PAPER

Performance Issues and Network Design for Sensor Networks*

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SUMMARY   This paper discusses performance issues for a sensor network. It describes the unique features of the sensor network and discusses studies on its protocols. Performance measures for the sensor network are investigated and studies related to them are surveyed. As an example of performance measures, this paper analyzes a sensor network’s availability, which is the probability that all the sensor nodes are working without any of them having run out of energy. An explicit formula for the sensor network availability is derived, and the optimal placement of sensor nodes is investigated.

key words: sensor network, ubiquitous, performance metric, performance measure, QoS metric, QoS measure, performance evaluation

1. Introduction

Many sensors are deployed in the world to measure things such as temperature, speed, and position and to detect chemical substances. They are located in factories, hospitals, automobiles, and so on. Recent developments in electronics and micro-mechanics enable us to make small, low-cost, low-power sensors with advanced functions [1]. Moreover, due to the recent rapid progress of telecommunication technologies (mainly wireless technologies), such sensors can have communication capabilities. (In the remainder of this paper, we call a sensor having communication capability a sensor node, and a network that includes sensor nodes a sensor network.) Table 1 summarizes the features of future sensor networks using new technologies and compares them with existing sensor networks. In the remainder of this paper, we focus on future sensor networks.

The sensor node and the sensor network have the following unique features that distinguish them from other nodes and networks.

i) The communication function in sensor nodes can be low quality.

ii) There can be an extremely large number of nodes in a sensor network. The node density can be extremely high.

iii) The position of sensor nodes may not be predetermined or designed because sensor nodes may be scattered, for example, from an airplane.

iv) Sensor nodes may run on an internal battery and stop working if the battery dies.

v) Sensor nodes are prone to stop working due to battery failure or expiry. Moreover, many sensor nodes may be added simultaneously.

vi) Sensor nodes may move because they may be installed in automobiles, cellular phones, and merchandise in transit.

vii) Sensor nodes may have transit node functions as well as end point functions.

viii) Sensor nodes may have high-layer information processing functions for computing data transmitted from other sensor nodes to reduce the amount of data that must be forwarded.

These sensor networks are used in many application fields. The following examples, which show some features of future sensor networks, are mainly at the initial stage of commercial services or commercial trials in Japan.

The first example is a house with security sensors. Houses that have sensors for detecting intrusion via the garden and the breaking of a window are sold and the sensors are connected to the security system company. Security is an important application field. Another example of using a sensor network in a house is to detect motion and count heart beats in the bathroom to enable a rapid response to sudden sickness, such as a heart attack in the bath. This example is in the field of health care.

Some homes for elderly people use a sensor network to detect the position of each elderly person and they are warned if they enter a dangerous place or leave the home. They also use sensors to detect when residents fall out of bed or experience incontinence, enabling quick action to be taken.

The following is a commercial application in an inventory system. Sensors in tanks such as car gasoline tanks and beer tanks measure the quantity remaining and an inventory management system receiving the sensor data determines the schedule for refilling the tanks.

Environment protection and disaster management is also a vast field for sensor network applications. By scattering sensors for temperature, moisture, and chemical substances in a forest, we can detect a forest fire and environmental destruction very quickly. It may also be possible to calculate the CO₂ processing capacity of the trees. Acceleration sensors and strain sensors can tell us when landslides and earthquakes occur, and shut down gas supply pipelines, stop high-speed trains, or set traffic lights to red because sensor data signals can be transmitted faster than the land-

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Table 1  Evolution of sensor networks.

<table>
<thead>
<tr>
<th></th>
<th>Existing</th>
<th>Future</th>
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<tbody>
<tr>
<td>Size</td>
<td>Large</td>
<td>Small or very small</td>
</tr>
<tr>
<td>Amount</td>
<td>Not many (sparse deployment)</td>
<td>Many (dense deployment)</td>
</tr>
<tr>
<td>Power supply</td>
<td>Mains power or batteries in other equipment such as PCs and mobile phones</td>
<td>Integrated battery</td>
</tr>
<tr>
<td>Communication partner</td>
<td>Gateway only</td>
<td>Gateway and other sensor nodes</td>
</tr>
<tr>
<td>Communication media</td>
<td>Wired</td>
<td>Wireless</td>
</tr>
<tr>
<td>Network configuration</td>
<td>Manual</td>
<td>Automatic</td>
</tr>
<tr>
<td>Use</td>
<td>Dedicated</td>
<td>Commonly shared</td>
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Fig. 1  Sensor networks.

slide or earthquake can propagate. In urban areas, sensors attached to buildings, bridges, tunnels, and highways detect structural deterioration due to age, enabling them to be repaired.

Another vast field for sensor networks is military applications. For example, a sensor network for motion detection on the battle field may be an important target for military research.

At present sensor networks are designed and operated for each application. However, some early examples of sensor network for multiple use are appearing. For example, the earthquake data used by the gas supply company to shut down the gas supply pipelines is being offered to insurance companies, research organization, and so on. Another example concerns automobiles. Some sensor signals are sent to both a security company and an insurance company. These examples suggest to us that a sensor network can be an infrastructure in the future, or at least, can work with many applications. Therefore, some standardization efforts are needed to enable data to be used commonly and a certain level of performance for a large-scale sensor network is needed.

2. Sensor Networks

We assume that a sensor network consists of sensor nodes, gateways, databases, resolvers, and application systems.

(Hereafter, we sometimes focus on the part of the sensor network consisting of the sensor nodes and the gateway and call this the sensor network too if it is not confusing.) Sensor nodes have sensing and communicating functions. They can be connected either to a gateway (Fig. 1(a)) or to other sensors (Fig. 1(b)). A gateway is a node connecting to an existing network (most probably, the Internet) and to sensor nodes. There may be multiple gateways in a sensor network. A gateway may have data processing functions, but it does not have a sensing function. When the gateway is an Internet host, it has an IP address, but sensor nodes may not have IP addresses. As a special case, there is no gateway (Fig. 1(c)) and sensor nodes have IP addresses and can be accessed directly from the host in the Internet. In this case, the gateway function is located in the sensor node.

Data sensed in the sensor node are transmitted to the database through the gateway. Application systems may access the database or the sensor node to get the sensed data. The resolver determines the IP address of the gateway (or the database or sensor node) that accommodates the sensor node sensing the requested data and sends back a reply to the request. Application systems process data obtained from the sensor nodes through the gateway or from the database and, for example, display the results to their users.
3. Protocols

Recently, there has been interest in the protocol used in sensor networks because people understand the importance of sensor networks and because some standardization may be necessary for an infrastructure sensor network (or at least a commonly shared one). At present, IEEE1451 is a standard for a sensor network using wired connections and its extension to wireless networks is under discussion. IEEE1451.5 discussing the extension may use IEEE802.15.4 as a low-layer protocol. The current discussion on IEEE802.15.4 is based on 2.4-GHz wireless technology and has not covered protocols providing power saving functions, for example.

Academic studies on protocols in sensor networks mainly concern the data link and network layers, although studies for the transport and application layers are needed [2]. Proposals for the data link protocol include neighbor discovery, transmission/reception scheduling, power saving modes, error control, support for mobile nodes, radio power optimization, and MAC layer design such as the application of TDMA and FDMA and modification of CSMA [3]–[5]. Those for the network layer include path selection, flooding/advertising/broadcasting metrics, interest, context, meta-data, and load-balancing [6]–[11]. (Reference [2] is a good survey of research on sensor network protocols. It lists the main sensor network projects in the U.S., but unfortunately does not cover studies outside the U.S., such as Disappearing Computing Initiatives [12] in Europe and Intelligent Cooperative Systems Laboratory of the University of Tokyo [13], Keio University [14] and National Institute for Environmental Studies [15] in Japan."

Some of the studies on these protocols are not limited to sensor networks but are also applicable to mobile ad hoc networks because power saving (reducing energy consumption) for example is a common target for these studies [16]–[20].

4. Performance Issues

Performance issues for the sensor network are classified into three categories: energy-related ones, sensing accuracy ones related to sensor position, and quality-of-service (QoS) issues in the sensor network (see Table 2). The most important issues are energy-related ones. (Sensor nodes whose energy is supplied by mains power or solar cells etc. can avoid these issues.)

Typical performance measures related to the energy in the battery are the remaining battery lifetime and data acquirable time. The former shows how long before the sensor node runs out of energy and the latter shows how long the sensing data can be acquired before it fails to reach the gateway due to the node itself or an upstream node running out of energy.

Using these measures, typical questions about the performance of a sensor network are:

i) How long is the remaining battery lifetime or the data acquirable time?

ii) Is the position of a sensor node in the sensor network sensitive to these values?

iii) What is the relationship between network topology (or protocol) and these values?

To reduce energy consumption, a sensor node may randomly fall into sleep mode. In this mode, the sensor may fail to detect events. But if there are enough sensor nodes nearby, they need not all stay awake. In this case, the relationship between detection failure rate and remaining battery lifetime (or data acquirable time) is a key question. (A protocol that determines the data transmission/reception schedule between neighboring sensor nodes or uses periodic transmission/reception may also use a sleep mode.)

Another technique for reducing the energy consumption is to process data at a transit sensor node to reduce the amount of data to be forwarded. Since this will take some energy, it is necessary to evaluate the overall energy gain or loss of this technique.

If sensor nodes are scattered, a new performance measure may be needed. Even if one sensor node runs out of energy or its sensing data is unable to reach the gateway, the sensor network still work if another sensor node nearby can sense and send its data to the gateway. Therefore, the length of time during which data can be acquired until none of the sensing data from nearby sensor nodes can reach the gateway is an important measure. We call this measure the area data acquirable time.

In the last few years, several papers have investigated energy-related performance issues. In [21], a simulation

<table>
<thead>
<tr>
<th>Performance issues</th>
<th>Performance measures</th>
<th>Related studies</th>
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<tr>
<td>Energy-related</td>
<td>Remaining battery lifetime / energy consumption</td>
<td>[21]–[24]</td>
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<tr>
<td></td>
<td>Data acquirable time</td>
<td>This paper.</td>
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<td></td>
<td>Sensor network availability</td>
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<tr>
<td>Sensing accuracy</td>
<td>Detection failure rate (sleep mode)</td>
<td>[25],[26]</td>
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<tr>
<td>caused by sensor</td>
<td>Area data acquirable time</td>
<td></td>
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<tr>
<td>position</td>
<td>Sensing accuracy</td>
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<td></td>
<td>Sensing accuracy with mobile node</td>
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<tr>
<td>Network QoS</td>
<td>Delay and loss</td>
<td>[27]–[29]</td>
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<tr>
<td></td>
<td>Throughput (due to limit of wireless communication capacity)</td>
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</table>
platform for sensor networks is established based on ns-2. The main performance objectives are energy consumption and battery lifetime. Three battery models are proposed: the linear model, discharge rate dependent model, and relaxation model. The effect of sleep mode is also investigated. In [22], the upper bound of the lifetime of a sensor network is derived. (In Sect. 5.3, the battery model in [22] is used.) This study is extended in [23]. The upper bound of the lifetime is derived when the sensor network topology is given. To derive it, the sensor node can play three sub-roles: sensor, relay, or aggregator and an optimal schedule of these sub-roles is determined using linear programming. In [24], a method of predicting energy consumption is investigated to make an energy map, which is useful for scattering sensor nodes in a low-energy area. A sensor node state transition model is proposed. Based on the model and the energy consumption rate reported by the sensor nodes, the energy consumption is predicted.

Another aspect of performance in sensor networks is related to sensing accuracy, which may be affected by the sensor’s position. Typically, position detection is sensitive to both the sensor node distribution and density. These factors also affect the area data acquireable time. Thus, the relationships among them are also important performance topics.

Sensor position and sensing accuracy are discussed in [25] and [26]. Breach-weight, which is the minimum distance between a sensor node and a target, is derived using the Voronoi diagram technique. Simulation evaluates the breach-weight when sensor nodes are added. In [26], another approach is used instead of the Voronoi diagram.

When we consider a mobile sensor node, other measures may be needed. If a sensor attached to a car tries to measure the outside temperature to forecast the weather, we need a measure of the probability that there are some sensors in a certain area and they can send data to the gateway. Some performance-related topics for mobile sensor nodes are covered by studies on wireless ad hoc networks.

Network level QoS of the sensor network can also be a performance issue. It includes the delay in the sensor network. As described in Sect. 1, some applications of a sensor network such as an earthquake sensor network are delay sensitive. Therefore, a network or protocol satisfying the delay constraint is needed. It also includes loss of the sensor network, which can be a performance measure indicating a certain level of sensing failure rate.

Similarly, wireless communication capacity has an impact on the performance in sensor networks. This topic is especially important when sensor nodes are scattered densely. Because the radio frequency that the sensor nodes can use is limited, the throughput between sensor nodes and between a sensor node and a gateway may be deteriorated. This topic is discussed in [27], [28], and [29].

A resolver resolving an attribute-based address, a geographical location based address, or a sensing data name address to an IP address may be requested. A scalable resolver is an important research area. The scalability of a distributed database for sensed data is also important if the sensor network becomes an infrastructure. However, these issues are not limited to the context of the sensor network. For example, an attribute-based address resolver is discussed in [10], [30], [31], a geographical location based address is discussed in [32] and a file name address resolver is discussed in [33]–[35].

This paper is about the performance issues related to energy. In this area, Refs. [21]–[24] studied the battery life or energy consumption. However, the fundamental relationships between the sensor network parameters and the performance have not been clarified. Simulation study, for example, can give us some numerical results but it is impossible to simulate all the combinations of sensor network parameters and a sensor network with many sensor nodes. Furthermore, sensor network availability has not been analyzed yet. By deriving explicit formulas, this paper clarifies the fundamental relationships between the sensor network parameters and the sensor network availability.

5. Numerical Examples of Performance of Sensor Networks

By using a simple model, this section describes numerical examples of the performance of a sensor network to determine its fundamental characteristics.

5.1 Performance Model

We use the reference model shown in Fig. 1(b). Each sensor node detects something and sends the data to a gateway. The sensed data is routed to the gateway by multihop wireless routing. To simplify the notation, the following explanation assumes that sensor nodes are connected in a line from the gateway (Fig. 2). However, it is possible to extend the sensor node network forming a line to a tree topology sensor node network and derive an explicit formula for the sensor network availability corresponding to Eq. (6).

We assume that there are \( n \) sensor nodes connected in a line. Each node has an index from 1 to \( n \), with the number decreasing closer to the gateway.

We assume that the energy needed to keep sensor node \( i \) awake is \( a_i \) per second, and that this sensor does not have a sleep mode. When sensor node \( i \) detects something, it consumes battery energy \( b_i \), which is exponentially distributed with mean \( 1/\beta_i \). When it relays sensing data, it consumes battery energy \( c_i \), which is exponentially distributed with mean \( 1/\gamma_i \). The transmission delay of sensing data is assumed to be negligible. Detection of something by node \( i \) happens according to a Poisson process with mean \( \lambda_i \) per second. Sensor node \( i \) is assumed to have energy \( h_i \) at its battery at time 0, and \( h_i \) is exponentially distributed with mean \( 1/\eta_i \).

5.2 Analysis

Now we consider the energy needed to keep a sensor node
working. Let $x_i$ be the energy consumption for detection and sensing data relay at sensor $i$ under the assumption that the energy consumption keeps increasing as if the battery never dies. Let $p_d(x_1, \ldots, x_n)$ be the joint probability density function of $x_1, \ldots, x_n$ at time $t$. Note that $p_d$ satisfies the following equation.

$$
d p_d(x_1, \ldots, x_n)/dt = - \sum_{i=1}^n a_i p_d(x_1, \ldots, x_n) + \sum_{i=1}^n \beta_i \prod_{j=1}^{i-1} \gamma_j \int_{y_j=0}^{y_i} \int_{y_i=0}^{x_i} p(y_1, \ldots, y_{i-1}, y_i, x_{i+1}, \ldots, x_n) \exp\left[\beta_i (x_i - y_i) - \sum_{j=1}^{i-1} \gamma_j (x_j - y_j)\right] dy_1 \ldots dy_i.
$$

The first term of the right-hand side of the above equation corresponds to none of the sensor nodes detecting anything. The second term corresponds to the following event: sensor node $i$ detects something and its energy consumption is $x_i - y_i$ and sensor nodes 1 through $i-1$ consume energy $x_1 - y_1, \ldots, x_{i-1} - y_{i-1}$ to relay the data sensed by sensor node $i$. The second term means, due to this event, the energy consumption reaches $(1)$.

Noting that $x_i - y_i$ is an exponentially random variable with mean $1/\beta_i$ and that $x_i - y_i, \ldots, x_{i-1} - y_{i-1}$ are exponentially random variables with mean $1/\gamma_j$, we can obtain the second term.

Define $q_i(s_1, \ldots, s_n)$ as the Laplace-Stieltjes transform (L.S.T.) of $p_d(x_1, \ldots, x_n)$. That is,

$$
q_i(s_1, \ldots, s_n) = \int_{v_1=0}^{s_1} \int_{v_2=0}^{s_2} \cdots \int_{v_n=0}^{s_n} e^{-v_1 x_1} \cdots e^{-v_n x_n} p_d(x_1, \ldots, x_n) dx_1 \ldots dx_n.
$$

Thus, Eq. (1) on $p_d(x_1, \ldots, x_n)$ can be converted into the following equation.

$$
d q_i(s_1, \ldots, s_n)/dt = - \sum_{j=1}^n \lambda_j q_i(s_1, \ldots, s_n) + \sum_{j=1}^n \lambda_j \prod_{k=j+1}^{n} \gamma_k \prod_{l=1}^{j-1} \gamma_l q_i(s_1, \ldots, s_n).
$$

This equation can be solved explicitly.

$$
q_i(s_1, \ldots, s_n) = \exp\left[-\sum_{j=1}^n \lambda_j t\right] + \sum_{j=1}^n \lambda_j \prod_{k=j+1}^{n} \gamma_k \prod_{l=1}^{j-1} \gamma_l \exp\left[-\sum_{j=1}^n \lambda_j t\right].
$$

Let $y_i$ be the energy consumption of sensor node $i$ under the assumption that the energy consumption keeps increasing as if the battery never dies. That is, $y_i = x_i + \alpha t$ at time $t$.

Let $r_i(y_1, \ldots, y_n)$ be the joint probability density function of $y_1, \ldots, y_n$ at $t$, and let $u_i(s_1, \ldots, s_n)$ be its L.S.T. Then,

$$
u_i(s_1, \ldots, s_n) = \exp\left[-\sum_{j=1}^n \alpha_i s_j t\right] q_i(s_1, \ldots, s_n).
$$

Now we are in a position to derive the sensor network availability, which is defined as the probability that all the sensor nodes are working. Let $u_i$ be the sensor network availability at time $t$.

$$
u_i = \int_{y_1=0}^{\infty} \cdots \int_{y_n=0}^{\infty} \prod_{j=1}^n \gamma_j e^{-\gamma_j y_j} r_i(y_1, \ldots, y_n) dy_1 \ldots dy_n.
$$

Note that the sensor network availability $u_i$ is exponentially decreasing with respect to $t$.

In particular, when all the above parameters ($\alpha_i, \beta_i, \gamma_i, \lambda_i$) are independent of $i$, the index of the sensor node (that is, $\alpha_i = \alpha, \beta_i = \beta, \gamma_i = \gamma, \lambda_i = \lambda$ for all $i$), we have

$$
u_i = \exp\left[- \alpha [m + n \lambda] - \frac{\beta \gamma_i}{\alpha \gamma_i} \left(1 - \left(\frac{\beta}{\alpha \gamma_i}\right)^n\right) t\right]
$$

Note that the sensor network availability $u_i$ is exponentially decreasing with respect to $t$ when all the parameters are independent of $i$.

5.3 Optimization

In many applications, sensor nodes are scattered to cover a certain area. Thus, an optimal scattering algorithm is an interesting topic. In addition, if the sensor network availability under the optimal sensor node placement is evaluated, the upper bound of the sensor network availability can be obtained. Thus, if the upper bound does not reach the target level of the sensor network availability, we can judge the sensor network to be infeasible.

We discuss this when the area (the section) is one-dimensional and its length is $D$. According to [22], the energy consumption of sensor node $i$ for transmitting and relaying data depends on the distance $d_i$ to a neighbor sensor node $i-1$ and takes the form of (constant)+(coefficient)*$d_i$. Here, $m$ is a parameter, and $m = 2$ or $m = 4$ is often used. Therefore, this paper assumes

$$1/\beta_i = b_{i1} + b_{i2} d_i^m
$$

$$1/\gamma_i = c_{i1} + c_{i2} d_i^m.
$$

We assume that the detection rate is proportional to the section (area) length that a sensor node covers. That is,

$$\lambda_i = l_i d_i.
$$

Fig. 2 Reference sensor networks.
In the numerical examples, this paper uses the following parameter values except when explicit values are indicated: \( t = 31536000 \) (s) = 1 (year); \( l_i = 0.0001 \) (1/s \cdot m); \( m = 2;\)
\( a_i = 15 (\mu J/s);\)
\( b_i = 228 (\mu J);\)
\( c_{i,1} = 0.02 (\mu J/m^2);\)
\( c_{i,2} = 432 (\mu J);\)
\( c_{i,2} = 0.024 (\mu J/m^2);\)
\( 1/\eta = 64800 (J)\) for \( i = 1, \ldots, n.\) These parameter values are based on [22], [23] and assumptions that the packet length of sensing data is 300 bytes and that two lithium batteries (CR-2430) are used.

5.3.1 Equal Division Case

First, we consider the case where the section is divided equally by placing sensor nodes. As a result, the distance \( d_i\) between sensor nodes is \( D/n.\) Now our focus is on how many sensor nodes should be placed and it is fairly easy for us to control the number of sensor nodes when we build a sensor network. That is, we want to derive the optimal \( n,\) which maximizes the sensor network availability \( w_j.\)

Although we can derive the optimal \( n\) through brute-force numerical optimization, this paper proposes

\[
\begin{align*}
    n &= \left\lfloor \frac{D(m - 1)c_{i,2}/c_{i,1}}{1/\eta} \right\rfloor, \\
    n &= \left\lceil \frac{D(m - 1)c_{i,2}/c_{i,1}}{1/\eta} \right\rceil
\end{align*}
\]

and shows that this \( n\) (the nearly optimal \( n\)) gives a very good approximation when \( c_{i,1}\) and \( c_{i,2}\) are independent of subscript \( i.\)

Originally, this nearly optimal \( n\) was derived to minimize the energy consumption for relaying among \( n\) sensor nodes for the given distance \( D\) in [22]. It said that placing sensor nodes equally minimizes the energy consumption for relaying and that the optimal \( n\) is the nearly optimal \( n\) mentioned above. From our point of view, this result is based on two approximations. The first one is optimization only of energy consumption for relaying and does not include the effects of detection and so on. The second one is where the analysis is limited to the case of relaying via \( n\) sensor nodes (the longest hop case). That is, the analysis does not include the cases of relaying via \( n - 1\) or \( n - 2\) sensor nodes and so on.

Due to these approximations, the result may be far from optimum. However, the nearly optimal \( n\) was a good approximation of the optimal \( n\) when the sensor nodes were placed at equal intervals. (See Fig. 3, where all the parameter values are independent of \( i,\) the index of the sensor node. Under the nearly optimal placement, the sensor network availability becomes maximum or nearly maximum.) This is because relaying is the main factor in energy consumption in many practical cases and because an optimal \( n\) for a non-longest hop case is the same as the optimal \( n\) for the longest hop case when all parameters are independent of subscript \( i\) and energy consumption due to relaying is minimized.

The sensor network availability using the nearly optimal \( n\) is plotted in the following figures where all the parameters are independent of \( i.\) Figure 4 shows the sensor network availability under the nearly optimal placement versus \( D\) (the area length). It shows that the sensor network availability decreases faster than exponentially versus \( D.\) When \( l_i\eta\) is fixed, the sensor network availability curves are almost the same. Figure 5 shows the sensor network availability under the nearly optimal placement versus \( l_i\) (a parameter related to the detection rate). It shows that the sensor network availability decreases almost exponentially versus \( l_i\) and that it becomes smaller as the area length \( D\) becomes larger. Surprisingly, sensor network availability was more sensitive to \( D\) than to the mean initial battery energy \( 1/\eta.\) Figure 6 shows the availability versus the mean initial battery energy \( 1/\eta.\) The sensor network availability was also
more sensitivity to $D$ than to the load (parameter $l_i$).

5.3.2 Unequal Division Case

Removing the condition that sensor nodes are placed at equal intervals, let us consider the optimal placement of sensor nodes for each fixed $n$.

As mentioned above, the energy is consumed mainly for relaying sensing data in many practical cases. Thus, we consider the following optimization problem to determine the sensor node placement. This optimization problem gives us the sensor node placement $d_i$ ($i = 1, \ldots, n$) that minimizes the energy consumption for relaying with the mean number of hops.

$$\min \sum_{i=1}^{n} d_i \sum_{j=1}^{k} (c_{i,j} + c_{i,j}d_j^m),$$
subj. to $\sum_{i=1}^{n} d_i = D$ \hfill (11)

Consider the case that $c_{i,1} \ll c_{i,2}d_j^m$, $l_i = I$ for all $i$, and $m = 2$. For this case, this problem can be solved explicitly. Set $d_i = \theta_i d_0$ for $i = 1, \ldots, n$, and $\theta_0 = 1$, $d_0 = D/\sum_{i=1}^{n} \theta_i$. By deriving $\sum_{k=1}^{n} b_k \sum_{j=1}^{k} c_{i,j}d_j^m$, the optimal $\theta_j$ ($j = 1, \ldots, n - 1$) is given as follows.

$$\theta_j = \left\{ \begin{array}{ll}
-\frac{c_{i,j} \sum_{k=j+1}^{n} \theta_k}{c_{i,j}^2 \left( \sum_{k=j+1}^{n} \theta_k \right)^2 + 2c_{i,j}^2 \left( 2c_{i,j}^2 \theta_j^2 + \sum_{k=j+1}^{n} \theta_k^2 \right) \left( 1/2 \right)} \\
\end{array} \right\} \hfill (12)

This optimal $d_i = \theta_i D / \sum_{i=1}^{n} \theta_i$ shows that the optimal $d_i$ is an increasing function on $i$ when $c_{i,1} \ll c_{i,2}d_j^m$ (Fig. 7). (Figure 7 denotes the cases when $n = 10$.) This means a sensor node near the gateway (that is, a smaller index sensor node) must relay more sensing data than one with a larger index. Thus, a smaller index sensor node should be placed nearer the neighboring sensor node than a larger index one.

Figure 8 shows the sensor network availability for each value of $n$ (the number of sensor nodes) under the placement mentioned above (we call it the nearly optimal unequal interval placement) and the placement assuming equal intervals between sensor nodes. When $c_{i,1} = 0.1$, the condition $c_{i,1} \ll c_{i,2}d_j^m$ is satisfied and the nearly optimal unequal interval placement is a little bit better than the equal interval placement. When $c_{i,2} = 0.01$, the condition $c_{i,1} \ll c_{i,2}d_j^m$ is not satisfied and the nearly optimal unequal interval placement is a little bit worse than the equal interval one. The nearly optimal $n$ for the equal interval placement is also plotted in this figure. For $c_{i,2} = 0.1$, the $n$ does not make the sensor network availability maximum.

6. Conclusions

This paper discussed performance issues for sensor networks and proposed performance measures. In particular, for sensor network availability, it derived an evaluation formula and proposed nearly optimal placements of sensor nodes. Through the numerical examples, it investigated the sensitivity of the sensor network availability on sensor network parameters such as area size, number of sensor nodes, detection rate, and initial battery energy. Among such parameters, area size was found to be a critical parameter.

This paper contributes to sensor network design and the analysis of sensor network scalability and the need for rerouting/backup-routes in sensor networks. As future work, we intend to study performance issues under more practical conditions, including the existence of a rerouting protocol, and radio wave propagation characteristics.
References


