ± 0.45	$2.7 \times 10^4 \pm 76.5$

Table 1: Network lifetime and amount of data delivered for the various BSP schemes.

Cooperative Diversity in Sensor Network

- Diversity techniques are well known for mitigating the effects of multi-path fading and improving the reliability of communication in wireless channels.
- Transmit diversity schemes require more than one antenna at the transmitter.
- Cooperative communication
  - Enables single-antenna mobiles in a multiuser environment to share their antennas
  - Generate a virtual multiple-antenna transmitter that allows them to achieve transmit diversity.
  - Suitably applicable in wireless scenario eg. Sensor motes,Handheld mobile nodes.
  - Improved SNR results in reduced transmitter power requirement.

Cooperative Diversity

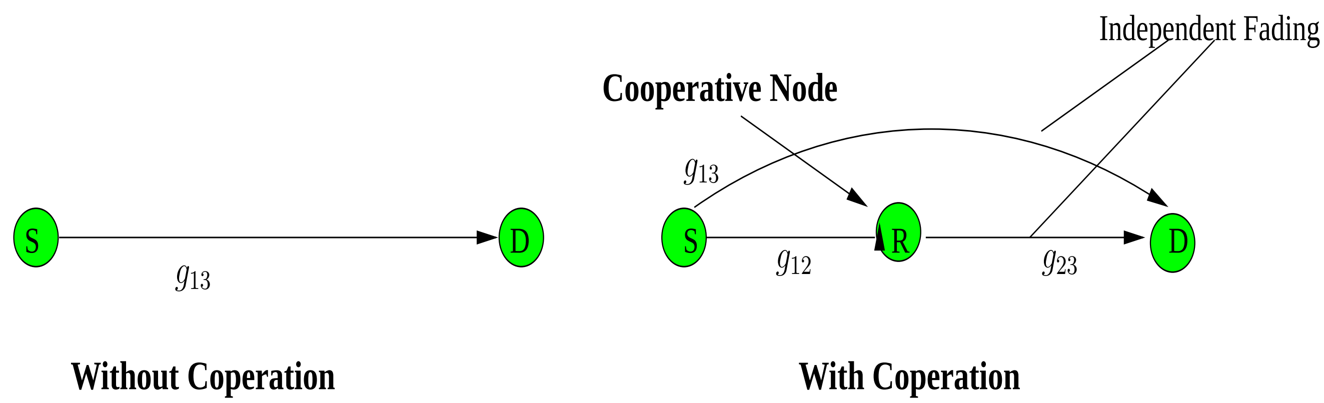


Figure15: *a) Cooperative Node Pair*

- Node S transmits a bit to D.
- Node R acts as a cooperative relay node for node S by retransmitting it to D.
- Participation of relay node may hurt the performance, particularly if S to R link is of poor quality.
- Use of relay node(s) for cooperation must be done judiciously.

Cooperative Diversity in Network Scenario

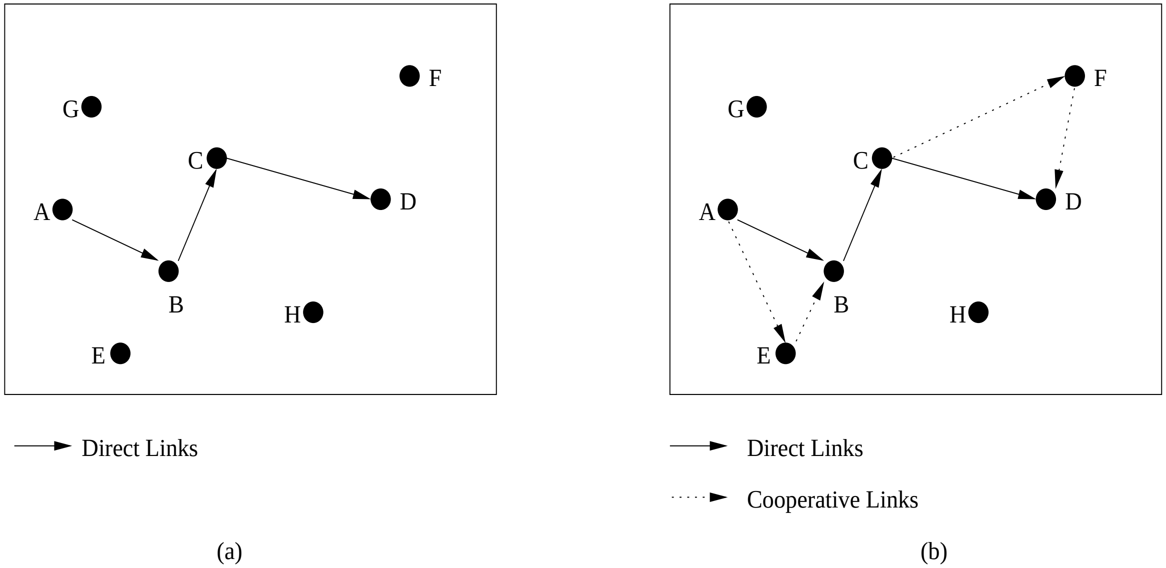


Figure16: *Cooperation in Sensor Network*

Cooperative Diversity Protocols

Protocol used in Cooperative Diversity

- Amplify and Forward
  - Relay nodes forwards an amplifi ed version of data. Noise is also amplifi ed.
- Decode and Forward
  - Relay nodes decodes and retransmits the data. Detection error is also propagated.
- Selection Relaying
  - Relay nodes forward only if it receives and can decode correctly.
- Incremental Relaying
  - Relay transmits only if requested by destination.

We have Used *Amplify and Forward Protocol* for further investigation.

Cooperative Diversity In Wireless Network

- Related Study
  - *Laneman, Tse and Wornell,* **IEEE Trans. on Info. Theory, 2004**
  - *Sendonaris, Erkip and Aazhang,* **IEEE Trans on Comm.**, *Nov'2001*
  - *Ribeiro, Cai and Giannakis* **IEEE Trans. on Wireless Comm.'2005**
  - *Herold and Zimmerman,* **SCIENCE DIRECT, Computer Network '2005**
  - *Shastry, Bhatia and Adve,* **Globecom'2005**
- Our Investigation
  - Derived upper bound on lifetime using Cooperative diversity

Radio Energy Model Recap

- The required transmitted power is expressed,

$$P_t = SNR_{th}\,\frac{1}{C}N_0\,d^2$$

Factor C includes antenna propagation characteristics

$$C = \left(\frac{\lambda}{4\pi}\right)^2\frac{G_tG_r}{L}$$

N_0 = AWGN noise power , d= link distance , SNR_{th} = received thresold SNR for proper decoding

- Received thresold SNR depends on receiver characteristcs

Radio Energy Model Recap

Energy model by Heinzelman -2000 (AWGN)

- Receiving

$$E_{rx} = \alpha_{12}$$

- Transmitting

$$E_{tx} = \alpha_{11} + \alpha_2 d^\eta$$

- Energy spent in Relaying 1 Bit

$$\begin{aligned} E_{relay}(d) &= E_{rx} + E_{tx} \\ &= \alpha_{12} + \alpha_{11} + \alpha_2 d^\eta \\ &= \alpha_1 + \alpha_2 d^\eta \end{aligned}$$

α_{11} and α_{12} are energy spent in transmit and receive electronics.

α_2 is energy spent in transmit electronics. It is a function of threshold SNR.

- Where,

$$\alpha_2 = (SNR_{th} \frac{1}{C} N_0) \frac{1}{r}$$

Radio Energy Model for Fading

Energy consumed in relaying 1 Bit

- Direct relaying (Rayleigh Fading)

$$\begin{aligned} E_{relay}(d) &= E_{tx} + E_{rx} \\ &= \alpha_{1_{fad}} + \alpha_{2_{fad}} d^{\eta} \end{aligned}$$

- Energy spent in receiving depends only on Tx,Rx electronics. Hence,

$$\alpha_{1_{fad}} = \alpha_1 \tag{1}$$

- α_2 depends on Tx amplifi er and channel characteristics

- BER can be expressed for BPSK ,

$$\begin{aligned} \overline{P_e} &= \frac{1}{2}\Big(1 - \sqrt{\frac{\overline{SNR}}{1+\overline{SNR}}}\Big) \\ \overline{P_e} &\approx \frac{1}{4\overline{SNR}} \end{aligned}$$

Radio Energy Model for Fading

- For Direct relaying (Fading channel)

$$P_t = \frac{N_0}{4\sigma^2}\frac{1}{C\overline{P_e}}d^{\alpha} \qquad W$$

Hence,

$$\alpha_{2fad} = (\frac{N_0}{4\sigma^2}\frac{1}{C\overline{P_e}})\frac{1}{r} \qquad J/bit/m^2$$

r = no. of bits transmitted per second

Minimum Energy Relay For Direct Transmission

- Energy dissipation rate of relaying a bit over distance D can be bounded as

$$P_{\text{link}}(D) \geq \left(\alpha_{1fad}\frac{\eta}{\eta-1}\frac{D}{d_{\text{char}_{fad}}} - \alpha_{12_{fad}}\right) r$$

with equality iff D is an integral multiple of $d_{\text{char}_{fad}}$

- Power dissipated in the network is always larger than or equal to the sum of this $P_{\text{link}}(D)$ and the power for sensing, i.e.,

$$P_{\text{nw}} \geq P_{\text{link}}(D) + P_{sense} = \left(\alpha_{1_{fad}}\frac{\eta}{\eta-1}\frac{D}{d_{\text{char}_{fad}}} - \alpha_{12_{fad}}\right) r + \alpha_3 r$$

Where,

$$d_{\text{char}} = \sqrt[\eta]{\frac{\alpha_{1_{fad}}}{\alpha_{2_{fad}}(\eta-1)}}$$

- As an approximation, sensing power can be ignored since the power for relaying data dominates.

Bound on NW Lifetime - Direct Transmission

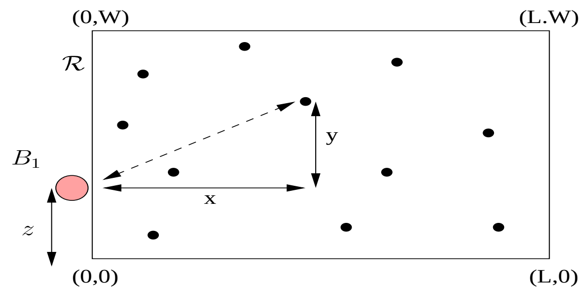


Figure17: *Data is transported to B_1 through multihop communication without Cooperative Diversity (Direct)*

- Let $P_{\text{NW}}^{(z)}$ denote the energy dissipation in the entire NW for a given BS z
- Assuming uniform distribution of N nodes

$$P_{\text{NW}}^{(z)} = N \int\int_{\mathcal{R}} P_{\text{nw}}(x,y)\,\frac{1}{WL}\,dx\,dy.$$

- By minimum energy relay argument, $P_{\text{nw}}(x,y) \geq P_{\text{link}}\left(\sqrt{x^2+y^2}\right)$, and hence

$$\begin{aligned} P_{\text{NW}}^{(z)} &\geq \frac{N}{WL}\int_{-z}^{W-z}\int_0^L P_{\text{link}}\left(\sqrt{x^2+y^2}\right)\,dx\,dy \\ &\geq r\alpha_1\,\frac{\eta}{\eta-1}\,\frac{N}{WL}\int_{-z}^{W-z}\int_0^L \frac{\sqrt{x^2+y^2}}{d_{\text{char}\,fad}}\,dx\,dy \end{aligned}$$

Radio Energy Model For Cooperative Nodes

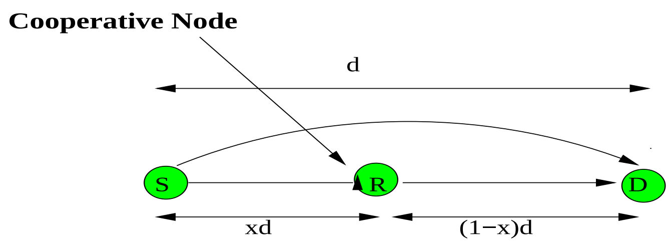


Figure18: *Cooperative Node Pair*

- Cooperative Relaying

$$E_{relay}(d) = 2\,E_{tx} + 3\,E_{rx}$$
$$= \alpha_{1_{coop}} + \alpha_{2_{coop}} d^{\eta}$$

- Energy spent in receiving depends only on Tx, Rx electronics.

  Hence,

$$\alpha_{1_{coop}} = (2\alpha_{12} + 3\alpha_{11}) \qquad (2)$$

- $\alpha_{2_{coop}}$ depends on Tx amplifi er ,channel characteristics and cooperative scheme used

Radio Energy Model For Cooperative Nodes Contd.

- Hence for Amplify and Forward cooperation

$$\overline{P_e} = \frac{3(K+1)^2}{4k^2}\Big(\frac{1}{\overline{\gamma_{12}}} + \frac{1}{\overline{\gamma_{23}}} + \frac{1}{\overline{\gamma_{13}}}\Big)$$

where $\gamma_{ij} = \frac{P_c}{N_0} g_{ij} \quad and \quad g_{ij} = d^{-\alpha} |a_{ij}|^2$

$$P_c = N_0 \, \frac{d^\eta}{C\,\overline{\sigma^2}} \sqrt{\frac{3}{16}} \sqrt{x^\eta + (1-x)^\eta} \sqrt{\frac{1}{\overline{P_e}}}$$

- The optimal location of relay node obtained by $\frac{dP_c}{dx} = 0$ is $x = \frac{1}{2}$ for $\eta = 2$.
- On comparing we get,

$$\alpha_{2coop} = 2 * \Big(N_0 . \frac{d^\eta}{C\,\overline{\sigma^2}} \sqrt{\frac{3}{16}} \frac{1}{\sqrt{2}} \sqrt{\frac{1}{\overline{P_e}}}\Big) \frac{1}{r}$$

- Thus energy spent by an intermediate node with cooperative relay node can be expressed in terms of the parameter $\alpha_{1_{coop}}$ and $\alpha_{2_{coop}}$.
- Again, we get the expression of $E_{relay}(d)$ in similar form as of part I. Hence we can apply similar analysis as of part I to obtain the upper bound on the lifetime.

Upper Bound Using Cooperative Diversity

Hence following the similar analysis steps done in part I, the upper bound can be derived as below:

- Power dissipated in the network is always larger than or equal to the sum of this $P_{\text{link}}(D)$ i.e.,

$$P_{\text{nw}} \geq P_{\text{link}}(D) + P_{sense} = \left(\alpha_{1_{coop}} \frac{\eta}{\eta - 1} \frac{D}{d_{\text{char}_{coop}}} - \alpha_{12_{coop}} \right) r + \alpha_3 r$$

Where,

$$d_{\text{char}_{coop}} = \sqrt[\eta]{\frac{\alpha_{1_{coop}}}{\alpha_{2_{coop}}(\eta - 1)}}$$

- The Network Lifetime can be Bounded using similar steps,

$$P_{\text{NW}}^{(z)} \geq N \int \int_{\mathcal{R}} P_{\text{link}} \left(\sqrt{x^2 + y^2} \right) (x, y) \frac{1}{WL} \, dx \, dy.$$

Upper Bound on the lifetime

- Upper Bound on the Lifetime obtained are tabulated below.

Case	Lifetime (in # of rounds)
Direct (without Cooperative)	55
Using Cooperative Diversity	76

- The parameter values are tabulated below

Parameter	$\alpha_{1_{fad}}$	$\alpha_{2_{fad}}$	$\alpha_{1_{coop}}$	$\alpha_{2_{coop}}$
values	60 nJ/bit	2.31 $pJ/bit/m^2$	150 nJ/bit	0.34 $pJ/bit/m^2$

Simulation Setup

- Simulated NW lifetime over several NW realizations
- Simulation parameters:
  - $N = 50$, $L = 1000$ m, $W = 500$ m, $E_{battery} = 0.5J$
  - Routing: MHR (Minimum Hop Routing) is protocol
  - MAC: Contention-free 'Self-organizing MAC for Sensor NW (SMACS)' protocol with a provision for handling cooperative packets
  - Data packets are of equal length (each packet has 200 bits)
  - Time axis is divided into rounds; each round consists of 300 time frames
  - Each node generates 1 packet every 30 frames; i.e., 10 packets per round
  - NW lifetime: time until fi rst node dies
  - Lifetime averaged over several realizations of the NW with 95% confi dence for different number

Simulation Results - Lifetime

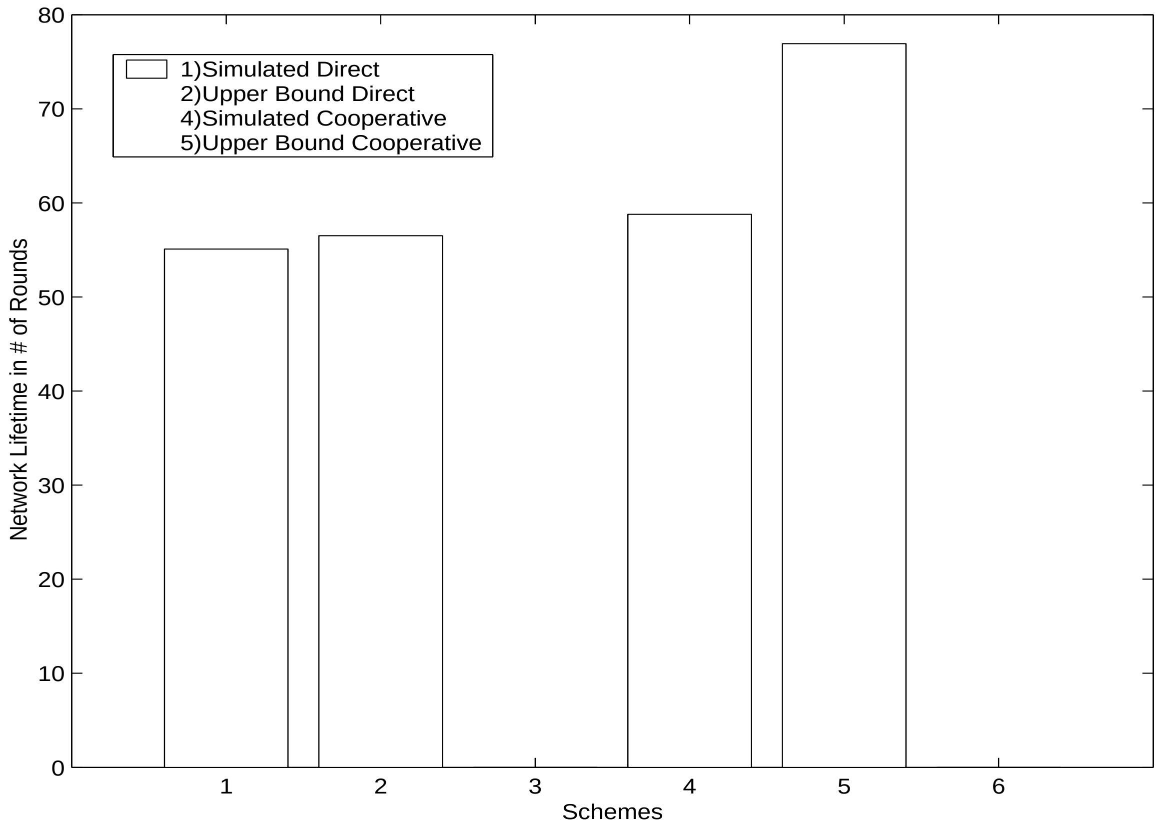


Figure 19: *Comparison of simulated network life time with theoretical upper bound for Direct and Cooperative case.* $L = 1000$ *m*, $W = 500$ *m*, $E_{battery} = 0.5$ *J.*

Simulation Results - Packet Received

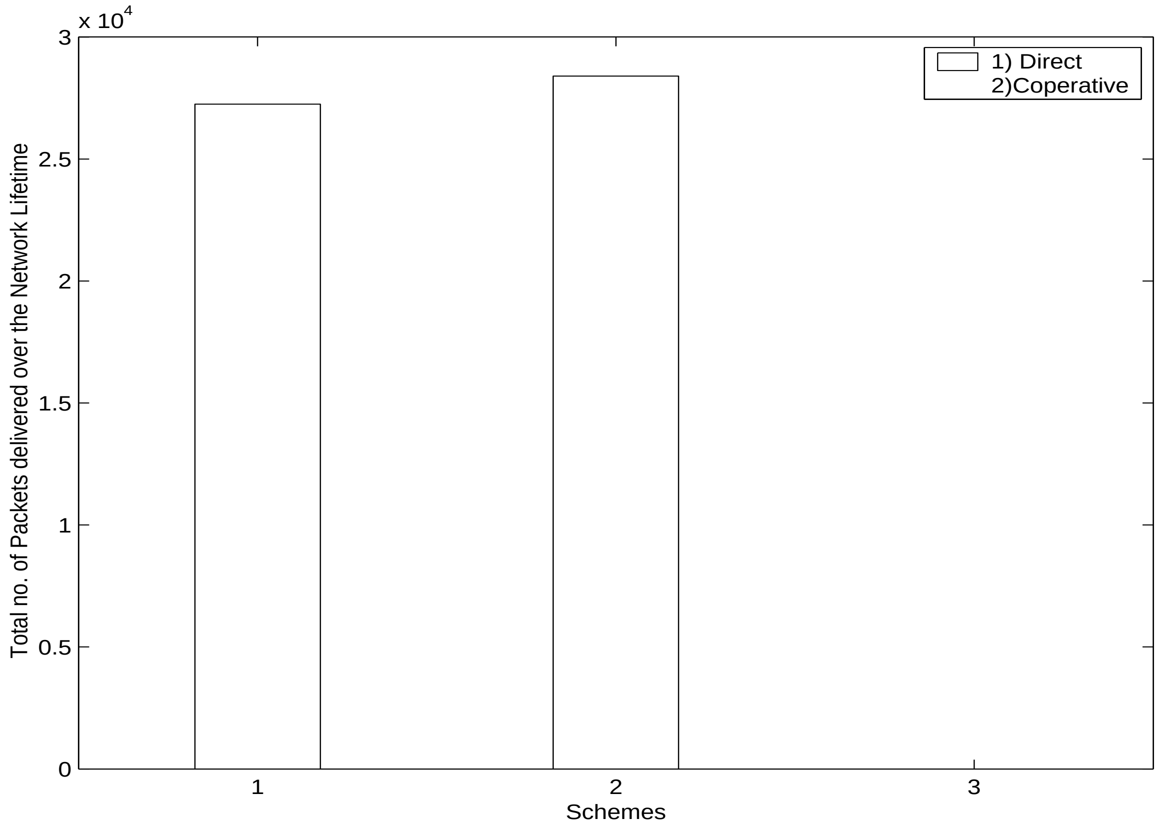


Figure 20: *Comparison of the no. of Packets Received for Direct and Cooperative case over the duration of Lifetime.* $L = 1000$ *m*, $W = 500$ *m*, $E_{battery} = 0.5$ *J.*

Summary

- In Multiple Base Station scenario
  - Upper Bound is derived which are validated with the help of simulation
  - Optimal locations of base stations are obtained and supported by simulation
  - Shown analytically that deploying multiple base stations extends lifetime
- In Mobile Base Station scenario
  - Algorithms are proposed for base station placement exploiting the residual node energy. Simulation results shows the performance of proposed algorithms are benefi cial to some extent in terms of
    - Lifetime extension
    - More number of packet delivery
- Use of cooperative diversity in sensor network can enhance network lifetime as well as number of succesful packet delivery.

Future work

In future work we can view some potential extensions,

- Study of cooperative diversity in sensor network using other protocols (Decode and Forward etc.).
- Optimizing the relay location to improve lifetime.
- Study of cooperative diversity in presence of multiple base station.

Publications From This Thesis

1. A. P. Azad and A. Chockalingam, “Mobile base stations placement and energy aware routing in wireless sensor networks,” accepted in *IEEE WCNC’2006*, Las Vegas, April 2006.
2. A. P. Azad and A. Chockalingam, “Energy effi cient mobile base stations placement algorithms in wireless sensor networks,” accepted in *NCC’2006*, IIT, New Delhi, January 2006.
3. A. P. Azad and A. Chockalingam, “Upper Bounds on the lifetime and optimal locations of multiple base stations in wireless sensor networks,” *being submitted to IEEE GLOBECOM’2006*, San Francisco, 2006.

Thanks..