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An adaptive virtual relaying set scheme for loss-and-delay sensitive WSNs

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ABSTRACT

In loss-and-delay sensitive wireless sensor networks (WSNs), especially when the duty cycles of nodes are extremely low, it is a challenge to ensure that data can be transmitted to sink nodes with high reliability and low delay. To address this problem, in this paper, we propose a data collection scheme named Adaptive Virtual Relaying Set (AVRS) where a set of relay nodes with more reliable connections to the sender node is selected to form its Virtual Relaying Set (VRS) to help transmit packets. In ring-based WSNs, each node in a VRS helps send packets in turn to the upper ring before the transmission is successful, or the packet is dropped if they all fail. Therefore, the larger the VRS (implying more retransmission chances), the higher the packet transmission reliability and the lower the delay will be. On the other hand, as the sender node has to stay active during the transmission stage, having a large VRS will cause huge energy consumption. Combined with the fact that the energy consumption of different parts of WSNs is unbalanced, nodes in the near-sink area (i.e., hotspots) have extremely high energy cost while nodes in the far-sink area (i.e., non-hotspots) still have ample energy remaining when the network dies. The main idea of the AVRS is the following rule. The size of the VRS of nodes is determined adaptively according to its energy usage pattern, making the size small in hotspots and relatively large in non-hotspots. The AVRS takes advantage of the residual energy of nodes in far-sink areas to achieve improved network data collection performance. Meanwhile, as nodes in near-sink areas have small VRS, the network can maintain a long lifespan without any reductions. Both theoretical analyses and simulative results demonstrate that the AVRS can improve data transmission reliability by more than 50% and reduce network delay by at least 33%.

1. Introduction

Wireless Sensor Networks (WSNs) are commonly used for environmental monitoring, surveillance operations, and home or industrial automation [1,3,8,16,19–21,24]. Together with current crowd-sensing networks and cloud computing [5,13,33,38,41], it is regarded as one of the most promising techniques for the future [12,14,22,25,37]. Since replacing or recharging sensor node batteries is extremely difficult, WSNs switch active and dormant states cyclically to save energy [27,42]. *When the sensor is in the active stage, it can perform all data operations, such as transmitting and receiving packets and*

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detecting and sensing environments [9,36,39]. In the dormant state, the sensor cannot perform any operations and just sleeps, but this state consumes 1000 times less energy than the active state [4,17,20]. From the view of saving energy, sensors should be set to the dormant stage as much as possible, but too long of a dormant period will lead to a decline in network performance, such as an increased probability of missed target detection, detection delay, and notification transmission latency. Sensor nodes in WSNs usually operate at a very low duty cycle style, implying that the sensor nodes sleep most of the time and stay active for only a short duration of each duty cycle [7,10]. Under such circumstances, when a sender node needs to deliver a message, it always has to wait until its destination node activates, thus resulting in sleeping latency. The sleeping latency in WSNs with large hop counts to sink nodes will lead to very long end-to-end delivery latencies. However, WSNs are usually applied to significant situations for detecting emergency incidents, such as fire and disasters, where a long end to end (e2e) delay may result in disastrous consequence. Thus, it is of great significance to be able to transmit sensed data to sink nodes rapidly. Owing to the inherent fallibility of wireless transmission, packets could be dropped during the collection process. Hence, another challenge is how one can guarantee that the sensed data can be reliably delivered to sink nodes. By selecting reliable relay nodes, sender nodes can have the best chance to transmit data. Many variants of this basic method have been proposed [2,29,30].

Currently, two general strategies are usually applied to enhance reliability. First is retransmission technology, which repeatedly transmits the failed packets, allowing nodes to provide more reliable communications. Second is increasing data transmitting power since increased power can improve the quality of network links, which in turn increases the probability of successful transmission. There are also two general methods for reducing transmission delay. First, by increasing the duty cycle of nodes, large duty cycles can shorten the interval of two adjacent active states, so nodes can transmit and receive packets earlier instead of waiting. Second, by increasing the size of the relaying nodes set, this can shorten the waiting time of sender nodes for its destination node (a node in the set) to become active, thus reducing the sleeping delay.

Lifespan is also a pivotal issue for WSNs. However, the aforementioned strategies all need to consume more energy, which may hasten the death of network. We observed that there is a special phenomenon called an "energy hole" in sensor networks [31]. To be more specific, nodes all send their sensed data to the sink node, which is at the center of the entire sensor network. However, this "many-to-one" data collection mode causes an imbalance. Nodes in the near-sink region help relay the packets generated by the outside nodes, so the amount of data they take is much greater than those in the far-sink area. Transmitting data is the main source of energy consumption, resulting in premature death of the nodes in hotspots and the network. Some related studies have shown that, due to the impact of the energy hole, there still remains up to 90% energy in the network when it dies [31]. Based on the above observation, we propose an innovative data collection scheme named Adaptive Virtual Relaying Set (AVRS) in this paper to achieve high network reliability and low delay without reducing the lifespan of networks by making use of the residual energy. The main contributions of our work are as follows:

(1) An Adaptive Virtual Relaying Set (AVRS) data collection scheme is proposed to correct for loss and delay in sensitive WSNs. Based on the unbalanced energy usage pattern, in an AVRS, a large number of nodes are selected to form a VRS in the far-sink region, while in the near-sink region fewer nodes are selected. This simple yet novel trick can greatly improve the overall data collection performance and, more importantly, not harm the network lifespan.
(2) The mathematical relations between the size of a VRS, energy consumption of nodes, data transmission reliability, and delay are provided. Based on these we design three algorithms (Section 4.3) that address the selection of the size of a VRS of nodes in different places in the network.
(3) Extensive simulations were conducted and the results were consistent with our theoretical analysis. In this paper, we measure the overall quality of the network using the weighting method, which uses the weighted sum of the nodal quality in proportion with the entire network. Both theoretical and simulative results demonstrate that the AVRS is efficient in enhancing both data collection reliability and delay under network lifespan constraints, which, on average, improves the network reliability by more than 50% and reduces transport delay by at least 33%.

The remainder of this paper is organized as follows. Section 2 reviews related works and compares them with our proposed scheme. Section 3 describes our network model and defines problem statements in the paper. Section 4 elaborates on the design of Adaptive Virtual Relaying Set (AVRS) for loss and delay in sensitive WSNs. In Section 5, the performances of AVRS are theoretically analyzed. Section 6 presents experimental results and comparisons. Finally, we conclude in Section 7.

2. Related works

In WSNs, lifespan, delay and reliability are the three most important properties that must be ensured. Much research has been done in this field [2,5,10,14,16,19,23,24,29,32,33,35,37,38,40]. This section briefly reviews some related works.

(1) *Large data transmitting power mechanism.* According to the basic principles of wireless communication, higher transmitting power leads to a larger signal-noise ratio, allowing easier packet reception. However, nodes will have larger energy consumption since their power increases, which shortens the lifespan of nodes. [40] obtained the values of data transmission reliabilities with different transmitting powers for different channel models (i.e., additive white Gaussian noise, Rayleigh fast fading and Rayleigh block-fading) in a linear network. Their conclusions are further verified using 2-dimensional Poisson networks using simulations. In [18], nodes in close-sink areas use higher transmitting power to improve reliability, whereas nodes in near-sink areas use relatively low power while guaranteeing