Upper Bounds on the Lifetime of Sensor Networks

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Abstract— **In this paper, we ask a fundamental question concerning the limits of energy efficiency of sensor networks - What is the upper bound on the lifetime of a sensor network that collects data from a specified region using a certain number of energy-constrained nodes? The answer to this question is valuable for two main reasons. First, it allows calibration of real world data-gathering protocols and an understanding of factors that prevent these protocols from approaching fundamental limits. Secondly, the dependence of lifetime on factors like the region of observation, the source behavior within that region, basestation location, number of nodes, radio path loss characteristics, efficiency of node electronics and the energy available on a node, is exposed. This allows architects of sensor networks to focus on factors that have the greatest potential impact on network lifetime. By employing a combination of theory and extensive simulations of constructed networks, we show that in all data gathering scenarios presented, there exist networks which achieve lifetimes equal to or >95% of the derived bounds. Hence, depending on the scenario, our bounds are either tight or near-tight.**

I. Introduction

RAPID commoditization and increasing integration of micro-sensors (MEMS), digital signal processing and low-range radio electronics on a single node has lead to the idea of distributed, wireless networks that have the potential to collect data more cost effectively, autonomously and robustly compared to a few macro-sensors [1], [2], [3]. Applications of such massively distributed sensor networks include seismic, acoustic, medical and intelligence data gathering and climate, equipment monitoring etc. Since these integrated sensor nodes have highly compact form factors and are wireless, they are highly energy constrained. Furthermore, replenishing energy via replacing batteries on up to tens of thousands of nodes (in possibly harsh terrain) is infeasible. Hence, it is well accepted that one of the key challenges in unlocking the potential of such data gathering sensor networks is conserving energy so as to maximize their post-deployment active lifetime [1].

Any effort to increase the network lifetime must necessarily be two-pronged. Firstly, the node itself must be made as energy efficient as possible [1], [4], [5]. Secondly, the *collaborative strategies* which govern how nodes cooperate to sense data must be energy efficient. Most work in this latter area has been directed towards energy-aware routing - both in the context of sensor and mobile ad-hoc networks (which share some of the characteristics of sensor networks). Some representative work in this area is [6], [7], [8], [9]. In this paper, our key objective is neither proposing new energy-aware routing heuristics nor new protocols. Instead, it is to explore the fundamental limits of data gathering lifetimes that these strategies strive to increase. Our motivation for doing so is several-fold. Firstly, bounds on achievable lifetime of sensor networks allow one to calibrate the performance of collaborative strategies and protocols being proposed regularly. Unlike strategies which are mostly heuristic due to the combinatorially explosive nature of the problem, the proposed bounds are crisp and widely applicable. Secondly, in order to prove that the proposed bounds are tight or near tight, we construct real networks and simulate data gathering and show that their lifetimes often come arbitrarily close to optimal. This exercise gives an insight into near-optimal data gathering strategies if the user has some level of deployment control. Thirdly, in bounding lifetime, we expose its dependence on source behavior, source region, basestation location, number of nodes, available initial energy, path loss and radio energy parameters. This allows us to see what factors have the most impact on lifetime and consequently where engineering effort is best expended.

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II. Terminology

We formally characterize a sensor network followed by the concept of network lifetime.

A. Data Gathering Sensor Networks

The goal of a sensor network is to gather information from a specified region of observation, say $\mathcal{R}$, and relay this to a *basestation* (B) or a set of basestations. This information originates due to one or more *sources* located in $\mathcal{R}$. At any given instant, nodes in a sensor network can be classified as *live* or *dead* depending on whether they have any energy left or not. Live nodes collaborate to ensure that whenever a source resides in $\mathcal{R}$, it is sensed and the resultant data relayed to the desired basestation(s). In the collaborative model we assume, live nodes play one of three roles:

- Sensor: The node observes the source via an integrated sensor, digitizes this information, post-processes it and produces data[1]. It is this data which needs to be relayed

[1]Hence, when we refer to "sensing" we mean all these operations,

back to the basestation.

- Relay: The node simply forwards the received data onward without any processing.
- Powered down: The node is live but does not participate in either sensing or relaying the data.

Note that nodes can change their roles dynamically with time (although their *locations* are fixed). Hence, a given node might be sensing a source for a while, but when the source moves to a different location, this node might act as a relay or power itself down. The figure below illustrates this collaborative behavior.

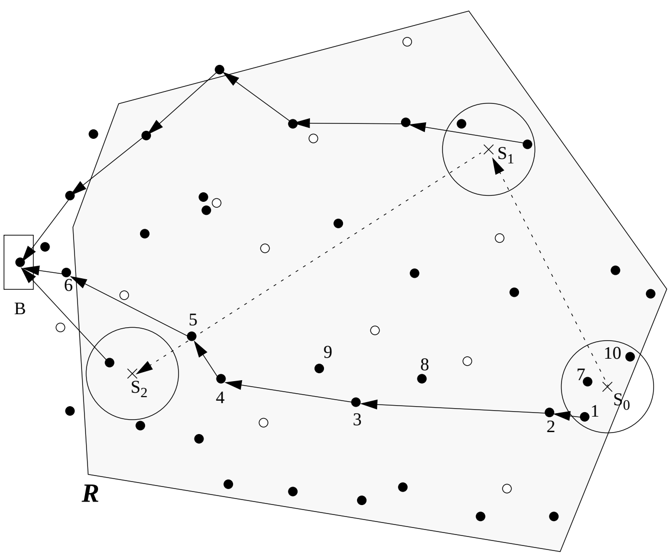

Fig. 1. A sensor network gathering data from a circularly observable source (denoted by a $\times$) residing in the shaded region $\mathcal{R}$. Live nodes are denoted by $\bullet$ and dead ones by $\circ$. The basestation is marked B. When the source is at S_0, node 1 acts as the sensor and nodes $2 \to 3 \to 4 \to 5 \to 6$ form the relay path. This is not the only possible role assignment that allows the source to be sensed. For instance, node 7 could act as the sensor and nodes $1 \to 2 \to 8 \to 9 \to 5$ could form the relay path. While nodes 1, 7 and 10 can all sense simultaneously, we assume in this paper that only one sensor needs to observe the source. Finally, note how the sensor and relay paths must change as the source moves from S_0 to S_1 to S_2.

B. Characterizing Source Behavior

In addition to specifying the region of observation and the topology of the network, it is necessary to specify how the source resides in $\mathcal{R}$. Barring few exceptions, the source behavior is *not* known in a deterministic sense at the time the network is deployed. Rather, one must make do with stochastic knowledge of source behavior. In this paper, we use a simple but effective stochastic model - the spatial probability distribution function (p.d.f.) of a source (denoted $l_{source}(x, y)$) with the usual properties,

$$\Pr(\text{Source} \in \mathcal{A}) = \iint_{\mathcal{A}} l_{source}(x, y)\,\mathrm{d}x\,\mathrm{d}y \qquad (1)$$

$$\iint_{\mathcal{R}} l_{source}(x, y)\,\mathrm{d}x\,\mathrm{d}y = 1 \qquad (2)$$

Next, it is important to note that sources have finite regions of observability. We assume circularly observable sources with a radius of observation equal to d_S. This implies that only live nodes less than d_S away can observe the source. Finally, we assume that observing a source entails relaying data at a certain *source rate* measured in bits per second.

C. Modelling Node Energy Behavior

Every node has a sensor, analog pre-conditioning and data conversion circuitry (A/D), digital signal processing and a radio link [4], [10]. Since we are dealing with nodes that are either sensors or pure relays (or powered down), the key energy parameters are the energy needed to sense a bit (E_{sense}), receive a bit (E_{rx}) and transmit a bit over a distance d (E_{tx}). Assuming a $1/d^n$ path loss [11], these take the form,

$$E_{tx} = \alpha_{11} + \alpha_2 d^n \qquad (3)$$

$$E_{rx} = \alpha_{12} \qquad (4)$$

$$E_{sense} = \alpha_3 \qquad (5)$$

where α_{11} is the energy/bit consumed by the transmitter electronics (including energy costs of imperfect duty cycling due to finite startup time), α_2 accounts for energy dissipated in the transmit op-amp (including op-amp inefficiencies), α_{12} is the energy/bit consumed by the receiver electronics and α_3 is the energy cost of sensing a bit. Hence, the energy consumed per second (i.e. power) by a node acting as a relay that receives data and then transmits it d meters onward is,

$$\begin{aligned} P_{relay}(d) &= (\alpha_{11} + \alpha_2 d^n + \alpha_{12})r \\ &\equiv (\alpha_1 + \alpha_2 d^n)r \qquad (6) \end{aligned}$$

where r is the number of bits relayed per second (or the *relay rate*). Typical numbers for current radios are α_1 = 180nJ/bit and α_2 = 10pJ/bit/m^2 (n=2) or 0.001pJ/bit/m^4 (n=4) [12].

III. The Lifetime Problem in Sensor Networks

Since nodes are deployed with finite, non-replenishable energy, a sensor network has a certain bounded lifetime beyond which it ceases to fulfill its contract of relaying information originating from any source in $\mathcal{R}$ to the basestation. In this paper, we measure network lifetime as the

and not just raw sensing.

cumulative active time to the *first* loss of coverage. We can now state the lifetime problem as follows:

The Lifetime Bound Problem: Given the region of observation ($\mathcal{R}$), the source radius of observability (d_S), the node energy parameters (α_1, α_2, α_3 and n), the number of nodes deployed (N), the initial energy in each node (E), what is the upper bound on the active lifetime ($\mathcal{L}$) of *any* network established using these nodes which gathers data from a source residing in $\mathcal{R}$ with spatial location behavior $l_{source}(x, y)$.

In the following sections, we solve this problem for a variety of source behavior. We also illustrate the tightness of these bounds by analytical construction and simulation.

IV. Characteristic Distance and Minimum Energy Relays

A recurring theme in bounding lifetimes of data gathering networks is the problem of establishing a data link with a certain rate r between a radio transmitter (at A) and a receiver (at B) separated by D meters. There are several ways of doing this. One can directly transmit from A to B or one can use several intervening nodes acting as *relays* to prevent any node from having to spend too much transmit energy. 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 we introduce $K-1$ relays between A and B (fig. 2), then the overall rate of dissipation is defined as:

$$P_{link}(D) = -\alpha_{12} + \sum_{i=1}^{K} P_{relay}(d_i) \tag{7}$$

The $-\alpha_{12}$ term accounts for the fact that the node at A need not spend any energy receiving. We disregard the receive energy needed at B because it is fixed regardless of the number of intervening relays.

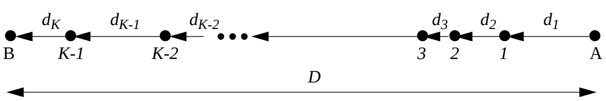

Fig. 2. Introducing $K-1$ relay nodes between A and B to reduce energy needed to transmit a bit.

Theorem 1: Given D and the number of intervening relays ($K-1$), $P_{link}(D)$ is minimized when all the hop distances (i.e. d_is) are made equal to $\frac{D}{K}$.

Proof: Since $P_{relay}(d)$ is strictly convex, the proof follows directly from Jensen's inequality.

Corollary: The minimum energy relay for a given distance D has either no intervening hops or K_{opt} *equidistant* hops where K_{opt} is completely determined by D. ∎

Theorem 2: The optimal number of hops (K_{opt}) is always one of,

$$K_{opt} = \left\lfloor \frac{D}{d_{char}} \right\rfloor \text{or} \left\lceil \frac{D}{d_{char}} \right\rceil \tag{8}$$

where the distance d_{char}, called the characteristic distance, is *independent of* D and is given by,

$$d_{char} = \sqrt[n]{\frac{\alpha_1}{\alpha_2(n-1)}} \tag{9}$$

Proof: The proof involves the optimization of $KP_{relay}(\frac{D}{K})$ w.r.t K and is omitted due to space constraints.

Corollary: The energy dissipation rate of a relaying a bit over distance D can be bounded thus:

$$P_{link}(D) \geq \left(\alpha_1 \frac{n}{n-1} \frac{D}{d_{char}} - \alpha_{12}\right) r \tag{10}$$

with equality if and only if D is an integral multiple of d_{char}. ∎

The corollary above makes several important points:

- For any loss index n, the energy costs of transmitting a bit can always be made *linear* with distance.
- For any given distance D, there is a certain optimal number of intervening nodes acting as relays that must be used (K_{opt}). Using more or less than this optimal number leads to energy inefficiencies.
- The most energy efficient relays result when D is an integral multiple of the characteristic distance.

V. Bounding Lifetime

We now derive the upper bounds on the lifetime of sensor networks for a variety of source behavior.

A. Fixed Point Source Activity

The simplest sensor network is one that harvests data from a single point source d_B away from the basestation as shown in figure 3.

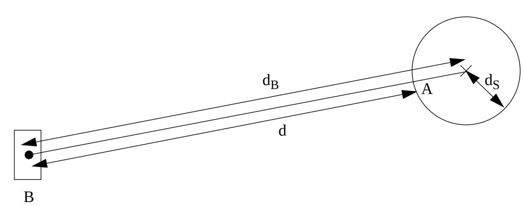

Fig. 3. Gathering data from a circularly observable fixed point source d_B away from the basestation (B). The source location is marked by ×.

It is easy to see that we have to establish a link of length equal to at least $d = d_B - d_S$ and sustain the source rate (say r) over this link. If we denote the energy dissipation in the *entire* network by $P_{network}$ then it follows from our discussion on minimum energy relays that,

$$P_{network} \geq P_{link}(d) + P_{sensing}$$
$$\geq \left(\alpha_1 \frac{n}{n-1} \frac{d}{d_{char}} - \alpha_{12}\right) r + \alpha_3 r \quad (11)$$

Clearly, achieving an *active* lifetime of say, $\mathcal{L}_{point}$, demands that the total energy consumed be no greater than the total energy available at the start, i.e.,

$$\mathcal{L}_{point} P_{network} \leq \sum_{i=1}^{N} e_i(0)$$

which reduces to,

$$\mathcal{L}_{point} \leq \frac{N.E}{\left(\alpha_1 \frac{n}{n-1} \frac{d}{d_{char}} - \alpha_{12} + \alpha_3\right) r} \quad (12)$$

for the case of a N node network with $e_i(0)$ (i.e. the energy of node i at deployment) set to E. While the bound in eqn. (12) is exact, we often use the following approximation noting that in most networks of practical significance, the cost of relaying data dominates,

$$\mathcal{L}_{point} \leq \mathcal{L}_{point_{max}} = \frac{N.E}{\alpha_1 \frac{n}{n-1} \frac{d}{d_{char}} r} \quad (13)$$

One can eliminate d_{char} in (13) to obtain,

$$\mathcal{L}_{point_{max}} = \frac{N.E}{\frac{n}{n-1} \sqrt[n]{\alpha_1^{n-1} \alpha_2 (n-1)} (d_B - d_S) r} \quad (14)$$

For the simplest path loss model ($n = 2$), this simplifies to,

$$\mathcal{L}_{point_{max}} = \frac{N.E}{2\sqrt{\alpha_1 \alpha_2} (d_B - d_S) r} \quad (15)$$

Theorem 3: The bound in eqn. (15) is tight when $d = d_B - d_S$ is an integral multiple of d_{char} and N is an integral multiple of $\frac{d}{d_{char}}$ i.e. with these conditions satisfied, there exist networks whose lifetime equals the upper bound.

Proof: We skip the proof due to space limitations. ■

To experimentally validate the derived bounds, a custom network simulator was used to simulate networks that gathered data from a point source using nodes with the energy behavior described earlier. Figure 4 charts the lifetimes achieved for networks with different values of N and d. As predicted, some networks do achieve a lifetime equal to the bound. The networks in figure 4 did *not* have random topologies. Rather, the networks and the collaborative strategies were designed with the express intention of defeating the upper bounds. Hence, the tightness apparent in figure 4 should not be interpreted as the lifetime expected of general networks but rather as the *best* possible lifetimes that *some* networks can achieve. Note that any network can achieve an arbitrarily poor lifetime and hence the issue of worst possible lifetime is vacuous.

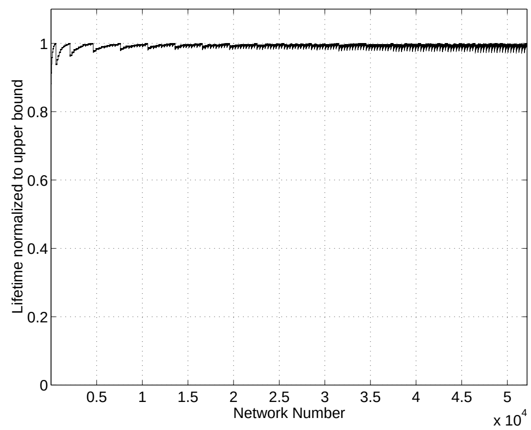

Fig. 4. Observed lifetimes of >50,000 actually constructed networks that gather data from a fixed point source. For each network, the lifetime was determined via simulation and then normalized to the upper bound in (13). These networks had $400 \geq N \geq 100$ and $20d_{char} \geq d_B - d_S \geq 0.1d_{char}$.

B. Activity Distributed Along a Line

We now consider the case of harvesting information from a source that is located along a line (S_0S_1) of length d_N as shown in figure 5. The minimal energy dissipation rate for sensing the source is[2],

$$P_{network}(x) \geq P_{link}(d(x)) \geq \frac{n}{n-1} \alpha_1 \frac{d(x)}{d_{char}} \quad (16)$$

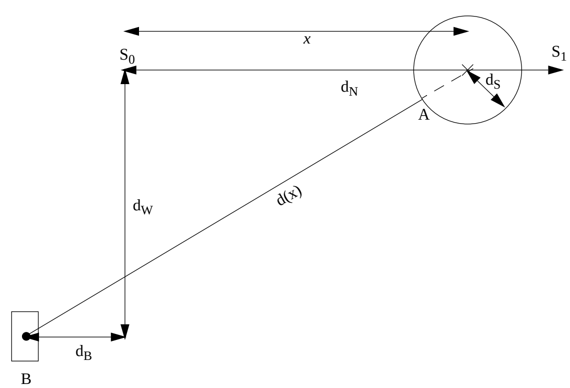

Fig. 5. Gathering data from a source that resides on a line (S_0S_1).

For the case when the source is located along S_0S_1 with equal probability $\frac{1}{d_N}$, the expected overall rate of dissipation for sensing is,

[2]Recall that we are ignoring the α_3 and $-\alpha_{12}$ term.

$$P_{network} \geq \int_{x=d_B}^{x=d_B+d_N} P_{network}(x) l_{source}(x)\mathrm{d}x$$
$$\geq \int_{x=d_B}^{x=d_B+d_N} \frac{n}{n-1}\alpha_1 \frac{d(x)}{d_{char}} \frac{1}{d_N}\mathrm{d}x$$
$$\geq \frac{n}{n-1}\alpha_1 \frac{d_{linear}}{d_{char}} \quad (17)$$

where,

$$d_{linear} = \frac{d_1 d_2 - d_3 d_4 + d_W^2 \ln(\frac{d_1+d_2}{d_3+d_4})}{2d_N} - d_S \quad (18)$$

Hence, the bound on the lifetime of a network gathering data from a source that resides on a line with equal probability is,

$$\mathcal{L}_{linear\,max} = \frac{N.E}{\frac{n}{n-1}\alpha_1 \frac{d_{linear}}{d_{char}}} \quad (19)$$

When $S_0 S_1$ passes through the basestation B i.e. $d_W = 0$ (or S_0, S_1 and B are collinear) we have,

$$\mathcal{L}_{collinear\,max} = \frac{N.E}{\frac{n}{n-1}\alpha_1 \frac{d_B + \frac{d_N}{2} - d_S}{d_{char}}} \quad (20)$$

Theorem 4: The bound for the collinear case (eqn. (20)) is tight when $2d_S$ and $d_B - d_S$ are both integral multiples of d_{char}, d_N is an integral multiple of $2d_S$ and N is an integral multiple of $\frac{d_N\left(d_B+\frac{d_N}{2}+d_S\right)}{2d_S d_{char}}$. The bounds for the general case (eqn. (19)) are *asymptotically tight* under the same conditions i.e. there exist networks which can come arbitrarily close to the derived bound.

Proof: We skip the proof due to space limitations. ■

Figure 6 plots the lifetime achieved by *non*-collinear networks gathering data from a source that resides along a line. For each simulated network, the lifetimes have been normalized to the upper bound in eqn. (19). Clearly, the bound is near tight.

C. Activity Distributed Over a Region

Consider harvesting information from a source that resides in a rectangle (fig. 7). Assuming $l_{source}(x,y)$ to be uniform, we have,

$$P_{network} = \iint_R P_{network}(x,y) l_{source}(x,y)\,\mathrm{d}x\,\mathrm{d}y$$
$$\geq \int_{x=d_B}^{x=d_B+d_N}\int_{y=-d_W}^{y=d_W} P_{link}(d(x,y))\frac{1}{2d_W d_N}\,\mathrm{d}x\,\mathrm{d}y$$
$$\geq \int_{x=d_B}^{x=d_B+d_N}\int_{y=-d_W}^{y=d_W} \frac{n}{n-1}\alpha_1 r \frac{\sqrt{x^2+y^2}-d_S}{2d_W d_N d_{char}}\,\mathrm{d}x\,\mathrm{d}y$$
$$\geq \frac{n}{n-1}\alpha_1 r \frac{d_{rect}}{d_{char}} \quad (21)$$

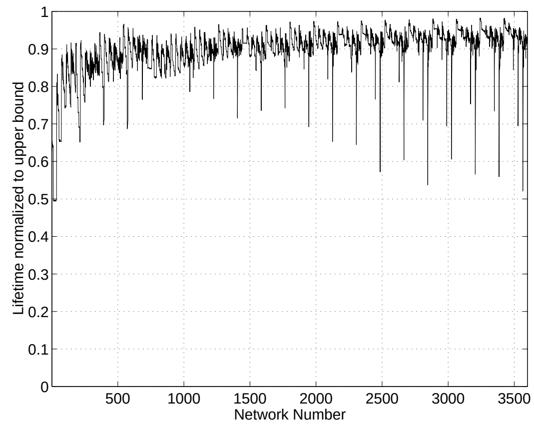

Fig. 6. Observed lifetimes of ≈3500 networks that gather data from a source residing on a line ($400 \geq N \geq 100$, $d_B \leq 10d_{char}$, $d_W \leq 7.5d_{char}$, $11d_{char} \geq d_N \geq d_{char}$, $1.5d_{char} \geq d_S \geq 0.25d_{char}$).

where

$$d_{rect} = -d_S + \frac{1}{12 d_N d_W}\Big[4d_W(d_1 d_2 - d_3 d_4) + \cdots$$
$$2d_W^3 \ln(\frac{d_1+d_2}{d_3+d_4}) + d_3^3\ln(\frac{d_4-d_W}{d_4+d_W}) + d_1^3 \ln(\frac{d_2+d_W}{d_2-d_W})\Big] \quad (22)$$

Hence, the bound on expected lifetime is,

$$\mathcal{L}_{rectangle_{max}} = \frac{N.E}{\frac{n}{n-1}\alpha_1 r \frac{d_{rect}}{d_{char}}} \quad (23)$$

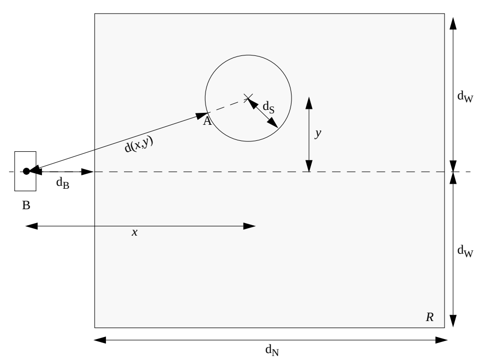

Fig. 7. Gathering data from a source that resides in a $2d_w$ by d_N rectangle that is d_B away from the basestation (B).

Figure 8 plots the lifetime of networks gathering data from sources that reside in rectangles. Once again, the lifetime of each network has been normalized to the bound in (23) and the tightness of the bound is apparent.

VI. Bounding Lifetime by Partitioning

The following theorem is useful in deriving lifetime bounds for source regions that can be partitioned into sub-regions for which the bounds are already known, or easier to compute.

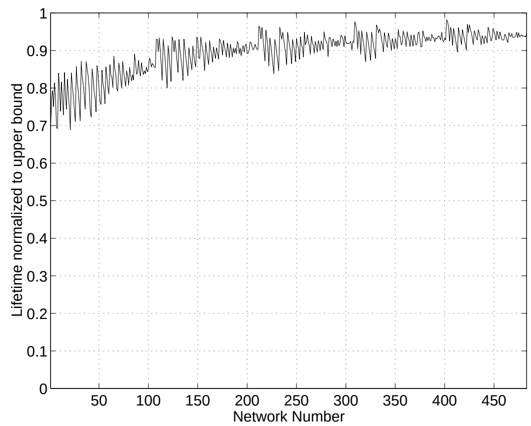

Fig. 8. Observed lifetimes of ≈500 networks that gather data from sources residing in rectangles ($1000 \geq N \geq 100$, $d_B \leq 10d_{char}$, $6.75d_{char} \geq 2d_W \geq 0.5d_{char}$, $13.5d_{char} \geq d_N \geq d_{char}$, $1.5d_{char} \geq d_S \geq 0.25d_{char}$).

Theorem 5: The lifetime of a network gathering data from a source region $\mathcal{R}$ that can be partitioned into P disjoint regions $\mathcal{R}_j, j \in [1, P]$ with their corresponding lifetime bounds, $\mathcal{L}(\mathcal{R}_j)$, can be bounded thus,

$$\mathcal{L}(R) = \left(\sum_{j=1}^{P} \frac{p_j}{\mathcal{L}(R_j)} \right)^{-1}$$

where p_j is the probability that a source resides in region R_j.

Proof: The result is derived by expressing the overall dissipation rate as a weighted sum of the dissipation rates of the sub-regions. We skip the details due to space constraints. ■

As an illustrative application, consider a source residing equiprobably along a line with the basestation's (i.e. B's) projection on S_0S_1 lying *within* the segment rather than outside it (fig. 9).

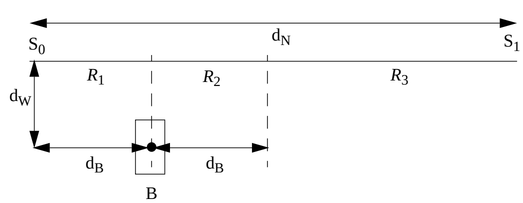

Fig. 9. Bounding lifetime when source moves along a line, but with basestation "between" S_0S_1.

While the lifetime expression derived in section 5.B (for sources residing on a line) can't be used directly, it can be used via partitioning $\mathcal{R}$ into three regions as shown in figure 9 thus,

$$\frac{d_N}{\mathcal{L}(R)} = \frac{d_B}{\mathcal{L}(\mathcal{R}_1)} + \frac{d_B}{\mathcal{L}(\mathcal{R}_2)} + \frac{d_N - 2d_B}{\mathcal{L}(\mathcal{R}_3)} \qquad (24)$$

Note that $\mathcal{L}(\mathcal{R}_1)$ (=$\mathcal{L}(\mathcal{R}_2)$) and $\mathcal{L}(\mathcal{R}_3)$ can both be obtained using eqn. (19).

VII. Conclusions

The key challenge in networks of energy constrained wireless integrated sensor nodes is maximizing network lifetime. In this paper, we derived fundamental upper bounds on the lifetime of data gathering sensor networks for a variety of scenarios assuming node energy models based on $1/d^n$ path loss behavior. Using both analytical arguments and extensive network simulations, the bounds were shown to be tight for some scenarios and near-tight (better than 95%) for the rest. Lastly, we presented a technique that allows bounding lifetime by partitioning the problem into sub-problems for which the bounds are already known or easier to derive. We hope that the work presented here will enable a rigorous understanding of the fundamental limits of the energy efficiency of wireless sensor networks.

Acknowledgments

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