Using data mules for sensor network data recovery

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ABSTRACT

In this paper, we study the problem of efficient data recovery using the data mules approach, where a set of mobile sensors with advanced mobility capabilities re-acquire lost data by visiting the neighbors of failed sensors, thereby avoiding permanent data loss in the network. Our approach involves defining the optimal communication graph and mules’ placements such that the overall traveling time and distance is minimized regardless to which sensors crashed. We explore this problem under different practical network topologies such as arbitrary graphs, grids and random linear networks and provide approximation algorithms based on multiple combinatorial techniques. Simulation experiments demonstrate that our algorithms outperform various competitive solutions for different network models, and that they are applicable for practical scenarios.

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1. Problem formulation

A data mule is a vehicle that physically carries a computer with storage between remote locations to effectively create a data communication link [21]. In ad-hoc networks, data mules are usually used for data collection [5] or monitoring purposes [11] when the network topology is sparse or when communication ability is limited. In this paper, we propose to extend the usage of data mules to the critical task of network reliability. That is, using the advantages of mobility capabilities to prevent losing crucial information while taking into consideration the additional operational costs. We propose to model the penalty of a sensor crash as the cost of restoring its information loss, and present several algorithms that minimize the total cost given any combination of failures. We use concepts from graph theory to model the deployment of the ad-hoc network and give special attention to linear and grid graph models, whose unique network characteristics makes them well suited for many sensor applications such as monitoring of international borders, roads, rivers, as well as oil, gas, and water pipeline infrastructures [11, 13].

Let T be a data gathering tree rooted at root r spanning n wireless sensors positioned in the Euclidean plane, where data propagates from leaf nodes to r. We model the environment as a complete directed graph \( G = (V, E) \), where the node set represents the wireless sensors and the edge represents distance or time to travel between that sensors. We assume the sensors are deployed in rough geographic terrain with severe climatic conditions, which may cause sporadic failures of sensors. Clearly, if a sensor v fails, it is undesirable to lose the data it collected from its children in T, \( \delta(v, T) \). Thus, a group of data gathering mules must travel through \( \delta(v, T) \) and restore the lost information. We define this problem as \((\alpha, \beta)\)-Mule problem, where \( \alpha \) is the number of simultaneous node failures and \( \beta \) is the number of traveling mules.

For \( \alpha = 1, \beta = 1 \), the mule visits the children of v over the shortest tour, \( t(m, \delta(v, T)) \), starting and ending at node m ∈ V, where the length of the tour is equal to the Euclidean length of distances; the goal is to find a data gathering tree T, the placement of the mule m, and the shortest tours, \( t(m, \delta(v, T)) \) for all v ∈ V, which minimize the total
traveling distance given any sensor can fail. Formally, find $T$ and $m$ such that $\sum_{v \in V} [t(m, \delta(v, T))]$ is minimized. In a similar way, we can define the problem for $\alpha > 1, \beta = 1$ (see example for $\alpha = 2$ in Fig. 1, where the edges are directed towards the root). Formally, find $T$ and $m$ such that $\sum_{F \subseteq V} [t(m, \bigcup_{v \in F} \delta(v, T))]$ is minimized. We can extend this scenario to the case where instead of a single mule, we have $\beta$ mules $\bar{m} = \{m_1, m_2, \ldots, m_\beta\}$ deployed at different coordinates of the graph. When a node fails, its children must be visited by one of the mules to restore the lost data, which can be viewed as a mule assignment per node for the single node failure, or per unique node failure combination for the multi-failures case. In addition to $T$, we must find the location of all mules $\bar{m}$, and an assignment of each node $v \in V$ to a mule $m_i \in \bar{m}$ that minimizes the total travel cost of all mules. Formally, for $\beta > 1$, let $t(m_i, \delta(v, T))$ be the shortest path tour that includes mule $m_i$ and the children of node $v$ that mule $m_i$ should visit. For $\alpha = 1$, the optimization problem is to find $T$ and $m$ such that $\sum_{v \in V} \sum_{m \in \bar{m}} [t(m, \delta(v, T))]$ is minimized.

We consider two network models, complete graphs and unit disc graphs. In the complete graph model, there is a directed edge between any pair of nodes in the graphs while in the unit disc graph model, there is an edge if and only if $d(u, v) \leq 1$, where $d(u, v)$ is the Euclidean distance between nodes $u$ and $v$.

A summary of symbols used throughout this paper are depicted in Table 1.

1.1. Our contribution

To the best of our knowledge, this is the first work exploring the mule approach for avoiding data loss due to communication failures. Our results are summarized in the following (Table 2):
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