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Full Length Article

New heuristics and meta-heuristics for the Bandpass problem

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ABSTRACT

The Bandpass problem (BP), modelled by Babayev et al., is a combinatorial optimization problem arising in optical communication networks using wavelength division multiplexing technology. The BP aims to design an optimal packing of information flows on different wavelengths into groups to obtain the highest available cost reduction. In this paper, we propose new methods to solve the BP. Firstly, we present two new heuristic algorithms which generate better solutions than the algorithm introduced by Babayev et al. for almost all of the problem instances of the BP library. Secondly, we present a new meta-heuristic algorithm using three different crossover and five different mutation operators. Totally, fifteen implementations have been created and tested using two different outputs which are obtained by our proposed heuristics as the initial population. The experimental results show that the proposed meta-heuristic algorithm improves the solutions.

1. Introduction

The Bandpass Problem (BP), which arises in telecommunication networks, was first discussed in 2004 [1] and modeled in 2009 [2]. According to this model, on a communication network, there is one sending point having m information packages to be sent to n different destination points. If an information package is sent to a destination point, it will be shown as 1, otherwise 0. Fig. 1 shows that Package 1 will be sent to Destination 1 but will not be sent to Destination 2, and so on. In order to formulate this communication network mathematically, we refer the information packages to rows and the destination points to columns of a matrix. This situation is described by a binary matrix $A = (a_{ij})$ of dimension $m \times n$. If the information package $i\ (i = 1, \ldots, m)$ is destined for a point $j\ (j = 1, \ldots, n)$, then $a_{ij} = 1$; otherwise, $a_{ij} = 0$ [2].

The *Bandpass problem* can be described as follows [2]: Given a binary matrix A of dimension $m \times n$ and a positive integer B called the *bandpass number*, B consecutive non-zero elements in a column form a *bandpass*. Any non-zero entry in a column can be included in only one bandpass. This implies that several bandpasses in the same column cannot have any common rows. However, not all non-zero entries have to be included in a bandpass. The aim of the Bandpass problem is to find a row permutation of the matrix such that the total number of bandpasses in all columns is maximized.

We illustrate the BP on a matrix of dimension 8×4 in Fig. 2a. $B = 3$ consecutive non-zero entries (colored in the same color) of the matrix form a bandpass. In Fig. 2a, there are three bandpasses. The question is if there is any row permutation π so that the total number of bandpasses in all columns is maximized. After a few number of row exchanges we may obtain a permutation $\pi = \{2, 3, 7, 4, 1, 8, 6, 5\}$. The resulting matrix in Fig. 2b according to the permutation π consists of four bandpasses totally.

Grouping information packages in a communication matrix as a bandpass may lead to an opportunity to reduce the cost in optical communication networks. For more detailed information about potential applications, the reader may refer to [2].

A mathematical formulation of the BP is as follows:

$$Maximize \sum_{j=1}^{n} \sum_{k=1}^{m-B+1} y_{kj} \quad (1)$$

subject to

$$\sum_{k=1}^{m} x_{ik} = 1, \quad \forall\, i = 1, \ldots, m \quad (2)$$

$$\sum_{i=1}^{m} x_{ik} = 1, \quad \forall\, k = 1, \ldots, m \quad (3)$$

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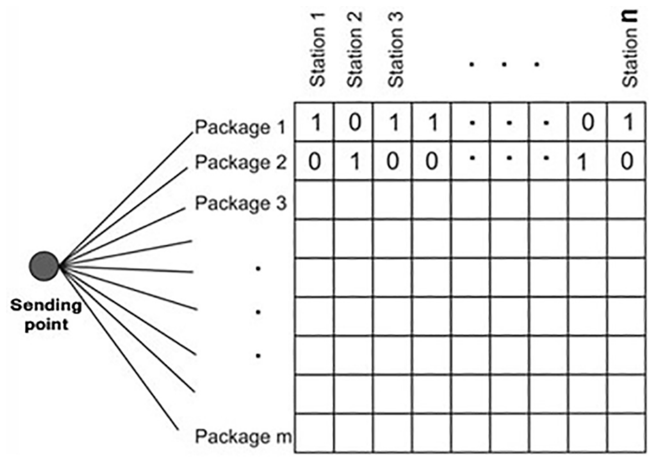

Fig. 1. A sending point, m packages and n destinations on a communication network.

$$\sum_{i=k}^{k+B-1} y_{ij} \leqslant 1, \quad \forall j = 1,\dots,n,\ k = 1,\dots,m-B+1 \tag{4}$$

$$B \cdot y_{kj} \leqslant \sum_{i=k}^{k+B-1} \sum_{r=1}^{m} a_{rj} x_{ri}, \quad \forall j = 1,\dots,n,\ k = 1,\dots,m-B+1 \tag{5}$$

$$x_{ik}, y_{kj} \in \{0,1\} \quad \forall i = 1,\dots,m\ j = 1,\dots,n,\ k = 1,\dots,m, \tag{6}$$

where

$$x_{ik} = \begin{cases} 1 & \text{if row } i \text{ is relocated to position } k, \\ 0 & \text{otherwise} \end{cases} \quad i = 1,\dots,m,\ k = 1,\dots,m$$

and

$$y_{kj} = \begin{cases} 1 & \text{if row } k \text{ is the first row} \\ & \text{of a bandpass in column } j, \quad j = 1,\dots,n,\ k = 1,\dots,m \\ 0 & \text{otherwise.} \end{cases}$$

The constraints (2) express the fact that row i must be relocated into one new position k only, (3) express that only one row i must be relocated to each new position k. (4) guarantee that no two bandpasses may have a common element. (5) guarantee to find the coordinates of bandpasses. The goal is to find an optimal permutation of rows of the matrix that maximizes the total number of bandpasses subject to the constraints (2)–(6). This model is called the Boolean Integer Mathematical Model of the Bandpass Problem for a fixed bandpass number [2]. Afterwards, Nuriyev et al. gave different models of the BP in [3]. The standard BP has a fixed Bandpass number B. However, Kurt et al. studied on the Multi-Bandpass problem including different Bandpass numbers B_j in each column j of the matrix [4].

There are total of $m!$ different permutations of m rows. This number grows faster than exponentially with m, thus it is not reasonable to solve the Bandpass problem by brute-force. The Bandpass problem is NP-hard. First, Babayev et al. proved the NP-hardness of the BP by showing equivalence to the 3-Satisfiability Problem [2]. Then, Lin proved the NP-hardness of the BP with any fixed Bandpass number $B \geqslant 2$ by providing a natural reduction from the Hamiltonian Path Problem [5]. Li and Lin showed that the three-column Bandpass problem is solvable in linear time [6].

Tong et al. presented the first improved approximation algorithm for the Bandpass problem when $B = 2$ using two maximum weight matchings. Their algorithm has a worst case performance ratio of $\frac{36}{19} \approx 1.8948$ [7]. Chen and Wang presented an alternative approximation algorithm to compute a second matching such that the union of the two matchings is guaranteed acyclic [8]. Their alternative algorithm achieves a better performance ratio of $\frac{220}{117} \approx 1.8805$. Afterwards, Huang et al. proposed an improvement to partition a 4-matching into a number of candidate sub-matchings, each of which can be used to extend the first maximum weight matching. This last improved approximation algorithm in the literature has a worst-case performance ratio of $\frac{128}{70-\sqrt{2}} \approx 1.8663$ [9]. We note that these approximation algorithms for the BP were designed when $B = 2$.

Laguna et al. approached the BP with a scatter search procedure which is a population-based meta-heuristic framework [10]. In [11], Tong et al. used the BP to prove that the general multiple RNA interaction prediction problem, either allowing or disallowing pseudo-knot-like interactions, is NP-hard.

In this paper, we propose two new heuristic algorithms and a meta-heuristic algorithm which takes the output of these heuristic algorithms as the initial input. These algorithms consider some additional criteria to select a row to be relocated. Our proposed heuristic algorithms give better results than the previous heuristic given in [2] for the problem instances of the BP library which was created by Babayev et al. for researchers to compare their algorithms [12]. The library consists of 90 problems of different sizes (numbers of rows, columns and density of non-zero elements of matrix A and bandpass number B). These instances are divided into

	1	2	3	4
1	0	1	0	0
2	1	0	1	0
3	1	1	0	0
4	1	1	0	1
5	1	0	0	1
6	1	0	0	1
7	1	1	0	1
8	1	0	1	1

(a)

		1	2	3	4
$\pi(1) =$	2	1	0	1	0
$\pi(2) =$	3	1	1	0	0
$\pi(3) =$	7	1	1	0	1
$\pi(4) =$	4	1	1	0	1
$\pi(5) =$	1	0	1	0	0
$\pi(6) =$	8	1	0	1	1
$\pi(7) =$	6	1	0	0	1
$\pi(8) =$	5	1	0	0	1

(b)

Fig. 2. (a) A binary matrix and bandpasses for $B = 3$, (b) the new matrix after relocations of rows according to π.

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