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A rock-paper-scissors evolutionary algorithm for the TDMA broadcast scheduling problem[☆]

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ABSTRACT

In wireless ad-hoc networks, the broadcast scheduling problem (BSP) is commonly viewed as a well-known NP-complete combinatorial optimization problem. The purpose of the BSP is to achieve a transmission schedule with collision-free time slots in a time division multiple access ad-hoc network. The transmission schedule is optimized by minimizing the frame length of the node transmissions and maximizing the utilization of the shared channel. In this work, we propose a new evolutionary algorithm to solve the BSP by adopting the rock-paper-scissors dynamics found in natural systems. We use three types of species with strategies of different levels of intensification and diversification to simulate the rock-paper-scissors dynamics. Based on this evolutionary game, in which the success of one species relies on the behavior of others, the dynamic coexistence of three species can be achieved to control the balance between intensification and diversification. The experimental results demonstrate that our algorithm is efficient and effective at solving large instances of the BSP.

1. Introduction

A broadcast packet radio network is a group of geographically distributed nodes, which are connected through a common radio channel. The radio channel is shared using time division multiple access (TDMA) MAC protocols. To avoid packet collisions, broadcast scheduling allows only one node transmission in each collision domain [1–3], and each node must be assigned at least one time slot for data transmission in each time frame. TDMA is an effective approach to minimize idle listening, which is a major source of energy wastage [4]. Since a node may receive data in the time slots of its neighboring nodes, each node only stays awake in the time slots of itself and its neighboring nodes to avoid unnecessary idle listening. TDMA also eliminates contention-avoidance overhead and packet collisions to further reduce energy consumption. The simplest TDMA schedule is to assign each node a unique time slot, but transmission delay and channel utilization for a large network would be too poor to be acceptable. Assigning more than one transmitting node in one time slot can improve both the transmission delay and utilization of the shared channel. A proper time slot assignment may also improve energy efficiency by considering the interference at the receiver node [5]. In this work, we merely focus on the basic broadcast scheduling problem (BSP), which aims at scheduling each node transmission with a minimum time frame length while maximizing the utilization of the shared channel.

The BSP can be treated as a combinatorial optimization problem that is known to be NP-complete [6,7]. Several scheduling algorithms have been proposed on exact [8], heuristic [9–20], and meta-heuristic [21–28] techniques. Exact techniques developed for the BSP (e.g., branch-and-bound) can optimally solve small problem instances. However, for large problem instances, the computation of exact techniques would be very time and memory consuming. Many applications of large-scale wireless sensor networks have been developed: for example, in battlefield surveillance and environmental monitoring [29]. Therefore, finding an efficient solution for large-scale BSP instances is becoming important.

Recently, meta-heuristic algorithms, such as the iterated local search [30], tabu search [25], GRASP with path relinking [28], and genetic algorithm [21,24,26,27], are widely recognized for their success in solving the BSP. Meta-heuristic algorithms possess two major strategies: namely, intensification and diversification. While intensification refines known solutions, diversification explores new solutions. In an evolutionary process, intensification is normally regarded as more powerful than diversification in finding local optima; it also restrains probing into new search space. Therefore, a meta-heuristic algorithm could be trapped in a local optimum due to an imbalance between the intensification and diversification of the search procedure [31]. By increasing the amount of diversification, the search procedure can probe new search space to increase the probability of finding a novel solution.

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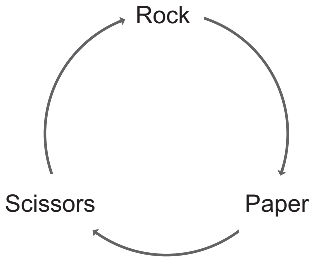

Fig. 1. Illustration of the cyclic dominance of rock, paper, and scissors.

When the level of diversification is higher than that of intensification, there is a greater chance for local optima to be missed by meta-heuristic algorithms. Therefore, it is necessary to leverage the levels of intensification and diversification to improve the performance of meta-heuristic algorithms. Interestingly, such dynamic yet balanced systems exist in nature; they have been observed in the competition for survival between different species or within a species, as exemplified by the side-blotched lizard [32] and Escherichia coli [33]. The mathematical model underlying these systems reflects an evolutionary dynamics of biodiversity that can be viewed as conforming to the rules of the rock-paper-scissors game (Fig. 1).

In this paper, we use rock-paper-scissors rules to achieve a dynamic balance between intensification and diversification in meta-heuristic algorithms. We propose a new rock-paper-scissors evolutionary algorithm for the BSP to minimize the lengths of the TDMA time frame while maximizing the number of transmitting nodes in a time frame. In our implementation, we use three types of species: namely, rock, paper, and scissors. Each type of species uses a specific method to generate offspring, and each method serves a different purpose. The method of the rock species is designed to shorten the TDMA time frame, while the method of the paper species increases the channel utilization. The method of the scissors species avoids the search procedure becoming trapped in local optima. Therefore, these methods have different levels of intensification, i.e. the capability of searching for a local optimum of TDMA time frame lengths. The method of the rock species has the greatest level of intensification, while that of the scissors species is the weakest. In contrast, the method for the scissors species has the strongest level of diversification and that of rock species has the weakest. Therefore, the method of the rock species tends to search for a local optimum in the nearby region and the method of the scissors species usually leads the search procedure to a new region. Unlike the previous two methods, which only consider TDMA time frame lengths, the method of the paper species primarily improves the channel utilization.

The number of species of each type can illustrate the current state of our algorithm. When the number of rock species increases, the level of intensification of shortening the TDMA time frame lengths also increases. Therefore, the number of offspring of the scissors species is increased to improve the level of diversification. The rock species can be used to balance the operation of diversification from the scissors species. However, the intensification operation of maximizing the channel utilization from the paper species is constrained by the scissors species. The condition of suppressing each other's methods conforms to the rock-paper-scissors rule. By incorporating the rock-paper-scissors rules into our evolutionary algorithm, the levels of intensification and diversification can be dynamically stabilized in the evolutionary process of the species. As a result, solutions for BSP can be improved without being trapped in a local optimum. The new scheme only needs two parameters, one for the initialization and the other for the termination condition. Our experiments show that the new scheme can solve large BSP instances with 2500 nodes. The numerical results demonstrate that our algorithm is not only effective and efficient regardless of the network sizes, but to a greater extent, it also reduces the computation time.

The organization of this paper is as follows. The next section describes the TDMA broadcast scheduling problem. The rock-paper-scissors dynamics are introduced in Section 3. Section 4 presents our proposed rock-paper-scissors evolutionary algorithm for the BSP. Section 5 presents our performance analysis. Finally, we conclude our study in Section 6.

2. The broadcast scheduling problem

We assume that the broadcast scheduling problem is based on the graph $G=(V,E)$, where $V=v_1,v_2,\ldots,v_n$ denotes the set of n network nodes and $E=e_1,e_2,\ldots,e_m$ denotes the set of m transmission links. If an edge exists between two nodes i and j in V, these two nodes are one hop apart and can receive packets from one another. If they transmit packets simultaneously, a direct collision occurs. In another instance, nodes i and j are two hops apart. If both nodes transmit packets in the same time slot, a hidden terminal collision occurs. To simplify the problem, we also assume that all nodes have the same minimum requirement of transmitting packets. The packet length is constant and the period of a time slot is transmission delay of a packet.

The BSP aims at finding a TDMA time frame that satisfies the condition that each node cannot transmit and receive packets or receive more than one packet in a time slot to avoid direct and hidden terminal collisions. In addition, each node should be scheduled to transmit at least once in each time frame. The frame length is the number of time slots that each node transmits at least once.

To avoid both direct and hidden terminal collisions, an intuitive solution for the BSP is to assign a time slot to each node; however, such a solution may not be suitable for large networks with numerous nodes. To improve the transmission efficiency, a broadcast scheduling should maximize the number of transmitting nodes in a time slot. For each node, we define the node utilization as the ratio of the number of transmitting slots to the frame length. For a fixed frame length, the channel utilization is determined by the number of transmitting nodes in the same time slot. The overall channel utilization is defined as the average node utilization (i.e. the average ratio of per-node transmission slots to the frame length). A time frame with a shorter frame length and a higher channel utilization always has better transmission efficiency.

The BSP is defined as follows:

(1) Input data
- $G: G=(V,E)$, where $V=v_1,v_2,\ldots,v_n$ and $E=e_1,e_2,\ldots,e_m$.
- c_{ij}: a binary value indicates whether there exists an edge between nodes i and j. 1 indicates that both nodes are connected. Two connected nodes can receive packets from each other.

(2) Decision variables
- x_i^s: a binary variable indicates whether node i transmits packets at the s_{th} time slot.
- F: the time frame of a TDMA schedule.
- $|F|$: the number of time slots in a time frame F.

A time frame F is a set of time slots in which at least one node i exists that satisfies $x_i^s=1$, $1 \le i \le n$, for each time slot s in F. The channel utilization for the whole network, U, is provided by

$$U=\frac{1}{|F|n}\sum_{s=1}^{|F|}\sum_{i=1}^{n} x_i^s \tag{1}$$