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A novel multicast algorithm for collaborative multimedia applications in heterogeneous networks

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Abstract

In this paper, we study the problem of QoS group communication in a heterogeneous network, which consists of multiple MANETs attached to the backbone Internet. We propose a heuristic multicast algorithm called MCMA (Multi-Constrained Multicast Algorithm). MCMA is designed for solving the DVBMT (Delay- and delay Variation-Bounded Multicast Tree) problem, which has been proved to be NP-complete. The literature studies are limited to end-to-end delay bound and delay variation minimization. In this paper, we improve and extend previous well known from literature heterogeneous network algorithms to provide scalable and stable multicast services on the Internet by introducing a new Delay–Variation Estimation Scheme for heterogeneous networks. This Scheme helps the MCMA algorithm achieve better performance in terms of the multicast delay variation than some well-known algorithms. The algorithm defines QoS parameters as constraints on both delay and delay variation. Theoretical analysis is given to show the correctness of MCMA and its performance in terms of the multicast delay variation.

Keywords: heterogeneous networks, QoS group communications, DDVCA, DDVMA, MCMA

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1. Introduction

Heterogeneous Networks (HTs) involves the integration of various kinds of existing networks under a single environment with an efficient cooperation between the functional operation networks. These HTs should have the ability to use multiple broadband transport technologies and should support universal mobility. The heterogeneous network architecture will promote the trend of moving to an all-IP wireless communication environment. In these futuristic networks, a gateway is a fixed node connecting a single MANET to the Internet. Gateways forward data packets and relay them between MANETs and the Internet. When a MANET is connected to the Internet, it is important for the mobile hosts (MHs) to detect

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available gateways providing access to the Internet. Therefore, a gateway discovery mechanism is required [1]. Lots of efforts have been devoted to the problem of Internet gateway discovery and gateway forwarding strategies [2][3]. These works have provided the foundation for the practical implementation of our algorithm.

Without loss of generality, we assume a group communication scenario in the heterogeneous network: one team leader is the source and wants to multicast messages to several other team leaders called destinations. The source will transmit the messages to its Internet gateway called the source gateway using the AODV protocol. Then the source gateway will transmit the messages to all the destination gateways using a multicast tree in the backbone Internet. Finally, each destination gateway will forward the messages to the destination node in its MANET also using again, the AODV protocol, separately [1].

Quality of Service support in highly heterogeneous networking environments composed of both fixed and mobile networks, wired as well as wireless networks remains a challenging area of research and continues to attract a lot of attention. *Delay* is a significant factor in a heterogeneous network and is taken as a constrained metric in our proposed algorithm. In addition, *end-to-end delay* is precisely used rather than the average delay or the total delay of the whole tree, because each user is mostly concerned with receiving information from the source as quick as possible. Besides, in this paper, we pay also special attention to *inter-destination delay variation* as it is a factor of great importance in this situation, too. It is necessary that all participants receive information from the source at the same time so as to guarantee fairness. There are several situations in which we need to limit the delay-variation (or jitter) among all paths by a certain given maximum bound. During a teleconference, it is important that a speaker is heard by all participants at the same time; otherwise, the communication may lack the feeling of an interactive face-to-face discussion.

In [1], the authors proposed a heuristic multicast algorithm called DDVMA (Delay and Delay Variation Multicast Algorithm). DDVMA is designed for solving the Delay- and delay Variation-Bounded Multicast Tree (DVBMT) problem [7], which has been proved to be NP-complete. It can find a multicast tree satisfying the multicast end-to-end delay constraint and minimizing the multicast delay variation. In DDVMA the authors introduced two concepts. The first concept is the proprietary second shortest path and the second one is the partially proprietary second shortest path. The authors declared that these two concepts can help DDVMA to achieve better performance in terms of the multicast delay variation than DDVCA [4]. Unfortunately, in their heuristic, the delay variation was only minimized and not constrained.

In [4], Sheu and Chen studied the problem of minimizing multicast delay variation under the multicast end-to-end delay constraint. As a result, they have proposed the Delay and Delay Variation Constraint Algorithm (DDVCA) that was derived from the Core Based Tree (CBT) [5] and the minimum path algorithm [6]. It has a complexity of $O(|E||V|^2)$ (where V is the set of vertices and E *represent* the set of edges in a graph). When several nodes are possible candidates for a core node, the DDVCA chooses one of them randomly. However, in DDVCA, the delay variation was only minimized and not constrained.

In [8], an algorithm with a complexity of $O(|E||V|^2)$ and based on CBT [5] was proposed. It produces multicast trees with low multicast delay variation. The algorithm consists of two parts. In the first part, a core node is selected. In the second part, a multicast tree is constructed. The simulation results show that the proposed scheme obtains a better minimum multicast delay variation than what the DDVCA achieved.

In [15], authors improved greedy based multi-constrained multicast solutions and proposed the ICRA algorithm that improves the well known Mamcra algorithm. In the quest to enhance the execution time, they further proposed a taboo search algorithm coined the Taboo-MQR algorithm. In [14, 16], the authors proposed the mQMA algorithm; a QoS multicast aggregation algorithm which handles multiple additive QoS constraints. mQMA deals with two important problems of traditional IP multicast, i.e., multicast forwarding state scalability and multi-constrained QoS routing. It builds few trees and maintains few forwarding states for the groups thanks to the technique of multicast tree aggregation, which allows several groups to share the same delivery tree. Moreover, the algorithm mQMA builds trees satisfying multiple additive QoS constraints.

In [9], the authors have considered the problem of determining a multicasting sub-network with an end-to-end delay bound and with a tight delay variation for multimedia applications on overlay network. Then they have presented an algorithm Chain, which (as they declared) achieves the tightest delay variation for a given delay bound. At the initial phase of their heuristic, they have used the *k*-shortest path technique proposed by [6] to find the paths for each destinations for which the delays are less than or equal to a bound Δ. Then using these delays, they have determined the delay chain, which gives the minimum delay variation and constructed the multicasting sub-network by retrieving the paths from the delays. However, again in their heuristic, the delay variation was only minimized and not constrained.

Although, all the above algorithms are attractive, we still think that it is more important to constrain the delay-variation rather than minimizing it. Consequently, we address the problem of improving the previous algorithms by constraining the delay-variation and by decreasing their time complexity.

Therefore, the main contribution of our work is the discovery of a simple yet effective heuristic that exhibits very good performance and that can be easily implemented in a wide range of heterogeneous networks. Furthermore, we extend the DDVCA, DDVMA, Kim's and Chain algorithms by *(a)* adding the delay-variation constraint (rather than minimizing it), *(b)* proposing an algorithm with lower time complexity and *(c)* introducing a new delay-variation estimation method, which, to the best of our knowledge, is the first of its kind to be used with heterogeneous networks.

In the remainder of this paper, section 2 will present the multi-constrained heterogeneous network problem definition. In section 3, we propose a new delay-variation estimation scheme. In section 4, we propose our Delay and Delay-Variation constrained Multicast algorithm (MCMA). In section 5, we prove the correctness and time complexity analysis of our MCMA algorithm. Finally, section 6 concludes the paper. Next, we formulate our network model as it was defined in [1].

2. Network Model and Problem Specifications

The backbone network can be modeled as a weighted digraph $G(V,E)$, where V represents the set of nodes including gateways, and E represents the set of links between the nodes. For each link $l \in E$, a *link-delay* function $D{:}l \rightarrow r+$ is defined. A nonnegative value $D(l)$ represents the transmission delay on link l. Multicast messages are sent from the leader MH of the source MANET. Messages are first forwarded to the source gateway $v_s \in V$ through the route discovered by AODV, then they arrive at a set of destination gateways $Z \subseteq V - \{v_s\}$ through the multicast tree T in the backbone network. Finally they are forwarded to the leader MHs of the destination MANETs through the wireless routes between each destination gateway and each leader MH, respectively. To guarantee the QoS of group communication, the multicast end-to-end delay between the leader MH of the source MANET and the leader MH of each destination MANET should not exceed the multicast end-to-end delay constraint Δ, and the multicast delay variation among the leader MHs of destination MANETs should not exceed a tolerance δ. Let $P_T(v_s, v_w)$ denote the path from the source gateway v_s to a destination gateway $v_w \in Z$ on *T*. Then the transmission delay between v_s and v_w on T is defined as

$$Delay[v_w] = \sum_{l \in P(v_s,v_w)} D(l) \tag{1}$$

where $P(v_s, v_w)$ is the unique path considered from v_s to v_w.

For each gateway $g \in \{s\} \cup Z$, we define a *gateway-delay* function $W: g \rightarrow r^+$. It assigns gateway g a nonnegative value $W(g)$, which represents the delay of the wireless route discovered between gateway g and the leader MH of the MANET g serves.

In our paper, the problem of QoS group communications in the heterogeneous network model is to find an optimal multicast tree $T^*(V_{T^*}, E_{T^*})$, $\{v_s\} \cup Z \subseteq V_{T^*}$, $E_{T^*} \subseteq E$, satisfying

$$W(v_s) + \sum_{l \in P(v_s, v_w)} D(l) + W(v_w) \leq \Delta \tag{2}$$

$$\left| \sum_{l \in P(v_s, v_u)} D(l) + W(v_u) - \left(\sum_{l \in P(v_s, v_w)} D(l) + W(v_w) \right) \right| \leq \delta, \ \forall v_u, v_w \in Z \tag{3}$$

where T denotes any multicast tree spanning v_s and Z in $G = (V, E)$. If we assume $W(g) = 0$, for each $g \in \{v_s\} \cup Z$, the problem turns to be a DVBMT problem, which has been proved to be NP-complete [7]. Our problem is also NP-complete because it contains, as a special case, the DVBMT problem. Hence, only heuristic algorithms can be developed for our problem. In this paper, our work focus on the DVBMT problem in heterogeneous networks, which consists of several MANETs attached to the backbone Internet.

3. The proposed delay-variation estimation method

To estimate the delay variation in the heterogeneous network, we propose an estimation based on a modified average-delay method mentioned in [10]. For that purpose, the delay from the source v_s to each destination v_i , $Delay[v_i]$, is computed. The network average-delay $AvDelay(T)$ can be calculated as:

$$AvDelay(T) = \frac{\sum_{v_i \in Z}\left(Delay[v_i] + W(v_i)\right)}{|Z|}, \forall v_i \in Z \tag{4}$$

where $|Z|$ represents the size of the multicast group (destination gateways), $W(v_i)$ the delay of the wireless route discovered between gateway v_i and the leader MH of the MANET v_i serves. Consequently, constraint (4) is substituted by the following simpler constraint:

$$|Avdelay(T) - (Delay(v_u) + W(v_u))| \leq \delta, \ \forall v_u \in Z \tag{5}$$

The delay and delay variation bounds are two conflicting objectives. The delay constraint dictates that short paths must be used. However, choosing short paths may lead to a violation of the delay variation constraint among nodes which are close to the source and nodes which are far away from it. Consequently, it may be necessary to select longer paths for some nodes in order to satisfy the latter constraint. A balance must be struck between the two constraints. Consequently, we address the problem of designing a multicast routing algorithm heterogeneous network that overcomes these conflicts. For this purpose, we give the following observation:

Observation 1

To omit some short paths leading to the destination nodes, and select long paths instead, we propose a new computation for the average delay in a heterogeneous network as follows:

$$AvDelay(T) = \begin{cases} \Delta_{max}, \ if \ Delay[v_i] + W[v_i] \leq \delta, \ \forall v_i \in Z \\ \Delta_{aver} = \frac{\Delta_{max} + \Delta_{min}}{2}, \quad otherwise \end{cases} \tag{6}$$

where v_i the destination node, Δ_{aver} is the average end-to-end delay bound, δ is the user delay variation tolerance and $|Z|$ the size of the multicast group. The minimum and maximum delay bounds, Δ_{min} and Δ_{max} respectively, are calculated in *the least delay tree (LDT*) at the beginning of our algorithm execution (Algorithm 1). Hence (6) replaces (4) in (5). Next, we give a formal definition of our proposed MCMA algorithm

4. MCMA algorithm

Similar to DDVCA [4] and Kim's algorithms [8], our MCMA algorithm **(**Algorithm 1) basically comes from CBT [5], and the Dijkstra's shortest path algorithm [11]. The CBT algorithm establishes a multicast tree by choosing some Core Routers, which compose the Core Backbone. Afterwards, all node operations related to joining and leaving the multicast group are based on issuing a request toward an appropriate Core Router. In our MCMA algorithm (as in DDVCA), we select a Core Router addressed as a central node.

We denote *a core-selection algorithm* as *delay-bounded,* if the algorithm considers a given delay-bound for the group during the selection process, and the resulting core is such that there exists a path between each source-receiver pair in the group *which passes through this core* without violating the delay-bound [12]. Furthermore, we denote *a core-selection algorithm* as *delay-variation bounded,* if the algorithm considers a given delay variation tolerance for the group during the selection process, and the resulting core is such that the difference between the end-to-end delays along the paths from the source *s* to any two- destination nodes, which passes through this core, satisfies the delay variation tolerance.

Motivated by the simulation results provided in [13], we adopt a strategy similar to "Topological Center of Z in Z", which dictates that core candidates are restricted to be *multicast group members*. In link-state routing-based networks, where centralized algorithms can be used by individual routers, this restriction reduces the computational overhead $O(|M||V|^2)$ [13]. In our algorithm, rather than using topological center, we use a *QoS parameter center*. That is, based on the delay, we select such core node among destination nodes having the least delay average. That is, by this value, it is situated the nearest to all the remaining destination nodes in the *LDT*. It is as if it is situated at the center of the remaining destination nodes. We will use the term *center member*, as a synonym for such a destination core node in our heuristic. To avoid message retransmission and alleviate the network traffic, we adopt a strategy based on the hypothesis that if a message passes through a destination node first, then it is received immediately by this node. Thus, we avoid the needed time to reach the core node and then this core relays the message to each of the destination nodes. Our MCMA algorithm (Algorithm 1) contains five stages. The first stage (lines 2-4) is the initialization. The second one (line 5), during which the Least Delay Tree (*LDT*) is computed by using Dijkstra's algorithm [11]. Subsequently, the user input data are verified. If these data are too tight, then they are relaxed (line 6). The third one (lines 8-10) is the computation of the center member parameters based on formula (7) in order to form an ordered set of candidate center members. This phase is described next. The fourth stage (lines 14-21) constitutes the center member selection verifying both delay and delay variation constraints. The fifth algorithm phase (lines 24-28) represents the multicast tree construction process. Next, we describe the third phase.

Algorithm 1. Our MCMA algorithm

```
Input: a backbone network $G=(V,E)$, a set of destination nodes (gateways) $Z$, a source node $s$, an upper bound $\Delta$ of end-to-end delay. $\delta$- Delay variation tolerance.
Output: a delay and delay-variation bounded network $T=(V_T,E_T)$ $(T \subseteq G)$ spanning all nodes in $Z$.
Step1  Using AODV protocol to get the delay of the wireless routing path between each team leader and its gateway.
Step2  Multicast tree construction in the backbone Internet.
1.  Begin
2.  $Cost[s]=0, Delay[s]=0$; $T = \emptyset, Q \leftarrow \emptyset, v_c \leftarrow \emptyset$

12.     Sort $Q$ in an increasing order
13.         /*   Center member selection process   */
14.   For each $v_i \in Q$ do
15.       { For each $v_i \in Z$ do
16.   $Delay[s,v_j] \leftarrow Delay[s,v_i] + Delay[v_i,v_j] + W[v_j]$;
17.    if $Delay[s,v_j] < \Delta$ and $|AvDelay(T) - Delay[s,v_j]| < \delta$
18.               Flag =1;  else  Flag=0; endif; next $v_j$; }
19.   If flag =1   { $v_c = v_i$ ;  Exit; }  else next $v_i$
       /*if the first destination node verifying both constraints is
20.   considered core node and no need to consider the remaining dest.
      nodes in Q */
```

```
3.  For each vertex $u \in V - \{s\}$ do
4.  $\{Cost[u] = \infty, Delay[u] = \infty, Centerp(v_i)' = \infty\}$
5.  Call Dijkstra's algorithm to compute the least Delay Tree (LDT) . Find out $\Delta_{max}$ and $\delta_{max}$ .
6.  If $\Delta_{max} < \Delta$ and $\delta_{max} < \delta$, then relax $\Delta$ and (or) $\delta$
7.  /* For this LDBT, compute $C(v_i, v_j)$ of all LDBT paths connecting each destination node $v_i$ with another destination $v_j$. Then calculate
8.  For each $v_i \in Z$ do {
9.      For each $v_j \in Z$ do { Delay[$v_i$]=$D[v_i, v_j] + W[v_j]$}
10.         $Cmp(v_i)' = \frac{1}{degd(v_i) \times |Z|}$ Delay[$v_i$]
11.         $Q \leftarrow Cmp(v_i)'$ }
21. }   /* External For loop end */
22. if $v_c = \emptyset$  $v_c = s$
23. /* The source node is selected as a center member node*/
    /*   Multicast Tree construction process   */
24. If $v_c \neq s$ $T = T \cup \{L / L \in$ minimum Cost path from $s$ to $v_c$
25.     For each $v_j \in Z$ , $v_j \notin path(s, v_c)$ do
26.     { $T = T \cup \{L / L \in$ minimum Cost path from $v_j$ to $v_c$
27. else Call Dijkstra's algorithm to compute the delay bounded and delay- variation constrained multicast tree spanning M $\cup$ $\{s\}$ and rooted at s.
28. Return T; End (of the Algorithm)
```

4.1. Proposed center member selection method

The center member selection is executed into two stages:

a. *Center member pre-selection method*

The pre-selection operation (lines 8-10) consists in finding for every destination node v_i the following results: (a) The delay between vi and every destination node vj through the shortest delay and in LDT and then summate all these values. (line 9); and (b) the average delay value computed as follows (line 10):

$$\mathrm{Cmp}(\mathrm{v_i})' = (\frac{1}{\mathrm{degd}(\mathrm{v_i})}) \times \frac{1}{|\mathrm{Z}|} \times \sum_{\substack{j=1 \\ i \neq j}}^{|z|-1} (\mathrm{D}[\mathrm{v_i}, \mathrm{v_j}] + \mathrm{W}[\mathrm{v_j}]) , \forall\, \mathrm{v_i}, \mathrm{v_j} \in \mathrm{Z}, \quad \mathrm{v_i} \neq \mathrm{v_j} \tag{7}$$

The $Cmp(v_i)'$ is calculated for every destination node vi and then introduced in a priority queue Q (line 11). Subsequently, Q is sorted in an increasing order (line 12) such that the first node Q has the least $Cmp(v_i)'$ and therefore, has the highest priority. The selection method execution is described next.

The idea behind integrating $\frac{1}{degd(v_i)}$ in the formula (7), is to give priority to a favorite destination node to participate in the core selection process. The advantage of such selection is to reduce the computational overhead and to alleviate the traffic through relay nodes and orient it to *a favorite destination center member node*.

b. *Center member selection method*

The center member selection constitutes the fourth stage algorithm execution. At this stage (lines 14-28), we test whether for the picked node from Q, the Dijkstra's shortest path from the source to any destination node passing through this picked node satisfies the delay bound Δ (2) and the delay variation tolerance (5). If it does, then it is selected as a center member (vc=vi) (line 19). Therefore, there is no need to treat the other remaining nodes in Q. Otherwise, we pick from Q the next candidate (line 19) and the same constraints (2) and (5) are tested. If all nodes in Q are treated and no one verifies the delay bound and the delay variation tolerance, then the source s is considered as the only candidate (vc=s) (line 22). The fifth algorithm phase (lines 24-28) represents the multicast tree construction process. We first connect the source node with the center member vc (line 24), and then we connect to this center member all the remaining destination nodes (lines 25-26). If the source is selected as a center member, we apply Dijkstra's delay shortest path algorithm to compute the delay and delay-variation bounded multicast tree rooted at the source s and spanning all destination nodes (line 27).

Observation 2

In our proposed MCMA algorithm, $AvDelay(T)$ and $Cmp(v_i)$ are updated when a new member joins or leaves the multicast group *Z*.

c. MCMA algorithm operation

A detailed example in Fig. 1 is provided to show how the MCMA algorithm works on the original graph depicted in Fig. 1(a). [1][4][9] used the same graph with the same settings but without delay variation constraint. We applied Kim's Algorithm on this graph. Our resulting multicast tree is shown in Fig. 1(c). In the original graph, each number *d* of numbers along any edge, represent the delay *(d)* for that edge. *s* is set to be the source node. The delay bound Δ is set to 60 (as in [5]), the delay-variation tolerance δ is set to 15 (our input data), and the set of destination nodes *Z* is set to: Z=*{B,E,H}*. The number in the parentheses near gateway g (including the source gateway and all the destination gateways) represents the corresponding wireless route delay *W(g)*. Because the wireless route delay between the source leader MH and the source gateway is 1, the multicast end-to-end delay constraint used in MCMA will be 59 (i.e., 60-1).

d. Comparison with other algorithms

In the first part of Table 1, we compare the execution of the mentioned algorithms on the original graph depicted in Fig. 1 (a). The delay bound Δ is set to 60, the delay-variation tolerance δ is set to 15, and the set of destination nodes M is set to: M={B,H,E}. In this table, we calculate the delay variation between every pair of destination nodes using (3). Then the maximum delay variation tolerance δ_T is fixed and calculated for every tree as follows:

$$\delta_T = \delta_{\max} = \max_{v_i, v_{j \in Z}} \{ |\mathrm{Delay}[v_i] + W[v_i] - (\mathrm{Delay}[v_j] + W[v_j])| \} = \max\{\delta_{BE}, \delta_{EH}, \delta_{BH}\} \quad (8)$$

It is to be noticed that the tree constructed by our MCMA algorithm is similar to that constructed by the Kim's algorithm. Both trees have the least total delay and the least delay variation tolerance and are feasible trees (these trees verify both delay and delay variation constraints).

5. Correctness proof and time complexity analysis of MCMA algorithm

The correctness and time complexity of the algorithm MCMA results from the following theorems. The proofs are omitted for lack of space.

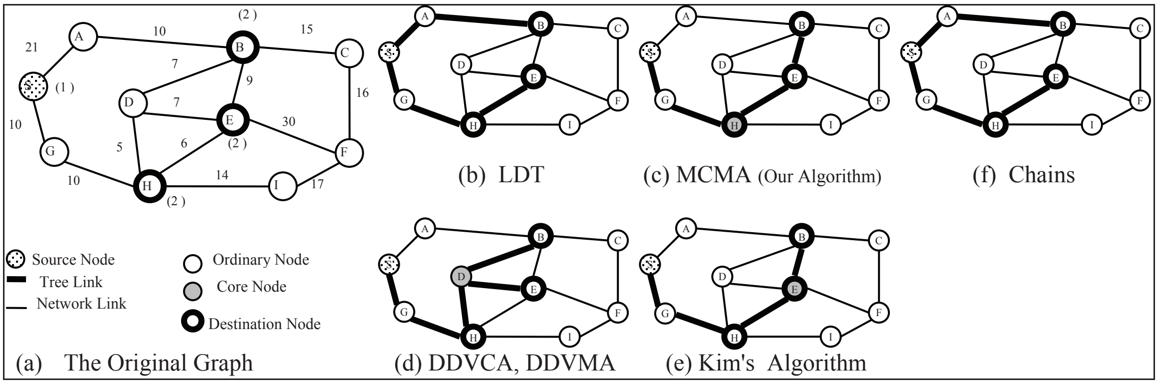
Theorem 1

The algorithm MCMA always constructs a delay and delay variation-bounded multicast tree if such a tree exists.

Theorem 2

The time complexity of MCMA is $O(|E||V|)$.

Table 1, proves that our MCMA algorithm has better complexity than others well-known algorithms to which it is compared. In this Table, *E, V* and *Z* are as mentioned before, *k*-number of shortest paths.



(a) The Original Graph (b) LDT (c) MCMA (Our Algorithm) (d) DDVCA, DDVMA (e) Kim's Algorithm (f) Chains

Fig. 1. Comparison between MCMA and other algorithms

Table 1 Algorithm Complexities and Comparison between MCMA and other algorithms

	Total Delay	δ_{BH}	δ_{BE}	δ_{EH}	δ_T	Time Complexity
Chain	77	11	5	6	11	$O(\|E\|^2 k)$
DDVCA	84	12	0	12	12	$O(\|E\|\|V\|^2)$
DDVMA	84	12	0	12	12	$O(\|E\|\|V\|^2)$
Kim's Algorithm	81	15	9	6	15	$O(\|E\|\|V\|^2)$
MCMA	81	15	9	6	15	$O(\|E\|\|V\|)$

6. Conclusion

In this paper, we considered the problem of generating minimum delay multicast trees that satisfy certain bounds on the end-to-end delay from the source to the destination nodes and the inter-destination delay variations between paths from the source to the destination nodes in a heterogeneous network. These constraints are imposed by the user process. Furthermore, extending previous works, we have proposed new delay-variation estimation. This scheme is adjusted dynamically in response to the connection of new destination nodes. Therefore, based on the combination of CBT and the Dijkstra's shortest path algorithm, we proposed MCMA with much lower time complexity $O(|E||V|)$ than DDVCA, DDVMA and Chains.

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