Distributed Flooding-based Storage Algorithms for Large-scale Sensor Networks

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Abstract—In this paper we propose distributed storage algorithms for large-scale wireless sensor networks. Assume a wireless sensor network with \( n \) nodes that have limited power, memory, and bandwidth. Each node is capable of both sensing and storing data. Such sensor nodes might disappear from the network due to failures or battery depletion. Hence it is desired to design efficient schemes to collect data from these \( n \) nodes. We propose two distributed storage algorithms (DSAs) that utilize network flooding to solve this problem. In the first algorithm, DSA-I, we assume that every node utilizes network flooding to disseminate its data throughout the network using a mixing time of approximately \( O(n) \). We show that this algorithm is efficient in terms of the encoding and decoding operations. In the second algorithm, DSA-II, we assume that the total number of nodes is not known to every sensor; hence dissemination of the data does not depend on \( n \). The encoding operations in this case take \( O(C\mu^2) \), where \( \mu \) is the mean degree of the network graph and \( C \) is a system parameter. We evaluate the performance of the proposed algorithms through analysis and simulation, and show that their performance matches the derived theoretical results.

I. INTRODUCTION

Wireless sensor networks consist of small devices (nodes) with limited CPU, bandwidth, and power. They can be deployed in isolated, tragedy, and obscured fields to monitor objects, detect fires, temperature, flood, and other disaster incidents. They can also be used in areas difficult to reach or where it is dangerous for a human being to be involved. There has been extensive research work on sensor networks to improve their services, power, and operations [10]. They have taken much attention recently due to their varieties of applications.

Assume a wireless sensor network \( \mathcal{N} \) with \( n \) nodes thrown in a field to detect fires or to measure temperatures. Those sensors are distributed randomly and cannot maintain routing tables or network topology. Some nodes might disappear from the network due to failure or battery depletion. One needs to design storage strategies to collect sensed data from those sensors before they disappear suddenly from the network. Such problem and their solutions have been considered in [1], [2], [6], [7].

Distributed network storage codes such as Fountain codes and random walks in graphs are used to solve this problem, in case of the total number of sensor and storage nodes may or may not be known. In this paper we assume a model where all \( n \) nodes in \( \mathcal{N} \) can sense and store data. Each sensor has a buffer of total size \( M \). Furthermore, every sensor can divide its buffer into \( m \) slots (small buffers), each of size \( c \), i.e. \( m = \lceil M/c \rceil \).

In this paper we propose a distinct model for a wireless sensor network, wherein all nodes serve as sensors/sources as well as storage/receiver nodes. The main advantages of the proposed algorithms are as follows:

i) Using analysis and simulation, we show that the encoding operations, of a node to disseminate its data, take less computational time in comparison to the previous work.

ii) One does not need to query all nodes in the network in order to retrieve information about all \( n \) nodes. Only \( \%20 - \%30 \) of the total nodes can be queried.

iii) One can query only one arbitrary node \( u \) in a certain region in the network to obtain an information about this region.

II. NETWORK MODEL AND ASSUMPTIONS

In this section we present the network model and problem definition. Consider a wireless sensor network \( \mathcal{N} \) with \( n \) sensor nodes that are uniformly distributed at random in a region \( \mathcal{A} = [0, L]^2 \) for some integer \( L \geq 1 \). The network model \( \mathcal{N} \) can be presented by a graph \( G = (V, E) \) with a set of nodes \( V \) and a set of edges \( E \). The set \( V \) represents the sensors \( S = \{s_1, s_2, \ldots, s_n\} \) that will measure information about a specific field. Also, \( E \) represents a set of connections (links) between the sensors \( S \). Two arbitrary sensors \( s_i \) and \( s_j \) are connected if they are in each other’s transmission range.

We ensure that the network is dense, meaning with high probability there are no isolated nodes. Let \( r > 0 \) be a fraction. We say that two nodes \( u \) and \( v \) in \( V \) are connected in \( G \) if and only if the distance between them is bounded by the design parameter \( r \), i.e., \( 0 < d(u, v) \leq r \).

Given \( u, v \in V \), we say \( u \) and \( v \) are adjacent (or \( u \) is adjacent to \( v \), and vice versa) if there exists a link between \( u \) and \( v \), i.e., \((u, v) \in E \). In this case, we also say that \( u \) and \( v \) are neighbors. Denote by \( \mathcal{N}(u) \) the set of neighbors of a node \( u \). The number of neighbors, with a direct connection, of a node \( u \) is called the node degree of \( u \), and denoted by...
We will use this probability distribution in the algorithms developed in the next section.

A. Assumptions

We have the following assumptions about the network model $\mathcal{N}$:

i) Let $\mathcal{S} = \{s_1, \ldots, s_n\}$ be a set of sensing nodes that are distributed randomly and uniformly in a field. Each sensor acts as both a sensing and storage node. Thus, this assumption differentiates between our work and the problems considered in [1], [7].

ii) Every node does not maintain routing or geographic tables, and the network topology is not known. Every node $s_i$ can send a flooding message to the neighboring nodes. Also, every node $s_i$ can detect the total number of neighbors by broadcasting a simple query message, and whoever replies to this message will be a neighbor of this node. Therefore, our work is more general and different from the work done in [3], [4]. The degree $d(u)$ of this node is the total number of neighbors with a direct connection.

iii) Every node has a buffer of size $M$ and this buffer can be divided into smaller slots, each of size $c$, such that $m = \lfloor M/c \rfloor$. Hence, all nodes have the same number of slots. Also, the first slot of a node $u$ is reserved for its own sensing data.

iv) Every node $s_i$ prepares a packet $\text{packet}_{s_i}$ with its $ID_{s_i}$, sensed data $x_{s_i}$, counter $c(x_{s_i})$, and a flag that is set to zero or one.

v) Every node draws a degree $d_u$ from a degree distribution $\Omega_{is}$. If a node decided to accept a packet, it will also decide on which buffer it will be stored.

III. DISTRIBUTED STORAGE ALGORITHMS

In this section we will present a networked distributed storage algorithm for wireless sensor networks, where all nodes act as sensing and storage nodes, and study its encoding and decoding operations.

A. Encoding Operations

We present a distributed storage algorithm (DSA-I) for wireless sensor networks. DSA-I algorithm consists of three main phases: Initialization, encoding/flooding, and storage phases. Each phase can be described as follows.

1) Initialization Phase: Every node $s_i$ in $\mathcal{S}$ has an $ID_{s_i}$ and sensed data $x_{s_i}$. The node $s_i$ in the initialization phase prepares a packet $\text{packet}_{s_i}$ with these values. Also, the packet contains a hop count field, $c(x_{s_i})$, and a flag indicating whether the data is new or an update of a previous value. Each node will have a different hop count value depending on the number of its neighbors $d(s_i)$. Such that if a node $s_i$ has a few neighbors, then $c(x_{s_i})$ will be large. Also, a node with large number of neighbors will choose a small counter $c(x_{s_i})$. This means that every node will decide its own counter.

\[
\text{packet}_{s_i} = (ID_{s_i}, x_{s_i}, c(x_{s_i}), \text{Flag})
\] (3)

The node $s_i$ broadcasts this packet to all neighboring nodes $\mathcal{N}(s_i)$.

2) Encoding and Flooding Phase:

- After the flooding phase, every node $u$ receiving the packet $\text{packet}_{s_i}$ will check $ID_{s_i}$, accept the data $x_{s_i}$ with probability one, and will add this data to its buffer slots $y$. 

\[
y_u^+ = y_u^- \oplus x_{s_i}.
\] (4)

This is because the node $u$ is a direct neighbor of $s_i$. The data $x_{s_i}$ is disseminated rapidly to all neighbors of $s_i$.

- The node $u$ will decrease the counter by one as

\[
c(x_{s_i}) = c(x_{s_i}) - 1.
\] (5)
The node $u$ will select a set of neighbors that did not receive the message $x_u$, and it will unicast this message to them.

- For an arbitrary node $v$ that receives the message from $u$, it will check if the $x_u$ has been received before, if yes, then it will discard it. If not, then it will decide whether to accept or reject it based on a random value drawn from $\Omega_{v}(d)$. If accepted, it will add the data to one of its buffer slots $y_v = y_v \oplus x_u$, and will decrease the counter $c(x_u) = c(x_u) - 1$.

- The node $v$ will check if the counter is zero, otherwise it will decrease it and send this message to the neighboring nodes that did not receive it.

3) Storage Phase: Every node will maintain its own buffer by storing a copy of its data and other nodes’ data. Also, a node will store a list of nodes ID’s of the packets that reached it. After all nodes receive, send, and store their own and neighboring data. Therefore, each node will have some information about itself and other nodes in the network.

B. Decoding Operations

The stored data can be recovered by querying a number of nodes from the network. Let $n$ be the total number of alive nodes; assume that every node has $m$ buffer slots such that $m = [M/c]$, where $c$ is a small buffer size, and $M$ is the total buffer size in a node. In the next section, we show that the data collector needs to query at least $(1 + \epsilon)n/m$ nodes in order to retrieve the information about the $n$ variables. This is much better than previous approaches [1], [2], [7] that require querying large number of sources.

IV. DSA-I Analysis

We shall provide analysis for the DSA-I algorithm shown in the previous section. The main idea is to utilize flooding and the node degree of each node to disseminate the sensed data from sensors throughout the network. We note that nodes with large degree will have smaller counters in their packets such that their packets will travel for minimal number of neighbors. Also, nodes with smaller degree will have larger counters such that their packets will be disseminated to many neighbors as possible. The following lemma establishes the number of hops (steps) that every packet will travel in the network.

Lemma 1: On average, with a high probability, the total number of steps for one packet originated by a node $u$ in one branch in DSA-I is $O(n/\mu)$.

Proof: Let $u$ be a node originating a packet $p_u$ with degree $d(u)$. For any arbitrary node $v$, the packet $p_u$ will be forwarded only if it is the first time to visit $v$ or the counter $c(x_u) \geq 2$. We know that every packet originated from a node $u$ has a counter given by

\[ c(x_u) = [n/d(u)]. \]  \hspace{1cm} (6)

Let $\mu$ be the mean degree of the graph representing the network $\mathcal{N}$. On average, assuming every packet will be sent to $\mu$ neighboring nodes, approximating the mean degree of the graph to the degree of any arbitrary node $u$, the result follows.

If the total number of nodes is not known, one can use the method developed in [1] to estimate $n$. In other words, a random walk initiated by the node $u$ can be run to estimate the total number of nodes.

Lemma 2: Let $\mathcal{N}$ be an instance model of a wireless sensor network with $n$ sensor nodes. The total number of transmissions required to disseminate the information from any arbitrary node throughout the network is $O(n)$.

Proof: Let $d(s_i)$ be the degree of a sensor node $s_i$. On average $\mu$ is the mean degree of the set of sensors $S$ approximated by $\frac{1}{n} (\sum_i d(s_i))$. Every node does flooding...
that takes $O(1)$ running time to $d(s_i)$ neighbors. In order to disseminate information from a sensor $s_i$, at least $n/\mu$ steps are needed using Lemma 1. Also, every sensor $s_i$ needs to send $\mu$ messages on average to the neighbors. Hence the result follows.

Note that this is much better than previous results shown in [1] that take $n \log n$, where $n$ is the number of sources.

**Theorem 1:** The encoding operations of DSA-I algorithm are the total number of transmissions required to disseminate information sensed by all nodes that is $O(n^2)$.

V. DSA-II ALGORITHM WITHOUT KNOWING GLOBAL INFORMATION

In algorithm DSA-I we assumed that the total number of nodes are known in advance for each sensing/storing node in the network. This might not be the case since arbitrary nodes might join and leave the network at various times due to the fact that they have limited CPU and short life time. Therefore, one needs to design a network storage algorithm that does not depend on the value of the total number of nodes.

We extend DSA-I to obtain a distributed storage algorithm (DSA-II) that is totally distributed without knowing global information. The idea is that each node $u$ will estimate a value for its counter $c(u)$, the hop count, without knowing $n$. In DSA-II each node $u$ will first perform an inference phase that will calculate value of the counter $c(u)$. This can be achieved using the degree of $u$ and the degrees of the neighboring nodes $N(u)$. We also assume a parameter $c_u$ that will depend on the network condition and node’s degree.

**Inference Phase:** Let $u$ be an arbitrary node in a distributed network $N$. In the inference phase, each node $u$ will dynamically determine value of the counter $c(u)$. The node $u$ knows its neighbors $N(u)$. This is achieved in the flooding phase. Furthermore, the node $v$ in $N(u)$ knows the degrees of its neighbors.

The inference phase is done dynamically in the sense that every node in the network will independently decide a value for its counter. Nodes with large degrees will have a higher chance of forwarding their data throughout the network to a large number of nodes.

Let $v$ be a node connected to a source node $u$. Let $b_v$ be the degree of a node $v$ without adding nodes in $N(u) \cup u$. We can approximate the counter $c(u)$ as

$$ c(u) = c_u \left( \frac{1}{d(u)} \sum_{v \in N(u)} b_v \right) $$

Once the hop counts $c(u)$ is approximated at each node $u$, the encoding operations of DSA-II algorithm are similar to encoding operations of DSA-I algorithm.

**Lemma 3:** Let $N$ be a sensor network with $n$ sensor nodes uniformly distributed. The total number of transmissions required to disseminate the information from any arbitrary node throughout the network for the DSA-II is given by

$$ O(\mu(\mu - \lambda)), $$

where $\lambda$ be the average node density [9].

VI. PRACTICAL ASPECTS

In this section we shall provide evaluation and comparison analysis between DSA-I and DSA-II algorithms and related work in distributed storage algorithms. Previous work focused on utilizing random walks and Fountain codes to disseminate data sensed by a set of sensors throughout the network. Also, global and geographical information such as knowing total number of nodes, routing tables, and node locations are used.

In this work, we disseminate data throughout the network using data flooding once at every sensor node, then adding some redundancy at other neighboring nodes using random walks and packet trapping. Every storage node will keep track of other node’s ID’s, from which it will accept/reject packets.

The main advantages of the proposed algorithms are as follows

i) One does not need to query all nodes in the network in order to retrieve information about all $n$ nodes. Only $\%20 - \%30$ of the total nodes can be queried.

ii) One can query only one arbitrary node $u$ in a certain region in the network to obtain an information about this region.

iii) The DSA-I and DSA-II algorithms proposed in this paper are superior in comparison to the CDSA- and CDSA-II storage algorithms based on Fountain and Raptor codes proposed in [1], [2]. The later utilize random walks to disseminate the information from a set of sources to a set of storage nodes.

The proposed algorithms work also in the case of data update. Assume a node $u$ sensed data $x_u$ and it has been disseminated throughout the network using flooding as shown in DSA-I and DSA-II algorithms. In this case the flag value is set to zero; and a packet from the node $u$ is originated as follows:

$$ packet_u = (ID_u, x_u, c(x_u), flag) \tag{9} $$

We notice that every node $v$ stores a copy from this data $x_u$ will also maintain a list of ID’s including $ID_u$. Assume $x_u$ is the new sensed data from the node $u$. The node $u$ will send update message setting the flag to one.

$$ packet_u = (ID_u, x_u', x_u, c(x_u), flag). \tag{10} $$

The new and old data are Xored in this packet. Every storage node will check the flag, whether it is an update or initial packet. Also, the node $v$ will check if $ID_u$ is in its own list. Once a node $v$ accepts the coming update packet, it will update its target buffer as

$$ y_u^+ = y_u^- \oplus x_u' \oplus x_u \tag{11} $$
VII. PERFORMANCE AND SIMULATION RESULTS

In this section we simulate the distributed storage algorithms, DSA-I, presented in Section III. The main performance metric we investigate is the successful decoding probability versus the decoding ratio. We define the successful decoding probability $\rho$ as percentage of $M$, successful trials for recovering all $n$ variables (symbols) to the total number of trials. We define $h$ to be the total number of queries needed to recover those $n$ variables. Also, we can define the decoding ratio as the total queried nodes divided by $n$, i.e. $h/n$.

We ran the experiment over a network with area $A = [0, L]^2$ grid and with different node densities. We evaluated the performance with various decoding ratios depending on the total number of nodes inside the network with incremental step $= 0.1$.

Fig. 3 shows the decoding performance of DSA-I algorithm with Ideal Soliton distribution with small number of nodes. We ran the experiment over a network with area $A = [0, 2]^2$ grid, and evaluated the performance with various decoding ratios $0.1 \leq \eta \leq 1$. From these results we can see that the successful decoding probability increases with the gradual increases of the decoding ratio $\eta$ and reached it upper bound when $\eta \geq 30$.

Fig. 4 shows the decoding performance of DSA-I algorithm with Ideal Soliton distribution with large number of nodes. The network is deployed in $A = [0, 5]^2$. From the simulation results we can see that the decoding ratio increases with the increase of $\lambda$ and approaches to 1 for $\eta > 20$. Therefore the proposed algorithms perform well for large-scale wireless sensor networks.

VIII. CONCLUSION

We presented two distributed storage algorithms for large-scale wireless sensor networks. Given $n$ storage/sensing nodes, we developed schemes to disseminate sensed data throughout the network with a lesser computational overhead. The algorithms’ results and performance demonstrated that it is required to query only $20 - 30$ of the network nodes in order to retrieve the data collected by the $n$ sensing nodes, when the buffer size is $10$ of the network size. Our future work will include practical and implementation aspects of these algorithms.

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