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Fault-tolerant routing mechanism based on network coding in wireless mesh networks

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ABSTRACT

As an essential part of next generation Internet, Wireless Mesh Networks (WMNs) have attracted much research attention due to their potential advantages, including low up-front cost, ease of deployment, enhanced capacity and service coverage. However, the inherit features of wireless channels (e.g., interference, noise, fading and limited bandwidth) have put forward a severe challenge for network reliability. Conventional fault-tolerant techniques either waste too many bandwidth resources or postpone the recovery speed. This paper proposes a random linear network coding based fault-tolerant routing mechanism to instantaneously recover the native packets omitted by the source. This mechanism couples the multi-path routing and random linear network coding technique by improving the conventional method of coding nodes selection. Simulation results demonstrate that our proposed fault-tolerant routing mechanism, which includes Random linear Network Coding in Multi-path with Source Coding (RNCM-SC) and Random linear Network Coding in Multi-path with Source Forwarding (RNCM-SF), perform better in terms of packet delivery ratio, resource redundancy degree, end-to-end delay and useful throughput ratio than the traditional method.

1. Introduction

As a new type of broadband wireless access network, Wireless Mesh Networks (WMNs) (Akyildiz et al., 2005; Bruno et al., 2005; Liu et al., 2012a, 2012b) have taken on a promising perspective and valuable application in military, environment monitoring, medical and neighboring networks, etc. WMNs are dynamically self-organized and self-configured, with nodes in networks automatically establishing and maintaining mesh connectivity among themselves. These features bring many characteristics such as low up-front cost, ease of deployment, enhanced capacity and reliable service coverage. All these advantages will witness more and more networks deploying WMNs in the future. However, the inherit features of a wireless channel, such as interference, noise, fading and limit bandwidth, have put forward a severe challenge for network reliability. Therefore, the problem of how to ensure reliable data transmission with limited wireless resource is becoming significant in WMNs.

Fault-tolerant function denotes the capacity of a network to deliver the data successfully within the prescribed time when some node or link failure occurs. For network subscribers, a network fault-tolerant mechanism can offer reliable Quality of Service (QoS) guarantee. Since it is difficult to predict and handle various network attacks, interferences and faults, conventional defense-oriented network protection methods seem to be hysteretic and passive. So current fault-tolerant mechanisms focus on keeping up maintaining the transmission of important information as far as possible even when the network cannot completely withstand and eliminate faults. In addition, some mesh routers might be deployed to complete the task of video surveillance and environmental monitoring. Packet loss due to network faults will cause great damage in emergency events. Therefore, it is necessary for WMNs to supply fault-tolerant functions to ensure the successful transmission of important data in a timely manner.

Fault-tolerant mechanisms aim at providing reliable and robust computing service for network users, so that the network system can continue to complete the scheduled task to meet the QoS demands when some fault occurs. It is expected that the whole system can automatically adjust and self-configure to ensure normal network operation without interruption by fault-tolerant technology in the presence of failure. Since correctness and reliability are two critical requirements to popularize the wireless network applications, both industry and researchers have attached importance to researches on fault-tolerant technology in recent years.

Fault-tolerant mechanism has been a hot topic in the reliability researches of wireless networks. Since WNMs have promising market potential, the network would carry more and more

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applications and services. Even network interruption or one failure might cause service interruption of many users. Meanwhile, the wireless interference and noise would frequently cause packet loss or service interruption. Therefore, designing WMNs with fault-tolerance capacity has become a very practical and important issue. Studies on network fault-tolerance include hardware and software levels. The software level contains a fault-tolerant control mechanism, fault-tolerant routing, data fusion and network coding based methods, etc. The hardware level often includes dense placement of nodes and backup station deployment. In this paper, we focus on the software level fault-tolerant mechanism, which aims to enhance the reliability of communication sessions, and not prolong the survivability of individual network components.

Peterson and Davie (2003) designed the Automatic RepeatreQuest (ARQ) scheme, a conventional method for error recovery. Regardless of the hop-by-hop ARQ or end-to-end ARQ manner, they both require the receiver to be aware of the packet loss and then request the sender to retransmit the lost packet, which would result in a long delay before the lost packet succeeds to arrive. Moreover, this method would lead to traffic congestion due to the continual retransmission when channel environment degrades.

The Forward Error Correction (FEC) schemes proposed by Clark and Cain (1981) and Xie and Cui (2007) proactively add redundant information into original packets, so that the receiver can detect and correct the error parts without retransmitting. But the amount of redundant information is difficult to determine for obtaining the accurate error-rate estimate (Cui et al., 2006). To reduce the complexity of encoding and decoding operation, Saha et al. (2006) improved the Red-Solomn (Li and Hou, 2004) based coding method. They discussed how to minimize the energy expense in the *k*-connected topology control problem, and also proved that the link reliability could be greatly enhanced if the packet loss probability is less 10%.

Multi-path routing (Seah and Tan, 2006; Xie et al., 2006; Guo, 2007; Guo and Li, 2007; Nicolaou et al., 2007) is the mainstream approach to strengthen the fault-tolerant capacity. They use many redundant copies on the multiple node–disjoint or link-disjoint paths to ensure the reliable delivery of packets. However, this multi-path method would consume at least 50% of the bandwidth resources in a communication session to supply the destination with redundant information, which can be made use of only when a network failure or packet loss occurs. Restoration based fault-tolerant mechanisms proposed in Perkins et al. (2003) and Virendra et al. (2005) consume fewer resources than multi-path method. However, they require detecting the failure first and then the rerouting mechanism is invoked without providing recovery at the speed of multi-path method.

Conventional fault-tolerant techniques have made rapid progress in the past few years. The multi-path technique can provide fast recovery speed, but this resource-hungry method would waste at least twice the normal working resources for redundant transmission. The backup path based fault-tolerant mechanism (such as 1:N) might cost less redundant resources due to sharing backup path. However, this reactive protection mechanism may need more recovery periods to cause service interruption. As to ARQ and FEC, they are only applicable for some specific occasions.

To overcome the deficiency and to make the fault-tolerant scheme more feasible, we need to reduce the utilized network resources to provide reliable packet delivery without compromising the recovery speed. In this paper, we present a network coding-based fault-tolerant routing technique that overcomes the deficiencies of the traditional schemes. The network coding based fault-tolerant routing mechanism proposed can efficiently improve the reliability of WMNs, which not only overcomes the disadvantage of resource-hungry features in the multi-path technique, but also reduces the delay and interruption in the backup path based fault-tolerant routing mechanism. To the best of our knowledge, this paper is the first study on the design of a fault-tolerant routing mechanism with integration of network coding and multi-path method for WMNs.

The remainder of this paper is organized as follows. We first review related work in Section 2. In Section 3, we introduce the motivation. In Section 4, we give the network model. In Section 5, we design two fault-tolerant routing strategies for fast error recovery over a small finite field. In Section 6, we perform extensive simulations to evaluate the performance of our schemes. Finally, conclusions and directions for future work are given in Section 7.

2. Related work

In the past few years, a great deal of research effort has been made on reliability problems in wireless multi-hop networks. Koetter and Medard (2003) first proposed the idea of using network coding for instantaneous recovery from edge failures. Chaudhry et al. (2006) studied the problem of node connectivity in the network deployment stage. They also investigated the fault-tolerant capacity under certain levels of node redundant degree in some monitoring regions. Hoblos et al. (2000) theoretically analyzed how to enhance the fault-tolerant capacity of wireless networks by appropriately deploying relay nodes. Since network connectivity offered foundation and guarantee for fault-tolerant function, they assumed that each node at least connected with several neighbor nodes. Dasgupta and Biswas (2012) addressed the design of a multi-path data routing algorithm based on network reliability, and calculated reliability of the selected paths for a given *s*–*t* pair for taking routing decisions. Bari et al. (2012) considered a two-tier, hierarchical sensor network architecture, and designed fault tolerant wireless sensor networks satisfying survivability and lifetime requirements by placing the relay nodes appropriately. Sen et al. (2006) studied the domain-based connectivity problem, and concluded that connectivity can be maintained by the percentage information of failure nodes in fault domain.

Ould-Ahmed-Vall et al. (2006) adopted a distributed voting algorithm to enhance the fault-tolerant capacity for event detection in heterogeneous Wireless Sensor Networks (WSNs). Park et al. (2004) divided the network nodes into reliable and unreliable ones to ensure the energy-efficient reliable data delivery, and proposed respective packet loss acknowledgment mechanisms. Srinivasan and Wu (2007) studied the problem of directional flooding and propose a flooding tree model with fault-tolerant capacity. Zhu and Gupta (2007) studied the one-to-many group communication in WSNs with grid deployment, and focused on designing fault-tolerant routing algorithm for the mobile destination scenario. Stann et al. (2006) adopted the idea of cross-layer design, and proposed an energy-efficient reliable broadcast scheme to cope with node failures. Vuran and Akyildiz (2006) discussed the problems of ARQ and FEC from cross-layer perspective, and considered performance of the error correction, delay and energy-efficiency, etc. Oh and Gerla (2009) designed an efficient fault-tolerant mechanism to increase the robust and reliability in MANET, which adaptively turns “on and off” path redundancy and network coding depending on measured packet loss.

Guo et al. (2009) designed an energy-efficient error recovery with network coding in underwater sensor networks. Comprehensive surveys on the error control techniques for multimedia communications in WSNs are available in a recent paper (Naderi et al., 2012). Al-Kofahi and Kamal (2009) studied the problem of