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Static and dynamic minimum energy broadcast problem in wireless ad-hoc networks: A PSO-based approach and analysis

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ABSTRACT

In this paper, we address the minimum energy broadcast (MEB) problem in wireless ad-hoc networks (WANETs). The researches in WANETs have attracted significant attentions, and one of the most critical issues in WSNs is minimization of energy consumption. In WANETs the packets have to be transported from a given source node to all other nodes in the network, and the objective of the MEB problem is to minimize the total transmission power consumption. A hybrid algorithm based on particle swarm optimization (PSO) and local search is presented to solve the MEB problem. A power degree encoding is proposed to reflect the extent of transmission power level and is used to define the particle position in PSO. We also analyze a well-known local search mechanism, *r*-shrink, and propose an improved version, the intensified *r*-shrink. In order to solve the dynamic MEB problem with node removal/insertion, this paper provides an effective simple heuristic, Conditional Incremental Power (CIP), to reconstruct the broadcast network efficiently. The promising results indicate the potential of the proposed methods for practical use.

1. Introduction

A wireless ad-hoc network (WANET) is a collection of nodes dynamically forming a connected network without relying on any preexisting infrastructure. There has been an increasing interest in the use of WANETs due to their convenient deployment, flexible communication, and a variety of applications. Wireless sensor network (WSN), which is composed of a large number of sensor nodes, is one of the typical manners of WANET. These nodes are ordinarily equipped with sensing, communication, and computing abilities. Each sensor node can measure environmental parameters such as temperature, humidity, sound, and vibration, perform simple computations, and communicate with neighboring nodes or base station. WSN have already been applied broadly on civil and military applications including forest surveillance, factory automation, disaster monitoring, border protection, battle field surveillance, and animal tracking [1–4].

Generally speaking, each sensor node in the network has limited energy (usually a battery or an embedded form of energy resource), which is in some cases completely non-rechargeable or non-renewable [5]. It connotes that these nodes are likely to be on their tasks for a long time without reorganization or provision. One of the utmost issues in WANETs is the determination of network routing. In the routing problems, we have to maximize the network lifetime; in the meantime, we have to prevent the loss of network connectivity. Compared with traditional link-based networks, WANETs can be deployed costlessly in a very short time, and they do not depend on the preexistent facilities, e.g., basement station or router. Different from traditional networks, in WANETs there is usually more than one receiver in a single transmission. The packets are receivable for all the nodes which locate in the transmission range of the sender node. This evident difference is also called Wireless Multicast Advantage (WMA) [6]. Hence, the network construction algorithms used in the link-based networks cannot be forthright applied to WANETs due to their differences in innate transmission properties.

The minimum energy broadcast (MEB) problem is one of the important scenarios in WANETs, where the packets need to be disseminated from the source node to all other nodes. The MEB problem is aimed at minimizing the total energy consumption, and it has been proven to be NP-complete [7,8]. This paper intends to provide a solution to the MEB problem in WANETs. We take

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advantage of the fast convergence nature of particle swarm optimization (PSO) to solve the problem. We propose the power degree to define the particle position. We then go a step further to analyze one well-known local search mechanism, *r*-shrink, and propose an improved version. Apart from the static scenario, we also study on the dynamic MEB problem where a number of nodes are added to/deleted from the network. We propose a simple heuristic, Conditional Incremental Power (CIP), to deal with the changing environment. Part of this study has been presented earlier in [9].

This paper is divided into six sections. Section 2 provides a brief introduction to the MEB problem and some existing literatures. We also review two present encoding mechanisms for the wireless network topology. Section 3 details the algorithm, and we present a repairing scheme to solve the dynamic MEB problem in Section 4. Section 5 presents the experimental results for benchmark instances. Finally, conclusions and some plans for future development are given in Section 6.

2. The minimum energy broadcast (MEB) problem

2.1. Problem description

In the network model with wireless fashion, the power required to send packets is

$$P = \xi \times d^{\alpha}, \quad (1)$$

where ξ is the power threshold, and d is the distance between the sender node and the receiver node. The variable α is the path loss exponent, depending on the transmission medium in the environment. It is usually set to a real number ranging between 2 and 4 [10]. All of the nodes located within the distance d from the sender node can receive the packets. Without loss of generality, power threshold ξ is normalized to 1, and the power required for sending packets from node i to node j can be reduced to

$$P_{ij} = d_{ij}^{\alpha}, \quad (2)$$

where d_{ij} is the distance between node i and node j. Then, the total power consumption $f(T)$ of a broadcast tree $T=(V, E)$ is defined by

$$f(T) = \sum_{i \in V} \max_{\{j | e_{ij} \in E\}} d_{ij}^{\alpha}, \quad (3)$$

where V is the set of sensor nodes in T, E is the set of directed edges in T, e_{ij} is the directed edge from node i to node j, standing for node j can receive the packets transmitted from node i. The broadcast tree represents routing paths from a specified source node s to all other nodes in V. The objective of this problem is to minimize the total power consumption in (3).

Before going any further, we would like to define the key terminological terms we will be using in this paper.

Definition 1. (critical child). The transmission power level of a sensor node hinges on the *critical child*, which is the farthest child node of this sensor node [11]. A critical child $cr(i)$ of node i can be represented by

$$cr(i) = arg \max_{\{j | e_{ij} \in E\}} d_{ij}^{\alpha}, \quad (4)$$

Definition 2. (leaf). A broadcast tree must contain a number of *leaf* nodes, which do not need to retransmit the packets to other nodes. They do not need any power consumption for transmission.

Definition 3. (ascendant and descendant). In a broadcast tree, if node i is on the path from the source node s to node j, then node i is an ascendant node of node j; on the contrary, node j is a descendant node of node i [12]. The source node s, therefore, is the ascendant node of all other nodes in the network.

Sometimes, the energy consumption in transmission can be reduced by using one or more intermediate nodes to indirectly transmit packets [13]. Nonetheless, a far-reaching transmission is sometimes preferred in the broadcast scenario. The more spacious the transmission range is, the more nodes can receive the packets. For instance, in Fig. 1(a) node *A* broadcasts through multiple intermediate transmissions; on the contrary, in Fig. 1(b), node *A* uses a single long-distance transmission range to reach all nodes. The traditional link-based routing algorithms are not suitable for the MEB problem because they only consider uni-path routing, i.e., a single receiver in a transmission.

2.2. Related work

Various groups of researchers have worked with the MEB problem. The algorithms can be categorized into (a) simple heuristics, (b) local search algorithms, and (c) metaheuristics.

Although there is a substantial space for improvement in simple heuristics, they are popular since they are able to construct a broadcast solution in a very short time. Various simple constructive heuristics for the MEB problem have been proposed, and most of these works are based on Prim's algorithm [14–16], which is a greedy algorithm for finding a minimum weighted spanning tree. Some examples are Adaptive Broadcast Consumption (ABC) [17], Broadcast Incremental Power (BIP) [14], Greedy Perimeter Broadcast Efficiency (GPBE) [15], and Shortest Path Tree (SPT) [14]. These heuristics start by the source node and then repeat adding the links by a specific greedy function. For instance, BIP adds into the broadcast tree the node which brings the minimum incremental power. Some of previous studies claimed that their work is a heuristic, but they are actually combinations of existing simple heuristics and local search algorithms [18–20].

Recent research has also suggested that the use of local search can achieve more desirable solutions. Examples of notable local search methods include Sweep [14], Embedded Wireless Multicast Advantage (EWMA) [7], *r*-shrink [21], Broadcast Incremental-Decremental Power (BIDP) [22], and Largest Expanding Sweep Search (LESS) [23]. Among these algorithms, *r*-shrink, which reassigns the farthest *r* children to another node which produces the minimum incremental power, is the most widely used owing to its superior performance.

Metaheuristics have attracted significant attentions due to its abilities in solving large-scale problems. Many works have been done in several application areas in the WANETs [24–26]. Some works based on metaheuristics have been proposed to deal with the MEB problem, including Iterated Local Search Algorithm (ILS) [12], Evolutionary Local Search Algorithm (ELS) [27], Hybrid Genetic Algorithm (HGA) [28], and Ant Colony Optimization (ACO) [29–33]. In order to utilize metaheuristics algorithms, each solution has to be transformed into an encoded sequence in the search space. Common encoding schemes in WANET include power level encoding and permutation encoding.

2.2.1. Power level encoding

Some existing works in the research of WANETs use the power level encoding. It encodes a solution into a sequence of real values, which are transmission power levels of nodes [10]. A solution can be represented as

$$[P_1, P_2, P_3, \ldots, P_n], \quad (5)$$

where n is the number of nodes in the network and P_i is the transmission power level of node i.

Nevertheless, power level encoding has an undesirable feature. Fig. 2 shows an example of redundant solutions in the power level encoding. In Fig. 2(a), the critical child of node A is node B, but the transmission power level is greater than the required transmission