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Distributed network configuration in large-scale low power wireless networks

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ABSTRACT

One of key issues in the construction of a large-scale wireless sensor network (WSN) is how to securely allocate a unique address to each node in an energy-efficient manner. However, conventional network configuration mechanisms may suffer from energy inefficiency and/or addressing failure problem when applied to the construction of large-scale WSNs. In this paper, we consider the construction of a large-scale WSN by means of distributed addressing operation. We design a network configuration mechanism that allows each router to have its own addressing space for unique address allocation to its child nodes. We also design a node type selection (i.e., router or end device) algorithm that can allow the whole deployment area to be covered by using a less number of routers (i.e., lower energy consumption) than conventional ones. The proposed mechanism provides at least a neighboring router for each node, enabling to support the network connectivity in a distributed manner. Finally, the performance of the proposed scheme is evaluated by computer simulation, showing significant performance improvement over conventional schemes when applied to the construction of a large-scale WSN.

1. Introduction

The demand for large-scale wireless sensor networks (WSNs) has rapidly been increased, which may require multi-hop based network construction with scalability and energy efficiency [1]. Construction of a multi-hop based large-scale WSN needs the use of a routing header containing a large number of addresses to indicate the routing path and/or a routing table which contains a large number of entries. In practice, the sensor node uses a small size packet[1] and memory. The use of a large-size medium access control (MAC) address may cause large signaling and memory overhead [3]. To minimize the overhead, it may be desirable to allocate a short address to each node [4]. The addressing procedure needs to operate in a distributed manner to reduce the message exchange overhead.[2]

IEEE 802.15.4 is a standardization of MAC and physical (PHY) layer applicable to the construction of WSNs [2]. It allows two types of nodes; router and end device. The router can behave as an addressing server (i.e., a parent node which can have child nodes) and a packet relaying node, forming a cluster comprising a set of a parent node and plural child nodes. It can be employed to expand the network, but it may consume more energy than the end device. On the other hand, the end device can only be a leaf node that can transmit and receive its own packets. Unlike asynchronous MACs [7–9], the IEEE 802.15.4 beacon-enabled mode does not allow child nodes to overhear others packets, enabling to further reduce energy consumption of end devices. The

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1 IEEE 802.15.4 considers a maximum packet size of 128 bytes [2].

2 The message exchange process may require much more energy than the sensing and control process in WSNs [5,6].

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deployment of a large number of routers may improve the network connectivity while consuming more energy. The energy efficiency may be achieved by minimally deploying routers, which may in turn increase the number of orphan nodes.[3] It may be desirable to connect all the nodes to the sink node (i.e., the coordinator) using a small number of routers [10]. To the best of our knowledge, previous works have not well investigated the address allocation and the node type selection in the construction of large-scale WSNs. Instead, they have more concerned on the design of routing techniques assuming that all the nodes operate as routers with the use of conventional MAC addresses [11–15], and the performance enhancement of IEEE 802.15.4 networks with a single hop [16–21].

ZigBee has nice features of low power consumption and low complexity, making it quite feasible for the construction of low-rate WSNs. It employs a simple parent/child node type selection mechanism and distributed address allocation mechanism (DAAM), enabling to construct a network in a distributed manner [22]. However, addressing space of the DAAM exponentially increases in proportion to the network depth [23,24]. It may suffer from the restriction of network depth when applied to the construction of a large-scale WSN. Moreover, the parent/child node type selection mechanism may waste the network depth.[4] It may also make the node connection proceed to a certain direction, referred to networking bias problem [25,26]. As a consequence, it may not be applicable to the construction of a large-scale WSN.

Some previous works have considered the improvement of DAAM based network connectivity [22–26]. The DAAM problem can be alleviated by using a stochastic address allocation mechanism (SAAM) [22]. The SAAM allows each router to allocate its child node an address which is randomly selected from the whole addressing space, making it free from the network depth restriction. It confirms the addressing uniqueness by means of network-wide broadcast. However, the network-wide broadcast incurs a large message overhead as the network size increases, referred to broadcasting storm problem [27,28]. Recently, 6LoWPAN has updated the process for duplicate address detection (DAD), a standardized address allocation algorithm in IP networks, for application to WSNs [29]. It allows a new node to get its address by itself from the whole addressing space. The network coordinator confirms the addressing uniqueness by means of two-way multi-hop communications, resulting in a large amount of message exchanges between the nodes [30]. Moreover, the SAAM and the DAD do not consider the node type selection.

In this paper, we design a network configuration mechanism applicable to the construction of low power wireless networks with enhanced network scalability and reduced signaling overhead. We consider the address allocation and node type selection in a distributed manner, which can avoid network-wide broadcast and multi-hop communications. We consider the use of a multi-step DAAM (referred to M-DAAM) to construct a large-scale addressing tree, where the DAAM parameters are adjusted according to the network depth in a multi-step mode. We determine the node type so that the network coverage can be expanded with the network depth, while placing routers throughout the whole network area as uniformly as possible. The proposed mechanism first allows a node to join the network as an end device and then converts some end devices having few neighboring routers to routers. Finally, it also converts routers having no child node for a long time to end devices. It allows nodes to easily join the network in a distributed manner while utilizing a reduced number of routers.

The contributions of the paper can be summarized as follows:

- We design a distributed network configuration mechanism which can provide high connectivity with low energy consumption. Some previous works exploit distributed network configuration mechanisms for energy efficiency, but they may not provide high connectivity. Some new protocols employ broadcasting or centralized operation rather than distributed operation for the connectivity, but suffer from large overhead.
- We analytically show that the proposed mechanism requires less signaling overhead and computational complexity than broadcasting or centralized ones. We also show that the overhead and complexity of distributed mechanisms increase with the number of neighbor nodes, while those of others increase with the network size.
- We evaluate the performance in terms of the network connectivity, network depth, signaling overhead, network joining time, and the number of routers, by computer simulation. After the network construction, we evaluate the uplink performance in terms of the packet delivery ratio, latency, and power consumption. We also evaluate the connectivity performance in specific operation environments where some obstacles and holes exist.

The rest of this paper is organized as follows. Section 2 describes the WSN model in consideration. Section 3 briefly reviews previous network configuration mechanisms applicable to low-power WSNs. Section 4 describes the proposed network configuration mechanism. Section 5 evaluates the performance of the proposed scheme by computer simulation. Finally, Section 6 concludes this paper.

2. System model

As illustrated in Fig. 1, we consider a ZigBee/IEEE 802.15.4 based beacon-enabled cluster-tree network comprising a single network coordinator, multiple routers and end devices [2,22]. The network coordinator and router can have routers and end devices as their child nodes. Let *BO* be the beacon order and *SO* be the superframe order. Then, the superframe duration T_{SD} and the periodic beacon transmission interval T_{BI} can be determined as

[3] A new node cannot join the network without the presence of a router nearby.

[4] The network coverage may not easily be expanded even though increasing the network depth.