Bounds on the Lifetime of Wireless Sensor Networks Employing Multiple Data Sink

A. P. Azad and A. Chockalingam

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Department of Electrical Communication Engineering

Indian Institute of Science

Bangalore – 560012. INDIA

Outline

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- System Model
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  - Single Base Station
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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

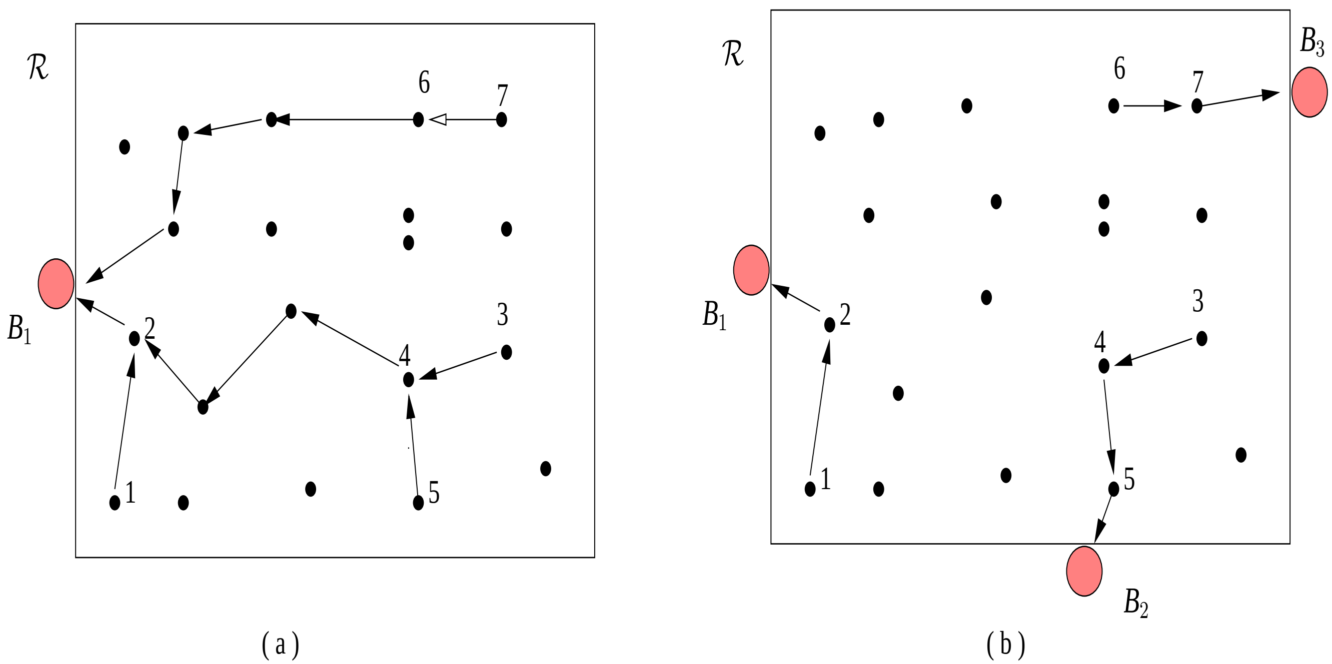

Figure 1: *A sensor network over a rectangular region of observation* $\mathcal{R}$ *with three base stations* B_1, B_2, B_3*. Node 1 sends its data to base station* B_1 *via node 2. Node 3 sends its data to* B_2 *via nodes 4 and 5. Node 6 sends its data to* B_3 *via node 7. However in Single base station 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 amplifier, 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

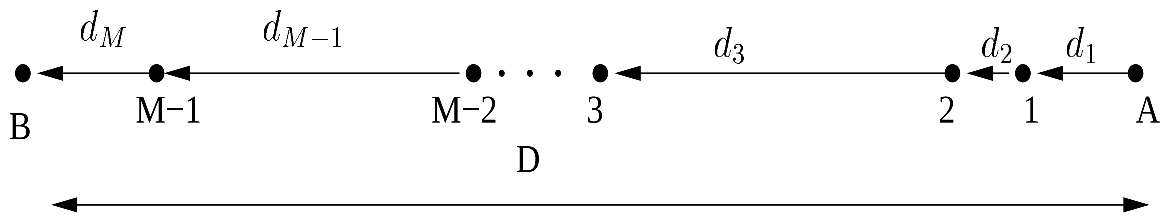

Figure2: *$M-1$ relay nodes between points A and B*

- *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 $\mathcal{R}$)

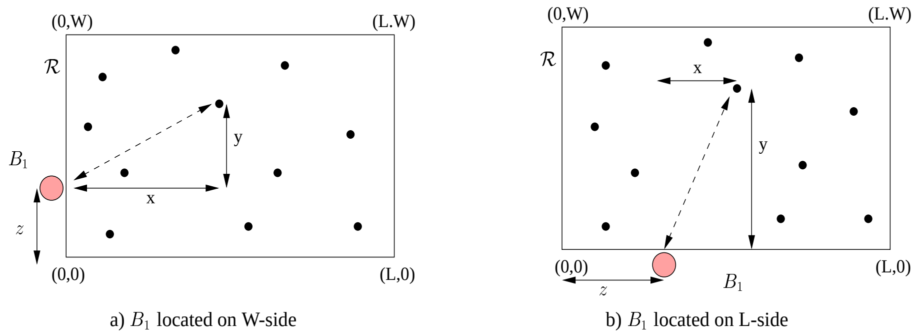

Figure3: *Single base station placements. a) B_1 located on W-side. b) B_1 located on L-side*

- 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

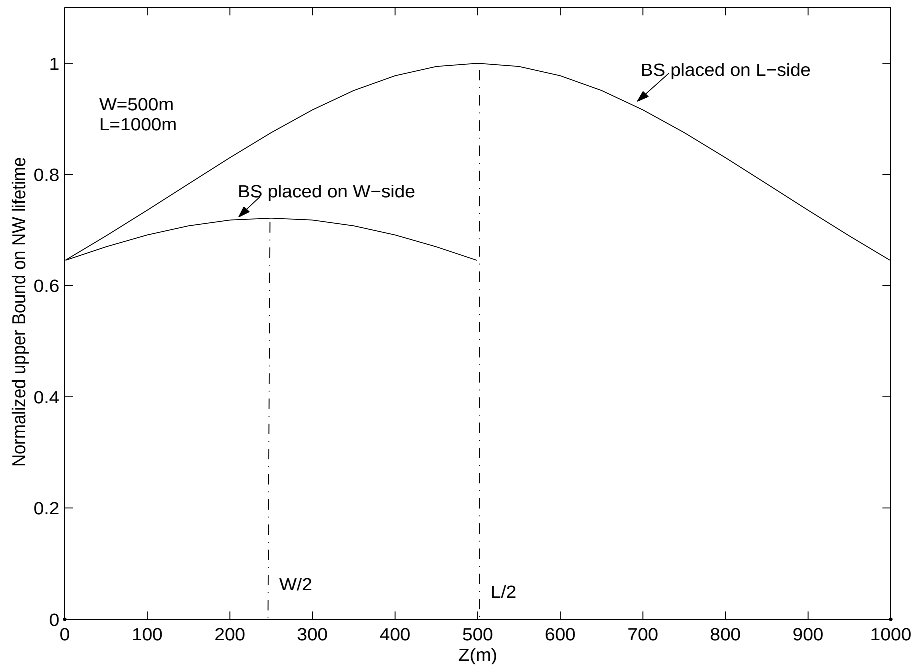

Figure 4: *Normalized upper bound on network life time as a function of base station location for* $L = 1000$ *m and* $W = 500$ *m*

- 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

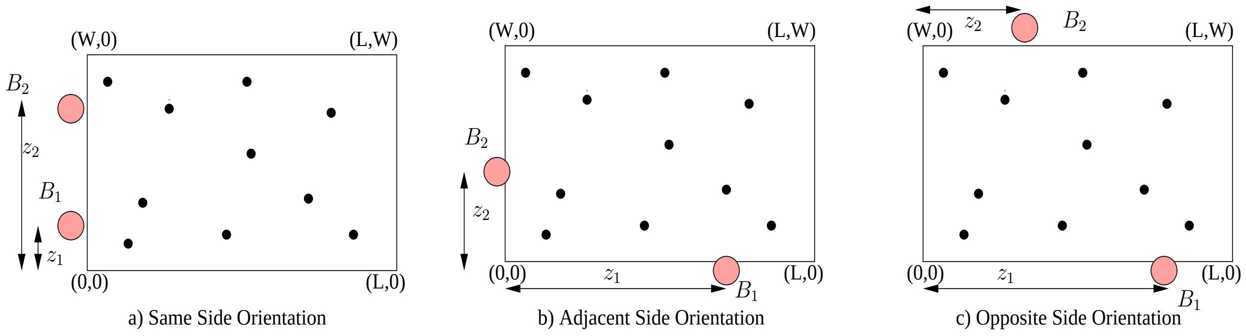

Figure5: *Placements of two base stations. a) Same side orientation, b) adjacent side orientation, and c) opposite side orientation*

- 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

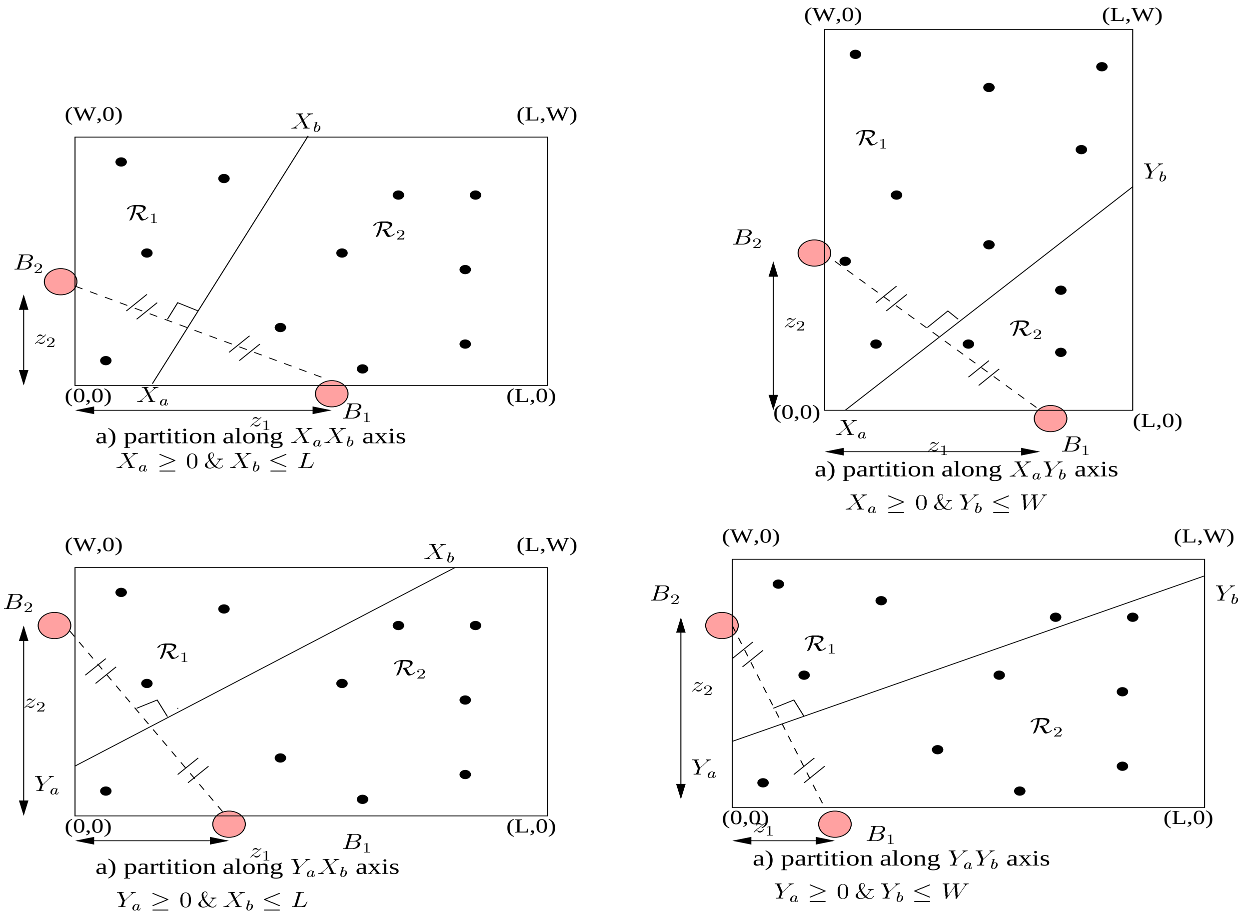

Figure6: *Adjacent side orientation of two base stations. $\mathcal{R}_1$, $\mathcal{R}_2$ partition can occur along a) X_aX_b axis, b) X_aY_b axis, c) Y_aX_b axis, and d) Y_aY_b axis.*

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

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

- 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

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

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

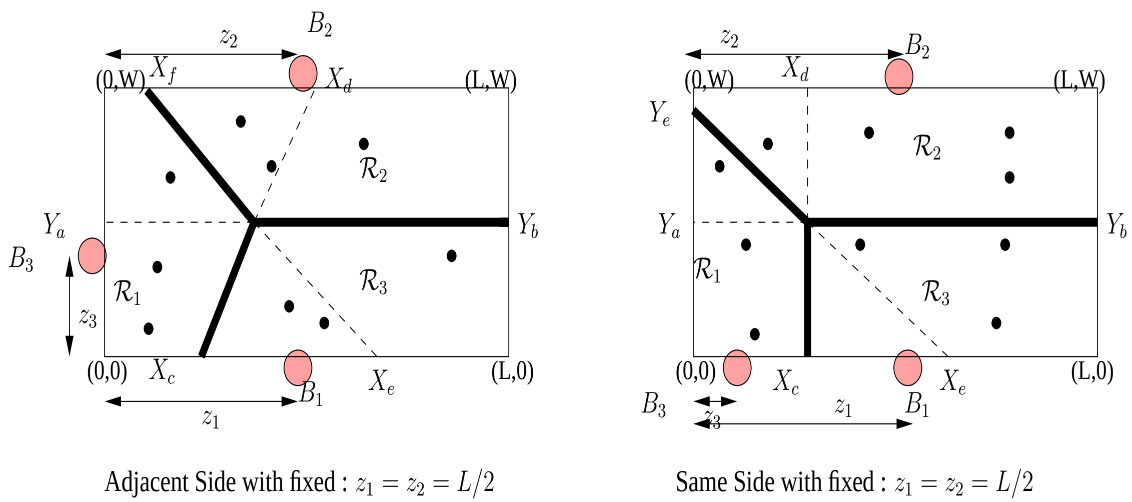

Figure7: *Placement of three base stations. B_1 and B_2 are placed at optimal locations obtained by solving the two base station problem. Location of B_3 is then optimized. a)B_3 on adjacent side of B_1. b) B_3 on same side as B_1.*

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 fixed 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

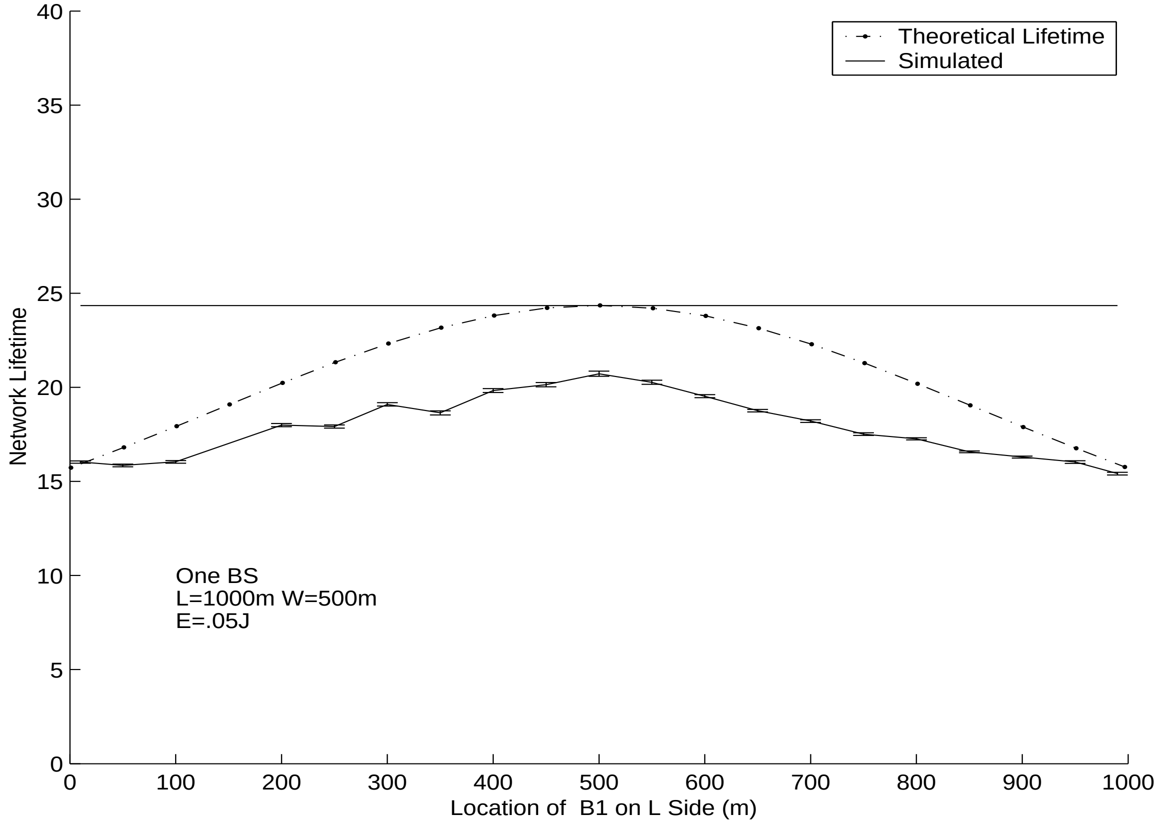

Figure 8: *Comparison of simulated network life time with theoretical upper bound for single base station case.* $L = 1000$ *m,* $W = 500$ *m,* $E_{battery} = 0.05$ *J. Location of* B_1 *varied from (0,0) to (1000,0)*

Simulation Results - Two BSs

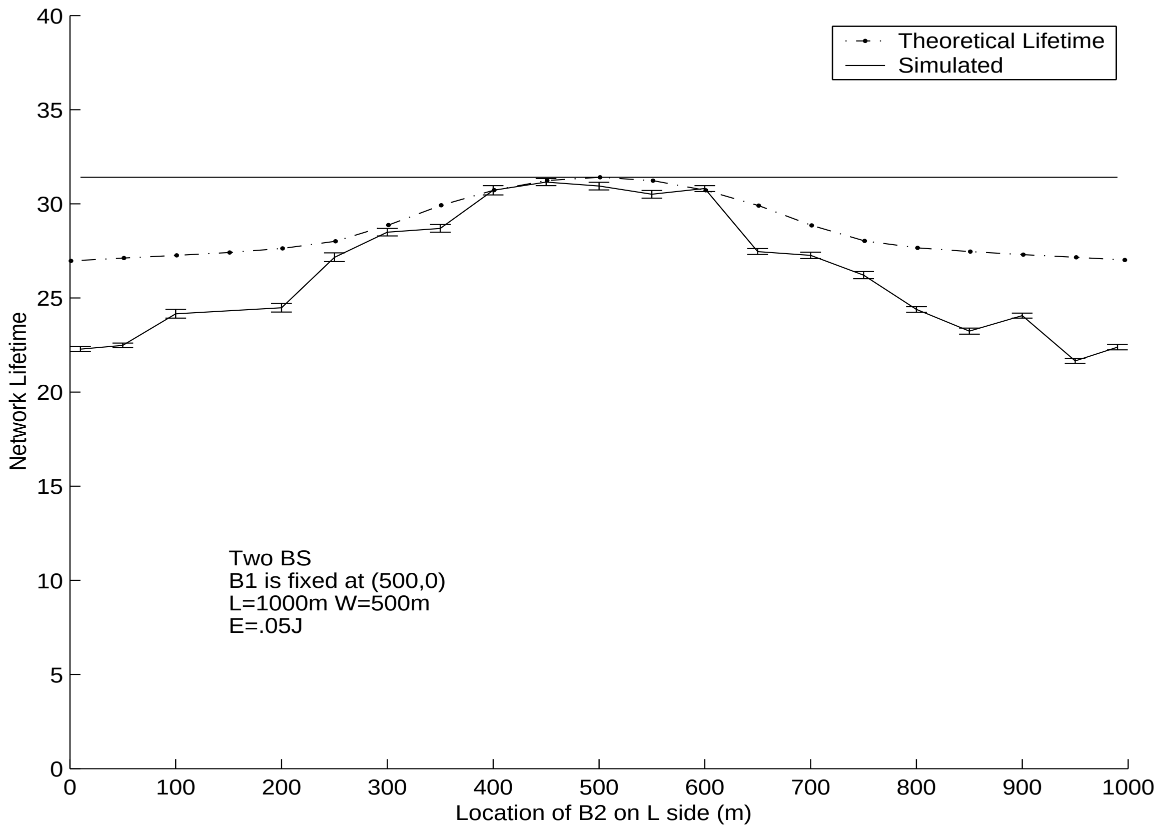

Figure 9: *Comparison of simulated network lifetime with theoretical upper bound for two base stations.* $L = 1000$ *m,* $W = 500$*,* $E_{battery} = 0.05$ *J.* B_1 *fixed at (500,0). Location of* B_2 *varied from (0,500) to (1000,500)*

Simulation Results - Three BSs

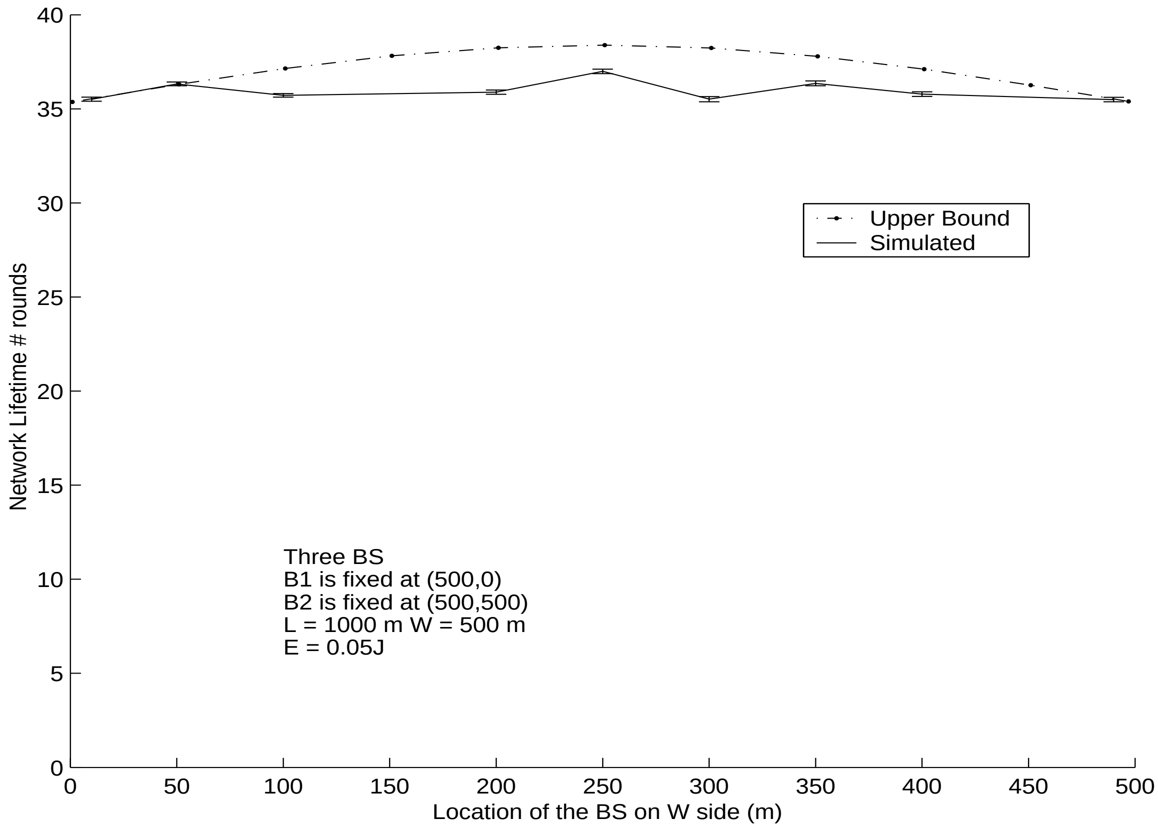

Figure 10: *Comparison of simulated network lifetime with theoretical upper bound for two base stations.* $L = 1000$ *m,* $W = 500$*,* $E_{battery} = 0.05$ *J.* B_1 *fixed at (500,0).* B_2 *fixed at (500, 500). Location of* B_3 *varied from (0,0) to (0,500)*

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

Thanks..