Optimal Base Station Selection for Anycast Routing in Wireless Sensor Networks

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***Abstract*—Energy constraints have a significant impact on the design and operation of wireless sensor networks. This paper investigates the base station (BS) selection (or anycast) problem in wireless sensor networks. A wireless sensor network having multiple BSs (data sink nodes) is considered. Each source node must send all its locally generated data to only one of the BSs. To maximize network lifetime, it is essential to optimally match each source node to a particular BS and find an optimal routing solution. A polynomial time heuristic is proposed for optimal BS selection and anycast via a sequential fixing procedure. Through extensive simulation results, it is shown that this algorithm has excellent performance behavior and provides a near-optimal solution.**

***Index Terms*—Anycast, energy constraint, network lifetime, optimization, routing, wireless sensor networks.**

I. Introduction

WIRELESS sensor networks consist of battery-powered nodes that are endowed with a multitude of sensing modalities including multimedia (e.g., video and audio) and scalar data (e.g., temperature, pressure, light, magnetometer, and infrared). The demand for these networks is spurred by numerous applications that require *in situ*, unattended, high-precision, and real-time observations over a vast area. Although there have been significant improvements in processor design and computing, advances in battery technology still lag behind, making energy resource the fundamental constraint in wireless sensor networks.

As a result, there has been active research on exploring optimal flow routing strategies to maximize the lifetime of the network (see, e.g., [4], [6]). Network lifetime refers to the maximum time that all nodes in the network remain alive until one or more nodes drain up their energy. Most prior efforts assume that the mapping between a sensor node and one (or more) sink node is given *a priori*. For example, for a sensor network having only a single sink node [e.g., a base station (BS)] [3], [11], [14], all the data traffic generated by the sensor nodes will be delivered to this sink node. For a sensor network having multiple sink nodes, the data traffic generated by any sensor node may be split and sent to multiple different BSs [4], [6].

In cases when multiple BSs are present, there has been little research to date addressing optimal BS selection for anycast routing (AR), where anycast is defined as that each source node must send all its locally generated data to only one BS. This problem is relevant from both the application's perspective and the wireless networking perspective. From an application requirement perspective, for some real-time multimedia sensing applications (e.g., surveillance video), it is necessary to have all the traffic generated from a source node be routed to the same BS (albeit that they may be split into subflows traversing different paths) so that decoding and processing can be properly completed. This is because for multimedia traffic such as video, the information contained in different packets from the same source node are highly correlated and dependent. If packets generated by a source node are split and sent to different BSs, any of these receiving BSs may not be able to decode the video packets properly. From a wireless networking perspective and communication power consumption in particular, which BS is chosen as the destination sink node could have a significant impact on the overall network lifetime performance. This is because communication power consumption is topology dependent; the optimal flow routing strategy (to maximize network lifetime) depends on the particular mapping between a source node and a destination BS. As a result, there appears to be a compelling need to understand how to perform anycast in energy-constrained sensor networks.

In this paper, we investigate the optimal BS selection problem for anycast with the aim of maximizing network lifetime. We show that the joint BS selection and anycast flow routing problem can be formulated as a mixed integer nonlinear programming (MINLP) optimization problem. Since MINLP is NP-hard in general [9] and our BS selection problem is likely to be NP-hard as well, we develop a heuristic algorithm in the hope of providing good solutions.

To provide a measure for the quality of our proposed heuristic, we first explore computing a tight upper bound on the maximization problem by applying a suitable relaxation technique. With this upper bound as a performance measure, we move on to develop a heuristic algorithm. Our heuristic, called "ABS" for anycast BS selection, is based on the conjecture that the optimal BS for a node should be closely related to the BS that receives the largest amount of traffic volume when there is no constraint on the number of destination BSs. We employ a sequential fixing procedure to find the optimal BS for each node. Numerical results show that the ABS algorithm yields a solution that has an objective value very close to the upper

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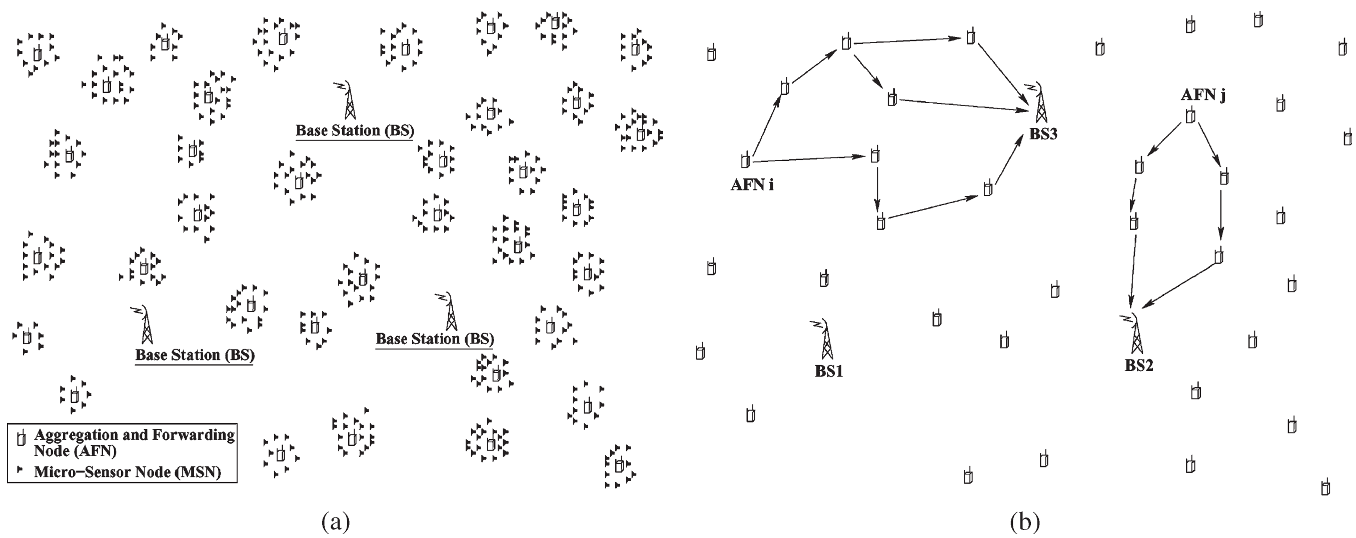


Fig. 1. Reference network model. (a) Physical network consisting of BSs, AFNs, and MSNs. (b) Two examples for anycast between an AFN and a BS.

bound produced by our relaxation procedure, hence suggesting that the solution offered by our heuristic algorithm must be even closer to the optimal solution.

The remainder of this paper is organized as follows. In Section II, we first describe the reference network model, which is based on a two-tier architecture. Our focus is to study optimal BS selection and anycast flow routing for the upper-tier aggregation and forwarding nodes (AFNs). We describe the power consumption behavior for AFNs and introduce the anycast optimization problem that we plan to investigate. In Section III, we formulate the anycast problem as an MINLP problem. Then, we develop an upper bound for this MINLP problem as a performance measure for any heuristic algorithm. Since the BS selection problem is likely to be NP-hard as well, in Section IV we develop a heuristic algorithm (ABS) to the anycast problem. In Section V, we offer extensive simulation results and show that the ABS algorithm is able to offer near-optimal solution. Section VI reviews related work and Section VII concludes this paper.

II. Reference Network Model and Problem Description

A. Reference Network Model

We consider a two-tier architecture for wireless sensor networks [7], [18]. Fig. 1(a) shows the physical network topology for such a network. There are three types of nodes in the network, namely, 1) microsensor nodes (MSNs), 2) AFNs, and 3) BSs. MSNs can be application-specific sensor nodes [e.g., temperature sensor nodes (TSNs), pressure sensor nodes (PSNs), and video sensor nodes (VSNs)] and constitute the lower tier of the network. They are small and low cost, and are deployed in groups (or clusters) at strategic locations for sensing applications. The objective of an MSN is to collect data and send it directly to the local AFN.

For each cluster of MSNs, there is one AFN that is different from an MSN in terms of physical properties and functions. The primary functions of an AFN are 1) data aggregation (or "fusion") for information flows coming from the local cluster of MSNs, and 2) forwarding (or relaying) the aggregated information to the next hop AFN (toward a BS). For data fusion, an AFN analyzes the content of each data stream (e.g., video) it receives, from which it composes a complete scene by exploiting the correlation among each individual data stream from the MSNs [7]. After data fusion, the aggregated bit rate from an AFN i (denoted as g_i) will be forwarded to a base station in either single or multiple hops. Although an AFN is expected to be provisioned with much more energy than an MSN, it also consumes energy at a substantially higher rate (due to wireless communication over large distances). Consequently, an AFN has a limited lifetime. Upon depletion of energy at an AFN, we expect that the sensing coverage for the particular area is lost despite the fact that some of the MSNs within the cluster may still have remaining energy.

The third component in the two-tier architecture is the BS. Essentially, BSs are the sink nodes for all the data collected in the network. In this investigation, we assume that there is sufficient energy resource available at a BS, and thus, there is no energy constraint for BS.

In summary, the main functions of the lower-tier MSNs are data acquisition while the upper-tier AFNs are used for data fusion and wireless networking for relaying sensing information to the BS. Our focus in this paper is on upper tier wireless multihop communications among AFNs and BSs via anycast. Table I lists notation used in this paper.

B. Power Consumption Model

As described, for AFN i, the aggregate bit rate generated locally is g_i, $i = 1, 2, \ldots, N$, which must be routed toward a BS. For an AFN, the energy consumption due to wireless communication (i.e., receiving and transmitting) is considered the dominant source in power consumption [1]. The power dissipation at a radio transmitter can be modeled as

$$p_t(i,k) = c_{ik} \cdot f_{ik} \tag{1}$$

TABLE I
NOTATION

Symbols	Definitions
N	The number of AFNs in the network
M	The number of base stations in the network
(x_i, y_i)	The location coordinates of AFN i
e_i	The initial energy at AFN i
g_i	The locally generated data rate at AFN i
ρ	Power consumption coefficient for receiving data
c_{ik}	Power consumption coefficient for transmitting data from AFN i to node k
α, β	Two constant terms in power consumption for transmitting data
d_{ik}	Physical distance between AFN i and node k
$f_{A_i A_j}^{A_k B_l}$ (or $f_{A_i B_l}^{A_k B_l}$)	The flow rate from AFN i to AFN j (or base station l) with the source and destination being AFN k and base station l
$\mathcal{F}_{AA}$ (or $\mathcal{F}_{AB}$)	The set of flows from an AFN to another AFN (or a base station)
$\mathcal{F}_{\mathcal{A}A_i}$	The set of in-coming flows to AFN i
$\mathcal{F}_{A_i\mathcal{A}}$ (or $\mathcal{F}_{A_i\mathcal{B}}$)	The set of out-going flows from AFN i to another AFN (or a base station)
$\lambda^{A_i B_l}$	If the data generated by AFN i will be transmitted to base station l, then $\lambda^{A_i B_l} = 1$; otherwise $\lambda^{A_i B_l} = 0$
$V_{A_i A_j}^{A_k B_l}$ (or $V_{A_i B_l}^{A_k B_l}$)	The data volume (in bits) transported from AFN i to AFN j (or base station l) with the source and destination being AFN k and base station l
$\mathcal{V}_{AA}$ (or $\mathcal{V}_{AB}$)	The set of volumes from an AFN to another AFN (or a base station)
$\mathcal{V}_{\mathcal{A}A_i}$	The set of in-coming volumes to AFN i
$\mathcal{V}_{A_i\mathcal{A}}$ (or $\mathcal{V}_{A_i\mathcal{B}}$)	The set of out-going volumes from AFN i to another AFN (or a base station)
$\mu^{A_i B_l}$	$= \lambda^{A_i B_l} T$ in LP-Relax
T_{UB}	An upper bound for the anycast network lifetime
$d(k)$	The destination base station for AFN k under ABS algorithm
T_{ABS}	Network lifetime under the ABS algorithm
T_{nearest}	Network lifetime under the nearest base station selection approach
T_{random}	Network lifetime under the random base station selection approach
L_{ABS}	$= \frac{T_{\text{ABS}}}{T_{\text{UB}}}$, normalized network lifetime under the ABS algorithm
L_{nearest}	$= \frac{T_{\text{nearest}}}{T_{\text{UB}}}$, normalized network lifetime under the nearest base station selection approach
L_{random}	$= \frac{T_{\text{random}}}{T_{\text{UB}}}$, normalized network lifetime under the random base station selection approach

where $p_t(i,k)$ is the power dissipated at AFN i when it is transmitting to node k, f_{ik} is the bit rate transmitted from AFN i to node k, and c_{ik} is the power consumption cost of radio link (i,k) and can be modeled as

$$c_{ik} = \alpha + \beta \cdot d_{ik}^m \tag{2}$$

where α and β are constants, d_{ik} is the distance between node i and node k, and m is the path loss index, with $2 \le m \le 4$ [20]. Example values for these parameters are $\alpha = 50$ nJ/b and $\beta = 0.0013$ pJ/b/m^4 (for $m = 4$) [10].[1] Since the power level of an AFN's transmitter can be used to control the distance coverage of an AFN (see, e.g., [19] and [21]), different network flow routing topologies can be formed by adjusting the power level of each AFN's transmitter. Therefore, throughout this paper, whenever we have a flow routing topology, we assume that the power level at the underlying physical node is also adjusted accordingly to achieve the corresponding internodal communications.

The power dissipation at a receiver can be modeled as [20]

$$p_r(i) = \rho \sum_{k \ne i} f_{ki} \tag{3}$$

where $\sum_{k \ne i} f_{ki}$ (in bit per second) is the aggregate rate of the received data streams by AFN i. A typical value for the parameter ρ is 50 nJ/b [10].

[1] In this paper, we use $m = 4$ in all of our numerical results.

C. Optimal BS Selection for AR: Problem Description

The anycast problem we investigate in this paper involves an optimal mapping between an AFN and a BS such that the network lifetime can be maximized. There are two components that are deeply coupled in this problem. The first component involves the mapping between each AFN and a particular BS. The second component deals with how to perform flow routing for a given mapping such that the network lifetime can be maximized. Many existing papers on optimal flow routing (e.g., [3] and [6]) only addressed the second component of this problem, i.e., assuming that the mapping between an AFN and one (or more) BS is known *a priori*. However, when the mapping is not given, the joint problem of base selection and flow routing (so that the network lifetime can be maximized) is an interesting and nontrivial problem. In addition to its intellectual interest, there are also important application scenarios that motivate us to pursue this problem. In particular, for certain applications (e.g., surveillance video), it is necessary to forward all bit streams generated by an AFN to the same BS (instead of to different BSs). This is because partial data streams from a video source may not be properly decoded and processed at a BS.

It is worth noting that AR is different from single path routing. That is, although we mandate that all bit streams generated by an AFN must be relayed to the same BS, the bit stream can be split into subflows and sent to the same BS through different paths [see Fig. 1(b)]. Although doing so will result in delay jitter and thus require playout buffer at the BS, this approach will be much more flexible and energy "wise" than mandating to send all the data from a source node to a BS along a single path.

III. Problem Formulation and an Upper Bound for Optimal Solution

A. Problem Formulation

For the BS selection/AR problem, denote $f_{A_iA_j}^{A_kB_l} \in \mathcal{F}_{\mathcal{A}A}$ as the flow (in bit per second) from AFN i to relay node AFN j with the source and destination of the flow being AFN k and BS l, where $\mathcal{F}_{\mathcal{A}A} = \{f_{A_iA_j}^{A_kB_l} : 1 \le i, j, k \le N, i \ne j, k \ne j, 1 \le l \le m\}$. Similarly, denote $f_{A_iB_l}^{A_kB_l} \in \mathcal{F}_{\mathcal{A}B}$ as the flow from AFN i to BS l with the source and destination of the flow being AFN k and BS l, where $\mathcal{F}_{\mathcal{A}B} = \{f_{A_iB_l}^{A_kB_l} : 1 \le i, k \le N, 1 \le l \le m\}$.

To formulate the optimization problem for the joint BS selection and anycast flow routing problem, we need to keep track of the incoming and outgoing flows at each AFN. Denote the set of incoming flows to AFN i as $\mathcal{F}_{\mathcal{A}A_i}$, the set of outgoing flows from AFN i to other AFNs as $\mathcal{F}_{A_i\mathcal{A}}$, and the set of outgoing flows from AFN i to BSs as $\mathcal{F}_{A_i\mathcal{B}}$. Then we have $\mathcal{F}_{\mathcal{A}A_i} = \{f_{A_mA_i}^{A_kB_l} : 1 \le m, k \le N, m \ne i, k \ne i, 1 \le l \le m\}$, $\mathcal{F}_{A_i\mathcal{A}} = \{f_{A_iA_r}^{A_kB_l} : 1 \le r, k \le N, r \ne k, r \ne i, 1 \le l \le m\}$, and $\mathcal{F}_{A_i\mathcal{B}} = \{f_{A_iB_l}^{A_kB_l} : 1 \le k \le N, 1 \le l \le m\}$. Denote T as the network lifetime, which is defined as the time until any AFN drains its energy. Then the optimization problem for the BS selection and AR can be formulated as the Problem BS-AR, shown in (4)–(7) at the bottom of the page.

Note that $\lambda^{A_iB_l}$ is a binary variable used for BS selection: if the data stream generated by AFN i will be transmitted to BS l, then $\lambda^{A_iB_l} = 1$; otherwise, $\lambda^{A_iB_l} = 0$. The set of constraints in (4)–(7) can be interpreted as follows. The set of constraints in (4) focuses on traffic flow generated locally at each AFN i. They state that, for each AFN i, if BS l is the destination, then the locally generated bit rate (i.e., g_i) will be equal to the outgoing data flows from AFN i toward BS l via a single hop (i.e., $f_{A_iB_l}^{A_iB_l}$) or multihop (i.e., $f_{A_iA_r}^{A_iB_l}$); otherwise, all flows corresponding to the source–destination pair (A_i, B_l) must be zero. The set of constraints in (5) focus on the traffic that uses AFN i as a relay node. They state that at each relay node i, the total amount of incoming traffic (i.e., $\sum_{m\ne i} f_{A_mA_i}^{A_kB_l}$) should be the same as the total amount of outgoing traffic (i.e., $\sum_{r\ne i,k} f_{A_iA_r}^{A_kB_l} + f_{A_iB_l}^{A_kB_l}$) for each source–destination pair (A_i, B_l). The set of constraints in (6) concerns energy consumption at AFN i. They state that, for each AFN i, the energy consumption due to transmitting and receiving [see (1) and (3)] over the course of the network lifetime should not exceed the initial energy provision e_i. Note that in (6) both flows generated locally at AFN i and those flows that use AFN i as the relay node are included. Finally, the remaining two sets of constraints enforce that AFN i can only transmit all of its data to one BS under our anycast requirement, along with the logical restrictions on the optimization variables $\lambda^{A_iB_l}$, $f_{A_iA_j}^{A_kB_l}$, and $f_{A_iB_l}^{A_kB_l}$. Note that ρ, g_i, e_i, $c_{A_iA_r}$, and $c_{A_iB_l}$ are all constants in this optimization problem.

The formulation of problem BS-AR is a mixed-integer nonlinear programming (MINLP) problem, which is, unfortunately, NP-hard in general [9]. Although we do not have a formal proof in this paper, we conjecture that our BS-AR problem is also NP-hard. Although there exists software (e.g., BARON [2]) to solve such problems, the solutions are obtainable only for small networks. As a result, we pursue a heuristic algorithm to address this problem.

In addition to designing a heuristic that offers a lower bounding solution, we also develop an upper bound to this problem, which can be used as a measure for the quality of the heuristic solution obtained. In particular, if our heuristic produces a solution close to this upper bound, then the solution offered by the heuristic must be even closer to the actual optimal solution, hence demonstrating its performance.

B. Upper Bound for Optimal Solution

In this section, we develop an upper bound for the BS-AR problem (see Section III-A) by studying a closely related problem that can be formulated and solved via linear programming (LP). This process involves two steps. As the first step, we

Problem BS-AR

Max T

$$\text{s.t.} \sum_{r\ne i} f_{A_iA_r}^{A_iB_l} + f_{A_iB_l}^{A_iB_l} - g_i\lambda^{A_iB_l} = 0 \qquad (1 \le i \le N, 1 \le l \le M) \tag{4}$$

$$\sum_{r\ne i,k} f_{A_iA_r}^{A_kB_l} + f_{A_iB_l}^{A_kB_l} - \sum_{m\ne i} f_{A_mA_i}^{A_kB_l} = 0 \qquad (1 \le i \le N, 1 \le l \le M, 1 \le k \le N, k \ne i) \tag{5}$$

$$\left[\sum_{f_{A_iA_r}^{A_kB_l} \in \mathcal{F}_{A_i\mathcal{A}}} c_{A_iA_r} f_{A_iA_r}^{A_kB_l} + \sum_{f_{A_iB_l}^{A_kB_l} \in \mathcal{F}_{A_i\mathcal{B}}} c_{A_iB_l} f_{A_iB_l}^{A_kB_l} + \sum_{f_{A_mA_i}^{A_kB_l} \in \mathcal{F}_{\mathcal{A}A_i}} \rho f_{A_mA_i}^{A_kB_l}\right] T \le e_i \qquad (1 \le i \le N) \tag{6}$$

$$\sum_{1\le l\le M} \lambda^{A_iB_l} = 1 \qquad (1 \le i \le N) \tag{7}$$

$$T, f_{A_iA_j}^{A_kB_l}, f_{A_iB_l}^{A_kB_l} \ge 0, \lambda^{A_iB_l} = 0 \text{ or } 1 \qquad \left(f_{A_iA_j}^{A_kB_l} \in \mathcal{F}_{\mathcal{A}A}, f_{A_iB_l}^{A_kB_l} \in \mathcal{F}_{\mathcal{A}B}, 1 \le i, j, k \le N, i \ne j, k \ne j, 1 \le l \le M\right)$$

relax the binary requirement on $\lambda^{A_i B_l}$ by letting $\lambda^{A_i B_l}$ be a real number with $\lambda^{A_i B_l} \in [0,1]$. Consequently, the integer component in the MINLP problem disappears and we now have a nonlinear programming (NLP) formulation. Apparently, the solution to this NLP formulation gives an upper bound to the BS-AR problem since the continuous relaxation of $\lambda^{A_i B_l}$ only increases the solution space to the original BS-AR problem. Under this NLP problem, we allow the data from AFN i to be sent to multiple BSs instead of to just one BS. The fraction is determined by $\lambda^{A_i B_l}$, i.e., AFN i sends a fraction of $\lambda^{A_i B_l}$ of its data to BS l.

Although the resulting bilinear problem is still NP-hard in general [9], the particular structure of problem BS-AR permits it to be transformed into a linear programming. To see this, let us multiply (4)–(7) by T and then use the linearizing substitutes $V_{A_iA_j}^{A_kB_l} = T \cdot f_{A_iA_j}^{A_kB_l}$, $V_{A_iB_l}^{A_kB_l} = T \cdot f_{A_iB_l}^{A_kB_l}$, and $\mu^{A_iB_l} = T \cdot \lambda^{A_iB_l}$. Also, denote $\mathcal{V}_{AA}$ as the set of traffic volumes being transported among the AFNs (i.e., the $V_{A_iA_j}^{A_kB_l}$ variables) and $\mathcal{V}_{AB}$ as the set of traffic volumes being transported between AFNs and BSs (i.e., the $V_{A_iB_l}^{A_kB_l}$ variables). Furthermore, for each AFN i, denote $\mathcal{V}_{\mathcal{A}A_i}$ as the set of in-coming traffic volumes (i.e., the $V_{A_mA_i}^{A_kB_l}$ variables), $\mathcal{V}_{A_i\mathcal{A}}$ as the set of out-going traffic volumes to other AFNs (i.e., the $V_{A_iA_r}^{A_kB_l}$ variables), and $\mathcal{V}_{A_i\mathcal{B}}$ as the set of outgoing volumes to BSs (i.e., the $V_{A_iB_l}^{A_kB_l}$ variables). Then, the NLP problem can be reformulated into the equivalent LP problem, shown in (8)–(10) at the bottom of the page, where (8) and (9) follow from the flow balance (4) and (5), (10) follows from the energy constraints in (6), and (11) follows from the energy constraints in (7). Note that T, $V_{A_iA_j}^{A_kB_l}$, $V_{A_iB_l}^{A_kB_l}$, and $\mu^{A_iB_l}$ are variables, and ρ, g_i, e_i, $c_{A_iA_r}$, and $c_{A_iB_l}$ are all constants.

We now have a standard LP formulation that was transformed directly from the NLP problem. By their equivalence, the solution to this LP problem yields an upper bound to problem BS-AR. We will use this solution as a performance measure for heuristics. Our numerical results show that this upper bound is extremely tight to the optimal solution to the MINLP problem, which is consistent to the convex hull results presented in [22].

IV. ABS: A Heuristic Algorithm

If we had known an optimal mapping between each AFN i and a BS, then we can find an optimal flow routing using an LP formulation similar to that in [6]. Since such an optimal mapping is not available, we develop our heuristic solution in two steps, namely, 1) find a good mapping between each AFN and a BS; 2) find an optimal flow routing for this mapping.

Our heuristic algorithm in the first step is called ABS and is motivated by the solution to the LP-Relax problem discussed in Section III-B. Under LP-Relax, each AFN is allowed to send its traffic to multiple BSs. This motivates us to assign a source AFN, say i, to the BS that receives the largest amount of traffic volume (in bits) from AFN i among all the BSs in the solution to LP-Relax. In particular, we use a sequential fixing procedure to find the destinations for all AFNs, which is described below.

Algorithm 1 **(ABS)**

1) Solve the LP-Relax problem.
2) Fix some AFNs' BS via the solution to the LP-Relax problem as follows.
   a) If there exists some AFN i that sends at least θ percentage of its data to one BS, i.e., $\lambda^{A_iB_l} (= (\mu^{A_iB_l})/T) \geq \theta$, select this BS as its destination.
   b) Else, i.e., there is no AFN that sends at least θ percentage of its data to one BS, denote $\mu^{A_iB_l}$ as the largest among all μ values and select B_l as AFN i's destination.
3) If all AFNs' destinations are fixed, stop; otherwise, reformulate the LP-Relax problem. In this LP-Relax, if AFN i's destination is fixed as B_l, then $\mu^{A_iB_l} = T$ (i.e., $\lambda^{A_iB_l} = 1$) and all other μ variables for AFN i are zero.
4) Go to Step 1.

Problem LP-Relax

Max T

$$\text{s.t.} \sum_{r \neq i} V_{A_iA_r}^{A_iB_l} + V_{A_iB_l}^{A_iB_l} - g_i\mu^{A_iB_l} = 0 \qquad (1 \leq i \leq N, 1 \leq l \leq M) \tag{8}$$

$$\sum_{r \neq i,k} V_{A_iA_r}^{A_kB_l} + V_{A_iB_l}^{A_kB_l} - \sum_{m \neq i} V_{A_mA_i}^{A_kB_l} = 0 \qquad (1 \leq i \leq N, 1 \leq l \leq M, 1 \leq k \leq N, k \neq i) \tag{9}$$

$$\sum_{V_{A_mA_i}^{A_kB_l} \in \mathcal{V}_{\mathcal{A}A_i}} \rho V_{A_mA_i}^{A_kB_l} + \sum_{V_{A_iA_r}^{A_kB_l} \in \mathcal{V}_{A_i\mathcal{S}}} c_{A_iA_r} V_{A_iA_r}^{A_kB_l} + \sum_{V_{A_iB_l}^{A_kB_l} \in \mathcal{V}_{A_i\mathcal{B}}} c_{A_iB_l} V_{A_iB_l}^{A_kB_l} \leq e_i \qquad (1 \leq i \leq N) \tag{10}$$

$$\sum_{1 \leq l \leq M} \mu^{A_iB_l} - T = 0 \qquad (1 \leq i \leq N) \tag{11}$$

$$T, V_{A_iA_j}^{A_kB_l}, V_{A_iB_l}^{A_kB_l}, \mu^{A_iB_l} \geq 0 \qquad \left(V_{A_iA_j}^{A_kB_l} \in \mathcal{V}_{AA}, V_{A_iB_l}^{A_kB_l} \in \mathcal{V}_{AB}, 1 \leq i,j,k \leq N, i \neq j, k \neq j, 1 \leq l \leq M\right)$$

Note that θ is a tunable parameter, and we use $\theta = 0.85$ in our numerical results in Section V.

There is one subtle detail in the ABS algorithm that deserves further consideration. Suppose that in Step 2(b) the largest traffic volume sent by AFN i to a BS is comparable to the second largest traffic volume sent by AFN i to a different BS. Which BS should we then choose as the optimal BS for anycast? Clearly, the distance factor should be taken into consideration since doing so would help reduce energy consumption and help increase the network lifetime. Under ABS, we choose the BS that is closer to source AFN i whenever the difference between the largest and second largest traffic volumes (generated by AFN i) destined to two difference BSs is within a certain range. More formally, we introduce a threshold parameter (ϵ) to quantify the gap between the largest traffic volume and other traffic volumes destined to different BSs. For source AFN i, if the largest traffic volume to a BS l is comparable to the second largest traffic volume to BS m under LP-Relax, i.e., $\lambda^{A_iB_l} - \lambda^{A_iB_m} < \epsilon$, where $\lambda^{A_iB_l} = (\mu^{A_iB_l})/T$ and $\lambda^{A_iB_m} = (\mu^{A_iB_m})/T$, respectively, in the solution to LP-Relax, and the BS m is closer to AFN i than BS l, then we choose BS m as AFN i's anycast destination. The parameter ϵ is a tunable parameter and is set to 0.1 in our numerical results.

We emphasize that the amount of traffic volumes to different BSs under LP-Relax is the dominant reason to map the AFN to a BS in our ABS algorithm. The proximity of a BS to the AFN is considered only if the largest and second largest traffic volumes to two different BSs are comparable. In Section V, we will show that choosing BS solely based on its distance to AFN i is not a good approach.

Denote $d(i)$ as the resulting destination for AFN i via the above mapping. Then, we have $\mu^{A_id(i)} = T$ and $\mu^{A_iB_l} = 0$ for $B_l \neq d(i)$. In the second step, we can find the routing solution via an LP formulation shown at the bottom of the page.

V. Performance Evaluation

A. Simulation Settings

In this section, we present numerical results demonstrating the performance of the ABS algorithm. In our experiments, we consider different network sizes and numbers of BSs under various topologies. In particular, we consider networks consisting of $N = 10, 20,$ and 30 AFNs along with $M = 4, 5,$ and 6 BSs. That is, we have a total of nine possible N and M combinations. For each combination, we run ten experiments (each under a randomly generated network topology for the AFNs), thus obtaining 90 sets of data.

For each topology, an AFN i is placed randomly with uniform distribution along both x and y dimensions within the range $x_i, y_i \in [0, 1000]$ (m). The BSs B_1, B_2, B_3, and B_4 are located at (0, 0), (0, 1000), (1000, 0), and (1000, 1000) (all in meters), respectively. When there are five BSs present, B_5 is located at (500, 500); when there are six BSs present, B_5 and B_6 are located at (0, 500) and (1000, 500), respectively. The initial energy at AFN i is also randomly generated following a uniform distribution with $e_i \in [250, 500]$ (kJ). The data rate generated by AFN i, g_i, is also uniformly distributed within [2, 10] (kb/s).

For each run (90 in total), we can obtain the upper bound for the network lifetime (denoted as $T_{\rm UB}$) through LP-Relax as discussed in Section III-B. Denote $T_{\rm ABS}$ as the network lifetime obtained via our ABS algorithm. For comparison against the performance of ABS, we also consider the network lifetime obtained under two other approaches. One approach is that each AFN i simply chooses the nearest BS as its anycast BS. We denote the network lifetime performance under this approach as $T_{\rm nearest}$. The other approach is that each AFN i chooses a random BS as its anycast BS. We denote the network lifetime under this approach as $T_{\rm random}$. For the ease of comparison among $T_{\rm UB}$, $T_{\rm ABS}$, $T_{\rm nearest}$, and $T_{\rm random}$ across all 90 sets of data, we present the normalized network lifetime for $T_{\rm ABS}$, $T_{\rm nearest}$, and $T_{\rm random}$ with respect to $T_{\rm UB}$ for each experiment and denote these normalized network lifetimes as $L_{\rm ABS} = T_{\rm ABS}/T_{\rm UB}$, $L_{\rm nearest} = T_{\rm nearest}/T_{\rm UB}$, and $L_{\rm random} = T_{\rm random}/T_{\rm UB}$, respectively.

B. Example

Before we present complete results for the 90 data sets, we illustrate the solution procedure using an example network consisting of ten AFNs and four BSs, where the locations, initial energy, and local bit rates for the AFNs are listed in Table II.

Using the ABS algorithm, we solve LP-Relax and obtain that $T_{\rm UB} = 52.31$ days. Moreover, we have: AFN 1 sends 86.75% of its total data volume to BS B_3; AFN 2 sends 80.12% of its total data volume to BS B_3; AFNs 3, 4, 5, and 6 send all their data volume to BS B_3; AFNs 7 and 10 send all their data volume to BS B_1; AFN 8 sends 84.79%

$$
\begin{aligned}
&\text{Max } T\\
&\text{s.t.} \sum_{r\neq i} V_{A_iA_r}^{A_id(i)} + V_{A_id(i)}^{A_id(i)} = g_iT \qquad (1 \le i \le N)\\
&\sum_{r\neq i,k} V_{A_iA_r}^{A_kd(k)} + V_{A_id(k)}^{A_kd(k)} - \sum_{m\neq i} V_{A_mA_i}^{A_kd(k)} = 0 \qquad (1 \le i \le N, 1 \le k \le N, k \neq i)\\
&\sum_{V_{A_mA_i}^{A_kd(k)} \in \mathcal{V}_{\mathcal{A}A_i}} \rho V_{A_mA_i}^{A_kd(k)} + \sum_{V_{A_iA_r}^{A_kd(k)} \in \mathcal{V}_{A_i\mathcal{A}}} c_{A_iA_r} V_{A_iA_r}^{A_kd(k)} + \sum_{V_{A_id(k)}^{A_kd(k)} \in \mathcal{V}_{A_i\mathcal{B}}} c_{A_id(k)} V_{A_id(k)}^{A_kd(k)} \le e_i \qquad (1 \le i \le N)\\
&T, V_{A_iA_j}^{A_kd(k)}, V_{A_id(k)}^{A_kd(k)} \ge 0 \qquad \left(V_{A_iA_j}^{A_kd(k)} \in \mathcal{V}_{\mathcal{A}\mathcal{A}}, V_{A_id(k)}^{A_kd(k)} \in \mathcal{V}_{\mathcal{A}\mathcal{B}}, 1 \le i,j,k \le N, i \neq j, k \neq j\right)
\end{aligned}
$$

TABLE II
AFN'S LOCATION, INITIAL ENERGY, AND LOCAL BIT RATE FOR A TEN-AFN AND FOUR-BS NETWORK IN SECTION V-B

AFN	(x_i, y_i) (m)	e_i (kJ)	g_i (kb/s)
1	(590, 530)	410	5
2	(710, 630)	430	2
3	(870, 460)	470	4
4	(800, 90)	320	6
5	(940, 160)	440	9
6	(1000, 110)	320	8
7	(300, 200)	260	3
8	(470, 670)	350	3
9	(80, 680)	490	4
10	(250, 240)	350	3

of its total data volume to BS B_2; and AFN 9 sends all its total data volume to BS B_2. Through the ABS algorithm (with $\theta = 0.85$), we have $d(1) = d(3) = d(4) = d(5) = d(6) = B_3$, $d(7) = d(10) = B_1$, and $d(9) = B_2$, where $d(i) = B_l$ denotes that the anycast BS for AFN i is BS B_l.

Then, we solve the second LP-Relax and obtain that $T_{\rm UB} = 52.28$ days. Moreover, we have that AFN 2 sends 59.69% of its total data volume to BS B_4 and AFN 8 sends 84.83% of its total data volume to BS B_2. There is no node sending more than 85% of its data volume to one BS, so we fix $d(8) = B_2$.

In the solution of the third LP-Relax, we have $T_{\rm UB} = 51.89$ days and AFN 2 sends 59.71% of its total data volume to BS B_4. Again, there is no node sending more than 85% of its data volume to one BS, and we fix $d(2) = B_4$.

After we have the above mapping ($d(i)$ for each AFN i), we obtain the network lifetime $T_{\rm ABS} = 49.93$ days by solving the LP-Routing problem. Then $L_{\rm ABS} = 49.93/52.31 = 95.45\%$. The following flow routing (all in kilobit per second) is obtained by dividing the traffic volumes (in the solution of LP-Routing) by $T_{\rm ABS}$, i.e.,

$$f_{A_1A_3}^{A_1B_3} = 5.0000, \quad f_{A_3A_5}^{A_1B_3} = 5.0000, \quad f_{A_5A_6}^{A_1B_3} = 5.0000,$$
$$f_{A_6B_3}^{A_1B_3} = 5.0000;$$
$$f_{A_2A_1}^{A_2B_4} = 0.4370, \quad f_{A_2B_4}^{A_2B_4} = 1.5630, \quad f_{A_1A_3}^{A_2B_4} = 0.2440,$$
$$f_{A_1A_4}^{A_2B_4} = 0.0578, \quad f_{A_1A_7}^{A_2B_4} = 0.0046, \quad f_{A_1B_4}^{A_2B_4} = 0.1306,$$
$$f_{A_3A_5}^{A_2B_4} = 0.2440, \quad f_{A_7A_{10}}^{A_2B_4} = 0.0046, \quad f_{A_5A_4}^{A_2B_4} = 0.0128,$$
$$f_{A_5A_6}^{A_2B_4} = 0.0800, \quad f_{A_5B_4}^{A_2B_4} = 0.1512, \quad f_{A_{10}A_9}^{A_2B_4} = 0.0046,$$
$$f_{A_4B_4}^{A_2B_4} = 0.0706, \quad f_{A_6B_4}^{A_2B_4} = 0.0800, \quad f_{A_9B_4}^{A_2B_4} = 0.0046;$$
$$f_{A_3A_5}^{A_3B_3} = 4.0000, \quad f_{A_5A_6}^{A_3B_3} = 4.0000, \quad f_{A_6B_3}^{A_3B_3} = 4.0000;$$
$$f_{A_4A_5}^{A_4B_3} = 6.0000, \quad f_{A_5A_6}^{A_4B_3} = 6.0000, \quad f_{A_6B_3}^{A_4B_3} = 6.0000;$$
$$f_{A_5A_6}^{A_5B_3} = 9.0000, \quad f_{A_6B_3}^{A_5B_3} = 9.0000;$$
$$f_{A_6B_3}^{A_6B_3} = 8.0000;$$
$$f_{A_7A_{10}}^{A_7B_1} = 0.2655, \quad f_{A_7B_1}^{A_7B_1} = 2.7345, \quad f_{A_{10}B_1}^{A_7B_1} = 0.2655;$$
$$f_{A_8A_1}^{A_8B_2} = 0.3271, \quad f_{A_8A_9}^{A_8B_2} = 2.6729, \quad f_{A_1A_7}^{A_8B_2} = 0.3015,$$
$$f_{A_1A_9}^{A_8B_2} = 0.0256, \quad f_{A_7A_{10}}^{A_8B_2} = 0.3015, \quad f_{A_{10}A_9}^{A_8B_2} = 0.3015;$$
$$f_{A_9B_2}^{A_8B_2} = 3.0000;$$
$$f_{A_9B_2}^{A_9B_2} = 4.0000;$$
$$f_{A_{10}B_1}^{A_{10}B_1} = 3.0000.$$

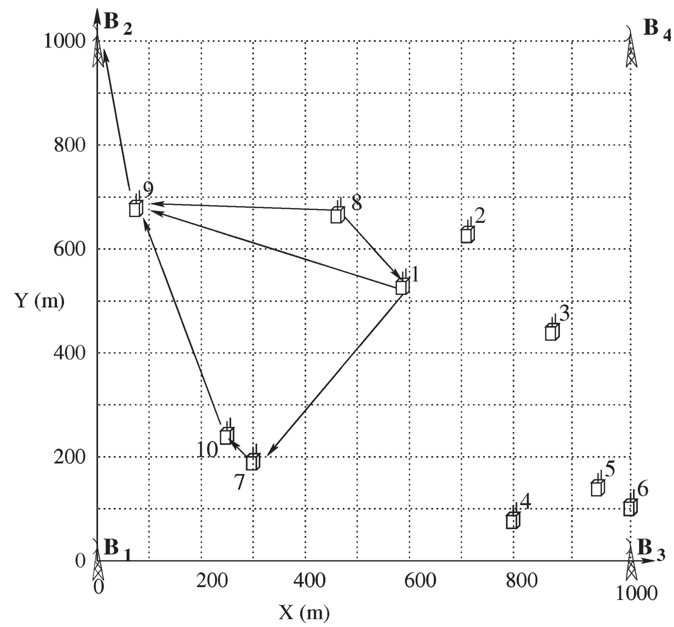


Fig. 2. Anycast flow routing for AFN 8.

Fig. 2 illustrates the routing paths for the data generated from AFN 8 in this example. It is easy to verify that for each AFN, the flow balance holds at any time during [0, 49.93] days and that the energy constraint is satisfied over 49.93 days.

Similarly, we can obtain that $T_{\rm nearest} = 23.34$ days for the nearest BS selection approach and $T_{\rm random} = 12.08$ days for the random BS selection approach. Then we have $L_{\rm nearest} = 44.61\%$ and $L_{\rm random} = 23.09\%$.

C. Results

We now perform the algorithms for all the 90 data sets. The normalized network lifetimes, $L_{\rm ABS}$, $L_{\rm nearest}$, and $L_{\rm random}$, are plotted in Fig. 3. Evidently, $L_{\rm ABS}$ is very close to the upper bound of 1 and exhibits a very stable performance. Since the optimal normalized lifetime for the original BS-AR problem lies between $L_{\rm ABS}$ and 1, we conclude that this upper bound is extremely tight and that the network lifetime performance under ABS is even closer to the optimal solution.

From Fig. 3, we can see that the heuristic ABS is significantly superior to the nearest approach (in most cases), which not only yields worse performance than ABS in most cases but also exhibits very wide oscillations in network lifetime performance ($L_{\rm nearest}$). Furthermore, the random BS selection approach offers a very poor performance (in most cases) compared to the ABS heuristic. Although in rare cases the random selection approach solution may coincide with that for the ABS heuristic, in most cases its performance falls far below that of the ABS algorithm.

Table III summarizes the statistical behavior of all the results from these 90 runs, which reveals some quantitative comparison among the approaches. In the worst case (among the 90 runs), the ABS algorithm stays within 20.0% of upper bound (even closer to the true optimum). On the other hand, the worst case performances for the nearest and random BS selection approaches are 75.6% and 99.2% away from the upper bound.

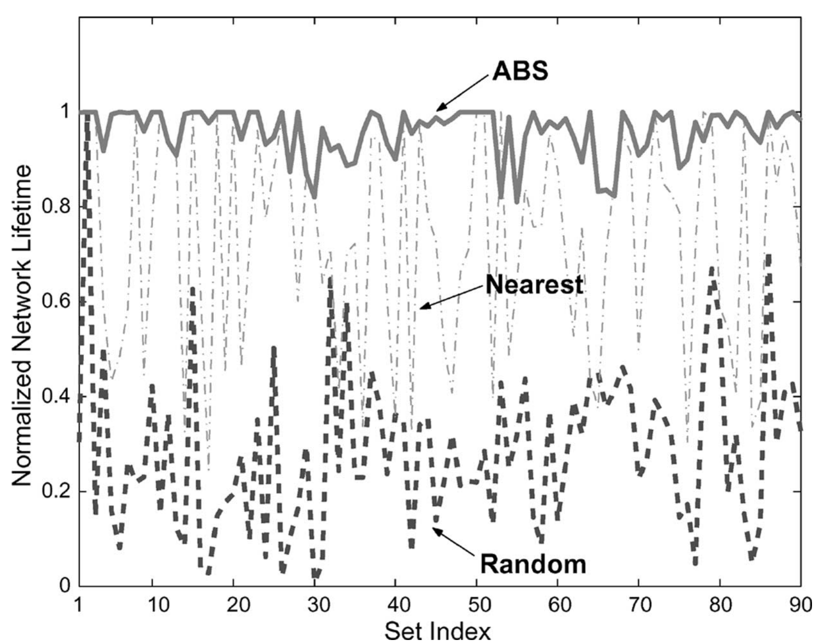


Fig. 3. Normalized network lifetimes under the ABS, nearest, and random BS selection for 90 data sets.

TABLE III
STATISTICAL COMPARISON OF THE NORMALIZED NETWORK LIFETIME FOR ABS, NEAREST, AND RANDOM BS SELECTION APPROACHES

	Worst Case	Average	95% Confidence Interval
ABS	0.8041	0.9585	[0.9455, 1]
Nearest	0.2445	0.7251	[0.6845, 1]
Random	0.0085	0.2794	[0.2483, 1]

TABLE IV
ACTUAL NETWORK LIFETIME PERFORMANCE (IN DAYS) FOR THE LAST TEN SETS OF DATA

Set Number	T_{UB}	T_{ABS}	T_{nearest}	T_{random}
81	129.68	125.68	70.59	25.71
82	105.09	105.09	43.15	33.64
83	172.16	169.81	169.81	26.44
84	193.63	185.15	65.15	9.51
85	185.28	173.41	71.84	24.20
86	30.98	30.98	30.98	21.93
87	106.83	103.35	91.06	32.22
88	47.84	47.84	45.52	19.57
89	131.23	131.22	116.13	56.03
90	92.62	90.90	61.30	30.09

On average, the ABS algorithm is within 4.2% of the upper bound, is 23.3% better than the nearest BS selection approach, and 67.9% better than the random BS selection approach. The 95% confidence interval for the ABS algorithm is also much narrower than that for the nearest and random BS selection approaches.

To get a sense of what real (instead of normalized) network lifetimes look like, we list the network lifetimes (all in days) for the last ten sets of data from the 90 sets of numerical results (with 30 AFNs and 6 BSs) in Table IV. Clearly, the ABS algorithm is superior than the nearest and random BS selection approaches in most cases. For set 86 in the table, we find that the nearest approach happens to coincide with ABS and the upper bound. This indicates that for this particular network topology and initial parameters, ABS and the nearest BS selection approach both yield the optimal solution. But, in general, the nearest BS selection approach cannot offer good performance as ABS algorithm.

VI. RELATED WORK

For the Internet environment, anycast has been addressed extensively (see, e.g., [17]), but the Internet environment is radically different from wireless sensor networks (e.g., severe energy constraint) and thus results on anycast for the Internet may not be directly carried over to wireless sensor networks.

A recent survey on a wireless sensor network research is given in [1]. Although there has been active research on energy-efficient unicast [11], [15] and multicast (including broadcast) [5], [8], [16], [23]–[25] wireless sensor networks, there is very limited research on how to perform anycast in such networks.

To the best of our knowledge, the first AR protocol for ad hoc wireless sensor networks was proposed in [13]. Under this protocol, packets are delivered to the nearest sink node. However, energy constraints and lifetime performance were not considered in this effort. As we have shown in Section V, the nearest sink node approach does not offer good performance for anycast flow routing.

A recent work on AR was presented in [12]. In this effort, Hu *et al.* studied AR by building a source-based tree. This approach is somewhat similar to the nearest-sink node approach in [13] in the sense that both approaches consider the minimum energy path; but adapting minimum energy paths does not guarantee good performance with respect to network lifetime.

VII. CONCLUSION

This paper considers a wireless sensor network having multiple BSs as data sink nodes. Since many real time multimedia applications require to have each source node send all its collected data to only one BS for data processing (e.g., video decoding), it is necessary to optimally map each source node to a BS. We investigated the joint problem of BS selection and anycast flow routing with the aim of maximizing the network lifetime. We proposed a heuristic algorithm called ABS that has polynomial time complexity. Simulation results show that this algorithm has near-optimal performance and is superior than some other approaches.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Comput. Netw. (Elsevier)*, vol. 38, no. 4, pp. 393–422, Mar. 2002.

[2] *BARON Global Optimization Software*. [Online]. Available: http://archimedes.scs.uiuc.edu/baron.html

[3] M. Bhardwaj and A. P. Chandrakasan, "Bounding the lifetime of sensor networks via optimal role assignments," in *Proc. IEEE INFOCOM*, New York, Jun. 23–27, 2002, pp. 1587–1596.

[4] T. X. Brown, H. N. Gabow, and Q. Zhang, "Maximum flow-life curve for a wireless ad hoc network," in *Proc. ACM MobiHoc*, Long Beach, CA, Oct. 4–5, 2001, pp. 128–136.

[5] J. Cartigny, D. Simplot, and I. Stojmenovic, "Localized minimum-energy broadcasting in *ad-hoc* networks," in *Proc. IEEE INFOCOM*, San Francisco, CA, Mar. 30–Apr. 3, 2003, pp. 2210–2217.

[6] J.-H. Chang and L. Tassiulas, "Energy conserving routing in wireless ad-hoc networks," in *Proc. IEEE INFOCOM*, Tel Aviv, Israel, Mar. 26–30, 2000, pp. 22–31.

[7] J. Chou, D. Petrovis, and K. Ramchandran, "A distributed and adaptive signal processing approach to reducing energy consumption in sensor networks," in *Proc. IEEE INFOCOM*, San Francisco, CA, Mar. 30–Apr. 3, 2003, pp. 1054–1062.

[8] A. K. Das, R. J. Marks, M. El-Sharkawi, P. Arabshabi, and A. Gray, "Minimum power broadcast trees for wireless networks: Integer programming formulations," in *Proc. IEEE INFOCOM*, San Francisco, CA, Mar. 30–Apr. 3, 2003, pp. 1001–1010.

[9] M. R. Garey and D. S. Johnson, *Computers and Intractability: A Guide to the Theory of NP-Completeness*. New York: Freeman, 1979, pp. 245–248.

[10] W. Heinzelman, "Application-specific protocol architectures for wireless networks," Ph.D. dissertation, Dept. Elect. Eng. Comput. Sci., Mass. Inst. Technol., Cambridge, MA, Jun. 2000.

[11] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Trans. Wireless Commun.*, vol. 1, no. 4, pp. 660–670, Oct. 2002.

[12] W. Hu, N. Bulusu, and S. Jha, "A communication paradigm for hybrid sensor/actuator networks," in *Proc. 15th IEEE Int. Symp. PIMRC*, Barcelona, Spain, Sep. 5–8, 2004, pp. 201–205.

[13] C. Intanagonwiwat and D. De Lucia, "The sink-based anycast routing protocol for *ad hoc* wireless sensor networks," Comput. Sci. Dept., Univ. Southern California, Los Angeles, Tech. Rep. 95-698. [Online]. Available: http://www.usc.edu/dept/cs/technical_reports.html

[14] K. Kalpakis, K. Dasgupta, and P. Namjoshi, "Efficient algorithms for maximum lifetime data gathering and aggregation in wireless sensor networks," *Comput. Netw.*, vol. 42, no. 6, pp. 697–716, Aug. 2003.

[15] Q. Li, J. Aslam, and D. Rus, "Online power-aware routing in wireless ad-hoc networks," in *Proc. ACM Mobicom*, Rome, Italy, Jul. 16–21, 2001, pp. 97–107.

[16] W. Liang, "Constructing minimum-energy broadcast trees in wireless *ad hoc* networks," in *Proc. ACM MobiHoc*, Lausanne, Switzerland, Jun. 9–11, 2002, pp. 112–122.

[17] C. Partridge, T. Mendez, and W. Milliken, *RFC 1546—Host Anycasting Service*. Internet Engineering Task Force, Nov. 1993.

[18] S. S. Pradhan, J. Kusuma, and K. Ramchandran, "Distributed compression in a dense sensor network," *IEEE Signal Process. Mag.*, vol. 19, no. 2, pp. 51–60, Mar. 2002.

[19] R. Ramanathan and R. Rosales-Hain, "Topology control of multihop wireless networks using transmit power adjustment," in *Proc. IEEE INFOCOM*, Tel-Aviv, Israel, Mar. 26–30, 2000, pp. 404–413.

[20] T. S. Rappaport, *Wireless Communications: Principles and Practice*. Upper Saddle River, NJ: Prentice-Hall, 1996.

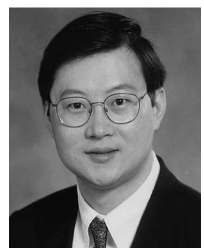
[21] V. Rodoplu and T. H. Meng, "Minimum energy mobile wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 8, pp. 1333–1344, Aug. 1999.

[22] H. D. Sherali, W. P. Adams, and P. J. Driscoll, "Exploiting special structures in constructing a hierarchy of relaxations for 0–1 mixed integer problems," *Oper. Res.*, vol. 46, no. 3, pp. 396–405, Mar. 1998.

[23] P.-J. Wan, G. Galinescu, X.-Y. Li, and O. Frieder, "Minimum-energy broadcast routing in static ad hoc wireless networks," in *Proc. IEEE INFOCOM*, Anchorage, AK, Apr. 22–26, 2001, pp. 1162–1171.

[24] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, "Resource management in energy-limited, bandwidth limited, transceiver-limited wireless networks for session-based multicasting," *Comput. Netw.*, vol. 39, no. 2, pp. 113–131, Jun. 2002.

[25] ——, "Energy-limited wireless networking with directional antennas: The case of session-based multicasting," in *Proc. IEEE INFOCOM*. New York, Jun. 23–27, 2002, pp. 190–199.



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