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Cluster-level based link redundancy with network coding in duty cycled relay wireless sensor networks

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ABSTRACT

Reliability and efficiency become more important in data transmission application in wireless sensor networks (WSNs). Many studies have been proposed to improve the network reliability and energy efficiency, but most of them were complicated to implement in energy-limited WSNs. This paper is dedicated to research a high performance protocol named NCCM-DC, which is a **N**etwork **C**oding based **C**luster-level **M**ultipath protocol in **D**uty-**C**ycled WSNs. While meeting the transmission reliability, NCCM-DC can also balance the workload and make full use of energy. In NCCM-DC protocol, the nodes are organized into a cluster and the cluster is used as a basic unit to construct the multipath. Thus, the traffic load can be dispersed to more nodes evenly and a topological structure for cooperative transmission can be formed. Meanwhile, with the advantage of path redundancy and network coding, NCCM-DC improves the transmission reliability. In order to improve the energy efficiency, we focus on the dormancy mechanism and collaborative state transition algorithm. As the low cost in routing discovery phase and the random operations of coding coefficient in Galois Field, NCCM-DC is applicable to energy-limited WSNs. Theoretical analysis and experimental simulation confirms that NCCM-DC can meet the requirements of network reliability and energy efficiency.

1. Introduction

Nowadays, wireless sensor networks (WSNs) become a hot research field in the world, which involves highly cross and integration among multiple subjects. It has many untouchable advantages when compared with traditional networks [1,2]. A large number of nodes are self-organized into network by the equipped radio transceiver. The nodes monitor the physical environment (temperature, sound, movement, etc.) collaboratively [3,4] and transmit the sensed data to the sink. WSNs can be employed to a wide range of engineering application, such as military reconnaissance, environmental monitoring and target tracking [5].

There are two critical issues exist in WSNs need to be researched: (1) compared with the wired networks, wireless links between nodes are more error-prone or failure under the influence of severe environment, the forwarded packets may be dropped through the unreliable links, which is the so called network reliability issue; (2) Meanwhile, as the energy of battery-supplied node is limited, the proposed protocols must be easy to implement and energy-saving, which is the so called energy efficiency issue. Therefore, the data transmission must consider both low energy consumption and high delivery reliability. But the characteristics of high bit error rate (BER), high energy consumption, limited bandwidth and low delivery rate are existed in wireless channel, it is a challenge to design a reliable and energy-efficient data transfer protocol.

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Nowadays, many researches have been proposed to solve those problems.

First, to deal with the network reliability issue, many traditional and emerging mechanisms were proposed including: some error correction mechanisms (automatic retransmission request (ARQ) [6], forward error correction (FEC) [7] and hybrid error correction [8]), multipath protocols and network coding-based mechanisms.

ARQ uses explicit ACK confirmation and retransmission mechanism to ensure reliable transmission. However, ARQ brings additional energy consumption, which will lead to premature failure of nodes and reduce the network lifetime. While replacing the explicit ACK, Improved ARQ [9] use implicit ACK to reduce the use of ACK. However, it is still belonged to ACK mechanism. FEC [7,10] mechanism corrects the mistakes on the sink instead of resending the data, which avoids the frequent use of ACK. So, it can improve the reliability without retransmission. However, as FEC only encode the data in source node, the packet may not be delivered successfully when the node failure or link quality is severe. Hence, it does not have good robustness.

Multipath routing [11–13] is another way to improve the transmission reliability with the help of link redundancy. But there are new challenges with multipath in WSN: (1) the network will sustain higher workload and maintenance cost with excessive paths; (2) due to the parallel transmission in multipath, the differences among all paths in bandwidth, hop counts and processing ability will lead to a great difference in transfer delay, which will further led to packet disorder in the destination; (3) the path interruption caused by the topology change and link error will lead to path congestion, which further result in packet loss. Therefore, traditional multipath routing also has limitations in the WSNs.

The birth of network coding (NC) [14] can overcome above issues to some extent. It can improve the network throughput, network reliability and reduce the energy consumption, etc. NC overturns the traditional views that “relay nodes (such as switches, routers) will not improve the network performance while performing data coding”. Li et al. [15] proved that the Linear Network Coding (LNC) can achieve multicast capacity in the butterfly multicast network. Ho et al. [16] proposed Random Network Coding (RNC) and discussed the choice of coefficient in Galois Field. Ghaderi et al. [17] quantized the multicast reliability benefits based on NC, and compared it with ARQ. Katti et al. [18] realized the wireless protocol COPE based on NC on the operation platform first and proved that NC can improve the unicast and multicast performance. Nguyen et al. [19] provided the theory of bandwidth efficiency based on NC. As NC attracts widespread interests, it has been used in more and more applications [18,20].

Considering the broadcast nature of wireless channel which implicitly built multiple paths to the sink, many NC-based multipath mechanisms [21–23] are proposed to improve the transmission reliability. Research proved that the NC-based multipath protocols have better redundancy control when compared to the traditional multipath.

Second, to deal with the energy efficiency issue, many mechanisms from different aspects were proposed. As the node is battery-supplied, the limited energy becomes a hindrance in large-scale application of WSNs. It is an important direction that how to use the energy reasonable and improve the network lifetime further [24].

Data aggregation [25,26] is a way to reduce the energy consumption, and large amounts of data relayed by nodes can be reduced while using data aggregation. In addition, the duty cycled method [24] can also be used to reduce the energy consumption. Each node switches its state (active or sleeping state) reasonable in certain timeslot. Random duty cycle [24,27] and collaborative duty cycle [28] are two forms of duty-cycled WSNs. In the former, the nodes switch their own status independently and randomly. In the latter, the nodes switch their states by control message exchanges and cooperative communication.

Furthermore, as the data flows to the sink, the energy consumption of the nodes near the sink is far more than that of other nodes, which may cause energy bottleneck region around the sink. The bottleneck nodes consume energy rapidly and will lead to "energy hole" problem, and further decreasing the network reliability [24]. Thus, in this work, we also need to reduce the likelihood of “energy hole” through some methods.

Comprehensive the above analysis and in order to address the existing drawbacks in those mechanisms, we construct a high performance data transfer protocol considering both reliability and energy efficiency. While meeting the transmission reliability, the proposed protocol also needs to balance the nodes’ workload, improve the energy efficiency and reduce the likelihood of “energy hole” around the sink. Therefore, we present a NC based cluster-level multipath protocol in duty cycled WSNs (NCCM-DC): (1) NCCM-DC combines the path redundancy (multipath) and network coding that enhances the transmission reliability; (2) with the construction of cluster-level multipath, NCCM-DC scatters the traffic load to more nodes and provides a topological structure for cooperative transmission; further, NCCM-DC adopts a collaborative state transition mechanism within the cluster to reduce energy consumption. The main contributions of the paper are:

(1) For transmission reliability, based on the wireless broadcast characteristic, NCCM-DC protocol adopts network coding for data coding transmission without the use of ARQ or FEC; meanwhile, in order to ensure the expected reliability, the intra-cluster nodes will cooperate to transmit the coded data if the active nodes in a cluster is less than the slot queue’s size. Thus, NCCM-DC combines the collaborative communication and NC into data transmission process, which guarantees the transmission reliability, reduces the excessive data redundancy and decreases the nodes’ energy consumption.
(2) For energy efficiency, we prefer to scattering the traffic load to more nodes. Meanwhile, to provide a topological environment for cooperative transmission, we construct a cluster-level multipath routing which uses the cluster as basic route unit. Instead of building a new mechanism, our cluster-level multipath is based on a traditional mechanism [29] which is stable and easy-implemented. We modify the routing message (REEQ) format in NCCM-DC and