Deterministic Formulization of End-to-End Delay and Bandwidth Efficiency for Multicast Systems

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Abstract

End-System multicasting (ESM) is a promising application-layer scheme that has been recently proposed for implementing multicast routing in the application layer as a practical alternative to the IP multicasting. Moreover, ESM is an efficient application layer solution where all the multicast functionality is shifted to the end users. However, the limitation in bandwidth and the fact that the message needs to be forwarded from host-to-host using unicast connection, and consequently incrementing the end-to-end delay of the transmission process, contribute to the price to pay for this new approach. Therefore, supporting high-speed real-time applications such as live streaming multimedia, videoconferencing, distributed simulations, and multiparty games require a sound understanding of these multicasting schemes such as IP multicast and ESM and the factors that might affect the end-user requirements. In this paper, we present both the analytical and the mathematical models for formalizing the end-to-end delay and the bandwidth efficiency of both IP and ESM multicast system. For the sake of the experimental verifications of the proposed models, numerical and simulation results are presented in this paper. Finally, the proposed formulization can be used to design and implement a more robust and efficient multicast systems for the future networks.

Keywords: Bandwidth Analysis, End-to-End Delay, End System Multicast, IP Multicast, Overlay Networks.

1. INTRODUCTION

There is an emerging class of Internet and Intranet multicast applications that are designed to facilitate the simultaneous delivery of information from a single or multiple senders to multiple receivers. Different approaches of multicasting have been suggested to improve the overall performance of networks especially the Internet [1, 2, 3, 4]. These approaches are: multiple unicast, IP multicast, and end-system multicast. All of these methods have some advantages and disadvantages but the last two approaches (IP multicast, and end-system multicast) mentioned above have had more research effort in terms of performance evaluation of networks. Multiple unicast can be described as a service where one source sends the same copy of the message to multiple destinations. There is a one to one connection all the way from the source to the destination. No special configuration is required. In IP multicast, one source sends data to a specific group of receivers. In this case, a unique and special IP address is used, a class D address for the entire group. In addition, there is a special configuration adopted for efficiency reasons. A tree rooted at the source is constructed and only one copy of the message is sent since the routers along the paths to the destinations performed the necessary replication functionalities.

Finally, the end-system multicasting is a very promising application layer solution where all the multicast functionality is shifted to the end users [7]. In an end-system multicasting approach, host participating in an application session have the responsibility to forward information to other hosts depending on the role assigned by a central data and control server [15]. In this case, the architecture adopted is similar to that of IP multicast with the difference that only IP unicast service is required. End-system multicast uses an overlay structure, which is established on top of the traditional unicast services. In this way, every pair of edges (source-destination) is a unicast connection. The overlay has its meaning from the fact that the same link can have multiple unicast connections for multiple pair of edges. Although, end-system multicast seems to have many advantages (no further changes to the network are required, user has more control of the application layer, no need of special multicast router capability, etc), there is a penalty to pay. In the overlay structure, hosts are able to multicast information and consequently use the same link to redirect packets increasing the end-to-end delay of the entire transmission process [3, 8]. Another problem is the number of receivers that a potential “multicast” host can support. End users have a limited bandwidth and suffer the last mile problem [9].

While these different multicast approaches can displace some of the costs of face-to-face communications, their true potential business benefit lies in improving the accessibility and timeliness of information, vastly increasing its value to both the organization and individual employees. Although research on multicast dates back to the early days of the Internet, it has yet to produce a multicast service that is ubiquitously and economically available. In spite of the performance advantages, commercial deployment of multicast has not yet been fully realized. One of factors that prevent the wide-range deployment of multicast is the difficulty in providing reliable multicast transport.

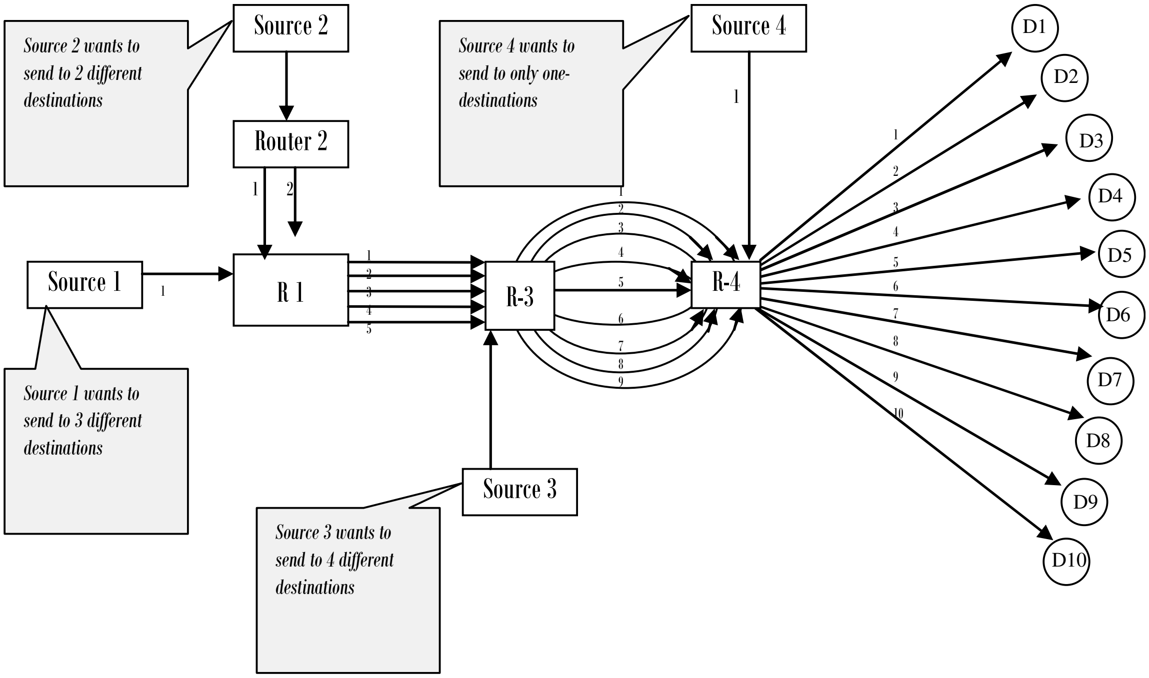
Fortunately, recently there has been a renewed effort to realize different approaches of multicasting. In this paper, we are also going to analyze these different methods of multicasting with respect to their performance differences.

2. THEORETICAL ANALYSIS OF MULTICAST SYSTEMS

The Internet consists of interconnected LANs. A LAN may or may not have native multicasting support and the same holds for the IP layer on top of the LAN. In this section, we will theoretically analyze the problems of different level of multicasting, which hinder their performance with respect to the bandwidth utilization and latency.

2.1 Multiple Unicast Systems

In the unicast IP network, the host acting as the source transmits a copy of the message to each destination host as shown in Fig. 1. No special configuration is needed either in the source or in the core network. The intermediate routers will have to carry all these messages to the proper destinations. If, for example, the source host transmits ten copies of the same message at the



Source 2 wants to send to 2 different destinations

Source 4 wants to send to only one-destinations

Source 1 wants to send to 3 different destinations

Source 3 wants to send to 4 different destinations

FIGURE 1: Example of Multiple Unicast

same time, then obviously ten times the bandwidth of one message is required on source host's network and on the router connected to the source host's network. The chains of protocol entities that take care of the transmission process also use processing capacity on the host for each transmission. In addition, the transmission time is increased ten times and it will affect the global end-to-end delay. We pay special attention to the nearest link between the first router and the source since it is mostly there where the maximum bandwidth consumption takes place. These are the reasons to consider a multiple unicast service an unpractical approach to implement on the network.

2.2 IP Multicast Systems

IP multicast is a service where one source sends data to a group of receivers each of them containing a class D address as membership identification. IP multicast has long been regarded as the right mechanism due to its efficiency. In IP multicast, a packet is sent only once by the source. Routers along the route take care of the duplication process.

The IP-multicast capable version of the network shown in Fig. 2 consists of network with native multicast support. IP multicast capable routers are consider along the path. Efficiently routing multicast protocols are implemented. The traditional process includes the construction of a source-rooted tree together with the members of the multicast group. Since only one copy of the message is required, we can say that a minimum bandwidth effort is being used for the transmission of the message to all group members connected in the network. The problem for IP multicast is that there is no commercial support for multicast routers. Investors still think that there is not enough multicast application demand and that multicast traffic could take their routers down due to congestion problems.

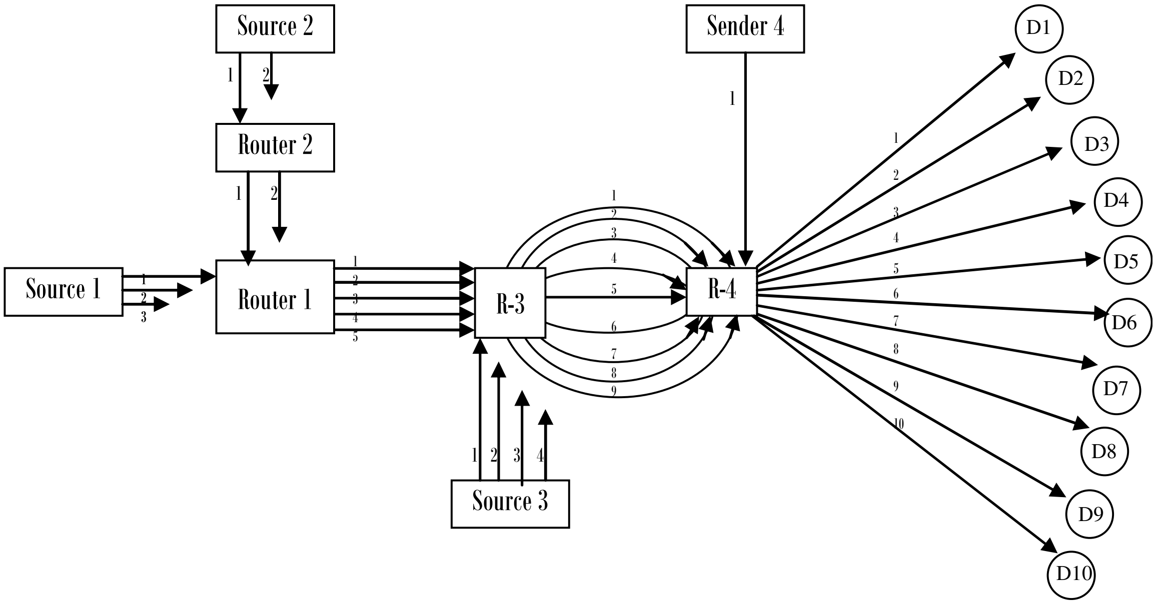


FIGURE 2: Example of IP Multicast

The IP-multicast transmission takes the same bandwidth on source host's network as a single copy, regardless of how many clients are members of the destination host group in the Internet. The obvious difference between the multiple-unicast and IP multicast is that IP multicast scales very well. Even if not all LANs have native multicast support, the added cost of transmitting copies will be limited to a single LAN.

Besides the advantages of IP multicast, there are also certain drawbacks of this approach. One of them, like we mentioned before, is the deployment problem of IP multicast, which imposes dependency on routers. The main disadvantage of IP multicast is the need of commercial routers supporting multicast protocol. In theory, almost all routers support multicast but in practice this is not the case [13]. This prevents multicast service fully implemented in Internet application (experimental research has been conducted in the Internet in a special platform named The Mbone) [10, 11].

Several approaches to multicast delivery in the network have been proposed which make some improvements or simplifications in some aspects, but they do not improve upon traditional IP multicast in terms of deployment hurdles. A major obstacle for deployment of multicast is the necessity to bridge from/to the closest multicast router to/from the end-systems. Existing IP multicast proposals [5, 6] embed an assumption of universal deployment, as all routers are assumed to be multicast capable. The lack of ubiquitous multicast support limits the deployment of multicast applications, which in turn reduces the incentive for network operators to enable multicast [12]. Therefore, from the above discussion one can expect that we need another multicast alternative in which network routers have not to do all of the work; instead each of the host will equally contribute in the overall multicast process of the messages.

2.3 End System Multicast (ESM) Systems

Because of the limitations in IP multicast, researchers have explored an alternative architecture named end-system multicast, which built a system on top of the unicast services with multicast functionalities. End-system multicast is a very promising application layer solution where all the multicast functionality is shifted to the end users as shown in Fig. 3. In this approach, host participating in an application session can have the responsibility to forward information to other

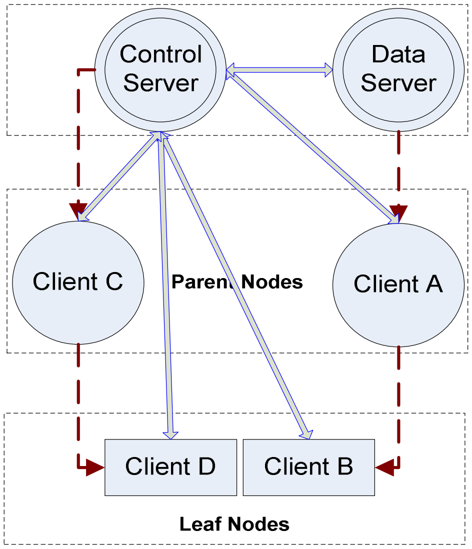


FIGURE 3: Example of ESM, Solid Lines Represent 2 Way Packet Transmission, Dotted Lines Represent One Way Packet Transmission.

hosts. Here, end users who participate in the multicast group communicate through an *overlay* structure.

However, doing multicasting at end-hosts incurs in some performance penalties. Generally, end-hosts do not handle routing information as routers do. In addition, the limitation in bandwidth and the fact that the message needs to be forwarded from host-to-host using unicast connection, and consequently incrementing the end-to-end delay of the transmission process, contribute to the price to pay for this new approach. These reasons make end-system multicast less efficient than IP multicast.

The structure of the end-system multicast is an overlay in a sense that each of the paths between the end systems corresponds to a unicast path [14]. In other words, end-system multicast is built on top of the unicast services provided by network on transport layer. Here the membership and replication functionality is performed by the end receivers, which connect together over unicast channels to form a multicast tree, rooted at one data source. The end receivers could play the role of parent or children nodes. The parent nodes perform the membership and replication process. The children nodes are receivers who are getting data directly from the parent nodes. There is one central control server and one central data server residing in the same root source. Any receiver can play the role of parent to forward data to its children. Each client has two connections: a control connection and a data connection.

3. END-TO-END DELAY APPROXIMATION FOR MULTICAST SYSTEMS

This section presents the mathematical model for approximating the end-to-end delays for all multicasting schemes. For the ease of simplicity, we divide our approximation for each type of multicasting approach such as unicast, multiple unicast, IP multicast, and ESM.

3.1 Model and Assumptions

Let G is an irregular graph that represents a network with a set of N vertices and M edges such as: $G = \{N, M\}$. Let L is a direct communication link between a single pair of source (s) and destination (*d*) where both source and destination belong to *N* such as: $\{s,d\}\in N$. In addition, each packet transmitted between source (*s*) and destination (*d*) must traverse one or more communication links in order to reach the final destination.

Let the value of *D(L)* denotes packet-delay (we sometime refer it as link delay) that is associated with each direct communication link. Therefore, each transmitted packet will typically experience a delay of *D(L)* on a particular link. The delay includes transmission, processing, and propagation delays such as: *Link-Delay = D(L) =* Transmission Delay + Propagation Delay + Processing Delay where $L \in M$. In connection less communication such as IP network, there might be multiple routes exist between a pair of source and destination. As a result, each packet might follow a different route in order to reach the final destination where each route requires traversing of one or more communication links (*L*). A single route between a pair of source and destination can be defined as: $R\{s,d\}\, where \{s,d\}\in N$. System parameters along with their definitions are presented in Table 1 and Table 2.

3.2 Mathematical Model for a Unicast System

In unicast, a packet is sent from one point (source) to another point (destination). As mentioned earlier, when packet transmit from one source (*s*) to a specified destination (*d*), there exist multiple routes where each route can have multiple links. This implies that the packet-delay for unicast is entirely dependent on the number of links a packet needs to traverse in order to reach the final destination system. Based on the above argument, one can define the packet delay such as: $D(R)=D(L_1)+D(L_2)+........+D(L_n)$ where *n* is the maximum number of links that need to be traversed on route *R* between *s* and *d*. The delay can be generalized for one particular route (*R*) that exist between source (*s*) and destination (*d*) such as:

$$D(R)=\sum_{i=1}^{n} D(L_i) \tag{1}$$

$$where \sum_{i=1}^{n}(L_i)=\{L_1+L_2+......+L_n\}\in M$$

Equation (1) can be further expressed as:

$$Delay = D_{(s-d)} = \sum\nolimits_{L\in R(s-d)} D(L) \tag{2}$$

where $L\in R\left(s-d\right)$ represents the value of the total delay associated with the route *R* between source *s* and destination *d*.

Based on (1) and (2), one can also simply derive a mathematical expression for estimating an average-delay (denoted by *AD*) which each packet may typically experience if it traverses one of the available routes. The mathematical expression for an estimated *AD* is as follows:

$$AD_{(s-d)} \; \square \left(\sum_{i=1}^{y} D\left(R_i\right) \Big/ y \right) \tag{3}$$

where *y* represents the maximum number of possible routes between source *s* and destination *d*.

In addition to the average delay, one can also chose the optimal route with respect to the minimum delay that each packet may experience when traverse from one particular source *s* to a destination *d* such as:

Parameters	Definition
$D(L)$	Denotes packet-delay that is associated with each direct communication link
s	Represents source
d	Represents destination
C_n	Represents the child node
P_n	Represents the parent node
$D(R)$	Denotes maximum number of links that need to be traversed on route *R* between *s* and *d*
AD	Average-delay
OD	Optimal-delay for pair of *s* and *d*
$D_{Total(MU)}$	Estimate of the total delay that the entire packet transmission will experience in a multiple unicast system
$D_{Total(M_G)}$	Approximation of total delay experienced by multicast packets when transmitted from a root node (*s*) to a multicast group (M_G)
y	Represents the maximum number of unicast routes between a source (*s*) and multiple destinations
n	Represents the maximum number of links a unicast route has
MU	Stands for multiple unicast system
M_G	Denotes a multicast group that consists of one or more destination systems
Z	Represents the size of the multicast group such as: $Z = \mid M_G \mid$
T	Represents spanning tree
D	Represents total delay experienced by multicast packets when transmitted from a root node (*s*) to a multicast group (M_G)
$L_{n,Z}$	Represents the total number of links (i.e., $Z \in R_T$) that a packet needs to traverse in order to reach the specific destination

TABLE 1: System and Parameters Definition.

$$OD_{(s-d)} = Min\left|\sum_{i=1}^{y} D\left(R_i\right)\right| \tag{4}$$

Equation (4) gives minimum delay that each packet experiences when transmitting between a pair of *s* and *d*. We refer this as an optimal delay (OD) for a pair of *s* and *d*. The above derivations can be further extended for the multiple unicast system where a single source (*s*) can transfer a packet simultaneously to multiple destinations. This hypothesis leads us to the following argument: multiple routes can be established between the source (*s*) and each destination system. The following mathematical expression can be used to estimate the total delay that the entire packet transmission will experience in a multiple unicast system:

$$D_{Total(MU)} = D_{\left\langle s \xrightarrow{multiple} \left(d_1, d_2, \ldots\ldots, d_y\right)\right\rangle} = \sum_{i=1}^{y} D\left(R_i\right) \tag{5}$$

where *y* in (5) is the maximum available unicast routes between a particular source (*s*) and multiple destinations.

Although, in multiple unicast system, a single packet can be transmitted from one source to multiple destinations, the transmitted packet may follow a different route in order to reach the appropriate destination. Consequently, each packet transmission may yield a different delay depending on the number of links the packet needs to traverse on the chosen unicast route. This leads us to the following mathematical expression for an average delay:

Parameters	**Definition**
ESM_G	Denotes an ESM group that consists of one or more end-system destination
X	Represents the size of the group such as $X = \mid ESM_G \mid$
N	An overlay network consists of a set of N end-system nodes connecting
R_T	Represents a route between a source node (s) and non-leaf nodes that could be parent or child nodes
T_T	Represents the transmission time
P_s	Represents the packet size
B_W	Denotes the bandwidth
L	Represents particular link (L) between a pair of source (s) and destination (d)
D_Q	Denotes queuing delay
τ	Represents the propagation delay
L_D	Denotes distance for a communication link
SoL	Represents speed of light
AB_W	Represents average-bandwidth between a pair of source (s) and destination (d)
OB_W	Represents optimal-bandwidth between a pair of source (s) and destination (d)

TABLE 2: System and Parameters Definition.

$$AD_{(s-d)} \square \left(\sum_{i=1}^{y} \frac{D(R_i)}{y} \right) where\ D(R_i) = \sum_{i=1}^{n} D(L_i) \tag{6}$$

where y represents the maximum number of unicast routes between a source (s) and multiple destinations and n represents the maximum number of links a unicast route has.

3.3 Mathematical Model for a IP Multicast System

In IP multicast system, a single source (s) sends a packet to a group that consists of multiple destination systems. In addition, a packet is sent only once by the source system where as the intermediate routers along the route perform replications with respect to the number of destinations a group has. Let M_G denotes a multicast group that consists of one or more destination systems whereas Z represents the size of the group such as $Z = \mid M_G \mid$. In an IP multicast system, all multicast groups (M_G) can be typically organized in a spanning tree. We consider a spanning tree rooted at the multicast source (s) consisting of one of the multicast groups (M_G) that has a size of Z. The spanning tree can then be expressed as: $T = (N_T, M_T)$ where the numbers of destinations in one multicast group (M_G) belong to the total number of nodes present in the network such as: $M_G \in M$.

Also, Based on the above discussion, we can give the following hypothesis: The total delay (D) experienced by multicast packets when transmitted from a root node (s) to a multicast group (M_G) can be defined as a sum of the total delay experienced by each link of a spanning tree from the root nodes (s) to all destinations ($d \in M_G$) and the delay experienced by each link of an intermediate routers.

Thus, this leads us to the following expression for total delay (D_{Total}) experienced by multicast packets transmitted from root node (s) to a destination node (d) that exists within M_G:

$$D_{Total(M_G)} = D_{(s-M_G)} = \sum_{i=1}^{Z} D(L_i) + \sum_{i=1}^{n} D(L_i) \tag{7}$$

where Z is the number of destination systems in one multicast group of a spanning tree (T) and n represents the total number of links a route has.

The first term of (7) yields the total delay associated with the number of links with in a spanning tree when a packet is transmitted from a root node (source) to all the leaf and non-leaf nodes. The second term of (7) provides a total delay that a packet may experience when transmitted along a certain route.

Equation (7) can be further generalized for one of the specific destinations (d) within a multicast group such as $d \in M_G$, if we assume that we have a route within a spanning tree (T) from multicast source (s) to a specific destination (d) such as R_T (s, d), then the multicast packets transmitted from a source node to a destination experience a total delay of:

$$D_{\langle s \longrightarrow (d\in M_G)\rangle} = \sum_{L_{n,Z}\in R_T(s,d)} D\left(L_{n,Z}\right) \tag{8}$$

where $L_{n,Z}$ represents the total number of links (i.e., $Z \in R_T$) that a packet needs to traverse in order to reach the specific destination d along a path of R_T with in the tree T as well as the number of links from source s to a multicast group M_G.

3.4 Mathematical Model for an End System Multicast (ESM)

Because of the limitations in IP multicast, researchers have explored an alternative architecture named ESM, which is built on top of the unicast services with multicast functionalities. In ESM, one of the end-system nodes (s) participating in an application session can have the responsibility to forward information to other hosts. Here, end users that participate in the ESM group communicate through an *overlay* structure. An ESM group can have at most N end-system nodes where we focus on one of the end-system nodes (s) that multicast information to the other participating nodes of a multicast end-system group. From the source host point of view, this ESM group can be considered a group of destination systems. For the sake of mathematical model, lets ESM_G denotes an ESM group that consists of one or more end-system destination where as X represents the size of the group such as $X = | ESM_G |$. Based on the derived expression of unicast in the previous sections, these unicast links can not exceed to M such as $m_1, m_2, \ldots\ldots\ldots, m_y \in M$ where one of the edges provides a unicast connection between two end-system nodes such as:

$$\{m\in M\} \xrightarrow{unicast-link} \{n_1, n_2\} \subset \{s, N\} \tag{9}$$

An overlay network consists of a set of N end-system nodes connecting though M number of edges where one of the end-system is designated as source host (s) such as: $G = \{s, N, M\}$. This also shows that an ESM is built on top of the unicast services using a multicast overlay network that can be organized in a spanning tree such as $T = (N_T, M_T)$ rooted as an ESM source (s) where the numbers of destinations in one multicast group (ESM_G) belong to the total number of nodes present in the network such as: $ESM_G \in M$. The end receivers in a multicast tree could be a parent or a child node depending on the location of the node.

In a multicast spanning tree (T), all the non-lead nodes can be both parent and child at the same time where as all the leaf nodes are considered to be the child nodes. Based on the above argument, one can say that a multicast packet originated from the root (s) of a spanning tree (T) need to traverse typically two links; source to non-leaf node (P_n, C_n) and a non-leaf node to a leaf node (C_n). Lets R_T (s, non-leaf node) represents a route between a source node (s) and non-leaf nodes that could be parent or child nodes such as:

$$R_T = \{P_n \vee C_n \in ESM_G\} \text{ where } P_n, C_n \in \{s \cup N\} \tag{10}$$

where, R_T (P_n, C_n) in (10) represents a route from a parent node to a child node such as: $R_T = \{P_n, C_n\} \in ESM_G$.

Equations (9) and (10) lead us to the following expression for computing the total delay involve in transmitting a multicast packet from a source node to one or more parent nodes (i.e., the delay associated with the first link of transmission):

$$D_{\left\langle s \xrightarrow{multiple-unicast} (P_n \vee C_n) \in \{s \mathrm{U} N\} \right\rangle} = \sum_{i=1}^{y} D\left(R_{i\left(s \longrightarrow P_n, C_n\right)} \right) \, where \; D\left(R_{ii\left(s \longrightarrow P_n, C_n\right)} \right) \mathrm{A} \sum_{i=1}^{n} D\left(L_i\right) \quad (11)$$

In (11), *y* is the maximum unicast routes between a source (*s*) and one or more non-leaf nodes and *n* represents the maximum number of links a unicast route can have. Similarly, the total delay experience by a multicast packet transmitted from a parent node to a child node can be approximated as follows:

$$D_{\left\langle P_n \xrightarrow{multiple-unicast} (C_n) \right\rangle} = \sum_{i=1}^{y} D\left(R_{i(P_n, C_n)} \right) \, where \; D\left(R_{i(P_n, C_n)} \right) \mathrm{A} \sum_{i=1}^{n} D\left(L_i\right) \quad (12)$$

By combining (11) and (12), the total delay experience by a multicast packet that transmitted from a source node (*s*) to a child node (C_n) can be approximated as:

$$D_{\left\langle s \xrightarrow{multiple-unicast} (C_n) \in \{s, P_n \mathrm{U} N\} \right\rangle} = \sum_{i=1}^{n} D\left(L_{i\left(s \longrightarrow P_n, C_n\right)} \right) + \sum_{i=1}^{n} D\left(L_{i(P_n, C_n)} \right) \quad (13)$$

4. FORMULIZATION OF BANDWIDTH EFFICIENCY FOR MULTICAST SYSTEMS

This section presents the formulization of the bandwidth efficiency for all multicasting schemes. For the ease of simplicity, we divide our proposed formulization for each type of multicasting approach such as unicast, multiple unicast, IP multicast, and ESM.

4.1 Generic System Model

In order to approximate the bandwidth for Unicast, multicast, and ESM, we use the classical definition of computing the transmission time. Based on this definition, the transmission time (T_T) can be defined as a product of the packet size (P_s) which we transmit between a pair of source (*s*) and destination (*d*) and the inverse of the bandwidth (B_W). Mathematically, this can be expressed as follows: $T_T = \left(P_s\right)\left(1/B_W \right)$

Let the value of ($D_{(\mathrm{s} \longrightarrow \mathrm{d})}$) denotes the total packet-delay which is associated with each direct communication link. Therefore, each transmitted packet will typically experience a delay of $D_{(\mathrm{s} \longrightarrow \mathrm{d})}$ on a particular link (*L*) between a pair of source (*s*) and destination (*d*). This delay is the sum of the transmission time, the queuing and the propagation delays such as: $D_{(\mathrm{s} \longrightarrow \mathrm{d})}$ = Transmission Time (T_T) + Propagation Delay (τ) + Queuing Delay (D_Q). Also, it can be expressed as: $D_{(\mathrm{s} \longrightarrow \mathrm{d})} = T_T + \tau + D_Q$. Changing the above expression for the transmission delay, we got

$$T_T = (D_{(s \longrightarrow d)}) - (\tau) - (D_Q) \tag{14}$$

Recall our classical definition for the transmission time, (14) can be rewritten as the product of bandwidth and packet size:

$$\left(\frac{1}{B_W}\right) P_s = (D_{(s \longrightarrow d)}) - (\tau) - (D_Q) \tag{15}$$

Solving (15) for approximating the bandwidth, we got

$$B_W = \frac{P_s}{(D_{(s \longrightarrow d)}) - (\tau) - (D_Q)} \tag{16}$$

It should be noted that the propagation delay (τ) is a ration between the distance for a communication link (L_D) and the speed of light (*SoL*). This allows us to further extend (16) as follows.

$$B_W = \frac{P_s}{(D_{(s \longrightarrow d)}) - \left(L_D / SoL \right) - D_Q} \tag{17}$$

Simplifying the above equation (17), we got

$$B_W = \frac{(P_s)(SoL)}{\left| (SoL)\ (D_{(s \longrightarrow d)}) - L_D - (SoL)(D_Q) \right|} \tag{18}$$

For the sake of simplicity, we can ignore the queuing delay. Equation (18) can now be written as:

$$B_W = \frac{(P_s)(SoL)}{\left| (SoL)(D_{(s \longrightarrow d)}) - L_D \right|} \tag{19}$$

4.2 Bandwidth Efficiency Formulization for a Unicast System

In unicast, a packet is sent from one point (source) to another point (destination). As mentioned earlier, when packet transmit from one source (*s*) to a specified destination (*d*), there exist multiple routes where each route can have multiple links. This implies that the packet-delay for unicast is entirely dependent on the number of links a packet needs to traverse in order to reach the final destination system. Based on the above argument, one can define the packet delay such as: $D(R) = D(L_1) + D(L_2) + ... + D(L_n)$ where *n* is the maximum number of links that need to be traversed on route *R* between *s* and *d*.

We generalize the delay for one particular route (*R*) that exists between source (*s*) and destination (*d*) such as: $D(R) = \sum_{i=1}^{n} D(L_i)$ where $\sum_{1}^{n} (L_i) = L_1 + L_2 + ... + L_n \in M$

This expression is further extended as: $Delay = D_{(s-d)} = \sum_{L\in R(s-d)} D(L)$ where $L\in R\left(s-d\right)$ represents the value of the total delay associated with the route *R* between source *s* and destination *d*. For a unicast system, taking the above expressions into account, the available estimated bandwidth (B_W) for a communication link (*L*) that exists between a pair of source (*s*) and destination (*d*) can be approximated in the following equation:

$$B_W = \frac{\left(P_s\right)\left(SoL\right)}{\left(SoL\right)\left\langle \sum_{L\in R\left(s\longrightarrow d\right)} D(L)\right\rangle - L_D} \tag{20}$$

The $D(L)$ in (20) represents the link delay where as the $L\in R\left(s-d\right)$ represents the value of the total delay associated with the route *R* between source *s* and destination *d*.

The above equation (20) represents the approximated bandwidth which can be used by the transmitted packet for each individual communication link between the source and destination. It should be noted that the above equation is not representing the bandwidth approximation for one particulate route between the source and destination. Instead, it represents the bandwidth approximation for *n* number of links that need to be traversed on route *R* between source (*s*) and destination (*d*).

Based on the above derivation, one can also simply derive a mathematical expression for an average-bandwidth, denoted by AB_W. The average bandwidth represents the available bandwidth that each transmitted packet may utilize if it traverses one of the available routes. Equation (19) can be modified for the average delay between a pair of source (*s*) and destination (*d*), denoted by as follows:

$$AB_W = \frac{\left(P_s\right)\left(\mathrm{SoL}\right)}{\left(SoL\right)\left\{AD_{\left(s\longrightarrow d\right)}\right\} - L_D} \tag{21}$$

The mathematical expression for an estimated AB_W can be derived as follows:

$$AB_W = \frac{\left(P_s\right)\left(SoL\right)}{\left|\left(SoL\right)\left\{\frac{\sum_{i=1}^{y} D\left(R_i\right)}{y}\right\} - L_D\right|} \tag{22}$$

Where $D(R) = \sum_{i=1}^{n} D(L_i)\ \sum_{1}^{n} (L_i) = L_1 + L_2 + \ldots\ldots + L_n \in M$ and y represents the maximum number of possible routes between source *s* and destination *d*.

In addition to the average bandwidth, one can also choose the optimal route with respect to the minimum bandwidth that each packet may require when traverses from one particular source (*s*) to a destination (*d*). In order to derive an expression for the optimal bandwidth, we may need to modify equation (19) for the optimal delay. This is due to the fact that we assume that for each link that offers minimum bandwidth must have an optimal delay. This leads us to the following modification of (19), such as:

$$OB_W = \frac{(P_s)(SoL)}{(SoL)\ (OD_{(s \longrightarrow d)}) - L_D} \tag{23}$$

where $OD_{(s \longrightarrow d)}$ represents the optimal delay with respect to the minimum delay that each packet may experience when traverses from one particular source to a destination.

Based on (23), we can derive an expression for the optimal bandwidth, denoted by OB_W, between a pair of source (s) and destination (d) such as:

$$OB_W = \frac{(P_s)(SoL)}{\left|(SoL)\ \left\langle Min\left|\sum_{i=1}^{y} D(R_i)\right|\right\rangle - L_D\right|} \tag{24}$$

where $D(R) = D(L_1) + D(L_2) + ... + D(L_n)$ and *n* is the maximum number of links that need to be traversed on route *R* between *s* and *d*.

4.3 Bandwidth Efficiency Formulization for a Multiple Unicast System

In addition to unicast systems, we can derive the similar mathematical expressions for the multiple unicast system where a single source (*s*) can transfer a packet simultaneously to multiple destinations. In other words, in a multiple unicast system, there exist a unicast route between a source (*s*) and one of the destinations. This hypothesis leads us to the following argument: multiple routes can be established between the source (*s*) and each destination (d_1, d_1, d_1,.......,d_y) where *y* represents the maximum number of unicast routes established in multiple unicast. Based on this hypothesis, we can modify (19) that account the total delay such as:

$$B_{W\left\langle s \xrightarrow{multiple} (d_1, d_2, ..., d_y)\right\rangle} = \frac{(P_s)(SoL)}{\left|(SoL)\left\langle D_{s \xrightarrow{multiple} (d_1, d_2, ..., d_y)}\right\rangle - L_D\right|} \tag{25}$$

The following mathematical expression can be used to estimate the total bandwidth that the entire packet transmission utilizes in a multiple unicast system:

$$B_{WB_{W\left\langle s \xrightarrow{multiple} (d_1, d_2, ..., d_y)\right\rangle}} = \frac{(P_s)(SoL)}{\left|(SoL)\ \left\langle \sum_{i=1}^{y} D(R_i)\right\rangle - L_D\right|} \tag{26}$$

Although, in multiple unicast system, a single packet can be transmitted from one source to multiple destinations, the transmitted packet may follow a different route in order to reach the appropriate destination. In particular, a bandwidth is always associated with links rather than the complete routes between the source and destinations.

As a result, each transmitted packet may use a different amount of bandwidth with respect to the number of links that the packet needs to traverse on the chosen unicast route. This implies that, in order to estimate an average bandwidth that each packer might utilize, one should consider the number of maximum links a unicast route has. This leads us to the following mathematical expression for an average available bandwidth for the multiple unicast system:

$$AB_W = \frac{(P_s)(\mathrm{SoL})}{(SoL)\ \left\{AD_{\left(s \longrightarrow d\right)}\right\} - L_D} \tag{27}$$

Further, solving (26) for average bandwidth approximation results (27) such as:

$$AB_{W\left(s \longrightarrow d\right)}\ \mathrm{A}\ \frac{(P_s)(SoL)}{\left|(SoL)\ \left\langle \frac{\sum_{i=1}^{y} D(R_i)}{y} \right\rangle - L_D\right|}\ where\ D(R_i) = \sum_{i=1}^{n} D(L_i) \tag{28}$$

where *y* represents the maximum number of unicast routes between a source (*s*) and multiple destinations and *n* represents the maximum number of links that a unicast route has.

4.4 Bandwidth Efficiency Formulization for IP Multicast System

In IP multicast system, a single source (*s*) sends a packet to a group that consists of multiple destination systems. In addition, a packet is sent only once by the source system where as the intermediate routers along the route perform replications with respect to the number of destinations a group has. Lets $\boldsymbol{M_G}$ denotes a multicast group that consists of one or more destination systems whereas $\boldsymbol{Z}$ represents the size of the group such as $\boldsymbol{Z = |\ M_G\ |}$. In an IP multicast system, in order to efficiently transmit a packet from a specific multicast source to all multicast destinations, all multicast groups (M_G) can be typically organized in a spanning tree ($\boldsymbol{T}$). For the ease of mathematical expression, we only consider a spanning tree rooted at the multicast source (*s*) consisting of one of the multicast groups (M_G) that has a size of *Z*.

Based on the above discussion, we describe the spanning tree such as: $T = (N_T, M_T)$ rooted as multicast source (*s*) where the numbers of destinations in one multicast group (M_G) belong to the total number of nodes present in the network such as: $M_G \in M$ where *M* represents the total edges that the network has. The terms N_T and M_T represent the vertices and the edges of the spanning tree (*T*), respectively. It should be noted that we consider a spanning tree (*T*) that includes only the multicast destinations of a multicast group (M_G) with the exception of intermediate routers. In other words, we assume that N_T of the spanning tree (*T*) only consists of one or more destination nodes. The reason for this assumption is to simplify the process of estimating the total available bandwidth involves with the packet transmission in an IP multicast system.

Based on the above proposed model, we can give the following hypothesis: *The total available bandwidth* (TB_W) *utilizes by multicast packets when transmitted from a root node* (*s*) *to a multicast group* (M_G) *can be defined as a ration of packet size and the available bandwidth on each link of a spanning tree (T) from the root nodes* (*s*) *to all destinations* ($d \in M_G$) *with the bandwidth available to one or more intermediate routers of each link.*

The above hypothesis leads us to the following expression for total available bandwidth (TB_W) utilizes by multicast packets transmitted from root node (*s*) to a destination node (*d*):

$$TB_W = \frac{(P_s)(SoL)}{(SoL)\ (D_{(\mathrm{s} \longrightarrow M_G)}) - L_D} \tag{29}$$

Computing the total delay for the IP multicast and using its resulting values in (29), we provide an expression for the total available bandwidth such as:

$$TB_W = \frac{P_s}{\left| \left\langle \sum_{i=1}^{Z} D\left(L_i\right) + \sum_{i=1}^{n} D\left(L_i\right) \right\rangle - \frac{L_D}{SoL} \right|} \tag{30}$$

where Z in the denominator of (30) represents the number of destination systems in one multicast group of a spanning tree (T) where n represents the total number of links a route has.

The first term of the denominator of (30) ($\sum_{i=1}^{Z} D\left(L_i\right)$)yields the total delay associated with the number of links within a spanning tree when a packet is transmitted from a root node (source) to all the leaf and non-leaf nodes (i.e., the multiple receivers with in T excluding the source node (s)). In other words, according to spanning tree, if a message is transmitted from a source node (s) to all the destination nodes, then the packet must traverse Z (i.e., the number of destinations in one multicast group) number of links which consequently experience a delay on each link.

The second main term of the denominator ($\sum_{i=1}^{n} D\left(L_i\right)$) in (30) provides a total delay that a packet may experience when transmitted along a certain route (i.e., from a source node (s) to multicast group (M_G) via one or more routers along the route). The last term of the denominator can not be considered as a design parameter and therefore its value completely depends on the type of network.

The above equation can be further generalized for one of the specific destinations (d) within a multicast group such as $d \in M_G$, if we assume that we have a route within a spanning tree (T) from multicast source (s) to a specific destination (d) such as R_T (s, d), then the multicast packets transmitted from a source node may utilize a total available bandwidth such as:

$$TB_{W\left\langle s \longrightarrow \left(d \in M_G\right)\right\rangle} = \frac{P_s}{D_{\left\langle s \longrightarrow \left(d \in M_G\right)\right\rangle} - \left\langle L_D \big/ \left(SoL\right) \right\rangle} \tag{31}$$

Determine the total delay for the multicast packets that transmit from a source node to one of destinations within a group and using the resulting expression in (31), we got,

$$TB_{W\left\langle s \longrightarrow \left(d \in M_G\right)\right\rangle} = \frac{\left(P_s\right)\left(SoL\right)}{\left| \left(SoL\right) \left\langle \sum_{L_{n,Z} \in R_T\left(s,d\right)} D\left(L_{n,Z}\right) \right\rangle - L_D \right|} \tag{32}$$

where $L_{n,Z}$ in (32) represents the total number of links (i.e., $Z \in R_T$) that a packet needs to traverse in order to reach the specific destination d along a path of R_T within the tree T as well as the number of links from source s to a multicast group M_G.

Since only one copy of the message is required in IP multicast, we can say that a minimum bandwidth effort is being used for the transmission of the message to all group members connected in the network. This minimum bandwidth is achieved due to the fact that a minimal transmission time is required for the IP multicast which in turns reduces the overall end-to-end delay as can be seen in the denominator of (32).

4.5 Bandwidth Efficiency Formulization for End System Multicast (ESM) System

An ESM group can have at most *N* end-system nodes where we focus on one of the end-system nodes (*s*) that multicast information to the other participating nodes of a multicast end-system group. From the source host point of view, this ESM multicast group can be considered a group of destination systems. For the sake of mathematical model, lets ESM_G denotes an ESM group that consists of one or more end-system-destinations where as *X* represents the size of the group such as $X = | ESM_G |$.

In an overlay network, all participating end-system nodes are fully connected to each other via the unicast links. Based on the derived expression of unicast in the previous sections, these unicast links that provide connection between end-system nodes can not exceed to *M* such as: $\{m_1, m_2, ..., m_y\} \in M$ where one of the edges (m) provides a unicast connection between the two end-system nodes such as: $\{m \in M\} \xrightarrow{unicast-link} \{n_1, n_2\} \subset \{s, N\}$.

The structure of the ESM is an overlay network in a sense that each of the paths between the end-systems corresponds to a unicast path. This implies that an overlay network consisting of a set of *N* end-system nodes connecting though *M* number of edges where one of the end-system is designated as a source host (*s*) can be expressed as: $G = \{s, N, M\}$.

This also shows that an ESM is built on top of the unicast services using a multicast overlay network that can be organized in a spanning tree such as $T = (N_T, M_T)$ rooted as an ESM source (*s*) where the numbers of destinations in one multicast group (ESM_G) belong to the total number of nodes present in the network such as: $ESM_G \in M$. Here, the membership and replication functionality is performed by the ESM receivers, which connect together over unicast channels to form a multicast tree (*T*), rooted at one data source (*s*). The end receivers (i.e., the number of end-systems in ESM_G) in a multicast tree could be a parent or a child node depending on the location of the node. In a multicast spanning tree (*T*), all the non-leaf nodes can be both parent and child at the same time where as all the leaf nodes are considered to be the child nodes. In other words, the parent nodes perform the membership and replication process where as the children nodes are receivers that receives multicast packet from the parent nodes.

Based on the above argument, one can say that a multicast packet originated from the root (*s*) of a spanning tree (*T*) need to traverse typically two links; source to non-leaf node (P_n, C_n) and a non-leaf node to a leaf node (C_n). Lets R_T (s, non-leaf node) represents a route between a source node (*s*) and non-leaf nodes that could be parent or child nodes such as: $R_T = \{P_n \vee C_n \in ESM_G\}$ where $P_n, C_n \in \{s \cup N\}$

Similarly, R_T (P_n, C_n) represents a route from a parent node to a child node such as: $R_T = \{P_n, C_n\} \in ESM_G$. The above arguments lead us to the following expression for computing the total bandwidth available for transmitting a multicast packet from a source node to one or more parent nodes (i.e., the bandwidth associated with the first link of transmission):

$$TB_{W\left\langle s \xrightarrow{multiple-unicast} (P_n \vee C_n) \in \{s \cup N\} \right\rangle} = \frac{P_s}{\left| D_{\left\langle s \xrightarrow{multiple-unicast} (P_n \vee C_n) \in \{s \cup N\} \right\rangle} - \left(L_D \big/ SoL \right) \right|} \qquad (33)$$

Determining the mathematical expression for the total delay involve in transmitting a multicast packet from a source node to one or more parent nodes and using the resulting expression in (33) yields (34) for approximating the total bandwidth such as:

$$TB_{W\left\langle s\xrightarrow{multiple-unicast}(P_n \vee C_n)\in\{s\mathrm{U}N\}\right\rangle} = \frac{P_s}{\left|\sum_{i=1}^{y} D\left(R_{i\left(s\longrightarrow P_n,C_n\right)}\right) - \left({L_D}/{SoL}\right)\right|} \qquad (34)$$

$$where\ D\left(R_{ii\left(s\longrightarrow P_n,C_n\right)}\right) \mathrm{A} \sum_{i=1}^{n} D(L_i)$$

where y in (34) represents the maximum unicast routes between a source (s) and one or more non-leaf nodes and n represents the maximum number of links a unicast route can have.

Based on (34), we can derive a similar mathematical expression for approximating the total bandwidth available for a multicast packet which is transmitted from a parent node to a child node as follows:

$$TB_{W\left\langle P_n\xrightarrow{multiple-unicast}(C_n)\right\rangle} = \frac{P_s}{\left|\sum_{i=1}^{y} D\left(R_{i(P_n,C_n)}\right) - \left({L_D}/{SoL}\right)\right|}\ where\ D\left(R_{i(P_n,C_n)}\right) \mathrm{A} \sum_{i=1}^{n} D(L_i) \qquad (35)$$

When comparing (34) with (35), it can be clearly evident that only the total delay component in the denominator of both equations differ with each other for both presented scenarios which in turns change the amount of available total bandwidth. By combining the above two equations, the total bandwidth that a multicast packet may utilize when transmitted from a source node (s) to a child node (C_n) can be approximated as follows:

$$TB_{W\left\langle s\xrightarrow{multiple-unicast}(C_n)\in\{s,P_n\mathrm{U}N\}\right\rangle} = \frac{(P_s)(SoL)}{\left|\left\langle\sum_{i=1}^{n} D\left(L_{i\left(s\longrightarrow P_n,C_n\right)}\right) + \sum_{i=1}^{n} D\left(L_{i(P_n,C_n)}\right)\right\rangle(SoL) - L_D\right|} \qquad (36)$$

As one can see in (36) that the hosts are able to multicast information and consequently use the same link to redirect the packets resulting in an increase in the end-to-end delay of the entire transmission process. The limitation in bandwidth and the fact that the message needs to be forwarded from host-to-host using unicast connection, and consequently incrementing the end-to-end delay of the transmission process as can be seen in the denominator of (36), contribute to the price to pay for this new approach. For the ESM, this price will be paid in terms of the second quantity of the denominator of (36). (i.e., $\sum_{i=1}^{n} D\left(L_{i(P_n,C_n)}\right)$). These reasons might make ESM slightly less efficient than the IP multicast system.

5. PERFORMANCE ANALYSIS AND EXPERIMENTAL VERIFICATIONS

In this section, we provide the simulation results for analyzing the performance of different multicast schemes with respect to the delay analysis and the bandwidth approximation.

5.1 System Model

Simulations are performed using OPNET to examine the performance of Multiple unicast, IP multicast, and ESM schemes. Figure 4 shows an OPNET model for the multiple unicast, IP multicast and ESM simulations. The OPNET simulation has run for a period of 900 seconds for all three scenarios where we collect the simulated data typically after each 300 seconds. For all scenarios, we have setup one sender node that transmits video conferencing data at the rate of

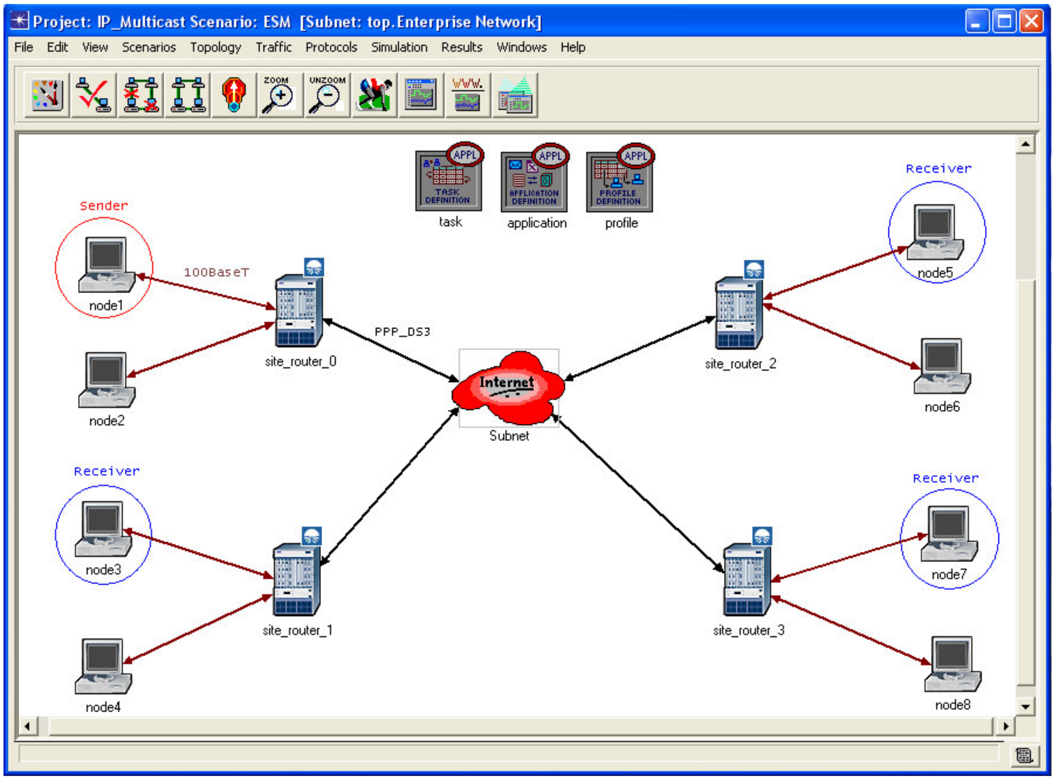


Figure 4: OPNET Model for Multiple Unicast, IP Multicast and End-System Multicast Video Conferencing Transmissions.

10 frames/s using 2,500-stream packet size to one or more potential receivers via a link that operates at 100 Mbps. In addition to these 100 Mbps licks, we use separate DS3 links for the core network (Internet). The same traffic pattern is assumed for all scenarios.

It should be noted in Fig. 4 that we use four backbone routers that connect multiple subnets to represent Bay Networks concentrator topology using ATM – Ethernet FDDI technology. In order to generate consistent simulation results, we use the same topology for the first two scenarios with some minor exceptions. For Multiple unicast, we disable the multicast capabilities of backbone routers where as for the IP multicast this restriction does not impose. Finally, in order to examine the behavior of the ESM, we use an OPNET Custom Application tool that generates the overlay links and the source root.

5.2 Experimental Verifications

For the Multiple unicast scenarios, video conferencing data is being sent by the root sender at the rate of 25 K-bytes per second. This implies that a total of three copies traveling which result in 75 K-bytes per second of total traffic. The last mile bandwidth limitation typically provides the most important delay impact. OPNET collected all the delays for all the receivers and calculated the average. The packet end-to-end delay for multiple unicast was 0.0202 seconds. For the IP multicast approach only *one copy* of the packet is generated at the root source. For this reason, the total video-conferencing traffic sent and received is only 25,000 bytes/s. Thus, a better performance in the average packet end-to-end delay can be observed. This is approximately 0.0171 seconds. Finally, after performing ESM simulations, we obtain an average end-to-end delay packet of 0.0177 seconds.

It can be seen in Fig. 5 that ESM packets transmission provides comparatively good performance than the Unicast but not as good as the IP multicast. The reasons are the RDP (Relative Delay

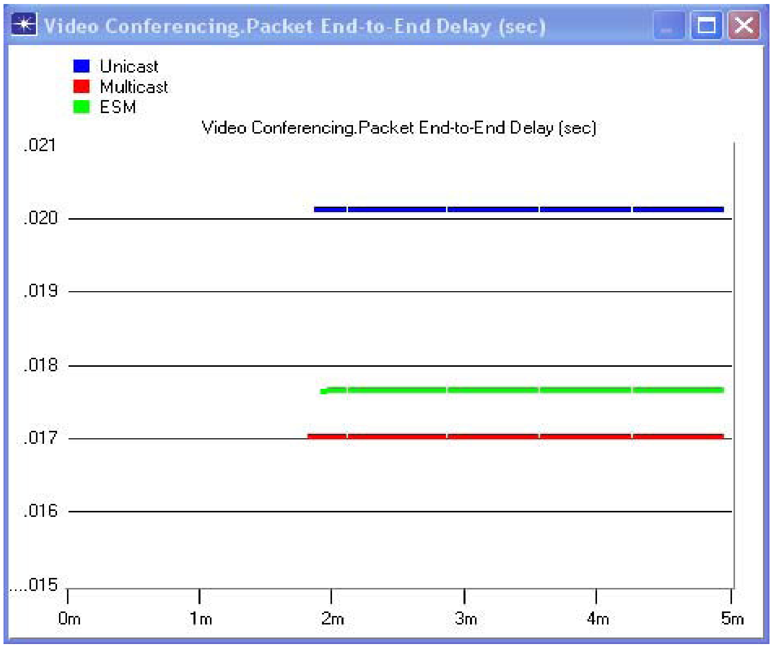


Figure 5: Average end-to-end packet delays for multiple unicast, IP multicast and ESM simulations.

Penalty or the ratio of the delay between the sender and the receiver) [6] and the LS (Link Stress or the number of identical copies of a packet carried by a physical link) experienced by each network schemes. Even though, a Unicast scheme provides comparatively low RDP, the value of LS is not optimal.

On the other hand, IP multicast performs with a little bit higher RDP but it gets a better LS. ESM has the inconvenience of RDP higher than IP multicast due to the fact that for a second receiver, there is an increasing delivery–delay because of the end-user replication (the second user has to wait for the data sent by its father node or sub-server). This is the penalty that ESM has to pay. One possible solution would be the design of a robust multicast protocol to optimize the delivery of data for the final users. Note that the additional delay could be reduced if we optimize the bandwidth utilization in the potential parent nodes. This is not a simple task because it requires a smart protocol to recognize bandwidth limitations in potential parent nodes and to establish an algorithm to limit the number of children nodes for these parent nodes.

6. CONSLUSION & FUTURE WORK

In this paper, we presented both analytical and mathematical models for all the multicast approaches currently available for multimedia applications. We first presented a mathematical model for multiple unicast systems in which the source host has to send a single copy of data to every single receiver. Our proposed formulization suggested that this approach wastes a lot of significant network bandwidth. Secondly, we presented a mathematical model for the IP multicasting approach which is a more efficient concept where the data source only sends one copy of data which is replicated as necessary when propagating over the network towards the receivers. Our proposed formulization shows that the IP multicast demonstrates some good bandwidth efficiency characteristics than the other multicast approaches. Finally, we presented a complete formulization of bandwidth efficiency for ESM systems, which is an alternate to router-dependent multicast service that allows end-systems participating in a multicast group to replicate and forward packets to other receivers. Our proposed formulization of bandwidth efficiency suggests that the ESM is a feasible, especially for sparse, medium size group. The simulation results presented in this paper fully support the proposed analytical model for the IP multicast and ESM.

7. REFERENCES

1. Y. Ma, R. Chbeir, and K. Yetongnon. "*An improved cluster-based P2P multicasting approach*". Proceedings of the 2nd international conference on Scalable information systems, Vol. 304, No. 59, June 2007.

2. D. Kostić, A. Snoeren, A. Vahdat, R. Braud, C. Killian, J. Anderson, J. Albrecht, A. Rodriguez, E. Vandekieft. "*High-bandwidth data dissemination for large-scale distributed systems*". Transactions on Computer Systems (TOCS)**,** 26(1), February 2008.

3. S. Fahmy and M. Kwon. "*Characterizing overlay multicast networks and their costs.*" IEEE/ACM Transactions on Networking (TON)*,* 15(2):373 – 386, April 2007.

4. S. Rizvi, A. Riasat, and M. Elleithy. "*Deterministic formulization of end-to-end delay for multicast systems.*" Accepted in International journal of Computer Networks & Communications, Vol. 2, No.1, 2010.

5. H. Holbroo and D. Cheriton. "*IP multicast channels: EXPRESS support for large-scale single-source applications*." In Proceedings of SIGCOMM, 1999.

6. B. Fenner, M. Handley, H. Holbrook and I. Kouvelas. "Protocol independent multicast-sparse mode (PIM-SM): protocol specification (Revised)." IETF Internet Draft, work in progress, March 2003, draft-ietf-pim-sm-v2-new-07.txt

7. D. Kosiur. "*IP Multicasting: The complete guide to interactive corporate networks.*" New York: John Wiley & Sons, Inc., 1998.

8. J. Saltzer, D. Reed, and D. Clark. "*End-to-End arguments in system design*." ACM Transactions on Computer Systems*,* 2(4):195–206, 1984.

9. Y. Chua, S.Rao, S.Sechan and H. Zhang. "*Enabling conferencing applications on the internet using an overlay multicast architecture.*" Proceedings of the ACM SIGCOMM'01, San Diego, CA, August 2001.

10. S. Deering. "*Multicast routing in inter-networks and extended LANs.*" Proceedings of the ACM SIGCOMM 88, pp. 55–64, Stanford, CA, August 1988.

11. Y. Chu, S. Rao, and H. Zhang. "*A case for end system multicast*." Proceedings of ACM Sigmetrics, June 2000.

12. S. Y. Shi and J.S. Turner. "*Multicast routing and bandwidth dimensioning in overlay networks*." IEEE Journal on Selected Areas in Communications (JSAC), 20(8):1444–1455, October 2002.

13. S. Shi. "*Design of overlay networks for Internet multicast.*" *PhD dissertation, Washington University in St. Louis*, August 2002.

14. M. Blumenthal and D. Clark. "*Rethinking the design of the Internet: The end-to-end argument vs. the brave new world*." ACM Transactions on Internet Technology, 1(1): 70–109, August 2001.

15. M. Kwon and S. Fahmy. "*Topology-aware overlay networks for group communication.*" Proceedings of the 12th international workshop on Network and operating systems support for digital audio and video, pp. 127 – 136, May 2002.