The Last Minute: Efficient Data Evacuation Strategy for Sensor Networks in Post-Disaster Applications

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***Abstract*—Disasters (e.g., earthquakes, flooding, tornadoes, oil spilling and mining accidents) often result in tremendous cost to our society. Previously, wireless sensor networks (WSNs) have been proposed and deployed to provide information for decision making in post-disaster relief operations. The existing WSN solutions for post-disaster operations normally assume that the deployed sensor network can tolerate the damage caused by disasters and maintain its connectivity and coverage, even though a significant portion of nodes have been physically destroyed. In reality, however, this assumption is often invalid for disastrous events like earthquakes in large scale, limiting the relief capability of the existing solutions. Inspired by the "blackbox" technique in flight industry, we propose that preserving "the last snapshot" of the whole network and transferring those data to a safe zone would be the most logical approach to provide necessary information for rescuing lives and control damages. In this paper, we introduce Data Evacuation (DE), an original idea that takes advantage of the survival time of the WSN, i.e., the gap from the time when the disaster hits and the time when the WSN is paralyzed, to transmit critical data to sensor nodes in the safe area. Mathematically, the problem can be formulated as a non-linear programming problem with multiple minimums in its support. We propose a gradient-based DE algorithm (GRAD-DE) to verify our DE strategy. Numerical investigations reveal the effectiveness of GRAD-DE algorithm.**

Keywords- post-disaster applications; data evacuation; sensor networks

I. INTRODUCTION

While disasters could result in tremendous cost to our society, access to environment information in the affected area, such as, damage level and life signals, has been proven crucial for relief operations. Hundreds of disasters in various scales, including earthquakes, flooding, tornadoes, oil spilling and mining accidents happen around the world each year. Not only do they bring in huge economic lost by destroying assets, but also can they take lives in large quantities. According to a disaster statistic report [1], the average number of people affected by disasters is more than two hundred million per year from 1991 to 2005, and thousands of them lost their lives. When disasters hit, relief operations often focus on saving lives and reducing property damages. Given the chaos in the affected areas, effective relief operations highly depend on timely access to environment information. For example, the life vitals of survivors would be extremely helpful for rescue workers to determine where to dig a tunnel to the spot. Previously, wireless sensor networks [2,3] have been proposed to gather useful information in disasters such as earthquake, volcano eruption and mining accidents.

However, even with sensor networks, gathering crucial information in post-disaster relief operations turns out unpredictably challenging. When a disaster strikes, the communication facilities, power units and roads will usually be destroyed, which, along with some concomitant accidents, e.g. building collapse, fires, and gas explosions, etc. may disrupt the normal functionalities of sensor networks. For example, sensor nodes could be damaged in the event of a fire and communication channels are thus disconnected. Previous researches [4-7] tend to overlook at this possibility and thus result in relief solutions that are inherently impractical. As a result, the decision-making process could be paralyzed with incomplete information.

In this paper, inspired by the "blackbox" solution in flight industry, we propose Data Evacuation (DE), an original idea which utilizes the surviving time interval of sensor nodes, namely the duration in which WSNs still function after the disaster, to transmit vital data to the sensor nodes in the safe zone. Our idea relies on the following observation. It is quite possible that the buildings or local resources do not get damaged or destroyed at the beginning of most disasters. As a result, the deployed sensor network can keep working for a while before it becomes completely paralyzed. This grace period can be used to transit vital data gathered by the WSN.

In this research, we first reveal a mathematical structure of our problem, and then our main focus turns to develop and evaluate scalable distributed algorithms for our proposed DE strategy. If one would trace the path of each bit of data transits in the network, this problem can be modeled as a non-linear programming problem with multiple minimums in its support.

Rather than seeking the analytical solution for such a formulation, we take a pragmatic approach to design distributed protocols to route the vital data to safe zones in an affected region. We propose a gradient-based data evacuation (GRAD-DE) protocol, which is related to Newton's method [10] for non-linear programming. In addition, we will evaluate their efficacy under the aforementioned design metrics with extensive simulation. Evaluation shows the significant effectiveness of DE strategies for post disaster applications. The major contributions of this works are as follows:

- To the best of our knowledge, we are the first to propose the idea of *Data Evacuation* for post disaster applications. The basic operation of DE is to send sensitive data from the whole network to the nodes in the safe zone; in that case, the relief efforts of rescue group will benefit a lot from the reproduction of "the last shot" of the monitoring region based on the saved sensitive data.
- Building the mathematical structure of our problem, we propose a distributed data-rescuing algorithm. Our algorithm is mathematic avatars of Newton's method on non-linear optimization.
- Simulation has been conducted to verify the efficacy of GRAD-DE, and illustrate the fundamental trade-off between the two design metrics: evacuation time and evacuation ratio.

The remainder of this paper is organized as follows: Section II discusses the related work. Section III gives the definitions and assumptions about disaster scenario and network model. Section IV presents the detailed design of GRAD-D, followed by its evaluations in section V. Section VI concludes the paper.

II. Related Work

One of the critical tasks for post disaster relief is to collect urgent information quickly and safely to rescue lives and control damages. There have been a lot of research works on data collection with wireless sensor networks. However, research on vital data collection in disaster circumstances has been rare.

Some previous research employ wireless sensor network to gather useful data in a hostile environment like earthquake or volcano [2-4]. Suzuki et al. present a high-density earthquake monitoring system in [2]. The raw data about earthquake is gathered by a sink node and can be used for further analysis after earthquake. But the collected data is just about earthquake rather than survivors.

To collect data more efficiently, some works have studied hybrid networks for data collection in disaster situations [5-7]. These systems employ cellular systems (or wires systems) and sensor networks in parallel to achieve superior performance, such as, high speed, high capacity and wide area coverage. A hybrid network model in [6] collects damage assessment information from a large number of nodes, and its connectivity is maintained by an alternative route in the event of disasters. However, in the hybrid network, the cellular network could be paralyzed by disasters quickly or congested by the sudden high load even if it survives so that the data collection system breaks down.

Among these works, they did not consider the possibility that some base stations of cellular networks or the sensor nodes might be collapsed or unreachable during or after disasters. Li presents SASA [9], a Structure-Aware Self-Adaptive wireless sensor network, for underground monitoring in coal mines. By regulating the mesh sensor network deployment and formulating a collaborative mechanism based on the regular beacon strategy, SASA is able to rapidly detect structural variations caused by underground collapses. However, the stationary mesh network could be ruined and become unreliable when a collapse occurs.

To the best of our knowledge, this paper is the first one that considers a wireless sensor network under stress and evacuates the critical data to the safe zone for post-disaster relief operations.

III. System Models and Problem Description

A. Network Model

In this paper, we assume that N sensor nodes are randomly uniformly deployed in an $M \times M$ square area A, and the communication radius of sensor node is r. The network can be modeled as an undirected graph $G=(V,L)$, where V is the set of sensor nodes in the network, $|V|$ is the number of sensor nodes and L is the set of links between sensor nodes in the network. For any two nodes v_i and v_j, if $dist(v_i, v_j) < r$, v_i and v_j are neighbors and there is a link $l(v_i, v_j)$ between them. For any node v_i, its neighbor node set is $neighbor\ (v_i)$.

In the event of a disaster, the capability of sensor nodes is assumed to be as follows:

- It can sense some meaningful event around. For example, sensor node can sense human vital signs through sound, infrared rays, temperature, image and vibration sensors.
- Sensor node can sense and measure the surrounding physical intensity (like the intensity of earthquake shock, temperature and smoke density in the fire, gas density before gas explosion, etc) variation caused by a disaster.
- Sensor node can rank itself as Safe, Critical or Dangerous, according to a predefined algorithm using the physical intensity variation it senses as inputs.

We do not assume the existence of a sink node that gathers all the data and routes to the relief center. When a serious disaster occurs, original communication infrastructure may be destroyed; even if some of them survive, they usually can not provide effective service for disaster relief applications. In our approach, data evacuation is accomplished by collaborative efforts of every sensor node in the network to route the critical information to a few safe zones in the affected region.

B. Disaster Model

In this subsection, summarizing a set of common characteristics in most disasters, we construct a simplified disaster model, as follows.

Definition 1 (Devastating Event). We use a Quaternion (C_i, I_i, T_i, A_i) to represent a devastating event E_i, where C_i is the centre point of the zone where the devastating event occurs,

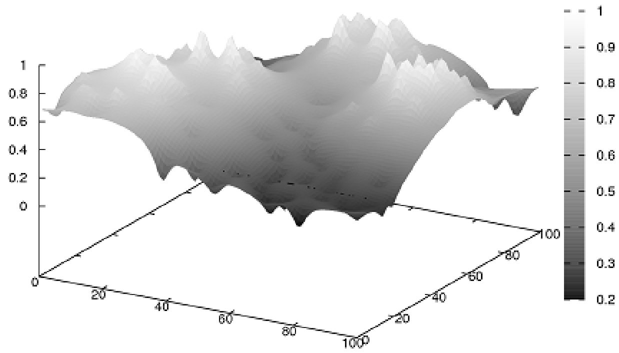

Figure 1. Devastating event intensity distribution in disaster

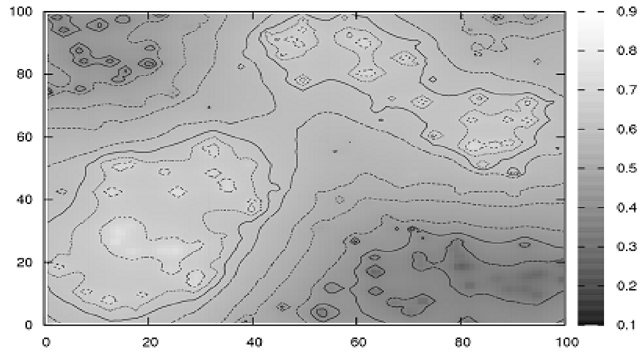

Figure 2. Vertical view of three zones distribution

given by the coordinate (x_i,y_i); I_i is the intensity of the devastating event, and T_i is the attenuation coefficient of disaster propagation; A_i is the region that the devastating event affects.

Definition 2 (Disaster). Disaster is a set of devastating events and could be denoted by $D = \{E_i \mid 0 \le i \le d-1, d \in \mathrm{N}\}$.

Let us look at an example. When a coal-mine accident (disaster) occurs, it probably consists of several gas explosions and water leak accidents, each of which corresponds to a devastating event. Each devastating event could be described by four elements: the position of event occurrence, the intensity of this event, the attenuation coefficient of this event, and the region affected by this event. The intensity I_i is highest in the centre point of a devastating event, and weakens as it gets further away from the center point. Usually T_i reflects the change of I_i in the region where disaster affects. There is no common attenuation coefficient for disasters. For simplicity, we assume a linear attenuation coefficient denoted as T_i. Under the impact of T_i, a devastating event can be depicted as a sub-area of which the intensity is linearly descending from a centre point. As an example, Fig. 1 illustrates a typical intensity distribution of a disaster with four devastating events, and the intensity is collected by sensors in the affected region.

The centers of the four devastating events are (15, 25), (25, 40), (55, 85) and (85, 60). It can be seen that the intensity function has multiple sets of minimum points in its support (i.e., the affected region).

In this paper, according to the data that the sensor nodes collect, we define an algorithm to classify the state of the senor node into three categories: Safe, Critical and Dangerous. Let $intens(v_i)$ be the intensity that the node v_i senses; I_s, I_d ($I_s < I_d$) are two thresholds which are predefined according to the disaster scene. Then, we have:

$$rank(v_i) = \begin{cases} \text{Safe}, & intens(v_i) < I_S \\ \text{Critical}, & I_S \le intens(v_i) < I_D \\ \text{Dangerous}, & I_D \le intens(v_i) \end{cases} \quad . \qquad (1)$$

Let V_S, V_C and V_D represent the set of Safe Nodes, Critical Nodes and Dangerous Nodes respectively.

When a disaster occurs in a certain place, the disaster usually only affects a limited area near the center, and similar disaster damage often share the same zone. According to this, the three sets V_S, V_C and V_D will have their own zones geographically, and since after a disaster happens, there exists a short period of time when the sensor nodes collect the intensity data and rank themselves, the disaster area will be divided into several zones, which could be Safe, or Critical or Dangerous.

Fig. 2 gives a vertical view for the disaster shown in Figure 1. Without loss of generality, we adopt a normalized threshold of 0.5 for non-safe zone in this discussion and the threshold can be any value that manifests the physical meaning of a specific disaster (e.g., the Richter magnitude in earthquakes). In Fig. 2, most area is covered by Dangerous Zone and Critical Zone ($intens(v_i) \ge 0.5, \forall v_i \in V_C \bigcup V_D$), due to the devastating event's influence, and only a small area is covered by Safe Zone ($intens(v_i) < 0.5, \forall v_i \in V_S$).

Sensor nodes in different ranks have varying surviving time, resulting in different roles in our data evacuation strategy. Sensor nodes in the Dangerous Zone have the shortest life time, only several seconds or dozens of seconds. Sensor nodes in the Critical Zone live longer, usually minutes or hours, because of less damage the devastating event causes in this Zone, but the continuous damage will make the sensor nodes in Critical Zone ultimately destroyed. Sensor nodes in Safe Zone can live much longer, usually hours or days or longer, because of the long distance from the Dangerous Zone and least damage the devastating event causes, so the sensor nodes in this Zone are suitable to store valuable data for assisting personnel rescue and disaster analysis.

In our scheme, if one follows a piece of information, it normally traverses from dangerous zones, with possible route via critical zones, to two alternative destinies. It either arrives at some safe zone, or is trapped in dangerous/critical zones (lost in the end). For the former case, we adopt a definition for the path through which the information traverses, as follows.

C. Problem Formulation and Its Mathematical Structure

The end goal of our proposed data-rescuing strategy is to route the critical data sensed in the Dangerous Zone and Critical Zone to the Safe Zone for disaster relief and disaster analysis. The process of data evacuation can be expressed like this: for every sensitive data in any sensor node $v, v \in V_C \bigcup V_D$, data evacuation is to find an effective path and transmit the data to the Safe Zone. Any solution in this domain should have at least two desirable features. First, it should route as much information as possible. Second, data evacuation should be fast, otherwise the sensor nodes in the Dangerous Zone and Critical Zone could lose their data, or the sensor nodes in the effective evacuation path could be inactive.

As a manifest of the aforementioned features, we will focus on the following two performance metrics: a) *Evacuation Time*: *the time to complete the data evacuation process.* Data evacuation should be quick; otherwise the sensor nodes in the Dangerous Zone and Critical Zone could be damaged. As a result, some effective evacuation paths could fail to send the sensitive data to the Safe zone. b) *Evacuation Ratio: the percentage of whole sensitive data preserved in safe zone after finish the data evacuation process.* The data evacuation protocols need to guarantee that the amount of preserved sensitive data can provide enough useful information for post disaster applications.

This formulation renders itself an elegant mathematical polymorphism. For each piece of information, it should strive to follow a path to any safe zone as fast as possible. If one considers the disaster intensity map as a two-dimensional function and any safe zone as a set of points with a minimum value, the data evacuation problem is equivalent to a non-linear programming problem with multiple (usually unknown) minimums in its support. This structural polymorphism with non-linear optimization will inspire the development of two efficient data-rescuing algorithms, both of which will be elaborated in next section and are distributed in nature.

IV. GRAD-DE PROTOCOL

A. *Detailed Design of GRAD-DE Protocol*

The GRAD-DE protocol stems from the Newton's method (gradient-based) for non-linear programming problems. One of the potential issues with Newton's method is that it could converge to local minimums. In our protocol, we allow a few steps to route the information to nodes with higher intensity, so that the critical message will not be trapped. Here is how the protocol works.

First, each sensor node obtains the intensity and the rank level of all its neighbors through a round of hello-message exchange. In the event of any disaster, a sensor node first sense the intensity of devastating event, and determine its rank level based on the predefined I_s and I_d. After that, it will broadcast a hello message, including its sensed intensity and self-determined rank level, to all neighbors.

Second, as water always flows downwards, in the GRAD-DE protocol, each sensor node forwards the sensitive data sensed locally or received from other nodes to its neighbor with the minimum sensed intensity. Obviously, in most cases, it is reasonable to send the sensitive data to the node with lower sensed intensity because it is the most logic step toward the safe zone (also suggested by the Newton's method). In order to avoid collision and reduce the communication cost, we adopt a single-copy forwarding strategy in the design.

B. *Pros and Cons of GRAD-DE Algorithm*

In this subsection, we will discuss the advantages and disadvantages of the GRAD-DE protocol respectively.

On one hand, the GRAD-DE protocol comes with a few desirable characteristics. First, the control-message overhead for the GRAD-DE protocol is limited and upper bounded by two times of the total number of sensor nodes. In most cases, each node broadcasts a one-hop hello message to all its neighbors. As a result, even in the worst case, the number of control messages sent by one node is 2. Second, the GRAD-DE protocol does not relay on detailed information of the network topology. Specifically, each node simply sends sensitive data to its neighbor with the minimum intensity. As a result, the *evacuation time* will not be too long since we do not incur additional delay in topology discovery. Third, the GRAD-DE protocol is a scalable and distributed algorithm for data rescuing under stress, with some resemblance to the famous Newton's method in non-linear programming domain.

On the other hand, the GRAD-DE protocol has several drawbacks. For example, any effective evacuation path is predetermined by the intensity distribution in the affected region. If a relay node is damaged by devastating events, sensitive data transmission can not be adapted to a new path. Although such an issue can be avoided by periodically sending hello messages, the control-message overhead would increase. Collision is another issue, which is caused by no topology control for the GRAD-DE protocol and cannot be solved thoroughly by relying on the IEEE 802.15.4 MAC protocol. Adjusting the time interval for data sending could be a way to avoid collisions; however, such a strategy would pay the penalty of prolonging *evacuation time*. Buffer overflow is also a problem for the GRAD-DE protocol. Unfortunately, the GRAD-DE protocol does not provide any information about safe zones, such as the number of safe zones, the storage capacity of safe zones, etc.

V. NUMERICAL STUDIES VIA SIMULATIONS

In our numerical study of data-evacuation strategy, we have implemented GRAD-DE protocol on ns-2.33 simulation platform. We compare the performance of GRAD_DE protocol to a simple flooding approach in terms of *evacuation ratio* and *evacuation time*.

A. *Simulation Setup*

In our simulations, 600 nodes are distributed in a $300x300m^2$ monitoring region. All sensor nodes have the same communication radius. Due to the limited bandwidth and the weakness of collision avoidance mechanism of IEEE 802.15.4 MAC protocol, the sensitive message evacuation velocity of each sensor is assumed to follows a Poisson process with an average arriving interval of 1.5s. To simulate the influence of disasters, we divide the whole network area into 2×3 small rectangles, and put a devastating event in every small rectangle. The location of each devastating event is randomly chosen in the corresponding small rectangle. For simplicity, we presume that the intensity of the centre place of any devastating event is a real number between [0.8, 1]. For any point P(x, y) in network, the intensity of P caused can be calculated according to Equation (2) as follows.

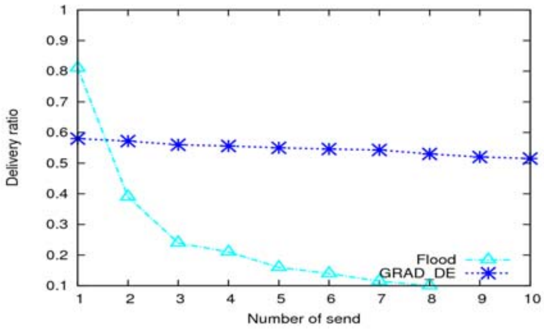

Figure 3. Impact of the number of sending sensitive messages on evacuation ratio

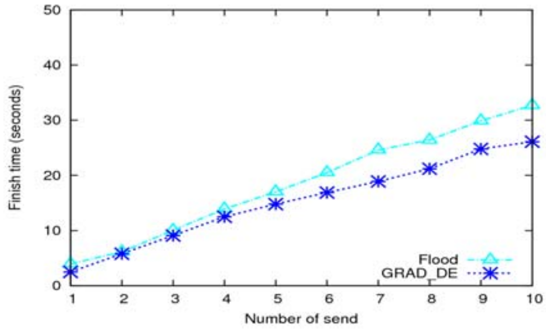

Figure 4. Impact of the number of sending sensitive messages on evacuation time

$$intens(p) = \begin{cases} 1 - k\dfrac{dist}{M} & dist < M \\ 0, & dist \geq M \end{cases} \qquad (2)$$

where *dist* denotes the Euclidean distance between P and D; *M* is the longer side of the small rectangles.

B. Impact of the number of sensitive messages

We study the performance of GRAD-DE protocol and flooding algorithm, with a rising number of sensitive data messages ranging from 1 to 10.

Simulation results are summarized in Figure 3 and Figure 4, which verifies our intuitions. As in Figure 4, the flooding algorithm has a higher evacuation ratio than the GRAD_DE protocol when the number of messages needed to be evacuated is very small. However, the *evacuation ratio* of the flooding approach drastically decreases and is lower than that of the GRAD_DE protocol as the number of messages increases. This observation can be traced back to two effects of the flooding algorithm. First, the chance of wireless collision is higher when flooding a lot of messages into the network; and second, the storage space in safe zones will be occupied by replicated message soon. Figure 4 shows the influence of the number of sending sensitive messages on *evacuation time*. For the same reasons, the *evacuation time* of the flooding algorithm is longer than that of GRAD-DE protocol especially when there are more messages to be evacuated.

VI. CONCLUSION

In this paper, we introduce the idea of Data Evacuation in post-disaster applications. We formulate the data evacuation problem with two competing design metrics: the evacuation ratio and the evacuation time. Then a gradient-based data evacuation (GRAD-DE) algorithm is proposed to verify our DE strategy. Numerical studies reveal the effectiveness of GRAD-DE algorithm compared with the flooding algorithm.

For future work, a direct extension of this work would be to compare different criteria to decide which evacuation paths to take. Another possible topic would be to allow multiply evacuation paths for each sensor node, and evaluate the associated trade-off between the evacuation time and the evacuation ratio.

ACKNOWLEDGMENT

This work was supported in part by the National Natural Science Foundation of China under Grants No.60703114, 60903158, 60721002, 60825205, 61073152. We also received partial support from Hong Kong RGC under the GRF Grant PolyU 5102/08E.

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