Finding Routes in Anonymous Sensor Networks

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Abstract

We consider networks of anonymous sensors and address the problem of constructing routes for the delivery of information from a group of sensors in response to a query by a sink. In order to circumvent the restrictions imposed by anonymity, we rely on using the power level perceived by the sensors in the query from the sink. We introduce a simple distributed algorithm to achieve the building of routes to the sink and evaluate its performance by means of simulations.

Keywords: Distributed computing, Anonymous systems, Sensor networks.

1 Introduction

A sensor network is a wireless network of simple elements, called sensors, that have sensing or monitoring capabilities related to some application domain, and have in addition limited processing and communication capabilities. Sensors are typically distributed irregularly in space and rely for operation on autonomous power sources that in general cannot be recharged, so expending energy as minimally as possible is a crucial concern. Sensor networks are currently being considered for use in a variety of contexts, ranging from biomedical to environmental monitoring tasks, often involving otherwise inaccessible monitoring sites or conditions that are too hazardous for direct human involvement.

Several typical tasks that sensor networks are planned to perform involve the use of more powerful processing and communicating elements, called sinks, that also communicate by wireless means with the sensors but have in addition the capability to connect to some outside network, like the Internet. In general, sinks

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are not constrained to using power as economically as the sensors. One common role performed by a sink is to broadcast a monitoring-related question to a group of sensors and to relay a compilation of their replies through the outside network for analysis. Because of the sensors' irregular spatial distribution and limited power resources, conveying such replies to the sink requires that clever routing and aggregation mechanisms be devised and has inspired the development of techniques and algorithms at various protocol levels. For recent reviews on such developments, we refer the reader to [1, 4].

Distributed algorithms for sensor-network operation invariably rely on the assumption that each sensor can be, for all relevant purposes, uniquely identified. This is a reasonable assumption to make: not only is it technologically feasible [5], but also it has been known since the seminal contributions in [2] that there exist severe inherent limitations to computing distributedly when the underlying processing elements are anonymous. Such limitations have been established under the assumption that point-to-point communication is available, and are therefore expected to be no less stringent in the wireless scenario.

However, approaching distributed computing from the perspective of anonymity is not so much a technology-related issue, but is rather a means of posing questions aimed at highlighting a system's fundamental capabilities and limitations. So the whole issue of distributed computing by anonymous elements makes sense in the sensor-network context as well, even though it appears to have remained untouched so far. In this paper we make what we think is the first contribution to understanding how the assumption of anonymity impacts the functioning of a sensor network.

We proceed in the following manner. In Section 2 we introduce the specific problem we address and give a simple distributed algorithm that attempts to solve it. The core premise behind the design of this algorithm is that the power level perceived by the sensors as they receive a transmission from a sink can be used to provide some level of differentiation among them and therefore compensate, to some degree, the assumption of anonymity. We then move to a performance evaluation of the distributed algorithm in Section 3 and finish in Section 4 with conclusions.

2 The problem and an algorithm

We consider n sensors placed arbitrarily in two-dimensional space and assume the existence of one single sink. Sensors are assumed to have no identifications, not even their coordinates in space. We assume that the sink broadcasts one single question to all sensors and that $n^\star$ of the n sensors are the ones to answer. We call each of these $n^\star$ sensors a source and assume that sources are distributed arbitrarily amid the n sensors. The problem we address is the problem of finding routes from all sources to the sink. Because sources can only broadcast at low power, their answers are likely not to reach the sink directly but need instead to be routed through the other sensors. All n sensors, even though $n - n^\star$ of them do not have an answer for the sink, may have a part to play in aggregating and relaying the sources' answers.

The question the sink broadcasts reaches each sensor at a power level that is inversely proportional to the square of its distance to the sink. The key premise underlying our approach is that each sensor is capable of measuring the amount of power it perceives in the sink's transmission. For sensor i, we denote this measure by P_i. Clearly, if for sensors i and j we have $P_i > P_j$, then i is closer to the sink than j is, provided that the sink's broadcast reaches all sensors isotropically (that is, at the same power level for the same distance from the sink), as we henceforth assume. While this is obviously no means of telling sensors apart from one another, since it only differentiates sensors radially with respect to the sink, we demonstrate in the remainder of the paper that it is possible to use such a property to provide routing from all sources to the sink.

In order to do this, we first introduce a simple distributed algorithm for execution by the sink and the sensors. We give the algorithm in a parametric form and in Section 3 provide simulation results that aim at clarifying which parameter ranges and values provide the desired results. We assume that an upper bound R on the greatest distance from the sink to a sensor is known to the sink. If B_0 is the power level at which the sink broadcasts its question, then sensor i, upon being reached by this broadcast and measuring P_i, can calculate its distance to the sink, denoted by R_i, and also its radial distance to the circle of radius R centered on the sink (that is, $R - R_i$): all it takes is that the sink broadcast, along with its question, the values of B_0 and R [6]. We let T and T_i denote the propagation times of an electromagnetic wave over the distances R and $R - R_i$, respectively (these can be computed easily given the wave's speed in the medium under consideration).

We describe our distributed algorithm loosely after the general template of reactive actions normally used for asynchronous distributed algorithms [3]. All we must specify is then the initial broadcast by the sink, the action to be taken by a sensor upon receiving this message, and also how the sink or a sensor reacts to receiving a message from a sensor. In our description of the algorithm, we use $\mathcal{S}_0$ and $\mathcal{S}_i$ to denote the (otherwise unspecified) data structure used respectively by the sink and sensor i to aggregate all information it receives. If sensor i is a source, then initially $\mathcal{S}_i$ is assumed to contain its answer to the sink's question.

The description that follows is given in terms of Actions 1 and 2, respectively for the sink and for a generic sensor i. Action 2, in particular, is dependent upon the product fr of the two parameters f and r. These are, respectively, a number in the interval $[0, 1]$ and the radius that a broadcast by a sensor is desired to reach. Once the value of r is known, we assume that sensors broadcast at a power level, the same for all sensors, such that the locations at which the message can be received are exactly those that are no farther apart from the sensor than r. We return to how the value of r is chosen in Section 3.

Action 1. The sink broadcasts $\mathit{Question}(B_0, R)$ and sets a timer to go off $2T$ time units later. In the meantime, upon receiving a message $\mathit{Answer}(*, \mathcal{S})$

the sink incorporates $\mathcal{S}$ into $\mathcal{S}_0$. When the timer goes off, the sources' answers to the sink are all summarized in $\mathcal{S}_0$.

Action 2. Upon receiving the message $\mathit{Question}(B_0, R)$, sensor i broadcasts $\mathit{Answer}(P_i, \mathcal{S}_i)$ if it is a source, and regardless of being a source or not sets a timer to go off $2T_i$ time units later. In the meantime, upon receiving a message $\mathit{Answer}(P, \mathcal{S})$ sensor i incorporates $\mathcal{S}$, suitably tagged with P, into $\mathcal{S}_i$. When the timer goes off, sensor i checks whether $\mathcal{S}_i$ has had any information incorporated into it from an *Answer* message. In the affirmative case, it selects from $\mathcal{S}_i$ the entry whose P tag is greatest among all entries that have a P tag such that $P < P_i$. If the selection is successful (i.e., there is at least one candidate entry), then let P_j be this greatest P tag; sensor i then calculates R_j from P_j. If it is unsuccessful, then sensor i lets $R_j = \infty$. It then broadcasts $\mathit{Answer}(P_i, \mathcal{S}_i)$ if $R_j - R_i > fr$.

For simplicity's sake, we have given these two actions under the further assumption that local computation, channel acquisition, and message transmission by sensors take only negligible time if compared to the time for wave propagation given the distances involved in the application at hand. This is reflected in the values timers are set to, but these can clearly be increased to satisfaction if the assumption does not hold. What is intended with Actions 1 and 2 is then the following. All sources broadcast their answers upon being reached by the sink's question. All sensors, source or otherwise, upon this same event, set timers proportionally to the round-trip time to the circle of radius R centered on the sink. As the timers go off in succession from the circle's outskirts inward, the sensors aggregate the answers they receive from farther out and pass the result on toward the sink. It all culminates with the sink's timer going off, at which time all activity has ceased and the sink has collected a set of aggregated answers, hopefully including answers from all sources.

Notice, in Action 2, that considering $\mathcal{S}_i$ entries whose P tags are such that $P < P_i$ excludes data received from sensors that are nearer the sink than sensor i. These excluded sensors are necessarily sources, since these are the only sensors that broadcast their answers independently of timers. Proceeding in this way is meant to prevent the progressive convergence of aggregated information onto the sink from being interrupted: by Action 2, a source's answer may go into $\mathcal{S}_i$ for some sensor i farther away from the sink, and proceeding differently would cause this sensor not to participate in the process, i.e., not to send an *Answer* message when its timer went off (the P tag of that source's data in $\mathcal{S}_i$ would be such that $P > P_i$ and thus lead to $R_j < R_i$).

Before moving on to simulation results, we pause for a pictorial illustration of how the algorithm works. This illustration is shown in Figure 1 for an arrangement of sensors generated uniformly at random. What the figure shows is a digraph whose set of nodes is the set of sensors enlarged by the sink, and whose edges represent some of the messages exchanged during the execution of the algorithm. Specifically, an edge exists either from sensor i to the sink, if an *Answer* message is received by the sink from i in Action 1; or from sensor j to

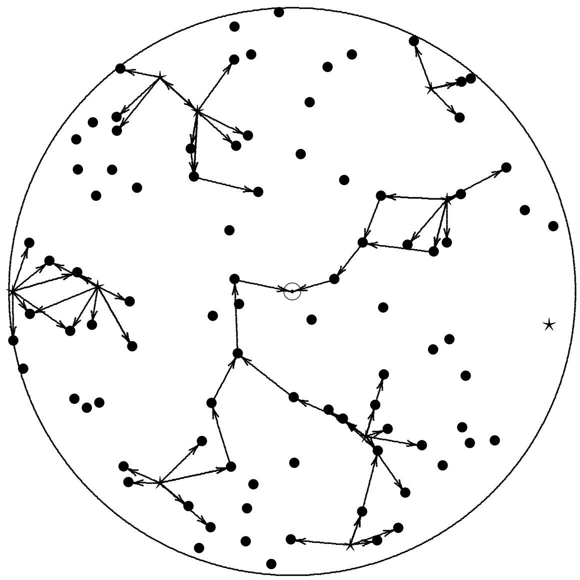


Figure 1: Digraph D for a circle of radius R centered on the sink with $n = 100$, $n^\star = 10$, $f = 0.3$, and $r \approx 0.26R$. The sink is represented by $\odot$, each sensor by either $\bullet$ or, if a source, $\star$.

sensor i, if i broadcasts an *Answer* message as its timer goes off in Action 2 and j is one of the sensors on which information is present in $\mathcal{S}_i$ at the time of the broadcast. We henceforth denote this digraph by D.

3 Simulation results

In this section we report on selected results from extensive simulations of the algorithm of Section 2. All our simulations were conducted on circles of radius R centered on the sink. For each simulation the n sensors were placed uniformly at random inside the circle and then the $n^\star$ sources were selected also at random.

Every broadcast by a sensor is during a simulation assumed to reach exactly those sensors that lie within a circle of radius r centered on the emitting sensor. The value of r is determined so that the expected sensor density inside the circle is the same as in the larger circle of radius R. If n_r denotes the expected number of sensors inside the circle of radius r, then we have $n_r/\pi r^2 = n/\pi R^2$, so it follows that

$$r = \sqrt{\frac{n_r}{n}}R. \tag{1}$$

The parameter r is then a function of n_r, so in our experiments the two parameters that we vary are f and n_r.

We evaluate the results of each simulation by means of the following three indicators:

Fraction of connected sources. The fraction, relative to $n^\star$, representing the number of sources from which a directed path exists to the sink in D. This indicator is a number in the interval $[0, 1]$.

Power usage ratio. Since every sensor broadcasts with the same power, the number of message broadcasts in Action 2 is proportional to the overall energy expenditure by the sensors. The minimum number of broadcasts is $n^\star$ (one for each source upon receiving the sink's *Question* message), so this indicator gives the ratio of the total number of broadcasts by sensors to $n^\star$. This indicator is a number no less than 1.

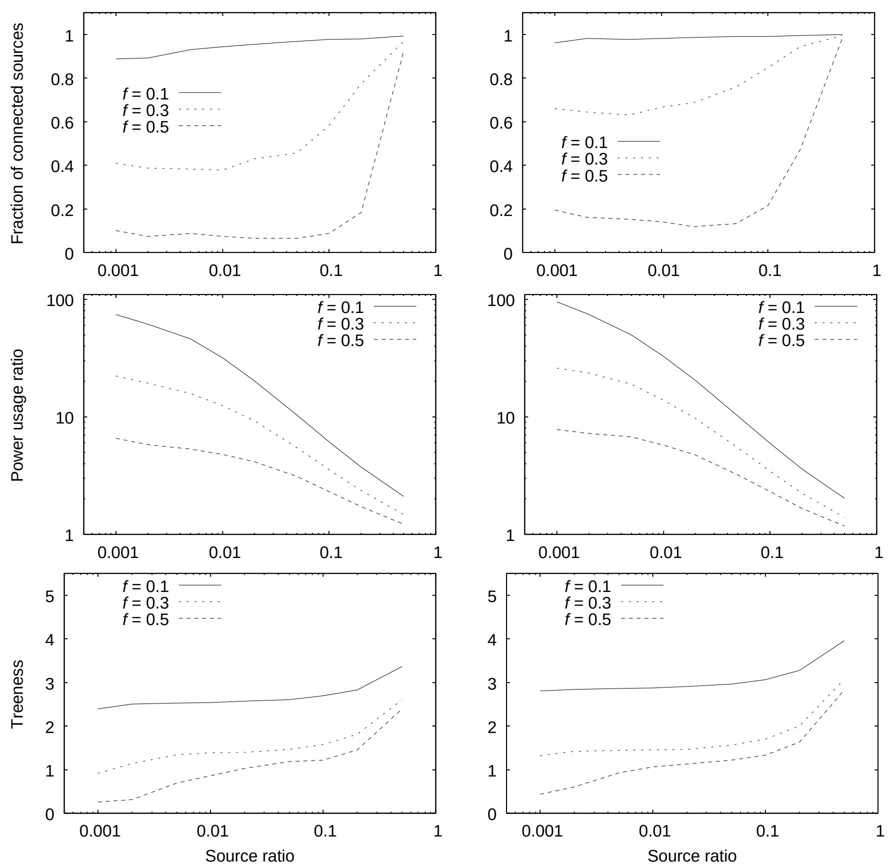
Treeness. Let c be the number of nodes from which a directed path exists in D to the sink. These nodes include the sink itself and are part of the weakly connected component of D that contains the sink.[1] Clearly, the least possible number of edges lying on directed paths from such nodes to the sink is $c - 1$. This indicator gives the ratio of the actual number of edges lying on directed paths to the sink to $c - 1$. It is a number no less than 1 (though we assume it is 0 when $c = 1$, hence an average may fall below 1).

We show results for $n = 2000$, $n^\star/n = a \times 10^{-b}$ with $a = 1, 2, 5$ and $b = 1, 2, 3$, $f = 0.1, 0.3, 0.5$, and $n_r = 9, 11, 13, 15$ (by (1), these values of n_r correspond to respectively $r \approx 0.067R, 0.074R, 0.081R, 0.087R$). For each combination of these values, we give each of the three indicators as the average over 200 independent simulations. The results appear in the plots of Figure 2, which are arranged into sets occupying four columns and three rows. Each of columns (a)–(d) corresponds to a different value of n_r, which increases as we move from (a) through (d). Each of the rows is specific to one of the three indicators.

As we move from (a) through (d) within the top row of plot sets, clearly the fraction of connected sources improves as n_r is increased. However, except for the very dense case of $n^\star/n = 0.5$, in which this indicator is consistently very near 1 regardless of the value of f, only values of f no larger than 0.3 seem to yield acceptable performance. The combination of $f = 0.1$ and $n_r = 13$, in particular, seems to already sustain a value of 1 throughout the entire range of $n^\star/n$.

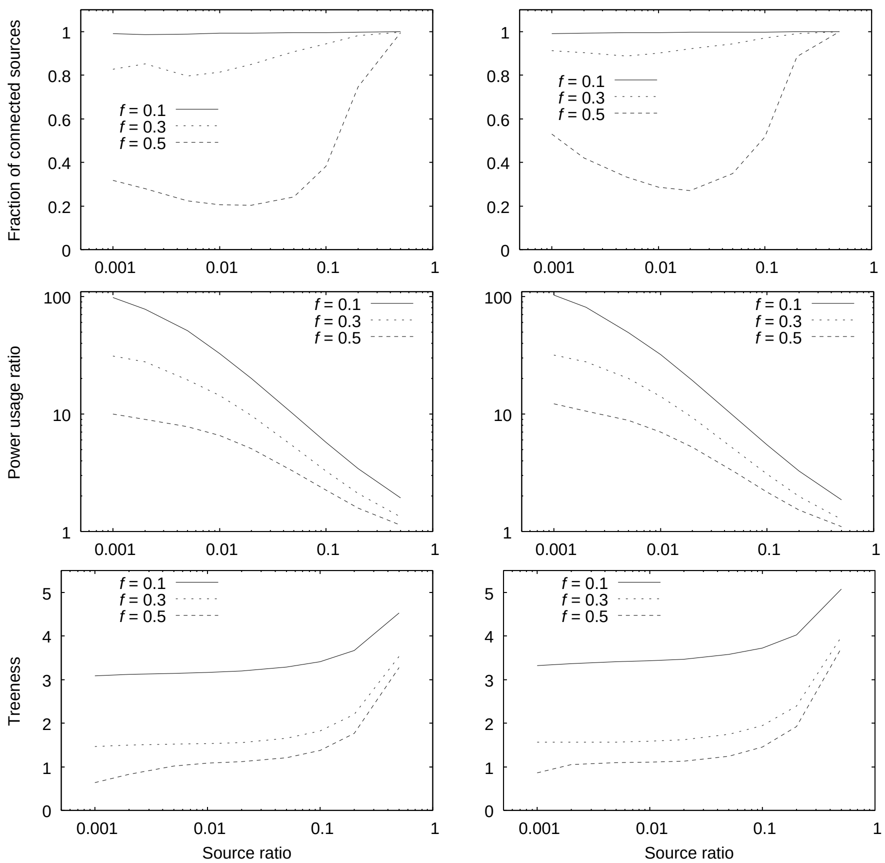
The middle row of plot sets indicates that increasing n_r within the four possibilities we have shown increases the power usage ratio only moderately (in fact, close to negligibly for $f = 0.1$, particularly near the upper end of n_r values). One must bear in mind, however, that this indicator is only a relative measure. The real energy expenditure involved grows with r^2 [6], therefore linearly with n_r, by (1). Other than this, the fact that the four plot sets follow roughly the

[1] A weakly connected component of a digraph is any sub-digraph whose underlying undirected graph is one of the connected components of the underlying undirected graph of the digraph.



(a) (b)

Figure 2: The three performance indicators plotted against the source ratio $n^{\star}/n$: $n_r = 9$ in part (a), 11 in (b), 13 in (c), and 15 in (d).



(c) (d)

Figure 2: Continued.

same functional forms is really easily interpretable: at the lower end of $n^\star/n$ values, very few sensors are sources, so conveying their answers to the sink must enlist the participation of several other sensors for routing and aggregation and consequently the number of broadcasts by sensors is many times larger than the number of broadcasts by sources; at the upper end, half the sensors are sources, so broadcasts still tend to occur in excess of broadcasts by sources but only moderately so.

The bottom row of plot sets refers to the treeness indicator and is therefore related to assessing how many hops are needed in excess of a tree for conveying to the sink the answers from the sources that really make it (i.e., those inside D's weakly connected component that includes the sink). All plots are roughly flat within the middle interval of $n^\star/n$ values, particularly so for smaller f values, thus indicating that inside that interval increasing $n^\star/n$ causes the component of D to acquire more edges in approximately the same rate as it acquires nodes. That treeness should be higher for lower f, finally, is really to be expected, since lower f means shorter (therefore more redundant) hops.

4 Conclusions

We have considered the heretofore untouched question of building routes in networks of anonymous sensors. We started with the basic premise that sensors can measure how much power reaches them from the sink, and proposed a simple distributed algorithm for building routes from sources to the sink that uses such measurements as a means of providing some differentiation among the sensors. The algorithm assumes an idealized broadcast model for the sink and the sensors, but adapting it to a more realistic setting is expected to be a relatively simple task.

We have provided simulation results that, in our understanding, are both surprising and encouraging. In particular, they seem to suggest that the radially decaying power perceived by the sensors as we move farther away from the emitting sink is capable of sustaining the construction of routes from randomly placed sources back to the sink. This is all achieved in the absence of unique sensor identifications, so what we really observe is that our simple algorithm leads the sensors to self-organize into conveying useful information to the sink.

Acknowledgments

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