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Network coding based reliable disjoint and braided multipath routing for sensor networks

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ABSTRACT

This paper presents network coding based reliable disjoint and braided multipath routing (NC-RMR) for sensor networks, which forms multipath by hop-by-hop method and only maintains local path information of each node without establishing end-to-end paths. Neighbors of each local node are divided into groups according to their hops to sink nodes to improve the network load balancing. For further performance improvement of NC-RMR with disjoint multipath model, local nodes select their own backup nodes in neighbor nodes to form additional logical paths, which implement a braided multipath model. Security advantages of NC-RMR with multipath and network coding mechanisms are analyzed. Analytical and simulation results prove that braided multipath routing model has better performance over disjoint model, and NC-RMR protocol can reduce the required number of transmission paths, ensure load balance of sensor network system, reduce the energy consumption of nodes.

1. Introduction

Sensor networks consist of distributed and networked sensors to cooperatively monitor physical or environmental conditions such as temperature, sound, vibration, pressure and motion at different locations. Networked sensors are usually deployed randomly and left unattended to perform their mission properly and efficiently, which makes providing reliability a challenge. The harsh environment and unreliable wireless communication can cause long periods of poor connectivity. Failure of some nodes may affect operations of network systems. Meanwhile, the energy and resource constraint on sensor platforms limit retransmission and buffer size, and thereby affect system reliability. These aspects require reliable data transmission.

Existing reliable transmission mechanisms for wireless sensor networks include traditional forward error correction (FEC), acknowledgement (ACK), multipath transmission, and some new technologies such as network coding.

Among these technologies, multipath routing establishes more than one path in procedure of routing discovery, then reduces the times of routing discovery. It utilizes link redundancy to enhance the system delivery rate and reduces control cost and end-to-end delay. It is typically proposed in order to increase the reliability of data transmission or provide load balance (Marina and Das, 2001; Moonseong et al., 2008; Stephen Mueller et al., 2004). A multipath expansion of single path ad hoc on-demand distance vector (AODV) routing is made by computing multiple loop-free and link-disjoint paths (Marina and Das, 2001). An energy efficient, scalable, and distributed node disjoint multipath routing algorithm adjusts traffic flows via a novel load balancing scheme (Moonseong et al., 2008) which has a higher average node energy efficiency, lower control overhead, and a shorter average delay. The necessary number of paths and next hop nodes is estimated by the desired reliability and channel quality as well as the number of hops from source to sink nodes, and one kind of data transmission mechanism called ReInForM is implemented to satisfy certain reliability (Deb et al., 2003). The Directed Diffusion Protocol (Intanagonwiwat et al., 2003) adopts a three-stage operation including diffusion, data spreading and cyclical path strengthening, which can adapt to node failure and topological change. Multipath Source Routing (MSR) protocol (Wang et al., 2001) is based on the establishment and maintenance of dynamic source routing (DSR) to adapt the multipath routing which returns some paths during the routing establishment.

Although multipath routing can increase reliability of transmission, too many paths may increase data redundancy and energy consumption. Multipath routing adopts parallel mechanisms to transmit data. The different performance of paths may lead to differences in data transmission delay and chaotic data in sinks. Moreover, the data loss increases due to frequent network topology change and link error. Network coding technology adds a new mechanism to overcome these disadvantages of traditional multipath routing.

In traditional networks, information is transmitted directly to a next node (unicast), or transmitted to many nodes after duplication (multicast) by implementing store-and-forward

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operation. Because information in networks is a continuous bit flow, besides the store-and-forward operations on information, other operations such as coding and decoding can be executed, too. Since Ahlswede et al. propose network coding of information for the first time in 2000 (Ahlswede et al., 2000), network coding has become an active research field. Some study explores theory and benefits of network coding (Ho et al., 2003; Li et al., 2003). Much research focuses on random distributed network coding and its implementation in actual environments (Katti et al., 2005; Ho et al., 2006; Dan Wang et al., 2006). Leong (Ho et al., 2004) presents a random network coding algorithm, and compares this algorithm with Steiner's tree generation algorithm and Dijkstra's shortest path algorithm. An optimal algorithm combining distributed source coding with network coding whose purpose is to improve the reliability and fault-tolerance of sensor networks (Zhang and Wicker, 2005). A detection strategy based on random network coding is proposed. All raw data are transformed simply by polynomial hash functions (Ho et al., 2008). COPE (Katti et al., 2005) is the first study on an implementation of network coding in a real wireless environment. However, the protocol requires nodes to store data packets and encode them. If the network has congestion, it may cost nodes more storage space.

There are some works addressing the network coding-based multipath mechanism to improve the reliability of networks (Toledo and Wang, 2006; Radunovic et al., 2007; Xinyu and Baochun, 2008a–c; Oh et al., 2009; Li et al., 2006; Jalel and Lynda, 2009; Chachulski Szymon et al., 2006). These works demonstrate that multipath routing with network coding has better redundancy control than traditional multipath methods.

In this paper, we present network coding based reliable disjoint and braided multipath routing (NC-RMR) for sensor networks in order to satisfy reliable transmission. In the second section of this paper, some related work is introduced to demonstrate the main operation principle and some improvement of our protocol. In the third section, multipath model and network coding parameter are described. In the forth section, NC-RMR design is discussed in detail. Analysis and simulation results are provided and compared in section five, which is followed by an improvement mechanism with braided mode in section six. Finally, the conclusion is made in section seven.

2. Related work

ReInForM (Deb et al., 2003) employs a probabilistic flooding scheme to create multiple paths from source to sink nodes. Each node is assumed to have knowledge of local channel errors. Reliability can be achieved by introducing redundancy in the form of copies of each packet sent through multiple paths. At a source node, reliability and current status such as channel quality and hops to sink nodes are employed to determine the number of transmission paths.

Our NC-RMR protocol, presented in this paper, employs the computation method of paths and next hop node selection in ReInForM. But the difference is very obvious. First NC-RMR protocol applies network coding mechanism to avoid the redundancy of copies of packets delivered through multiple paths from source to sink nodes. Secondly, it employs a hop-by-hop mechanism to establish disjoint and braided multipaths, which increases network reliability. Third, NC-RMR protocol includes load balance implemented by braided multipath and optimal next hop node selection which are not considered in ReInForM.

Traditional multipath routing has the disadvantage of increasing the overall traffic substantially. Stefan Dulman et al. (2003) introduce an idea of splitting original data packets into subpackets and sending each of them through one of the multiple paths. Even if some of them are lost, the original message can be reconstructed. Although this idea that data packets are split into more packets seems similar to network coding mechanism, the operation of information flow (Dulman et al., 2003) is still store-and-forward. NC-RMR protocol executes coding and decoding on information flow, and this algorithm in theory guarantees that some lost packets will not affect correct reconstruction of original data packets.

Node error in wireless sensor networks causes some path rebuilding by multipath protocol. Similarly, path recovery needs rebuilt paths, which leads to obvious energy consumption. Deepak Ganesan et al. (2002) propose braided multipath routing model to solve these problems for energy-efficient recovery from node failures. When a small number of paths are kept alive, failures on the main path can usually be recovered from without invoking network-wide flooding for path discovery. Our NC-RMR combines network coding mechanism with braided multipath which is not included in Ganesan et al. (2002). Moreover, NC-RMR has the braided multipath routing model implementation in detail.

Recent attempts on applying network coding mechanism to design multipath protocols for sensor networks have shown that it may achieve higher performance such as reliability and energy consumption (Lijuan et al., 2008; Zheng Guo et al., 2009; Xinyu and Baochun, 2008a–c). OMNC (Lijuan et al., 2008) takes advantage of network coding to adapt to lossy environments and path diversity of wireless broadcast. A distributed algorithm allocates the encoding and broadcasting rate to achieve throughput improvement over traditional routing. Zheng Guo et al. (2009) propose an efficient error recovery scheme that couples network coding and multipath in underwater sensor networks. Analysis and simulation results confirm that the scheme is efficient in both error recovery and normalized energy. The solution (Xinyu and Baochun, 2008a–c) exploits the advantages of random network coding, dense deployment of sensor networks, and directed diffusion, so the secure multipath protocol can achieve perfect internal security and maximal possible transmission rate at the same time.

There are other works on combinations of network coding with multipath routing as follows. A primal–dual algorithm that expresses optimization problem as a function of various flows in the network is proposed to incorporate opportunistic routing, multipath routing and network coding (Radunovic et al., 2008). Flow control (Radunovic et al., 2008) can be regarded as one kind of improvement on MORE (Chachulski Szymon et al., 2006), which does not integrate flow control or flow scheduling with the routing algorithm. In Xinyu and Baochun (2008a–c), source nodes continuously generate and broadcast packet streams using a random linear code, and receivers taken as node candidates are selected with a pseudo-broadcast mechanism to continue broadcasting if they are closer to the destination. The work is based on the presumption that link qualities in target networks are relatively stable over time.

All of these works are disjoint multipath protocol designs. Node error in wireless sensor networks would cause some paths rebuilt by multipath protocol. Similarly, path recovery need rebuild paths, which leads to obvious energy consumption. Deepak Ganesan et al. (2002) propose braided multipath routing and disjoint multipath routing models to solve these problems for energy-efficient recovery from node failures. Each node on the main path finds the best path from source to sink nodes that does not contain that node itself. This alternate path need not be completely node-disjoint with the main path, which is called a braided multipath model. When a small number of paths are kept alive, failures on the main path can usually be recovered from without invoking network-wide flooding for path discovery.