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

A. P. Azad and A. Chockalingam
Department of ECE, Indian Institute of Science, Bangalore 560012, India

***Abstract*— Employing multiple base stations is an attractive approach to enhance the lifetime of wireless sensor networks. In this paper, we address the fundamental question concerning the limits on the network lifetime in sensor networks when multiple base stations are deployed as data sinks. Specifically, we derive upper bounds on the network lifetime when multiple base stations are employed, and obtain optimum locations of the base stations (BSs) that maximize these lifetime bounds. For the case of two BSs, we jointly optimize the BS locations by maximizing the lifetime bound using a genetic algorithm based optimization. Joint optimization for more number of BSs is complex. Hence, for the case of three BSs, we optimize the third BS location using the previously obtained optimum locations of the first two BSs. We also provide simulation results that validate the lifetime bounds and the optimum locations of the BSs.**

Keywords – *Network lifetime, multiple base stations, optimal base station locations, energy efficiency.*

I. Introduction

Recently, employing multiple base stations as data sinks in order to enhance the lifetime of wireless sensor networks has received much research attention [1]-[6]. Multiple base stations approach is particularly attractive in scenarios where the data transport model is such that the data from sensor nodes need to be passed, on a multihop basis, to data collection platforms (i.e., data sinks/base stations). These platforms can be deployed within the sensing area if the sensing area is easily accessible (e.g., pollution or traffic monitoring). In case of remote/hostile sensing areas (e.g., battlefield surveillance), these platforms are expected to be deployed only along the boundary of the sensing area or far away from it. Each sensor node can send its data to any one of these base stations (may be to the base station towards which the cost is minimum). One key motivation to use multiple base stations (BSs) as data sinks (instead of a single BS) is that the average number of hops between data source-sink pairs gets reduced, which, in turn, can reduce the energy spent by a given sensor node for the purpose of relaying data from other sensor nodes towards the BS (i.e., reduce the overall energy spent for relaying purposes). This can potentially increase the network lifetime as well as the amount of data delivered during the lifetime, as has been shown, for example, in [5],[6],[7].

In the context of the above multiple BS scenario, a key issue that has not been addressed so far is the fundamental question concerning the limits on the network lifetime, which forms the focus of this paper. Analytical upper bounds on the network lifetime have been derived earlier, but only for single BS scenario [8],[9]. Our new contribution in this paper is that we derive upper bounds on the lifetime of sensor networks with multiple BSs, taking into account the region of observation, number of nodes, number of BSs, locations of BSs, radio path loss characteristics, efficiency of node electronics, and energy available in each node. In addition, we obtain optimum locations of the BSs that maximize these lifetime bounds. For a scenario with single BS and a rectangular region of observation, we obtain closed-form expressions for the network lifetime bound and the optimum BS location. For the case of two BSs, we jointly optimize the BS locations by maximizing the lifetime bound using a genetic algorithm based optimization. Joint optimization for more number of BSs is complex. Hence, for the case of three BSs, we optimize the third BS location using the previously obtained optimum locations of the first two BSs. We also provide simulation results that validate the network lifetime bounds and the optimal choice of the locations of the BSs.

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II. System Model

Network: We consider a sensor network comprising of sensor nodes distributed in a region of observation $\mathcal{R}$. The nodes are capable of sensing and sending/relaying data to a BS or a set of BSs using multihop communication. We assume that K BSs are deployed along the periphery of the region of observation to collect data from the nodes. Each node does sensing and processing, and the so generated data is sent to the BS(s). At any given time, the nodes are characterized as dead or alive depending on the energy left in their batteries as being below or above a usable threshold. Live nodes participate in sensing as well as sending/relaying data to the base station(s). While relaying data as an intermediate node in the path, the node simply forwards the received data without any processing.

Node Energy Behavior: Each node has a sensor, analog preconditioning and A/D conversion circuitry, digital signal processing and a radio [8]. The key energy parameters are the energies needed to $i)$ sense a bit (E_{sense}), $ii)$ receive a bit (E_{rx}), and $iii)$ transmit a bit over a distance d, (E_{tx}). Assuming a d^{η} path loss model where η is the path loss exponent

$$E_{tx} = \alpha_{11} + \alpha_2 d^{\eta}, \quad E_{rx} = \alpha_{12}, \quad E_{sense} = \alpha_3, \quad (1)$$

where α_{11} is the energy/bit consumed by the transmitter electronics, α_{12} is the energy/bit consumed by the receiver electronics, α_2 accounts for energy/bit dissipated in the transmit amplifier, and α_3 is the energy cost of sensing a bit [8]. Typically E_{sense} is much small compared to E_{tx} and E_{rx}. The energy/bit consumed by a node acting as a relay that receives data and then transmits it d meters onward is

$$E_{\text{relay}}(d) \;=\; \alpha_{11} + \alpha_2 d^{\eta} + \alpha_{12} \;=\; \alpha_1 + \alpha_2 d^{\eta}. \quad (2)$$

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where $\alpha_1 = \alpha_{11} + \alpha_{12}$. If r is the number of bits relayed per second, then energy consumed per second (i.e., power) is

$$P_{\text{relay}}(d) = r \cdot E_{\text{relay}}(d). \qquad (3)$$

We will use the following values for the energy parameters which are reported in the literature [8]: $\alpha_1 = 180$ nJ/bit and $\alpha_2 = 10$pJ/bit/m^2 (for $\eta = 2$) or 0.001pJ/bit/m^4 (for $\eta = 4$).

Battery and Network Lifetime: Each sensor node is powered by a finite-energy battery with an available energy of E_{battery} J at the initial network deployment. A sensor node ceases to operate if its battery is drained below a certain energy threshold. Often, network lifetime is defined as the time for the first node to die [8] or as the time for a certain percentage of network nodes to die. Here, as in [8], we define network lifetime as the time for the first node to die.

Given the region of observation ($\mathcal{R}$), number of nodes (N), node energy parameters (E_{battery}, $\alpha_1, \alpha_2, \alpha_3$), and path loss parameter (η), we are interested in i) deriving bounds on the NW lifetime when K, $K \geq 1$, BSs are deployed as data sinks, and ii) obtaining optimal locations of the BSs.

Minimum Energy Relay Theorem [8]: The bounding of network lifetimes often involves the problem of establishing a data link of certain rate r between a transmitter (A) and a receiver (B) separated by distance D meters. This can be done either by directly transmitting from A to B (single hop) or by 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* [8]. If $M - 1$ relays are introduced between A and B, i.e., M links between A and B (see Fig. 1), the overall rate of dissipation is given by

$$P_{\text{link}}(D) = \sum_{i=1}^{M} P_{\text{relay}}(d_i) - \alpha_{12}, \qquad (4)$$

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

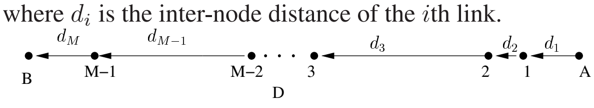

Fig. 1. $M - 1$ relay nodes between points A and B.

The following minimum energy relay theorem in [8] is relevant in the lifetime derivation for multiple BSs scenario.

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.

From the above and (4), the optimum number of hops (links) is the one that minimizes $MP_{\text{relay}}(D/M)$, and is given by

$$M_{opt} = \left\lfloor \frac{D}{d_{\text{char}}} \right\rfloor \text{ or } \left\lceil \frac{D}{d_{\text{char}}} \right\rceil, \qquad (5)$$

where the distance d_{char} is given by

$$d_{\text{char}} = \sqrt[\eta]{\frac{\alpha_1}{\alpha_2(\eta - 1)}}. \qquad (6)$$

That is, for a given distance D, there is an optimum number of relay nodes $(M_{opt} - 1)$; using more or less than this optimal number leads to energy inefficiencies. The energy dissipation rate of relaying a bit over distance D can be bounded as [8]

$$P_{\text{link}}(D) \geq \left(\alpha_1 \frac{\eta}{\eta - 1} \frac{D}{d_{\text{char}}} - \alpha_{12}\right) r \qquad (7)$$

with equality if and only if D is an integral multiple of d_{char}. From the minimum energy relay argument above, the actual 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 [8], i.e.,

$$P_{\text{nw}} \geq P_{\text{link}}(D) + P_{sense} = \left(\alpha_1 \frac{\eta}{\eta - 1} \frac{D}{d_{\text{char}}} - \alpha_{12}\right) r + \alpha_3 r. \quad (8)$$

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

III. Deriving Bounds on Network Lifetime

Consider a rectangular region of observation $\mathcal{R}$ with sensor nodes uniformly distributed in $\mathcal{R}$.

A. Single Base Station

First, consider the case of a single BS which is located on any one of the four sides of $\mathcal{R}$.

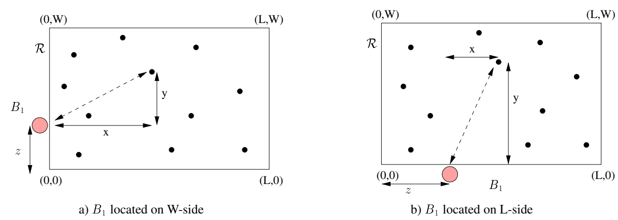

Fig. 2. Single BS placements. B_1 located a) on W-side, and b) on L-side.

Let the BS B_1 be located at a distance of z from the origin on the y-axis as shown in Fig. 2(a). Consider a source node in $\mathcal{R}$ at a distance of $D' = \sqrt{x^2 + y^2}$ from B_1. Denoting the energy dissipation in the entire NW for a given BS location z by $P_{\text{NW}}^{(z)}$, and taking uniform distribution of N nodes, we have

$$P_{\text{NW}}^{(z)} = N \int\int_{\mathcal{R}} P_{\text{nw}}(x, y) \frac{1}{WL}\, dx\, dy. \qquad (9)$$

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

$$\begin{aligned} P_{\text{NW}}^{(z)} &\geq \frac{N}{WL} \int_{-z}^{W-z} \int_{0}^{L} P_{\text{link}}\left(\sqrt{x^2 + y^2}\right) dx\, dy \\ &\geq r\alpha_1 \frac{\eta}{\eta - 1} \frac{d_{\text{one-BS}}(z)}{d_{\text{char}}}, \end{aligned} \qquad (10)$$

where

$$\begin{aligned} d_{\text{one-BS}}(z) &= \frac{N}{WL} \int_{-z}^{W-z} \int_{0}^{L} \sqrt{x^2 + y^2}\, dx\, dy \\ &= \frac{N}{12WL} \Bigg(4Lz\sqrt{L^2 + z^2} + 4L(W - z)\sqrt{L^2 + (W - z)^2} \\ &- (W - z)^3 \ln\left[\frac{(W - z)^2}{(L + \sqrt{L^2 + (W - z)^2})^2}\right] - z^3 \ln\left[\frac{z^2}{(L^2 + \sqrt{L^2 + z^2})^2}\right] \\ &+ 2L^3 \ln\left[W - z + \sqrt{L^{+}(W - z)^2}\right] \Bigg). \end{aligned} \qquad (11)$$

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

$$P_{\text{NW}}^{(z)} \mathcal{T}_{\text{one-BS}}^{(z)} \leq NE_{\text{battery}}. \qquad (12)$$

An upper bound on the network lifetime for a given BS location z is then given by [8]

$$\mathcal{T}_{\text{one-BS}}^{(z)} \leq \frac{NE_{\text{battery}}}{r\alpha_1 \frac{\eta}{\eta - 1} \frac{d_{\text{one-BS}}(z)}{d_{\text{char}}}}. \qquad (13)$$

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Now, optimal placement of the BS on the W-side in Fig. 2(a) can be obtained by choosing the z that maximizes the lifetime bound in (13), i.e.,

$$z_{\text{opt}}^{(W)} = \underset{z \in (0,W)}{\text{argmax}} \; \mathcal{T}_{\text{one-BS}}^{(z)}. \quad (14)$$

Maximizing (13) w.r.to z, we obtain the optimal BS location as $z_{opt}^{(W)} = W/2$, and substituting this in (11) gives a closed-form expression for $d_{\text{one-BS}}(z)$, which when substituted in (13) gives a closed-form expression for lifetime upper bound.

Likewise, the optimal BS location and the corresponding lifetime bound can be obtained for BS placement on the L-side as shown in Fig. 2(b) as $z_{opt}^{(L)} = L/2$, and the corresponding lifetime bound is obtained by simply interchanging W and L in the lifetime bound equation. It is seen that for $L > W$, the optimal BS location is the midpoint of the L-side, and for $L \leq W$ the optimal location is the midpoint of the W-side.

B. Two Base Stations

Next, consider the case of two BSs where the BSs B_1 and B_2 can be deployed in such a way that:

1) *1) Same side orientation (SSO):* Both BSs are on the same side as shown in Fig. 3 (a). There are four such possibilities (i.e., both BSs can be deployed on any one of the four sides).
2) *2) Adjacent side orientation (ASO):* One BS each on adjacent sides as in Fig. 3 (b). There are four such possibilities.
3) *3) Opposite side orientation (OSO):* One BS each on opposite sides as in Fig. 3 (c). There are two such possibilities.

It is noted that, in order to jointly optimize the locations of B_1 and B_2, the network lifetime bounds for all the above possibilities of base station placement need to be derived. Due to the symmetry involved in the rectangular region considered, one possibility for each orientation needs new derivation. In the following, we present the derivation for the three different orientations shown in Figs. 3 (a), (b), and (c). Derivation for other possibilities follow similarly due to symmetry.

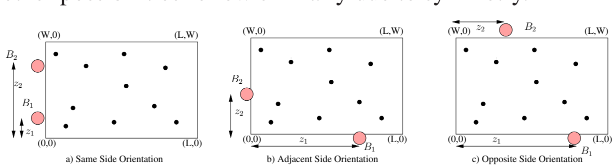

Fig. 3. Placements of two BSs. a) same side orientation (SSO), b) adjacent side orientation (ASO), and c) opposite side orientation (OSO).

Each node in the network must be associated with any one BS. For each node, this can be done by choosing that BS towards which energy spent for delivering data from that node is minimum. From the minimum energy relay argument, the minimum energy spent is proportional to the distance D between source node and the BS (see RHS of Eqn. (7)), and hence associating the node to its closest BS results in the least minimum energy spent. Accordingly, we associate each node with its closest BS. This results in the region $\mathcal{R}$ to be partitioned into two sub-regions $\mathcal{R}_1$ and $\mathcal{R}_2$ such that all nodes in sub-region $\mathcal{R}_1$ will be nearer to B_1 than B_2, and all nodes in sub-region $\mathcal{R}_2$ will be nearer to B_2 than B_1. It can be seen that this partitioning will occur along the perpendicular bisector of the line joining B_1 and B_2.

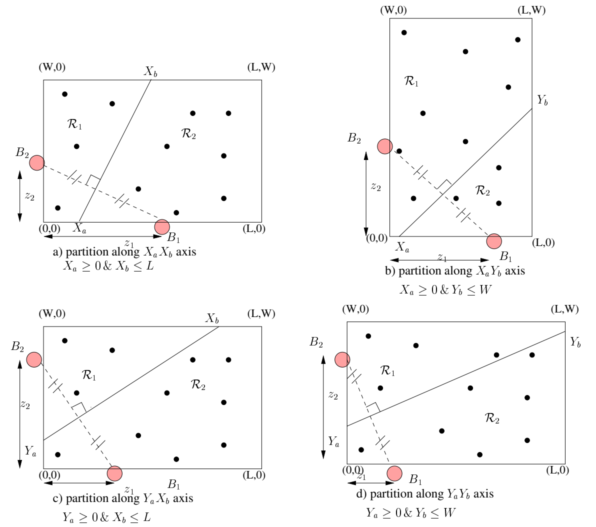

Fig. 4. Adjacent side orientation of two BSs. $\mathcal{R}_1$, $\mathcal{R}_2$ partition can occur along a) X_aX_b axis, b) X_aY_b axis, c) Y_aX_b axis, and d) Y_aY_b axis.

1) Derivation for Adjacent Side Orientation (ASO): We first consider the case of ASO shown in Fig. 3 (b), where B_1 is located on the x-axis at a distance of z_1 from the origin and B_2 is located on the y-axis at a distance of z_2 from the origin. The axis along which $\mathcal{R}_1, \mathcal{R}_2$ partition occurs depends on the locations of B_1 and B_2 (i.e., z_1 and z_2 in this case). For a given z_1 and z_2, the partition axis will belong to any one of the four possible axis types X_aX_b, X_aY_b, Y_aX_b and Y_aY_b as shown in Figs. 4 (a), (b), (c) and (d). The partition axis can be represented by the straight line

$$Y = mX + c, \quad (15)$$

where $m = \frac{z_1}{z_2}$ and $c = \frac{z_2^2 - z_1^2}{2z_2}$. Then, from (15) we have

$$X_a = X|_{Y=0} \implies X_a = -\frac{c}{m} = \frac{z_1^2 - z_2^2}{2z_1}, \quad (16)$$

$$X_b = X|_{Y=W} \Rightarrow X_b = \frac{W-c}{m} = \frac{Wz_2}{z_1} - \frac{z_2^2 - z_1^2}{2z_1}, \quad (17)$$

$$Y_a = Y|_{X=0} \implies Y_a = c = \frac{z_2^2 - z_1^2}{2z_2}, \quad (18)$$

$$Y_b = Y|_{X=L} \Rightarrow Y_b = mL + c = \frac{Lz_1}{z_2} + \frac{z_2^2 - z_1^2}{2z_2}. \quad (19)$$

It is noted that for a given z_1 and z_2, the partition axis type is
$i)$ X_aX_b if $X_a \geq 0$ and $X_b \leq L$ (Fig. 4(a)),
$ii)$ X_aY_b if $X_a \geq 0$ and $Y_b \leq W$ (Fig. 4(b)),
$iii)$ Y_aX_b if $Y_a \geq 0$ and $X_b \leq L$ (Fig. 4(c)), and
$iv)$ Y_aY_b if $Y_a \geq 0$ and $Y_b \leq W$ (Fig. 4(d)).

Now the energy dissipation in the entire network with BS locations z_1 and z_2 for the ASO case is given by

$$P_{\text{NW,aso}}^{(z_1,z_2)} = N\left(\iint_{\mathcal{R}_1} P_{\text{nw}}(x,y)\,\frac{1}{WL}\,dx\,dy + \iint_{\mathcal{R}_2} P_{\text{nw}}(x,y)\,\frac{1}{WL}\,dx\,dy\right). \quad (20)$$

By min. energy relay theorem, $P_{\text{nw}}(x,y) \geq P_{\text{link}}\left(\sqrt{x^2+y^2}\right)$. So

$$\begin{aligned} P_{\text{NW,aso}}^{(z_1,z_2)} &\geq \frac{N}{WL}\left(\int\int_{\mathcal{R}_1} P_{\text{link}}\left(\sqrt{x^2+y^2}\right)dx\,dy \right. \\ &\quad \left. + \int\int_{\mathcal{R}_2} P_{\text{link}}\left(\sqrt{x^2+y^2}\right)dx\,dy\right) \\ &\geq \frac{r\alpha_1}{d_{\text{char}}}\frac{\eta}{\eta-1}\frac{N}{WL}\left(d_{\text{2-BS,aso}}^{\mathcal{R}_1}(z_1,z_2) + d_{\text{2-BS,aso}}^{\mathcal{R}_2}(z_1,z_2)\right), \end{aligned} \quad (21)$$

where $d_{\text{2-BS,aso}}^{\mathcal{R}_1}(z_1,z_2)$ and $d_{\text{2-BS,aso}}^{\mathcal{R}_2}(z_1,z_2)$ are different for different partition axis types, and are of the form

$$d_{\text{2-BS,aso}}^{\mathcal{R}_1}(z_1,z_2) = \int_{y_1}^{y_2}\int_{x_1}^{x_2}\sqrt{x^2+y^2}\,dx\,dy + \int_{y_3}^{y_4}\int_{x_3}^{x_4}\sqrt{x^2+y^2}\,dx\,dy, \quad (22)$$

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Limits	For X_aX_b axis Fig.4(a)	For X_aY_b axis Fig.4(b)	For Y_aX_b axis Fig.4(c)	For Y_aY_b axis Fig.4(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 $x_1, x_2, \cdots, x_8$ in (22) and (23) for various partition axis types in Figs. 4 (a), (b), (c), and (d).

$$d^{\mathcal{R}_2}_{\text{2-BS,aso}}(z_1, z_2) = \int_{x_5}^{x_6}\int_{y_5}^{y_6}\sqrt{x^2+y^2}\,dy\,dx + \int_{x_7}^{x_8}\int_{y_7}^{y_8}\sqrt{x^2+y^2}\,dy\,dx. \quad (23)$$

Defining $X_{z_2} = X|_{Y=y+z_2}$ and $Y_{z_1} = Y|_{X=x+z_1}$ in (15), the values of the limits $y_1, y_2, \cdots, y_8$ and $x_1, x_2, \cdots, x_8$ in (22) and (23) for the various partition axis types in Figs. 4 (a), (b), (c), and (d) are tabulated in Table I.

Now, denoting $\mathcal{T}^{(z_1,z_2)}_{\text{2-BS,aso}}$ as the network lifetime with two BSs at locations z_1, z_2 for the ASO case, we have

$$P^{(z_1,z_2)}_{\text{NW,aso}}\,\mathcal{T}^{(z_1,z_2)}_{\text{2-BS,aso}} \leq NE_{\text{battery}}, \quad (24)$$

and hence an upper bound on lifetime for a given z_1 and z_2 and ASO can be obtained as

$$\mathcal{T}^{(z_1,z_2)}_{\text{2-BS,aso}} \leq \frac{NE_{\text{battery}}}{\frac{r\alpha_1}{d_{char}}\frac{\eta}{\eta-1}\frac{N}{WL}\left(d^{\mathcal{R}_1}_{\text{2-BS,aso}}(z_1,z_2) + d^{\mathcal{R}_2}_{\text{2-BS,aso}}(z_1,z_2)\right)}. \quad (25)$$

The optimum BS locations for ASO case that maximizes the above lifetime bound is then given by

$$\left(z_{1,\text{opt}}, z_{2,\text{opt}}\right)_{\text{aso}} = \underset{z_1\in(0,L),\ z_2\in(0,W)}{\text{argmax}} \mathcal{T}^{(z_1,z_2)}_{\text{2-BS,aso}}. \quad (26)$$

Following similar steps, we have derived lifetime bounds for SSO and OSO cases, $\mathcal{T}^{(z_1,z_2)}_{\text{2-BS,sso}}$ and $\mathcal{T}^{(z_1,z_2)}_{\text{2-BS,oso}}$, as well. Finally, the optimum locations of the BSs are chosen from the best locations of ASO, SSO and OSO cases, as

$$\left(z_{1,\text{opt}}, z_{2,\text{opt}}\right) = \underset{\substack{z_1\in(0,L),\\ z_2\in(0,W)\\ \text{orient}\,\in\,\{\text{aso,sso,oso}\}}}{\text{argmax}} \mathcal{T}^{(z_1,z_2)}_{\text{2-BS,orient}}. \quad (27)$$

2) Numerical Results for Two BSs: We carried out the optimization of (26) using genetic algorithm and obtained the network lifetime upper bound and the optimum BS locations. We present the network lifetime in terms of number of rounds where one round = 2000 secs. Same definition is adopted in the simulation results also. The results obtained for SSO, ASO, and OSO cases are given in Table II for $L = 1000$ m, $W = 500$ m, and $E_{battery} = 0.5$ J. From the above results, it can be observed that the maximum lifetime bound occurs when the base stations are placed with opposite side orientation (OSO) on the L-side, and the corresponding coordinates of the optimum locations of B_1 and B_2 are (716.6 m, 0 m) and (500 m, 282.6 m).

3) Jointly optimum vs Individually optimum: In the above optimization procedure, the locations of B_1 and B_2 are jointly optimized. Though such joint optimization is the best in terms of performance, its complexity is high. Also, such joint optimization will become prohibitively complex for more number of BSs. So, an alternate and relatively less complex solution

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	$(716.6, 0), (500, 282.6)$

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

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 BS locations. Two BSs. B_1 fixed at optimum location obtained from solving single BS problem. $L = 1000$m, $W = 500$m.

is to individually optimize B_1 and B_2, i.e., fix the location of B_1 at the optimal location obtained from the solution of the single BS problem and find the optimal location for B_2 and the corresponding lifetime bound. We carried out such an individual optimization for two BSs (by fixing BS B_1 at its individually optimum location $(L/2, 0)$), and the results of the optimization are given in Table III. From Table III, it can be seen that, as expected, the individually optimized solution results in reduced lifetime bound compared to the jointly optimized solution (e.g., 31.41 rounds vs 32.99 rounds for OSO). However, the individually optimized approach is attractive to solve the problem with more number of BSs. Like the jointly optimized solution, the individually optimized solution also results in the largest lifetime bound when the two BSs are deployed with opposite side orientation (OSO) on the L-side.

C. Three Base Stations

For the case of three BSs, jointly optimizing the locations of B_1, B_2, B_3 can be prohibitively complex. Hence, in solving the three BSs problem, we take the approach of fixing the previously optimized locations of B_1, B_2 obtained from the solution of two BS problem, and then optimize the location of B_3. Once the BSs B_1 and B_2 are fixed, the problem gets simplified to optimizing only over B_3 location. Fixing B_1 and B_2 on the midpoints of opposite sides (which is the individually optimum two BS solution), B_3 can be located on any one of four sides. Placement of B_3 with adjacent side orientation (ASO) and same side orientation (SSO) as shown in Figs. 5 (a) and (b), respectively, need to be considered separately. In each of these AS and SS orientation possibilities, the region $\mathcal{R}$ is partitioned into sub-regions $\mathcal{R}_1$, $\mathcal{R}_2$, and $\mathcal{R}_3$. The partition occurs along the three axes which are the perpendicular bisectors of the lines connecting the three different BS pairs as shown in Figs. 5(a) and (b). Similar to the two BS problem, we have derived expressions for the network lifetime upper bound for three BSs [7]. These expressions were then optimized using genetic algorithm to compute the lifetime upper bound as well as the optimum location of B_3. It has been found that the ASO of B_3 results in a larger lifetime bound compared to SSO, and that the maximum lifetime bound for ASO is 38.38 rounds and the optimum location at which this maximum occurs is $(0, 249.8)$ [7].

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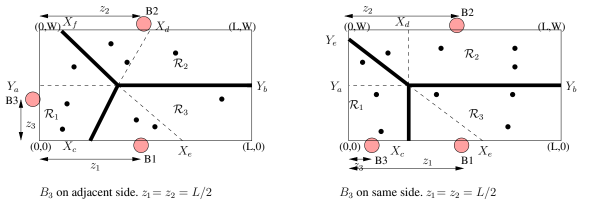

Fig. 5. Placement of three BSs. B_1 and B_2 are placed at optimal locations obtained by solving the two BS problem. Location of B_3 is then optimized. a) B_3 on adjacent side of B_1. b) B_3 on same side as B_1.

A comparison between the network lifetime bounds for one, two, and three BSs and their corresponding optimum BS locations are presented in Table IV. From Table IV, it can be observed that the lifetime bound increases for increasing number of BSs, as expected. For example, the lifetime bound is 24.3 rounds for one BS, whereas it gets increased to 38.4 rounds when three BSs are employed.

No. of BSs	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 IV: Comparison of the upper bounds on network lifetime for one, two, and three BSs. $L = 1000$ m, $W = 500$ m.

IV. Simulation Results

To validate the analytical bound on the network life time, we carried out detailed simulations and obtained the simulated network lifetime over several network realizations at different BS locations. In the simulations, 50 nodes are distributed uniformly in the rectangular region with $L = 1000$ m and $W = 500$ m. All nodes have an initial energy of 0.05 J. A modified version of the Minimum cost forwarding (MCF) routing protocol in [11] is employed to route packets from nodes to their assigned BSs. At the MAC level, Self-organizing Medium Access Control for Sensor networks (SMACS), a contention-free MAC protocol presented in [10] is employed to provide channel access for all the nodes. Data packets are of equal length. Each packet has 200 bits. Time axis is divided in to rounds, where each round consists of 300 frames. Each node generates 1 packet every 30 frames; i.e., 10 packets/round. For each network realization in the simulation, the number of rounds taken for the first node to die (i.e., NW lifetime in # rounds) is obtained. This lifetime averaged over several network realizations with 95% confidence is obtained for various number and locations of the BSs and plotted in Fig. 6.

Figure 6 compares the simulated network lifetimes with the theoretical upper bounds for one, two, and three BSs. In the one BS case, the B_1 location is varied from (0,0) to (1000,0). The theoretical analysis predicted that the maximum lifetime bound occurs at $L/2$ (i.e., (500,0) in this case). The simulated lifetime also is maximum at the B_1 location of (500,0). Also, the simulated lifetime is less than the analytical upper bound. The gap between the simulated lifetime and the upper bound implies that better protocols can be devised to achieve lifetimes closer to the bound. For the two BSs case, B_1 is fixed at (500,0) and the B_2 location is varied from (500,0) to (500,1000). Analytical prediction is that optimum B_2 location is (500,500). It is interesting to see that in the simulation also maximum network lifetime occurs when B_2 is located at (500,500). In addition, for the two BSs case, the protocols employed in the simulations are found to achieve lifetimes close to the upper bound. A similar observation can be made from Fig. 6 for the three BSs case as well. In summary, the simulations validate the analytical lifetime bounds derived, and also corroborate the expected result that network lifetime can be increased by the use of multiple BSs, and more so when their locations are chosen optimally.

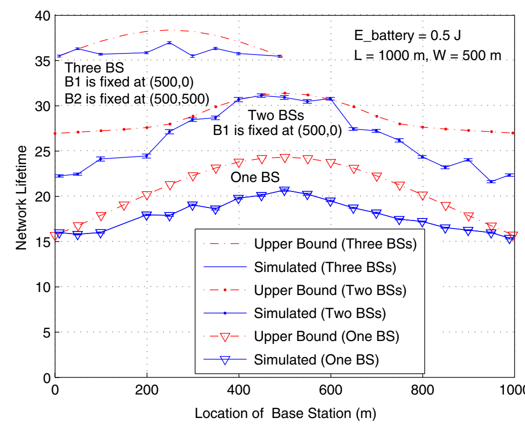

Fig. 6. Comparison of simulated network lifetime with theoretical upper bounds. $L = 1000$ m, $W = 500$ m, $E_{\text{battery}} = 0.5$ J. *a)* one BS: Location of B_1 varied from (0,0) to (1000,0); *b)* two BSs: B_1 fixed at (500,0) and location of B_2 varied from (0,500) to (1000,500); *c)* three BSs: B_1 fixed at (500,0), B_2 fixed at (500, 500) and B_3 varied from (0,0) to (0,500).

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