DISCRETE BANDWIDTH ALLOCATION CONSIDERING SESSION LOAD AND FAIRNESS IN OPTICAL MULTICAST NETWORK

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Abstract

Wavelength division multiplexing (WDM) is emerging as a key technology in communication networks. In WDM network, multicast is important issue for providing various applications. Layered multicast protocols such as RLM [1] and LVMR [2] are proposed to settle the network heterogeneity.

The fair bandwidth allocation can be implemented by the layered transmission in multicast network. To serve each multicast traffic at a fair rate commensurate with the receiver's capabilities and the capacity of the path of the traffic different numbers of layers are used by each traffic. Thus, reducing the number of layers for multicast sessions is also important to prohibit excessive overheads in multicast traffic. The bandwidth allocation problem considering fairness and the session load is formulated as a nonlinear integer programming problem.

To solve the fairness problem a dual objective tabu search is developed based on the intensification and diversification. Outstanding performance is obtained by the proposed tabu search in various multicast networks. The effectiveness of the tabu search becomes more powerful as the network size increases.

Key Words

layered multicast, fairness, WDM

1. Introduction

Wavelength division multiplexing (WDM) is emerging as a key technology in communication networks. In WDM networks, the fiber bandwidth is partitioned into multiple data channels that may be transmitted simultaneously on different wavelengths. Thus, WDM permits the use of enormous fiber bandwidth by providing data channels whose individual bandwidths more closely match those of the electronic devices at their endpoints.

Multicasting provides an efficient way of transmitting data from a sender to a group of receivers. Instead of sending a separate copy of the data to each individual group member, a single source node sends identical messages simultaneously to multiple destination nodes. An underlying multicast routing algorithm determines a multicast tree connecting the source and group members. Data generated by the source flows through the multicast tree, traversing each tree edge exactly once. As a result, multicast is more resource-efficient and is well suited to applications such as teleconferencing, video-on-demand (VOD) service, electronic newspapers, cyber education and medical images. With fast development of hardware technologies, commercialization of the Internet, and the increasing demand for quality of service (QoS) guaranteed and better than best effort services are requested by users.

Above multicast applications can be easily deployed in WDM networks due to fast and reliable network environments. Thus, the research of multicast in WDM network becomes more important for variable applications.

In multicast networks multicast sessions share the network resources simultaneously. Thus, it is ideal to provide a fair share of bandwidth to all sessions. This issue of inter-session fairness has been extensively studied in unicast networks. In case of multicast, the other notion of fairness, intra-session fairness, has to be considered because of the network heterogeneity which is due to various networks connected to the Internet. Users having high bandwidth connectivity would prefer to receive higher rate and higher quality service, while users with low bandwidth connectivity would be satisfied with a low rate service. Thus multi rate multicast should be used due to this network heterogeneity. RLM (Receiver-driven layered multicast) [1] and LVMR (Layerd video multicast with retransmission) [2] are well known protocols for layered Multicast. Every receiver prefers to receive service at a fair rate commensurate with its capabilities and the capacity of the path leading to it from the source. The rate should be independent of the capabilities of the other receivers of the same session. This is the issue of intra-session fairness. Therefore, in multicasting the intra-session fairness has to be considered in addition to the inter-session fairness.

Most of the work in fairness problem is concerned with notion of max-min fairness [3], [4], [5]. Sarkar et al. [6] proposed an algorithm in discrete bandwidth allocation. In continuous bandwidth allocation, multicast multirate utility maximization problem is addressed in [7]. Centralized and distributed algorithm is proposed for continuous bandwidth allocation [8].

In layered multicast transmission, a multicast session requires layers more as the required bandwidths of receivers are more various. However, a large number of layers would incur high overheads in sender encoding, multicast address allocation, network state, and receiver decoding. Thus, a sender can set the number of layers and the bandwidth assigned to each layer to prevent excessive overheads [9].

Thus, in this paper, we are interested in finding a fair bandwidth allocation and minimizing the number of layers to be used for each session simultaneously in discrete bandwidth allocation.

In Section 2 and 3, we briefly discuss the fairness and session load, and provide a nonlinear integer programming model for the fair bandwidth allocation. A tabu search is developed to solve the fairness problem in Section 4. Computational result and conclusion are presented in Section 5 and Section 6 respectively.

2. Session Load and Fairness in Bandwidth Allocation

When a network has profound heterogeneity, the fairness must include characteristics of multi-rate multicast network. Each multicast session transmit data to all of its receivers at different rate. One of the frequently used definitions of fairness in multi-rate multicast networks is max-min fairness [3], [4], [5]. Informally speaking, a rate allocation is max-min fair, if no receiver can be allocated a higher rate without hurting another receiver having equal or lower rate.

As an example, consider the network in Figure 1. There are two sessions and three virtual sessions. Virtual session 1 (1-3-4 path) and virtual session 2 (1-3-5 path) compose session 1. Virtual session 3 (2-3-5 path) composes session 2. The bandwidth of each link capacity is 3, 6, 3, and 5 units respectively. The max-min fair allocated rate vector in this network is (3, 2.5, 2.5) for each virtual session 1, 2, and 3. If we increase the bandwidth allocated to the second virtual session, we decrease the bandwidth allocated to the third virtual session. When continuous allocation of the bandwidth is allowed, the max-min fairness always exists and the allocation procedure is studied by Sarkar and Tassiulas [6]. However, in layered transmission scheme, bandwidth is allocated in discrete fashion. In this case, the max-min fair allocation may not exist.

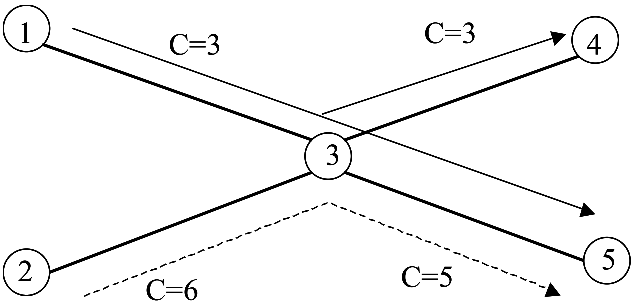


Figure 1. Network with 2 multicast sessions and 3 virtual sessions

A lexicographically optimal fair allocation, however, exists even in discrete case [6]. A bandwidth allocation vector is lexicographically optimal if its smallest component is the largest among the smallest components of all feasible bandwidth allocation vectors. Subject to this, it has largest second smallest component, and so on. In the network of Figure 1, if the bandwidth is allocated in discrete layer, the max-min fair allocation vector does not exist. However, a lexicographically fair optimal allocation exists and given by (3, 2, 3) or (3, 3, 2).

Note that max-min fairness and lexicographic optimality are not equivalent. The max-min fairness is stronger than lexicographic optimality. If a max-min fair vector exists, it is lexicographically optimal. However, a max-min fair bandwidth allocation may not exist in a discrete case. In view of the nonexistence of max-min fair bandwidth allocation vector, lexicographically optimal bandwidth allocation is the best solution to find fair allocation in discrete case. However, it is known that the lexicographically optimal bandwidth allocation is NP-hard in case of discrete layer allocation [6].

In view point of fairness, above two allocation vector (3, 2, 3) and (3, 3, 2) are same. However, in case of (3, 2, 3), the session 1 allocates 3 and 2 bandwidth units for virtual session 1 and 2 respectively. The session 1 must transmit two kinds of layers to satisfy the bandwidth allocation. Thus, the total number of layers for each session is 3. In case of (3, 3, 2), the session 1 allocates 3 and 3 bandwidth units for virtual session 1 and 2 respectively. Unlike the above (3, 2, 3) case, the session 1 just transmits one layer to satisfy the bandwidth allocation. Then, the total number of layers for each session is 2. Thus, (3, 3, 2) allocation vector is better than (3, 2, 3) in view point of session load. In this paper, we are interested in finding a fair bandwidth allocation and minimizing the number of layer to be used for each session simultaneously in discrete bandwidth allocation. In the next section, we will discuss modeling of this problem.

3. Bandwidth Allocation Problem for Fairness and Session Load

Consider a network with J multicast sessions and I multicast virtual sessions. The traffic of each session is transmitted from a source to a set of destination nodes across a predetermined multicast tree. We call a source and destination pair of a session as a virtual session.

For a virtual session i, let x_i be the bandwidth allocated to the virtual session i and u_i be the minimum bandwidth requirement, then we have

$$x_i \geq u_i \quad i = 1, \ldots, I$$

Now, consider a link l in the network where a set of virtual sessions of session j is passing through. Let $v(j,l)$ be the set of virtual sessions belonging to session j and traversing through link l. Note in the multicast tree that the actual bandwidth assigned to the session j is determined by the maximum bandwidth among the virtual sessions. Let y_{il} be the maximum, then

$$y_{jl} = \max_{i \in v(j,l)} x_i \quad j = 1, \ldots, J, \ l = 1, \ldots, L$$

Note, the total bandwidth assigned to sessions traversing through link l cannot exceed the capacity of link l. By letting $s(l)$ be the set of sessions passing through link l, and c_l be the link capacity, we have

$$\sum_{j \in s(l)} y_{jl} \leq c_l \quad l = 1, \ldots, L.$$

In addition to above constraints, we consider the restriction of the number of layers used for each session. Let z_{ib} be binary variables for all virtual session i and all available bandwidth layers b. If the allocated bandwidth layers for virtual session i is b, then $z_{ib} = 1$. We also define binary variables n_{jb} for all session j and all available bandwidth b. If a session j uses the bandwidth layers b, then $n_{jb} = 1$. The number of layers used for a session j is determined by the allocated bandwidths for virtual sessions belonging to the session j. By letting $v(j)$ be the set of virtual sessions belonging to session j, we have

$$\sum_{b=1}^{B} z_{ib} = 1 \qquad i = 1, \ldots, I$$

$$z_{ib} \leq n_{jb} \qquad j = 1, \ldots, J, \quad b = 1, \ldots, B, \quad i \in v(j)$$

The bandwidth Allocated for virtual session i, x_i is determined by the indicator variable, z_{ib} as follows.

$$x_i = \sum_{i=1}^{I} b\, z_{ib} \quad i = 1, \ldots, I$$

Now, our objective is to allocate the bandwidth for each virtual session such that the solution satisfies the lexicographically optimal fairness and minimize the total number of layers to be used for each multicast session. First, note in the lexicographic optimal solution that the minimum component is maximized among all feasible solutions. Subject to the maximization, the second minimum is maximized, etc.

Thus, we consider a nonincreasing convex function $1/x^p$ where p is a large integer. Clearly the function gives more credit to a virtual session x_i with smaller value, when we minimize the sum of $1/x^p$. Thus, we are interested in the objective function given for the lexicographical optimal fairness below.

$$\text{Min} \sum_{i=1}^{I} 1/x_i{}^p$$

The above objective function is consistent with the definition of the lexicographic optimal fairness in the following sense. For the unit increase of the bandwidth of a virtual session x_i the improvement of objective function becomes

$$\frac{(x_i+1)^P - (x_i)^P}{(x_i)^P (x_i+1)^P}$$

Clearly, better improvement is obtained with the smaller x_i. If the minimum virtual session is maximized, then the second minimum is supposed to be maximized when p is sufficiently large.

In addition to the lexicographic optimal fairness as the objective function, we are also interested in minimizing the number of layers to be used for each multicast session. $\sum_{b=1}^{B} n_{jb}$ is the number of layer for session j. For minimizing the number of layers to be used for each multicast, the objective function is represented as follow.

$$\text{Min} \sum_{j=1}^{J} \sum_{b=1}^{B} n_{jb}$$

We combine above two objective functions by a factor α. Thus, our bandwidth allocation problem is formulated as follows.

$$\text{Minimize } \alpha \sum_{i=1}^{I} 1/x_i{}^p + (1\text{-}\alpha) \sum_{j=1}^{J} \sum_{b=1}^{B} n_{jb} \tag{1}$$

subject to:

$$x_i \geq u_i \qquad i = 1, \ldots, I \tag{2}$$

$$y_{jl} = \max_{i \in v(j,l)} x_i \qquad j = 1, \ldots, J, \ l = 1, \ldots, L \tag{3}$$

$$\sum_{j \in s(l)} y_{jl} \leq c_l \qquad l = 1, \ldots, L \tag{4}$$

$$\sum_{b=1}^{B} z_{ib} = 1 \qquad i = 1, \ldots, I \tag{5}$$

$$z_{ib} \leq n_{jb} \qquad j = 1, \ldots, J, \quad b = 1, \ldots, B, \quad i \in v(j) \tag{6}$$

$$x_i = \sum_{i=1}^{I} b\, z_{ib} \qquad i = 1, \ldots, I \tag{7}$$

$$0 \leq \alpha \leq 1$$

$x_i \geq 0$ and integers

z_{ib}, n_{jb} are binary variables

As proved by Sarkar and Tassiulas [6], the computation of the lexicographically optimal fair allocation problem is NP-hard. The proposed nonlinear integer programming problem may not be effectively solved by any conventional optimization techniques. Thus, we examine a tabu search as a promising solution procedure for the above bandwidth allocation problem.

4. A Dual Objective Tabu Search for Bandwidth Allocation Problem

A tabu search is a higher level heuristic procedure for solving optimization problems, designed to guide other methods to escape the trap of local optimality. It uses flexible structured memory to permit search information to be exploited more thoroughly than by rigid memory systems and memory functions of varying time spans for intensifying and diversifying the search.

Intensification strategies utilize short-term memory function to integrate features or environments of good solutions as a basis for generating still better solutions. Such strategies focus on aggressively searching for a best solution within a strategically restricted region. A move remains tabu during a certain periods (or tabu size) to help aggressive search for better solutions. Diversification strategies, which typically employ a long-term memory function, redirect the search to unvisited regions of the solution space.

In this paper, two objectives are taken into account in the formulation of bandwidth allocation problem. Thus, we propose a dual objective tabu search to consider two objectives simultaneously. Dual objective tabu search consists of primary and secondary tabu search. If α of Eq. (1) is larger than 0.5, primary objective is $\sum_{i=1}^{I} 1/x_i^{p}$. Otherwise, primary objective is $\sum_{j=1}^{J}\sum_{b=1}^{B} n_{jb}$. In dual objective tabu search, we first solve the bandwidth allocation problem with primary objective. This process is primary tabu search. In primary tabu search, we obtain the best solution for the primary objective. Then, we determine a threshold based on the best solution found in primary tabu search and secondary tabu search finds the best solution within the threshold.

Each tabu search (primary and secondary tabu search) incorporates four components as shown in the figure 2.

1) Initial solution
2) Intensification with Short-Term Memory Function
3) Repair procedure
4) Diversification with Long-Term Memory Function

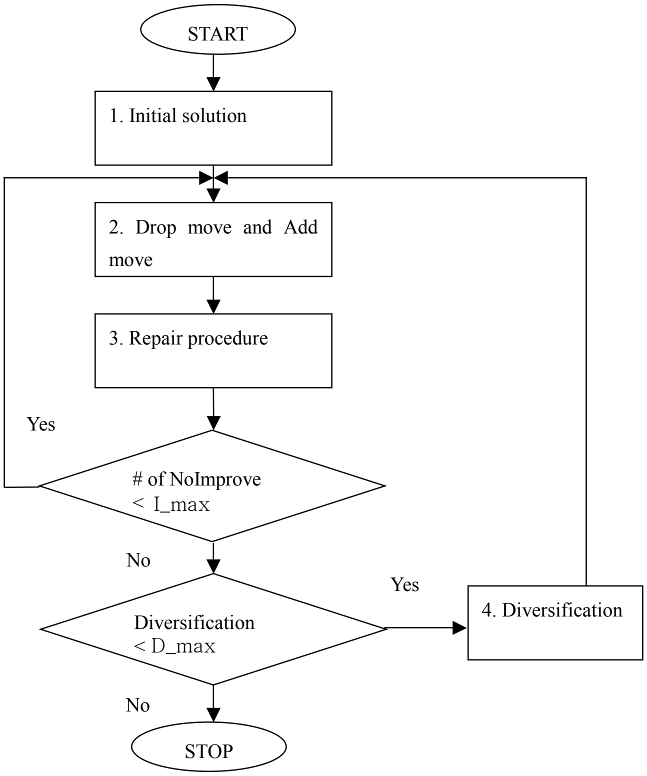


Figure 2. Proposed tabu search procedure

4.1 Initial solution

Since a solution has to satisfy the minimum required bandwidth constraint, each virtual session starts with the minimum required bandwidth. To have a solution that satisfies the link constraint (5) a virtual session with minimum bandwidth is selected and increased by one unit. Tie is broken randomly. This process is continued until all virtual sessions are saturated due to the link capacities. The solution obtained through this process is the initial solution for primary tabu search. The initial solution for secondary tabu search is the best solution of primary tabu search.

4.2 Intensification with Short-Term Memory

We define two types of moves for each objective function, $\sum_{i=1}^{I} 1/x_i^{p}$ and $\sum_{j=1}^{J}\sum_{b=1}^{B} n_{jb}$, respectively. They are “Drop move” and “Add move”. First, we explain two moves for the objective function, $\sum_{i=1}^{I} 1/x_i^{p}$. Add move selects a virtual session with the minimum bandwidth and increases the bandwidth of the virtual session by one unit. Tie is broken randomly. Add move is continued until the total bandwidth required by all sessions traversing a link l

Number of links	Number of sessions	Number of virtual sessions	Minimum requirement of each virtual session
10	3	10	1
15	4	20	1
20	5	30	1

Table 1. Multicast networks

may exceed the link capacity. Drop move is the opposite of add move. Drop move selects a virtual session randomly and then decrease the bandwidth of the virtual session by one unit.

For the objective function, $\sum_{j=1}^{J}\sum_{b=1}^{B} n_{jb}$, two moves are also defined. Let L(j,b) be the set of virtual sessions that belongs to the multicast session j and with allocated bandwidth b. Then, drop move selects virtual sessions in L(j,b) that has the minimum cardinality and then the bandwidth of the virtual sessions are decreased to b' of another set L(j,b') where b' is smaller than and closest to b. If such a set does not exist, another set of virtual sessions is selected for drop move. Add move selects a virtual session with the minimum bandwidth and increases the bandwidth of the virtual session till upper layer bandwidth of the same session. Tie is broken randomly. Add move is continued until the total bandwidth required by all sessions traversing a link l may exceed the link capacity.

4.3 Repair procedure

After a drop move and a add move for each tabu search are performed, the total bandwidth required by all sessions traversing a link l may exceed the link capacity. To have a feasible solution, we randomly select a session traversing through the link, and reduce the bandwidth by one unit. If it is impossible to reduce the bandwidth due to the minimum bandwidth requirement restriction, another session is selected. The process is repeated until the feasibility is satisfied.

4.4. Diversification with Long-Term Memory

The diversification strategy is helpful to explore new unvisited regions of the solution space. It enables the search process to escape from local optimality. The diversification is performed when no solution improvement results consecutively for *I_max* iterations in the intensification process. This diversification strategy has the effect of restarting the tabu search from a solution that is far away from the solutions obtained in the intensification procedure. The same diversification procedure is applied to both tabu search.

The following diversification procedure is applied.

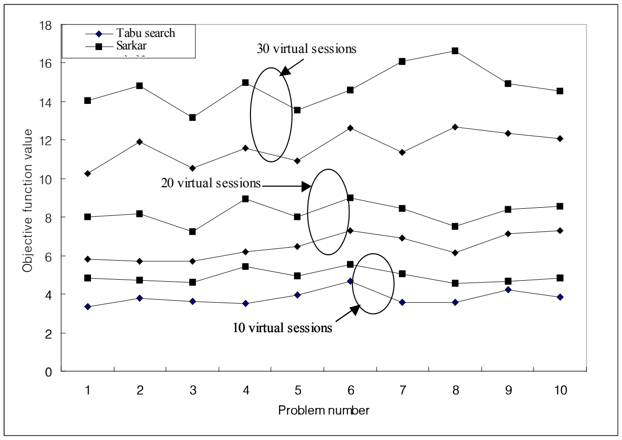


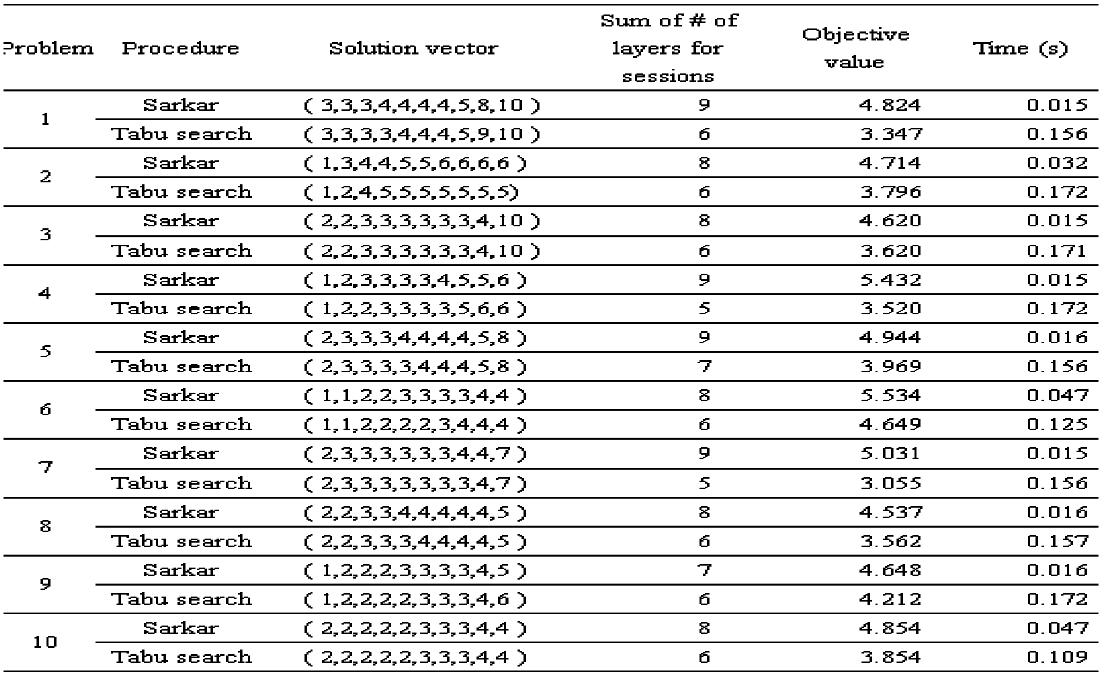
Figure 3. Performance of tabu search and Sarkar's algorithm

Step 1. For each virtual session, examine the frequency of applied add and droop moves.
Step 2. Order the frequency from minimum to maximum and select a fraction of virtual sessions from the minimum frequency.
Step 3. For each virtual session selected if the number of the add move is larger than the drop move, then decrease the bandwidth by one unit. Otherwise, increase the bandwidth by one unit.

5. Computational Results

In this section, we discuss the computational results of the Tabu Search for the bandwidth allocation. Three different sizes of multicast networks are generated as in Table 1. In each multicast network ten problems are tested with different link capacities. Each problem is run with the proposed tabu search and the algorithm by Sarkr and Tassiulas [6]. We set the combination factor α to 0.5. Since both procedures have randomness in the selection of virtual session to improve, each problem is run 100 times and the best solution is compared. All solution procedures are run on a Pentium III-500MHz PC.

Figure 3 shows the objective function values for 10, 20, and 30 virtual sessions respectively. As shown in the tables the solution by tabu search has better objective function values compared to the algorithm by [6]. The solution gap between the tabu search and Sarkar's algorithm is within 8-30% in problems with 10 virtual sessions, 15-31% with 20 virtual sessions, and 13-35% in 30 virtual sessions respectively. Table 2 shows the detailed solution vectors of ten problems for 10 virtual sessions. In most cases, the algorithm by Sakar gives slightly lexicographically fairer solutions than the solutions by the tabu search. However, the total number of layers used for all sessions by tabu search is less than that of the algorithm by Sarkar. Thus, the combined objective function values by the proposed tabu search outperforms the Sarkar's algorithm.



Problem	Procedure	Solution vector	Sum of # of layers for sessions	Objective value	Time (s)
1	Sarkar	(3,3,3,4,4,4,4,5,8,10)	9	4.824	0.015
	Tabu search	(3,3,3,3,4,4,4,5,9,10)	6	3.347	0.156
2	Sarkar	(1,3,4,4,5,5,6,6,6,6)	8	4.714	0.032
	Tabu search	(1,2,4,5,5,5,5,5,5,5)	6	3.796	0.172
3	Sarkar	(2,2,3,3,3,3,3,3,4,10)	8	4.620	0.015
	Tabu search	(2,2,3,3,3,3,3,3,4,10)	6	3.620	0.171
4	Sarkar	(1,2,3,3,3,3,4,5,5,6)	9	5.432	0.015
	Tabu search	(1,2,2,3,3,3,3,5,6,6)	5	3.520	0.172
5	Sarkar	(2,3,3,3,4,4,4,4,5,8)	9	4.944	0.016
	Tabu search	(2,3,3,3,3,4,4,4,5,8)	7	3.969	0.156
6	Sarkar	(1,1,2,2,3,3,3,3,4,4)	8	5.534	0.047
	Tabu search	(1,1,2,2,2,2,3,4,4,4)	6	4.649	0.125
7	Sarkar	(2,3,3,3,3,3,3,4,4,7)	9	5.031	0.015
	Tabu search	(2,3,3,3,3,3,3,3,4,7)	5	3.055	0.156
8	Sarkar	(2,2,3,3,4,4,4,4,4,5)	8	4.537	0.016
	Tabu search	(2,2,3,3,3,4,4,4,4,5)	6	3.562	0.157
9	Sarkar	(1,2,2,2,3,3,3,3,4,5)	7	4.648	0.016
	Tabu search	(1,2,2,2,2,3,3,3,4,6)	6	4.212	0.172
10	Sarkar	(2,2,2,2,2,3,3,3,4,4)	8	4.854	0.047
	Tabu search	(2,2,2,2,2,3,3,3,4,4)	6	3.854	0.109

Table 2. Bandwidth allocation for 10 virtual sessions

6. Conclusion

A bandwidth allocation problem considering fairness and session load in multicast networks is examined. The inter-session as well as the intra-session fairness is considered by the discrete layered transmission in the multicast network.

The problem is formulated as a nonlinear integer programming problem which provides a bandwidth allocation subject to the minimum bandwidth requirement by each virtual session, the actual bandwidth assigned to each session in a link and the link capacity constraint. The objective function represents a combination of finding a lexicographically fair allocation and minimizing the number of layers used for each session.

To solve the fairness problem a dual objective tabu search is developed based on the intensification and diversification. In the tabu search the add move increases the bandwidth of the virtual session by one unit and drop move decreases the bandwidth according to the short-term memory. Diversification by frequency is implemented by long-term memory.

Computational experiments are performed in a multicast network with 10, 20, and 30 virtual sessions. The proposed tabu search demonstrates outstanding performance in all problems compared to the algorithm by Sarkar [6]. The effectiveness of the tabu search becomes more powerful as the network size increases. The solution gap between the tabu search and Sarkar's algorithm is 8-35%.

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