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Power saving mechanism with network coding in the bottleneck zone of multimedia sensor networks

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ABSTRACT

Power consumption is one of the most important issues for the lifetime of a wireless sensor network (WSN). Specifically, the lifetime of a WSN depends on the power consumption of the nodes in the bottleneck zone near each sink node, where all sensing data is collected via the nodes in the bottleneck. However, these nodes' energy is depleted very quickly because of the heavy traffic imposed on them. Therefore, in this paper, we propose a power saving mechanism using network coding and duty cycling in the bottleneck zone of WSNs to prolong the lifetime of WSNs. We propose duty cycling, packet forwarding, and role switching schemes for nodes in the bottleneck zone. In our proposed approach, the packet forwarding in the coder nodes employs random linear network coding to enhance energy efficiency and reliability in the bottleneck zone. We evaluate the performance to show that the proposed protocol outperforms the conventional system in terms of the lifetime of WSNs, without reducing the reliability of packet delivery in the bottleneck zone. In a grid topology network, the lifetime achieved with the proposed protocol is doubled or tripled compared with the conventional system.

1. Introduction

Wireless sensor networks (WSNs) have been used for many applications, such as the military surveillance, disaster monitoring, environmental monitoring [1–3]. In the future Internet, WSNs are expected to be major components in the Internet of things (IoT) and the web of things (WoT) [4,5]. In a sensor network, thanks to low-cost hardware miniaturization and advances in wireless communication technologies, a large number of sensors can be deployed to monitor target areas and acquire sensing data that is autonomously collected in sink nodes [3]. However, WSN designs have many restrictions, such as fault tolerance, scalability, network topology, hardware constraints, and power consumption. Among these, power consumption is one of the most important issues related to the lifetime of a WSN. The sensor nodes in a bottleneck zone, which is the area near a sink node, can experience node failure quickly because all sensing data is collected in sink nodes from the other nodes in the bottleneck zone, which imposes heavy traffic on those nodes. Thus, the lifetime of a WSN is mainly determined by the lifetime of the sensor nodes in bottleneck zones [6]. For this reason, this paper focuses on a power saving mechanism for the bottleneck zones of WSNs. In our mechanism, we consider two major techniques for power saving in sensor networks: duty cycling and network coding (NC).

Power saving by switching between active and sleep states is called duty cycling. A large amount of literature addresses power saving in WSNs using duty cycling [7–17]. S-MAC introduced a periodic sleep scheme in which all nodes in a virtual group have the same active phase [7]. T-MAC

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enhances S-MAC by adjusting the active period according to the network traffic load [8]. B-MAC and X-MAC use preamble sampling to reduce the duty cycle and minimize idle listening [9,10]. One study [11] proposed that each sensor node switches randomly between active and sleep states. With DW-MAC, a low-overhead scheduling algorithm allows nodes to wake up on demand during a sleep period [12]. Opportunistic flooding employs a power saving mechanism using duty cycling in broadcast transmissions [13]. In [14], the upper bound of network lifetime for WSNs with bottleneck zones was studied. Pak et al. studied duty cycle allocation to maximize the lifetime of WSNs [15]. They used a tier-based anycast protocol and showed that network lifetime can be extended by allocating a different duty cycle. Han et al. solved the minimum-energy multicasting problem in WSNs for both one-to-many and all-to-all multicasting [16]. In [17], a control-based approach to duty cycle adaptation for WSNs was proposed. In particular, queue management was used to achieve high performance under a variable traffic rate. Duty cycling is an efficient method for power saving in WSNs. Moreover, duty cycling used in conjunction with NC could provide even greater power saving in WSNs.

NC is a promising technique that reduces network congestion by combining packets for distinct destinations. Many studies have investigated WSNs with NC to enhance their energy efficiency [18–29]. Platz et al. studied the energy efficiency of NC in all-to-all broadcast applications [18]. Shwe et al. enhanced the energy efficiency of the NC scheme in WSNs by using neighbor discovery [19]. In [20,21], researchers solved the optimization problem in WSNs with NC, based on theory. In [22,23], the authors proposed NC-based multipath routing for improved energy efficiency in WSNs. In [24], the authors proposed NC-based energy-efficient data fusion and transmission in WSNs with heterogeneous receivers. Glatz et al. implemented energy-harvesting aware routing and opportunistic NC in WSNs using TinyOS [25]. In [26], the authors solved the optimization problem for network lifetime and video distortion in multimedia sensor networks. These previous works improved the efficiency of power consumption in WSNs by using NC. However, most previous works do not consider the bottleneck zone. They also do not take into account interworking with duty cycling, which is a major technique for power saving in WSNs. Recently, power saving mechanisms considering both NC and duty cycling have been studied [27–29]. In [27], Chandanala et al. proposed DutyCode, combining NC with duty cycling by using information on packet streaming in flooding-based WSNs. However, they did not exploit power saving in the nodes of a bottleneck zone around a sink node. In [28,29], researchers derived the upper bound of network lifetime in WSNs using random duty cycling and NC. They showed that the lifetimes of coder nodes were prolonged because nodes in the bottleneck zone encoded packets using XOR NC. However, XOR NC can reduce the reliability of the sensing data delivery. Furthermore, nodes other than coder nodes in the bottleneck zone do not benefit from NC in terms of power consumption.

In this paper, we propose a power saving mechanism using NC and duty cycling in the bottleneck zone of WSNs to enhance the lifetime of WSNs. In particular, we propose a duty cycling scheme that yields more sleeping opportunities for nodes in the bottleneck zone. Furthermore, our power saving mechanism uses random linear network coding (RLNC) for packet encoding to enhance energy efficiency and the reliability in the bottleneck zone. Nodes in the bottleneck zone periodically switch roles to prolong the lifetime of all nodes in the bottleneck zone by using NC. The main contributions of the paper are as follows:

1. A duty cycling scheme for power saving in nodes of the bottleneck zone.
2. A packet forwarding scheme using RLNC in coder nodes to enhance the energy efficiency and the reliability in the bottleneck zone.
3. A role switching scheme for nodes of the bottleneck zone to prolong the lifetime of WSNs.

The rest of this paper is organized as follows. Section 2 presents the system model of the proposed protocol. In Section 3, we explain the operation procedure of the proposed protocol. In Sections 4 and 5, we present the performance analysis and describe the performance evaluation of the proposed protocol. Finally, the conclusions are provided in Section 6.

2. System model

The system model is composed of a sink node and sensor nodes, as shown in Fig. 1. All sensor nodes sense data periodically, and then the sensing data generated by all sensor nodes are aggregated at a sink node. To improve reliability of packet delivery in WSNs, sensing data travel via multi-path forwarding from a sensor to a sink [30,31]. Thus, a node broadcasts the data for multi-path forwarding. Around a sink node, there is a bottleneck zone (B) as shown in Fig. 1. The bottleneck zone B is defined as the area within distance D from the sink node, where D is the transmission range of the sensor nodes [6,14]. Thus, nodes in B consume more power than nodes outside B because all data are relayed through the nodes in B. In this paper, we consider a fixed multimedia sensor network used in applications such as multimedia surveillance, traffic monitoring and control systems, and environmental monitoring [1–3]. Therefore, an IEEE 802.11 system is used to convey the sensing data [3].

In a WSN, sensor nodes have constrained energy resources, although the sink has no such limitation. Therefore, power saving is important to the WSN's network lifetime. In an IEEE 802.11 system, a power saving mechanism (PSM) exists that uses an announcement traffic indication message (ATIM) [32]. The procedure of the PSM is shown in Fig. 2. In an IEEE 802.11 system, time is divided into beacon intervals by means of a distributed protocol using beacon transmission. At the start of each beacon interval, all nodes stay awake to announce the packet transmission for an ATIM window. For example, Node A announces packets destined for Node B by transmitting an ATIM frame during the ATIM window. Upon receiving the ATIM frame, Node B responds by sending an ATIM-ACK message. This message is transmitted using CSMA/CA in IEEE 802.11. When the node has sent an ATIM frame or ATIM-ACK message to another node, such as Node A or B in Fig. 2, the node remains awake for the entire beacon interval to transmit packets. If a node has not received an ATIM frame and has no data packet to be transmitted, it