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Pseudo geometric broadcast protocols in wireless sensor networks: Design, evaluation, and analysis

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ABSTRACT

With increasingly popular wireless and low-power sensors/devices, broadcast is one of essential operations to enhance information accessibility and availability. Due to the lack of centralized coordination and limited resources, however, designing an efficient broadcast protocol is challenging in Wireless Sensor Networks (WSNs). Although on-board Global Positioning System (GPS) based broadcast protocols that heavily rely on the geographical information and its accuracy have been proposed, the positional inaccuracy and non-negligible deployment cost may become an issue. Thus, we investigate a pseudo geometric broadcast problem and propose its corresponding protocols, called pseudo geometric broadcast protocols, in resource constrained WSNs: (i) Approximating Neighbor Nodes based Broadcast Protocol (Approx), (ii) Enhanced Ad Hoc Broadcast Protocol (AHBP) with Target Forwarding Nodes (EBP($|N_f|$)), and (iii) Node Distribution Sensitive Broadcast (NDS). The basic idea is that a packet sender approximates the locations of its neighbor nodes and searches a set of forwarding nodes located close to the strategic positions without the support of GPS in a heuristic manner. We develop a customized discrete-event driven simulator using OMNeT++ to conduct our experiments by varying the key simulation parameters, and analyze the performance of broadcast protocols in terms of packet delivery ratio, number of broadcasts, propagation delay, and computational overhead. Extensive simulation results indicate that the proposed broadcast protocols achieve competitive performance and become viable approaches in WSNs.

1. Introduction

The growing presence of WiFi and 4G LTE enables users to pursue seemingly insatiable access to Internet services and information wirelessly. It is predicted that 40.9 billion wirelessly connected devices will be available by 2020, nearly triple the number that exist today [1]. The spread of these devices and hybrid networks is leading to the emergence of an Internet of Things (IoT), where a myriad of multi-scale sensors and heterogeneous devices are seamlessly blended for ubiquitous computing and communication. The prevalence of cloud, social media, and wearable computing and the reduced cost of processing power, storage, and bandwidth are fueling explosive development of IoT applications in major domains (i.e., personal and home, enterprise, utilities, and mobile) [2]. These IoT applications have the potential to create an economic impact of \$3.9 trillion to \$11.1 trillion annually by 2025 [3]. It is envisioned that wirelessly connected smart and low-power sensors/devices (later in short nodes) will further change life as we live it.

To realize this vision, *broadcast* is one of essential operations to share locally sensed information among each other to enhance information accessibility and availability. Flooding is a simplest broadcast protocol, where each node rebroadcasts any received packet in the network. Since broadcast has the inherent constraints in terms of redundant retransmissions and packet contentions and collisions [4], however, a blind broadcast followed by a series of unconditional forwarding operations is inefficient and even harmful. The redundant retransmissions can also negatively affect the communication performance, such as the network lifetime. Note that when a node intends to transmit a unicast packet, unlike a wired network, all neighbor nodes located within its communication range can overhear the packet, as if it is a broadcast packet [5]. Due to the lack of centralized coordination and limited resources, designing an efficient broadcast protocol is admittedly challenging in Wireless Sensor Networks (WSNs).

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In light of this, we investigate a pseudo geometric broadcast problem and propose its corresponding protocols, called *pseudo geometric broadcast protocols*, in WSNs. The definition of pseudo geometric broadcast problem is to select a set of forwarding nodes in a heuristic manner to minimize the number of broadcasts, propagation delay, and computational overhead, but to maximize the packet delivery ratio without the support of an on-board Global Positioning System (GPS) in a pre-deployed network. The number of broadcasts is counted whenever a node broadcasts a newly received packet. If the node received the packet that has been broadcasted before, it does not count but simply drops the packet to avoid a cycle. In this paper, we do not pursue an optimized solution and its corresponding proof, but try to achieve it in best effort. Note that unlike geometric broadcast, where geographical information (e.g., node location) and its accuracy are important, the pseudo geometric broadcast roughly estimates the location without the support of GPS. Since GPSes often suffer from the positioning inaccuracy, non-negligible deployment cost and energy consumption, and intermittent unavailability of GPS signal in an indoor environment, they are limited to be deployed in resource-constrained WSNs. For example, a NAVSTAR GPS has about 50 to 100 (m) error bounds [6], which can negatively affect the communication performance. Thus, the pseudo geometric broadcast that does not rely on GPS is essential. Note that the pseudo geometric broadcast problem in this paper is different from the network coverage problem [7].

The basic idea of the proposed protocols is that a packet sender approximates the location of its neighbor nodes and searches a set of forwarding candidate nodes located close to the boundary of its communication range. The sender further selects the forwarding candidate nodes that are located at the closest to the strategic positions based on a virtual hexagon-based coverage. The proposed approach is different from prior geometric broadcast protocols [8,9], where each node is equipped with an on-board GPS and selects the best forwarding nodes based on the knowledge of adjacent nodes' locations to minimize the number of broadcasts. Our contributions are briefly summarized in three-fold:

- First, we propose three sender-initiated pseudo geometric broadcast protocols in WSNs: (i) Approximating Neighbor Nodes based Broadcast Protocol (Approx), (ii) Enhanced Ad Hoc Broadcast Protocol (AHBP) with Target Forwarding Nodes (EBP($|N_f|$)), and (iii) Node Distribution Sensitive Broadcast (NDS), where $|N_f|$ is a number of forwarding nodes. A simple random backoff mechanism is also proposed to avoid possible packet contentions and collisions because of simultaneous rebroadcasts.
- Second, we modify the AHBP [10] to work in WSNs for the purpose of performance comparison. A variation of the GPS supported Broadcast Protocol for Sensor networks (BPS) [8], denoted as BPS*, is also modified by adding a sender-initiated broadcast approach.
- Third, we evaluate the performance of five broadcast protocols in terms of packet delivery ratio, number of broadcasts, and propagation delay by changing the node density and network size: AHBP, BPS*, Approx, EBP($|N_f|$), and NDS. The COUNT scheme is also used to compare the number of broadcasts measured as a part of our preliminary research in Section 3. In addition, we measure and compare the computation overhead of four broadcast protocols in terms of number of operations in a microscopic way: AHBP, Approx, EBP($|N_f|$), and NDS.

We develop a customized discrete-event driven simulator using OMNeT++ [11] to conduct our experiments and multi-dimensional analyses. Extensive simulation results indicate that the proposed Approx shows a scalable performance in terms of the number of rebroadcasts as the number of deployed nodes increases in the network. The proposed EBP($|N_f|$) and NDS protocols also show competitive performance and become viable approaches in resource constrained WSNs. This paper is significantly extended based on our prior work published in part at [12,13].

The rest of paper is organized as follows. The prior work is reviewed in Section 2. The impact of network densities and sizes is discussed in Section 3. The proposed pseudo geometric broadcast protocols are presented in Section 4.1. Section 5 is devoted for performance evaluation and analysis, followed by the issues for possible extensions of the proposed broadcast protocols. Finally, Section 6 concludes the paper.

2. Related work

In this section, we categorize and review prior broadcast techniques in terms of threshold-, structure-, probability-, and geometry-based approaches.

2.1. Threshold-based approach

When a node sends a packet, all of its neighbor nodes can overhear the packet because of a promiscuous receiving mode. Then an immediately following unconditional forwarding (i.e., flooding) can incur redundant transmissions and lead to the broadcast storm problem [4]. In order to avoid the redundant rebroadcasts that can lead to packet contentions and collisions, several threshold-based broadcast schemes have been proposed, in which their threshold values (i.e., number of same overheard packets, additional covered area, or number of neighbor nodes who have not received the packet) are adjusted based on local connectivity information [4,14]. Under the consideration of distance- and counter-based schemes [4], receiver's signal strength can be measured to approximate the distance to a packet sender [15]. The node located at the farthest from the sender rebroadcasts the packet to increase the coverage area. This approach is further extended to a heterogeneous network topology in the presence of obstacles [16], where nodes are non-uniformly deployed in the network. In [17], since packet losses are unavoidable (e.g., a predefined rebroadcast probability, $p = 0.55 < 1$) during a broadcast period, each node buffers failed broadcast packets and periodically rebroadcasts them to compensate any missed packet.

2.2. Structure-based approach

A broadcast tree between a source and multiple destination nodes is deployed to improve energy efficiency and reliability, i.e., a flood tree [18–20]. Depending on the connectivities in the tree, each node can decide whether to rebroadcast or drop a packet to minimize the redundant rebroadcasts but to maximize the network coverage. In [19], a connected dominating set (CDS) is built in a localized and distributed manner by constructing independent DSs (called dominators) and connecting all nodes (called connectors) in DSs. Then the dominators create a virtual backbone for efficient broadcast. In [20], a single node is elected as a single-initiator in a distributed manner, and it constructs a dominator tree to form a CDS based on the timers. Multiple-initiators are also considered to avoid a single-point of failure at the single-initiator. As pointed out in [18], however, the problem of finding a minimum tree that has the minimum number of forwarding nodes is proven to be NP-complete. Frequent constructing and maintaining the tree can also occur non-negligible communication overhead because of the mobility and energy constraints in mobile ad hoc networks (MANETs) and WSNs, respectively.

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