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Localization-free and energy-efficient hole bypassing techniques for fault-tolerant sensor networks

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ABSTRACT

Nowadays, since wireless sensor networks (WSNs) are increasingly being used in challenged environments such as underground mines, tunnels, oceans and the outer space, fault-tolerance need has become a major requirement for routing protocols. So far, the proposed fault-tolerance methods or algorithms aim to recover the isolated failures which occur at different parts of the network in different times. However, there is another type of failure for WSNs which is more destructive for the applications. By collapsing sensor nodes as a group at the same time, a hole can appear at the network which may cut the data delivery drastically. In the literature, previous studies for bypassing holes are based on localization which may have significant energy and economic costs. In this paper, two localization-free and energy-efficient algorithms are proposed for bypassing the holes formed by group collapse. We realized that when holes are modeled with clusters, hole bypassing can be solved by cluster bypassing. Our algorithms, intra-cluster bypass and inter-cluster bypass, aim to heal the corrupted communication links in the presence of holes. We show the operation of the algorithms, analyze them and provide extensive simulation results in an ns-2 environment. We compare our proposed algorithms with the other approaches and show that our algorithms significantly improve the fault recovery percentages while consuming a reasonable amount of energy even in the presence of high collapse ratio.

1. Introduction

Advances in hardware and wireless network technologies have resulted in low-cost, low-power, multi-functional miniature sensor devices (Tubaishat and Madria, 2003; Mendes and Rodrigues, 2011; Lin, 2013; Hadjidj et al., 2013; Pantoni and Brando, 2013; Dai et al., 2013). These sensor nodes are small, with limited processing and computing resources, and they are inexpensive compared to traditional sensors. These tiny sensor motes can sense, measure, and gather information from the environment and, based on local decision processes they can transmit the sensed data to a base station (sink). By communicating with each other and conveying information, which is gathered from the environment, they form a huge network which cannot be compared with the other type of networks. WSNs are generally large scale and distributed systems which are composed of ten to thousand of sensor motes that are communicating with each other. They are used in diverse applications such as military target tracking and surveillance, natural disaster relief and biomedical health monitoring (Yick et al., 2008). Although WSNs are used for various purposes, they contain challenges such as limited energy and wireless communication problems.

WSNs are increasingly being used in challenged environments such as underground mines, tunnels, oceans and the outer space. Wireless communication in challenged environments has transmission failures, mainly as a consequence of direct impact of physical world. In addition to energy constraints and wireless communication problems, tiny sensor motes are prone to failures. In Paradis and Han (2007), sources of all fault types are proposed in detail. In many critical applications of WSNs, the communication in challenged environments has to be reliable and therefore these requirements bring a need for the faults to be detected and recovered timely.

In particular, in a sensor network which is deployed in an extreme environment, each node may individually fail or a group of geographically close located nodes may collapse which forms holes (Fang et al., 2006). A hole may prune the communication links in a sensor network where data transfer from hole affected regions of the network becomes impossible without necessary topology recreation. In this case, sensor network applications have to suspend their communications and data delivery during construction of

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new paths. Thus, network recovery in the presence of holes is a very important problem. Although, this problem is addressed and studied by the researchers (Fang et al., 2006; Yu et al., 2007, 2008, 2009a; You et al., 2009b; Shiow-Fen et al., 2010), the main focus lies in node localization based approaches where sensor nodes should be equipped with a position tracker or localization algorithms should be executed a priori on these nodes. Equipping nodes with a position tracker like a global positioning system (GPS) receiver may cause significant costs. On the other hand, executing complicated localization algorithms may exhaust the batteries of sensor nodes which may cause new faults. In either cases, localization may introduce a considerable cost to the sensor network.

In this study, we aim to design localization-free and energy efficient hole bypassing techniques for fault-tolerant sensor networks. Our idea is firstly to construct a cluster tree rooted at a sink node where the network is partitioned into multi-hop clusters. By applying this strategy, we aim to model holes with clusters. Afterwards, to recover the communication links in the network, we propose an intra-cluster energy-efficient solution in the first step and an inter-cluster robust solution in the second step. By applying these methods, we aim to avoid the cost of localization and network-wide topology recreation.

The rest of this paper is organized as follow. In Section 2, we review the related work on fault recovery techniques. We show the network model and the hole problem formulation in Section 3. In Section 4, we introduce the proposed intra-cluster and inter-cluster based methods. We show the simulation results of the proposed methods and its performance is compared with the related work in Section 5. The conclusions are drawn in Section 6.

2. Related works

Routing is an attractive research area in all networks. Like other networks, researchers have proposed various protocols and algorithms for conveying messages to sink and dealing with the challenges of WSNs.

The early studies on routing in WSNs dealt with the energy problem and they tried to optimize the energy consumption. One of the answers to this problem was the data-centric routing mechanism. Sensor protocols for information via negotiation (SPIN) (Heinzelman et al., 1999) is one of the earliest works to pursue the data-centric routing mechanism in WSNs. Then, directed diffusion (Intanagonwiwat et al., 2003) was proposed which is an important milestone in data-centric routing mechanisms. After these studies, many approaches which pursue data-centric routing were proposed including the study in Braginsky and Estrin (2002). On the other hand, clustering-based protocols were proposed around the same time, in order to solve the energy problem. Low energy adaptive clustering hierarchy (LEACH) (Heinzelman et al., 2000) forms clusters regarding received signal strength indicator (RSSI) of sensor nodes which is one of the earliest studies in clustering-based protocols. However, LEACH is inefficient in terms of energy since it lacks multi-hop routing. Then, the threshold-sensitive energy-efficient sensor network protocol (TEEN) (Manjeshwar and Agrawal, 2001) and the adaptive periodic threshold-sensitive energy-efficient sensor network protocol (APTEEN) (Manjeshwar and Agrawal, 2002) were proposed which are designed to respond reactively to sudden energy changes efficiently.

Then, the focus of network community shifted to fault-tolerance because sensor nodes are prone to failures. Since the event packets are conveyed over the sensor nodes hop by hop toward sink, any fault of sensor nodes can cause event packet losses. In particular, this is a serious problem for critical systems. In Boukerche et al. (2006a), the periodic event-driven and query-based protocol (PEQ) and its variation clustering periodic event-driven query-based protocol (CPEQ) which are fault-tolerant and low-latency routing protocols are proposed. In Boukerche et al. (2008), the inter-cluster communication based energy aware and fault-tolerant protocol (ICE) is proposed which is a cluster based, energy aware and fault-tolerant routing protocol for WSNs. In Boukerche et al. (2006b), the variable transmission range protocol (VTRP) is proposed for smart dust networks, a special type of WSN, which is an energy-efficient and fault-tolerant protocol using a variation of the transmission range. This is the first study for data propagation in the literature which uses a varying transmission range technique. It is pointed out in this paper that additional knowledge, obtained by increasing the transmission power in a distributed manner, improves the data propagation to sink in terms of fault tolerance. In Chatzigiannakis et al. (2007), a fault-tolerant and efficient data propagation protocol for WSNs is proposed which uses the varying transmission range technique same as in Boukerche et al. (2006b). In Ganesan et al. (2001), the resilience of directed diffusion is increased by constructing disjoint and braided multipaths.

When the fault-tolerant routing algorithms and protocols in the literature are examined, they usually gather around the same fault-tolerant techniques including disjoint and braided multipaths, instant recovery and reconstructing the routing paths. Although these techniques provide reasonable recoveries, they do not intend to recover the holes which are formed by sudden group collapse. Although there are some studies intended to solve hole problem (Fang et al., 2006; Yu et al., 2007, 2008, 2009a; You et al., 2009b; Shiow-Fen et al., 2010), they are mainly based on bypassing holes using localization techniques. Since our concern is localization-free hole bypassing methods, we omit these localization based studies. The related methods are as follows:

- *Disjoint multipath routing*: In this routing scheme, the alternate paths are node disjoint with the primary path and with each other (Ganesan et al., 2001). Because of this property, a node failure in the primary path does not affect the alternate paths and so on. Node disjoint paths can be constructed by executing localized algorithms like directed diffusion (Intanagonwiwat et al., 2003). Although node disjoint paths are fault-tolerant, it may not always be possible to construct disjoint paths especially in sparse networks. Besides, node disjoint paths can be energy inefficient since alternate paths can be longer than the primary path.
- *Braided multipath routing*: Node disjointedness requirement is relaxed in braided multipath routing where alternate braided paths are partially disjoint from the primary path (Ganesan et al., 2001; Boukerche et al., 2008). Braided paths from a source node to the sink node can be constructed as follows: for each node v on the primary path, find the best possible path from source node to sink node that does not include node v. The alternate paths are expected to be geographically close to the primary path, thus the technique is energy-efficient intuitively. Alternate paths can be constructed with a localized algorithm similar to disjoint multipath routing. Although this technique provides a fault-tolerant infrastructure, it is bounded with the parent–child relationships which are constructed a priori, and it may not reactively recover faults in the presence of holes.
- *Instant recovery*: In this technique, when a node detects its parent's fault, it reactively tries to recover the fault by searching alternative parent (Boukerche et al., 2006a). In order to find a suitable alternative parent, the node m broadcasts a *Search* ($m.level$) message to its neighbors. When the neighbor node v receives a *Search*($level$) message, it replies with an acknowledgment if $v.level \leq Search.level$ and it is not the child of the sender of *Search* message. In this manner, the loops are prevented. PEQ and CPEQ protocols use this technique to