CliqueStream: An Efficient and Fault-resilient Live Streaming Network on a Clustered Peer-to-peer Overlay

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Abstract

Several overlay-based live multimedia streaming platforms have been proposed in the recent peer-to-peer streaming literature. In most of the cases, the overlay neighbors are chosen randomly for robustness of the overlay. However, this causes nodes that are distant in terms of proximity in the underlying physical network to become neighbors, and thus data travels unnecessary distances before reaching the destination. For efficiency of bulk data transmission like multimedia streaming, the overlay neighborhood should resemble the proximity in the underlying network. In this paper, we exploit the proximity and redundancy properties of a recently proposed clique-based clustered overlay network, named eQuus, to build efficient as well as robust overlays for multimedia stream dissemination. To combine the efficiency of content pushing over tree structured overlays and the robustness of data-driven mesh overlays, higher capacity stable nodes are organized in tree structure to carry the long haul traffic and less stable nodes with intermittent presence are organized in localized meshes. The overlay construction and fault-recovery procedures are explained in details. Simulation study demonstrates the good locality propoerties of the platform. The outage time and control overhead induced by the failure recovery mechanism are minimal as demonstrated by the analysis.

1. Introduction

With the widespread adoption of broadband residential Internet access, live multimedia streaming over the IP network may be envisioned as a dominating application on the next generation Internet. Global presence of the IP network makes it possible to deliver large number of commercial as well as amateur TV channels to a large population of viewers. Based on the peer-to-peer (P2P) communication paradigm, live multimedia streaming applications have been successfully deployed in the Internet with up to millions of users at any given time. With commercial implementations like CoolStreaming [20], PPLive [8], TVAnts [14] and UUSee [19], among others, large volume of multimedia content from hundreds of live TV channels are now being streamed to users across the world.

Although naive unicast over IP works for delivering multimedia stream to a restricted small group of clients, the overwhelming bandwidth requirement makes it impossible when the number of user grows to thousands or millions. Several different delivery architectures are used in practice for streaming of live video content, which include IP multicast [5], infrastructure-based application layer overlays [7] and P2P overlays. P2P overlays are gaining popularity due to their ease of large-scale deployment without requiring any significant infrastructure.

Live multimedia streaming over P2P networks has several challenges to be addressed. Unlike file sharing, the live media need to be delivered almost synchronously to large number of users, with minimum delay in playback compared to the playback at the source. Due to the large volume of data in the media stream, it is of paramount interest to avoid redundant transmission of the stream. Constructing efficient paths for streaming is especially hard because the nodes participating in the overlay have very minimal information regarding the topology of the underlying physical data transmission network. Moreover, the intermittent joining and leaving behavior, or *churn*, of the nodes makes it harder to maintain the overlay delivery paths once constructed. Heterogeneity of node bandwidths adds further complexity to the problems.

Existing P2P live streaming platforms can be broadly classified into two categories – *tree based* and *mesh based*. In the tree based platforms, nodes are organized in a tree topology with the streaming source at the root. The media content is pro-actively pushed through the tree. Although efficient in terms of avoiding redundant transmissions, the nodes that happen to be interior nodes in the tree bear an unfair burden of forwarding the content downstream compared to the nodes that become leaves of the tree. Some multi-tree approaches like SplitStream [2] and ChunkySpread [16] have been proposed that avoid this imbalance taking advantage of multiple description coding of the media. Nevertheless, a major argument against the tree-based overlays is that it is expensive to maintain the trees in presence of frequent node join and leave or *churn*.

A dramatically different approach is to allow each node to choose a small random set of overlay neighbors and thus create a mesh topology. The stream is divided into small fragments and each node comes to know what fragments are possessed by its neighbors through periodic exchange of their buffer-maps [20]. Required fragments to fill the current playback buffer are then downloaded or *pulled* from the neighbors as needed. Because of the unstructured and random nature of the topology, the mesh-based platforms are more robust to *churn*. However, there are several inherent disadvantages in the pull process such as longer delay and higher control overhead.

In most of the P2P streaming platforms, the overlay neighbors are chosen randomly [19, 20], which is important for maintaining global connectivity of the overlay network. However, this causes nodes that are distant in terms of proximity in the underlying physical network to become neighbors. There are two problems that arise from such random selection of neighbors. First, data travels unnecessary distances before reaching the destination. Second, because the data travel path is uncorrelated with the locality of the destination nodes, two nodes of very close proximity may receive data through completely disjoint paths from the source. This causes significant redundancy in data transmission and costs a huge amount of network bandwidth for the whole platform.

In this paper, we present the design of a P2P media streaming platform named CliqueStream that exploits the properties of a clustered P2P overlay to achieve the locality properties and robustness simultaneously. The clustered peer-to-peer overlay named eQuus [11] organizes the nodes into clusters of proximal nodes. It assigns identifiers to clusters and replicates the routing information among all nodes in a given cluster. The assignment of identifier also imposes a structured mapping of the identifier space to the proximity space.

We also exploit the existence of more stable and higher bandwidth nodes in the network to allow construction of efficient delivery structures without causing too much overhead from churn. Existence of stable nodes, or *super nodes*, are observed both in file sharing networks and media streaming networks [17]. Our proposed platform elects one or more stable nodes of highest available bandwidth in each cluster and assigns special relaying role to them. To maintain transmission efficiency, a content delivery tree is constructed out of the stable nodes using the structure in the underlying routing substrate and content is pushed through them. Less stable nodes within a given cluster then participate in the content dissemination and pull the content creating a mesh around the stable nodes.

In most implementations of P2P streaming platforms, a separate streaming overlay is created for distribution of media from each source, usually called a *channel*. We argue that the user's participation behavior for individual channel is significantly different from the participation behavior with respect to the whole streaming platform. A user usually switches channels frequently while keeping the TV turned on for a long time. Therefore it is intuitively beneficial to have a two-layer architecture, where a single routing overlay is maintained for the whole platform and streaming paths are rapidly constructed for individual channels based on the structure of the substrate. Comparison between per-channel overlay and single overlay supporting multiple channel also supports the latter organization [4].

The rest of the paper starts with a review of the relevant features of the clustered P2P overlay named eQuus and discussion on the modifications we made into it. The design of the platform with details of its functional components is presented in Section 3. In Section 4 we discuss the locality and fault-tolerance properties of the platform.

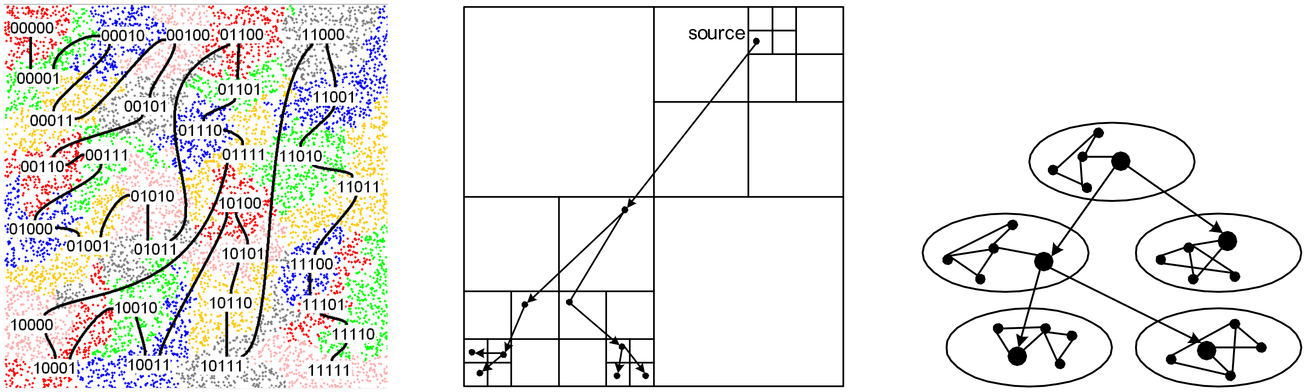
2. eQuus: a Clustered DHT

2.1. Overview of eQuus

eQuus [11] is a structured peer-to-peer overlay which forms a distributed hash table (DHT) consisting of clusters or *cliques* of nodes instead of individual nodes. A unique id is assigned to each clique instead of each individual node. Nodes in the same clique are closer to each other than nodes in different cliques, based on some proximity metric such as latency. These nodes are close enough to maintain an all-to-all neighborhood among them, and hence they are termed as *clique*.

Unlike many DHT overlays, the nodes or the cliques do not assume random ids. Rather, the segmentation of the id-space closely resembles the segmentation of the proximity space into cliques. If all possible ids define the id space, each clique occupies a certain numerically contiguous segment of the id-space. Due to the id assignment process explained later in this section, cliques with numerically adjacent ids occupy adjacent segments of the proximity space. All the existing cliques in the network can thus form a successor-predecessor relationship based on the numerical sequence of the ids such that the successor and predecessor cliques are adjacent to each other.

As a new node joins eQuus network it becomes a member of the closest clique in the proximity space. If this causes a clique to contain more nodes than a system-defined



(a) The mapping of id-space to proximity space in eQuus (reproduced from [11])

(b) Streaming tree over eQuus cliques

(c) Streaming topology in CliqueStream

Figure 1. Proximity and streaming topology

threshold, the clique offshoots a new clique by splitting itself into two halves. One of the halves retains the previous id. The other half gets a new id that differs from its parent's id by only one bit, effectively splitting the id space occupied by the parent clique into two halves. As the network grows, numerically consecutive segments of the id space is thus assigned to adjacent cliques. In fact, if the cliques are ordered by their numerical id they occupy the consecutive positions in a space-filling curve that fills the whole proximity-space. This is illustrated in Figure 1(a). Thus two cliques with numerically close ids are always close to each other in the proximity space, although the reverse may not always be true. Moreover, the longer the matching prefix of two different ids, the closer they are positioned. In other words, all the nodes in the whole id space may be hierarchically divided into local groups based on the length of the matching prefix in their ids. For example the cliques sharing id prefix 1011 may resemble a local group which is further divided into two sub-groups with prefix 10110 and 10111 respectively.

A message is routed towards a clique containing a certain id using the standard prefix matching algorithm. All nodes in the same clique share the same routing table. The routing table contains clique ids with different length of prefix match with the current cliques id. For each clique id, address of k random nodes of that particular clique is stored.

The prefix-matched routing implies that if a message is routed from clique A to clique B and clique C, the message will be first carried to a region that shares the common prefix of B and C along a common path. The path will then diverge towards each of B and C. The id assignment process ensures that the closer B and C are in terms of proximity, the longer is their common prefix. This implies that messages from a single source to multiple destinations in close proximity will travel along a long common path before diverging (Figure 1(b)). We exploit this property to create network efficient dissemination trees for live video streaming from a single source.

2.2. Introducing Stable Nodes

We modify the original design of eQuus by introducing stable nodes. Heterogeneous stability and capacity characteristics of the nodes are common in peer-to-peer networks. Thus the existence of stable nodes, or *super nodes*, is well-established in both file sharing and streaming peer-to-peer networks. Even though all the nodes that are recipient of the streams are similarly low capacity and unstable, some high capacity servers may be deliberately introduced in locations across the network which may act as stable nodes.

We assume that each clique maintains t stable nodes all the time, where t is a system parameter. Stable nodes are elected from the existing eligible nodes in the clique. A node becomes eligible to be a stable node after being alive for a certain threshold amount of time T. The clique always elects t nodes having highest outgoing bandwidths among the eligible nodes. For bootstrapping, when there is a single node in the whole network, it immediately becomes a stable node. The election is initiated whenever a new node becomes eligible to be a stable node.

To reduce the overhead of replicating the routing table to each node of a clique, we replicate the table among the stable nodes only. Each node however maintains connection with all other nodes in the same clique. Also, whenever a node is elected as stable node or a stable node loses its stable node status, this information is updated to all nodes in the clique. A stable node remains a stable node in the cliques that are born after the split of a clique. New stable nodes are elected at the event of split to maintain sufficient number of stable nodes in each clique.

2.3. Modification in the Routing Mechanism

Inclusion of the stable nodes have caused some modifications to the original routing method of eQuus. These modifications also assist in the construction of the streaming network such that the stream of any particular channel is carried between two different cliques through only one link. Each node in a clique maintains addresses of k nodes for each clique it has as its routing table entry. Each node periodically updates this list of k nodes and always tries to have at least one of them to be a stable node. While routing a message to a particular clique, based on the routing table match, the stable node is preferentially selected instead of randomly choosing one of the k nodes. However, the routing works even if none of the k nodes is a stable node. If a non-stable node receives a message, it forwards the message to any of the stable node in the same clique.

In the live streaming platform, a CliqueStream layer is implemented on top of the modified eQuus routing substrate. When a CliqueStream message is received by the eQuus routing layer, it invokes the *forward* method in the CliqueStream layer with the message as parameter, before forwarding the message to another clique. The *forward* method may modify the message including its destination. The eQuus routing layer then processes the modified message and forwards it accordingly. When a message arrives its destination node, the *deliver* method in the CliqueStream layer is invoked.

The header of each eQuus layer message includes source and destination addresses and the message type. The message type denotes the application which is CliqueStream in this case. The source and destination addresses, each has two segments – one is the clique id and one is the node's IP address. The clique id is used to route a message to any node in a particular clique and then the node IP address is used to deliver the message to a particular node. The IP address may be set to all 0's to denote any node in the clique. The forwarding of any message can be stopped by setting the clique id to a special *null* value.

3. System Overview

In this section we present the details of the CliqueStream video streaming platform that is built on top of the modified version of eQuus presented in Section 2.1. The purpose of the platform is to facilitate live streaming of multimedia content generated from arbitrary source node to a large set of destinations nodes. A large number of streaming channels can be delivered through a single platform instead of creating and maintaining a separate overlay for each channel. This allows better balancing of the forwarding load among the participating nodes.

3.1. Streaming Topology and Procedure

The stream dissemination topology of CliqueStream is a combination of tree and mesh structure. We exploit the proximity features of the eQuus clustered overlay described in Section 2.1 to form an efficient topology. Because the nodes in a single clique are close to each other, arbitrarily interconnecting them in a mesh does not incur any significant inefficiency in the network. Therefore, if at least one node in a clique receives the stream, other nodes in the same clique can form data-exchange partnerships as in CoolStreaming [20] and receive the channel. Therefore we need some mechanism to deliver the stream to at least one node in each clique that has some nodes trying to receive the stream. For each channel, a dissemination tree is formed including only one stable node from each participating clique. The source of the stream is at the root of the tree. The stream is pushed from the source to all the participating stable nodes. The tree-mesh topology for dissemination of a streaming channel is illustrated in Figure 1(c). The routing properties of the eQuus overlay are exploited to construct efficient dissemination trees for each channel. The following sub-section explains the tree formation protocol.

3.2. Group Membership Management

All the nodes that want to receive a particular channel form a multicast group. There may be some stable nodes that do not intend to receive the stream but participate in the group as relay nodes. We use the term *member* node to collectively denote the *recipient* and the *relay* nodes. The group (or channel) is identified by a globally unique name. We assume the existence of a directory service that returns the address of the source node for each channel name.

Each stable node in a clique maintains a table *channelList* that maps channel name to a *channelInfo* data structure and includes all channels being received or relayed by at least one node in the clique. There may be a single or several stable nodes in each clique depending on the replication strategy. In case there are multiple stable nodes, a consistent replica of the *channelList* is maintained in each of them. In our design, we decided to use at least two stable nodes per clique, to facilitate the failure recovery mechanism discussed later. For each channel, if one of the stable nodes acts as a relay node, the other is maintained as a backup-relay. This also facilitates sharing of the relaying load among the stable nodes. The number of stable nodes in a clique may increase based on the relaying load.

The *channelInfo* contains the meta-data needed to maintain the structure of the streaming tree for the channel. This includes *relayNode* and *backupRelayNode* – addresses of the relay node and backup relay nodes in the clique, *childList* – list of children nodes in the streaming tree, *parent* – parent node in the streaming tree, and *backupParent* – the *backupRelayNode* in the parent clique designated for the channel. To avoid inconsistency, updates to the *channelInfo* is always initiated by the relay node and then propagated to the other stable nodes. In addition to this replicated information, each relaying stable node maintains a *streamBuffer* that holds a certain number of current segments of the stream when relayed, and a corresponding bitmap *bufferMap* to identify the segments. The relay node also maintains a *recipientList* that lists all the nodes in the same clique that are receiving or relaying the channel, including the relay node itself. Each node in the clique, regardless of being stable or not, maintains a *streamBuffer*, a *bufferMap* and *partnerList* for every channel it currently receives. *partnerList* is a list of the nodes in the same clique with whom this node is exchanging the stream segments.

When a node wants to join a group to receive a channel, it sends a *join* request to one of the stable nodes in its own clique. Receiving a join request, the stable node first looks up the *channelList* if the requested channel is already there and which stable node is relaying it. If found then the join message is forwarded to that stable node. The relaying stable node maintains a *recipientList* that lists the nodes in the same clique that are receiving the channel. When the relaying stable node receives the request, it adds the requesting node to the list and returns a random subset of the *recipientList* to the requesting node. Receiving the reply, the requesting node can now request those nodes for their current *bufferMap* download stream segments. In turn, those nodes also know the presence of the new node in *recipientList* and may include it in their *partnerList*.

If the stable node, on receiving the *join* request, does not find the requested channel in its *channelList*, it looks-up the address of the source node for the channel from the directory service and sends a *joinRemote* request to the source node to include the stable node as a member of the group. On receiving the *joinRemote*, the source sends an *addNode* message using the eQuus routing substrate, towards the node that sent the *joinRemote* request. The *addNode* message travels through nodes in several other cliques before reaching the joining clique. While traveling through the cliques, the *addNode* message creates or extends the streaming tree and establishes a streaming path from the root to the joining stable node using one stable node in each intermediate clique.

In each of the intermediate cliques the *addNode* reaches, the data structures are updated as follows. When a stable node in a clique receives an *addNode* message and the *forward* method is invoked, it performs a lookup in its *channelList* table to find the relaying stable node for the particular channel. In case no entry for the channel is found in the *channelList*, the stable node initiates the relay election protocol to elect one of the stable nodes as relay node for the channel. The simplest version of this protocol is to select this stable node. Alternatively, the protocol may select the stable node with highest available uplink bandwidth, to ensure balancing of relaying load among the stable nodes. At the same time, a *backupRelayNode* is also selected to complement the relay node.

An *addNodeFwd* message is then sent to the relay node encoding the source and destination addresses of the *addNode* message as parameter. The original *addNode* message is dropped by modifying its destination to *null*. The relay node then updates the *channelInfo* data for the channel or creates a new *channelInfo* record in the *channelList*, depending on whether it was already relaying the channel or not. A new *addNode* message is routed towards the joining node. The relay node also sends an *addNodeAck* message to the parent node, which is a relaying stable node in an upstream clique. Receiving the *addNodeAck*, the upstream relay node adds the sender of the message to its *childList* table and initiates pushing of the stream to the new child along with others.

When the *addNode* message is finally delivered to the stable node that sent the *joinRemote* request, it initializes itself as a relay node for that channel and updates the data structures to maintain the streaming tree in a similar manner as above. A response is then sent back to the node that initially sent the *join* request, containing the current *recipientList* and *bufferMap*. The joining node then starts downloading the stream segments from the relay node or other nodes possibly included in the *recipientList*.

3.3. Graceful Departure of Nodes

A node may leave a group for a channel or leave the whole system. The underlying routing substrate needs to be updated when a node leaves the system. In case the number of nodes in a clique becomes lower than a threshold, the clique merges with its successor clique. Details of this are discussed in [11]. When a non-stable node leaves a channel group, it sends *leave* message to all its mesh neighbors, including the relaying stable node. The relay node updates the *recipientList* and other neighbors update their neighborhood table. If number of mesh neighbors becomes lower than a system defined threshold, a node can refresh the neighbor list by asking the relay node for a random list of recipients in the clique.

A stable node does not depart from relaying a channel if it is alive and participating in the CliqueStream platform, unless both of its *childList* and *recipientList* are empty. If it wants to leave the CliqueStream platform, then it initiates a relay election protocol among the other stable nodes in the clique and the stable node with highest available bandwidth is selected. Then the leaving node initiates the *handOver* protocol to transfer the relaying role for the channel it was relaying. The parent node is notified of the new relay node and *channelInfo* for the particular channel updated in all the stable nodes in the clique to reflect the assumption of new relay node. The departing stable node also initiates a stable node election protocol concurrently. The node departs after initiating the *handOver*.

3.4. Failure of Nodes and Reconstruction of Delivery Tree

Apart from graceful departure, nodes may suddenly depart or crash. Here we describe how nodes failures are detected and how the delivery tree is reconstructed.

Failure of non-stable nodes are detected by their mesh neighbors and their neighbor list is replenished by finding new neighbors, in the same way as in graceful departure.

When a stable node fails, all the downstream stable nodes in the dissemination tree for each of the channels the stable node was relaying, stop receiving the stream. After passing a small threshold of stoppage time, all of them will react to recover from the failure of the upstream relay node. However, the protocol we devised quickly resolves which relay node actually failed and then transfers its responsibility to the back-up relay node in the same clique. Failure of the relay node is also detected by the backup node as they periodically exchange heartbeat messages.

Any stable node, detecting the stoppage of receiving the pushed stream to itself, checks whether its parent is still alive by sending an *isAlive* message to the parent and waits for an *alive* message as reply. In case the reply timeouts, it sends a *recoverTree* message to the node designated as *backupParent* to take over. On receiving the *recoverTree* message or detecting the failure of the relay node through heartbeat timeout, the *backupRelayNode* initiates a recovery of the link. It retains a replica of the *channelInfo* data structure, and it knows the parent node of the failed relay node. A *handOver* message is sent to that parent to consider the backup node as a child instead of the failed node. Thus the failure is recovered completely locally. A new backup relay node is also designated at this time.

In the very unlikely event when both the relay node and backup relay node fails concurrently, the tree will not be recovered and the node that sent the *recoverTree* message to the backup parent will not receive any stream data. Passing a threshold amount of time without receiving any stream data after receiving the *alive* message from the parent or after sending the *recoverTree* message, the downstream nodes will realize that both relay and the backup relay failed in some upstream node. All of these downstream relay nodes will join the streaming group independently using the join procedure.

3.5. Split and Merge of Cliques

As described in Section 2.1, when arrival and departure of nodes make a clique too large or too small, the clique splits into two or merge with its successor clique. In addition to the routing table updates done by the eQuus substrate, the tree structure maintained by the relay nodes may also need to be updated during split and merge.

When a clique merges with its successor, we denote the former as merging clique and the latter as merged clique. The new clique after merger retains the id of the merging clique and the id of the merged clique vanishes. The stable nodes of the previously individual cliques maintain their stable status for a while. Each of the relaying stable nodes of both the merging and merged cliques update all the stables nodes in the merged clique with the *channelInfo* data for all the channels it is relaying. This allows each stable node to get all the channelInfo data. For the channel, whose relay node comes from the merged clique, only the children whose clique id matches some routing table entry, is kept as children. All the other children are requested to rejoin the streaming tree and inform back after the join procedure completes. Relaying to those children stops after confirmation of the join is received or timeout occurs. In case two relay nodes are found for the same channel, the one that earlier belonged to the merging clique prevails and the valid children from the relay in the merged clique are transferred to that node. All the invalidated relay nodes keep relaying to all the invalidated children until confirmation of re-join is received or timeout occurs.

When overpopulated, a clique splits into two and one of them retains the previous clique's id. Let us denote this clique as primary the other clique as offspring. The stable node of the previous clique remains as stable node in the new cliques and they belong to either the primary or the offspring clique according to the proximity rules of splitting. The channels relayed by the stable nodes belonging to the offspring clique may need to be handed over to the stable nodes in the primary clique to make the streaming tree consistent with the routing tables. This is needed only if the channel has a non-empty *childList*. In case there are some recipient nodes in the offspring clique for that channel, the stable node re-joins the channel using the new clique id before performing the hand-over. In case a channel relayed by a stable node in the primary clique has some recipient now belonging to the offspring clique, they are requested to re-join the channel. This will result in a stable node in the offspring clique to become a relay node for that channel. Note that new stable nodes are recruited in both the primary and the offspring clique as necessary to accommodate the channels. At the beginning, the stable nodes in offspring clique are underloaded. However, they soon get new relay loads when new join messages are routed through them.

4. Analysis of System Features

In this section we discuss the notable features of the CliqueStream platform. The main argument of the paper is that clique-based overlays allow creation of streaming topology with good locality properties compared to other approaches. The CliqueStream approach also allows fast

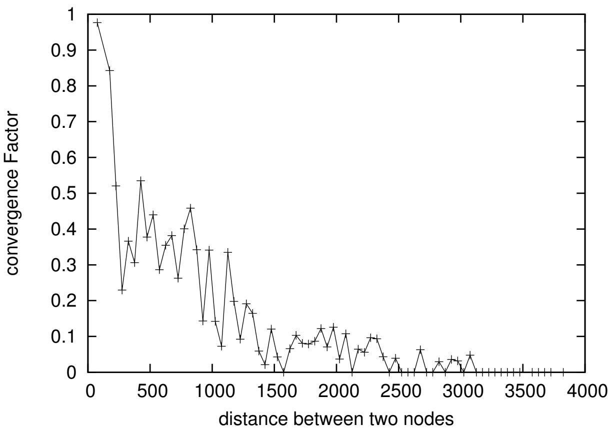


Figure 2. Convergence of streaming route

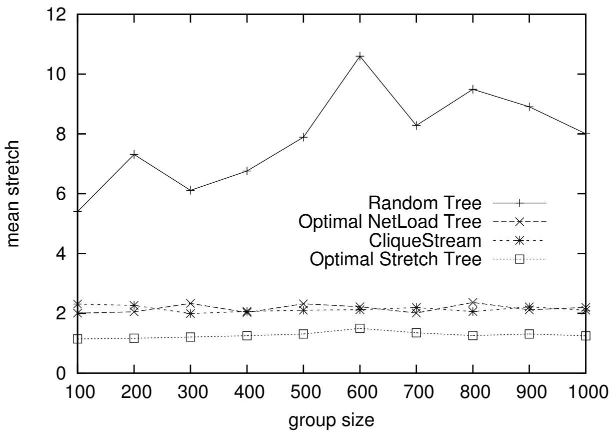


Figure 3. Stretch of the streaming path in different tree construction protocols

and localized recovery mechanism in presence of node departures. The following sub-sections discuss each of these features in details.

4.1. Locality

The locality property in the overlay network is achieved when overlay neighbors are in close proximity in the physical network. There are twofold benefits of forming a locality-aware overlay – first, the stretch of the streaming path from the source to the recipient nodes is minimized, and second, a significant portion of the streaming paths from the source to each individual recipient are shared. To demonstrate these two aspects of locality we performed some simulation experiments.

For the simulation model, we assumed that the nodes can be laid out in a 2-dimensional euclidean space based on some proximity metric, such as network latency. We also assume that the nodes are uniformly distributed in the 2-dimensional space. While the uniform distribution does not accurately reflect the node distribution in large networks like the Internet, several works have shown that nodes in the Internet can be mapped on an euclidean space with good accuracy [6].

First, we tried to demonstrate that if a message is routed from a source node to two different destination nodes, the fraction of the path that is common to both routing paths is correlated to the distance between the two destinations. This implies, when two nodes are close enough in the euclidean space, a large portion of the paths from the source to the two nodes are shared. We measure the commonality of the two paths using a convergence metric used in [1]. If d_c is the length of the common path and d_1 and d_2 are the lengths of the paths from the diverging point to the two nodes, then the convergence metric $C = (\frac{d_c}{d_c+d_1} + \frac{d_c}{d_c+d_2})/2$. C has a value 0 when the two paths are completely disjoint and 1 when they are completely shared.

We created an eQuus overlay of 100000 nodes, where minimum and maximum clique size parameters were set to be 32 and 128, respectively. The length of the id was 64 bits. The parameter b that defines how many bits of the id are matched in each routing hop was set to 2. Note that maximum fan-out of a streaming tree in CliqueStream is 2^b. We chose 100 random nodes as source, and for each source we chose 100 random pairs of destination nodes. Convergence metric is then computed for each pair of paths. In the simulation runs, we placed the nodes on an arbitrariliy chosen 3500×3500 2-d plane. Length (or cost) of an overlay link between two nodes, which is used for computing convergence factor and network load (defined later), is computed as the euclidean distance between the two nodes on the given plane. Figure 2 plots the average convergence metric against the distance between two destinations. This clearly shows the correlation of convergence to the distance between the pair of destinations.

In the next set of experiments, we evaluated the properties of the streaming tree created over the eQuus substrate. We constructed a eQuus substrate with 50000 nodes and constructed a streaming tree using a random subset of nodes. For comparison, a random tree was created with the same set of node joining the tree in the same order. Each newly joining node randomly chooses one of the existing tree-nodes as its parent. To evaluate the stretch of the source-to-recipient streaming paths we used the ratio of length of the routing path to the length of the shortest possible source to recipient path (which is the euclidean distance). The average stretch for source to node paths is computed for various group sizes. To evaluate the load on the network due to redundant data transmission paths, we

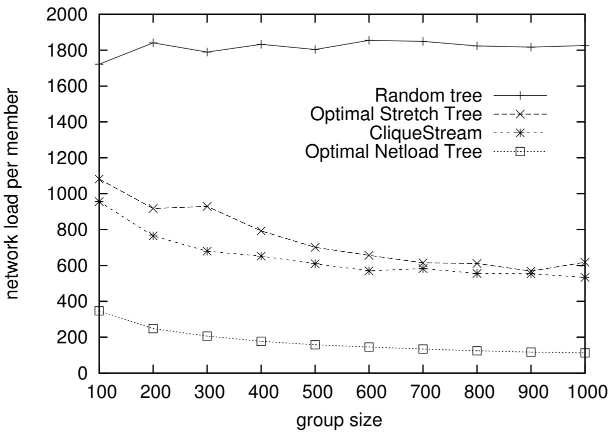


Figure 4. Network load per member in different tree construction protocols

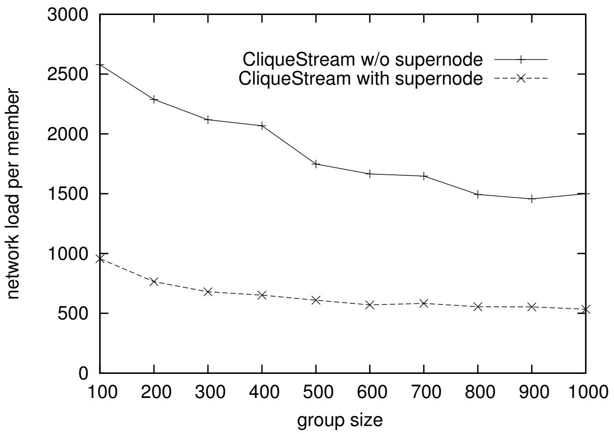


Figure 5. Use of stable nodes reduces the network load

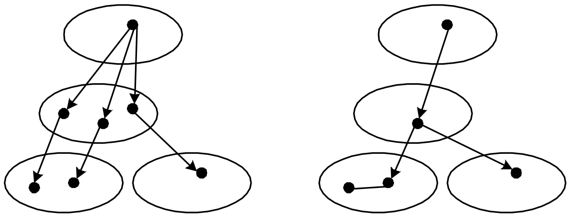
used a network load metric that counts the total length of paths traveled by a message (and its replicas) to disseminate the message from the source node to all the recipients. For comparison across different sizes of groups, the metric is normalized through dividing by the size of the group.

We considered two other types of optimally constructed trees for comparison– one that has minimal average stretch of the source to destination path, and the other that has minimal network load. The optimal stretch tree is constructed by connecting the newly joining node as close as the root, subject to the maximum fan-out constraint which is the same as CliqueStream. The optimal load tree is constructed by connecting each newly joining node to the node that has shortest distance from the new node.

Figure 3 compares the average stretch of the source to recipient paths for different tree construction protocols. The CliqueStream trees has significantly lower stretch than random trees and pretty close to the optimal stretch tree. In fact the stretch of the CliqueStream tree is defined by the stretch of the lookup paths in eQuus, which is bounded by the logarithm of total number of nodes in the substrate.

Figure 4 compares the network load per member metric for different tree construction protocols. It shows that network load per node in CliqueStream is significantly lower than that in the random tree. The network load of CliqueStream is also lower than that of optimal stretch tree and pretty close to that of optimal load tree. Another observation is that network load per node actually decreases when more nodes are added in the tree. This implies better scalability of the CliqueStream platform.

The benefits of using stable nodes in CliqueStream is evaluated in Figure 5. The main argument behind using stable nodes is that it eliminate redundant streaming paths and thus reduces the network load. This effect is demonstrated in Figure 5, where the tree in CliqueStream with stable nodes causes less network load irrespective of the size of the group. If stable nodes are not considered and a stream is forwarded along the eQuus routing paths from source to individual nodes, there may be multiple overlay links carrying the traffic between the nodes in the same pair of cliques, as illustrated in Figure 6(a) and 6(b).



(a) No stable node (b) With stable node

Figure 6. Stable nodes eliminate redundant paths

The use of stable nodes, however, causes some of these nodes to act as relay node even if the node itself is not receiving the particular channel. This may result in unnecessary relay load for the stable nodes. The worst case scenario occurs when each member of every clique is recipient of a different channel. In that case, if there is only one relay node per clique, each relay node has to relay all the channels to 2^b downstream relay nodes. On the other extreme, the maximum benefit of aggregation of streaming paths in the stable nodes can be achieved for very popular channels and when the popularity of different channels are concentrated in different network proximities. To avoid the worst case scenario, CliqueStream recruits more stable nodes in a clique when relay load exceeds the capacity of the existing stable nodes. The number of stable node in a clique is bounded only by the total number of nodes in the clique. In any case, the relay load on a stable node for a single channel is bounded by a constant 2^b.

4.2. Startup Delay and Playback Latency

Two important performance metrics that are of concern for live video streaming overlays are the startup delay for a newly joined node and the latency in the playback of the stream observed at the node. According to the node join protocol, $1 + \log_{2^b}(N/c)$ messages need to be exchanged in the worst case, to receive a new channel. So, the startup delay is $O(\log_{2^b}(N/c))$, where N is total number of nodes and c is number of nodes per clique. For a locally popular channel, only one message is required, so the delay is only one RTT in this case. The playback latency is the latency of the path from the source node to the stable node in the local clique, which is $O(\log(N/c))$, plus the number of hops in the local mesh. Assuming that the diameter of a random mesh is logarithmic to the number of nodes, the total latency is $O(\log(N/c) + \log c)$ or, $O(logN)$.

4.3. Fault Tolerance

Improved fault tolerance of CliqueStream results from two facts. On one hand, relatively more stable and higher capacity nodes are placed as internal nodes of the tree and less stable nodes are the leaves of the tree. Thus the effect of failure of non-stable nodes are localized inside the cliques. The use of receiver-driven pulling on a mesh-like topology inside the clique makes it further adaptive to the node dynamics. On the other hand, the clustered topology allows multiple stable node in a single clique, which in turn allows maintaining a backup relay node for each channel. The use of backup relay nodes facilitates fast and localized recovery from failure of stable nodes.

We can determine time impact of a failure in terms of average round trip time between nodes in adjacent cliques (*RTT*). The detection time for a stable node failure is bounded by the minimum of the follow two – the heartbeat message interval or the timeout period for the downstream node before invoking the *isAlive* message plus the timeout period waiting for the *alive* message plus $\frac{1}{2}$RTT for notifying the backup relay node. If the timeouts are set to 2RTT, the bound is 4.5RTT if the heartbeat interval is larger. The recovery time is $\frac{1}{2}$RTT for a backup relay node to notify the parent plus $2 \times \frac{1}{2} = 1$ RTT to send the stream from the parent to the failure detecting child through the backup relay. So, in total, failure detection and recovery time $t_{fr} = 6$RTT. For a 50 ms RTT, this amounts to 300ms only. The parent of the failed relay node is unaware of the failure until it receives the *handover* message from the backup relay node. So the video segments streamed during the failure-recovery period will be lost.

CliqueStream is also quite efficient in terms of control message overhead induced by each stable node failure. Instead of every downstream node rejoining the tree, only the immediate children initiate the recovery process and only a one step recovery process is conducted by the backup relay node. Each of the downstream nodes exchanges a (*isAlive*, *alive*) message pair except the immediate children of the failed relay node. The recovery process takes only 2 messages from the backup relay node. Each of the immediate children may send 1 request the backup parent to initiate the recovery process.

5. Related Work

There are quite few approaches for streaming video over P2P overlays both in industry and in academia. Widely used commercial implementations such as PPLive [8] and UUSee [19], use a receiver driven content pulling over unstructured mesh overlays with random neighborhood, which are variants of the CoolStreaming [20] protocol. The inefficiency of these platforms in terms of huge long-haul traffic burden is explained in [8].

There have been several efforts to create peer-to-peer overlays that select the overlay neighbors based on locality characteristics of the underlying physical network. CAN [12] has applied landmark based binning approach to assign d-dimensional coordinates to each node and routing is performed based on the proximity of the nodes in the coordinate space. Zigzag [15] is another architecture that organizes the nodes into locality based clusters. It creates a hierarchy of clusters, grouping leaders of lower level clusters into higher level clusters and streaming the media content through this hierarchy.

Among the video streaming or group multicast topologies on structured peer-to-peer overlays, Scribe [3] is a prominent one. Scribe creates the multicast tree based on the reverse path of the routing of messages in the Pastry [13] routing substrate. However, since pastry assigns random ids to each node, the routing path is likely to have random hops between locally uncorrelated nodes. Some form of locality is however achieved by careful selection of routing table entries. In CliqueStream, the multicast streaming tree is constructed based on the forward paths of the messages from source to the receivers on the clustered and structured peer-to-peer overlay named eQuus. Because node id assignment in eQuus is strongly correlated with locality, the routing paths are more directionally controlled and has predictable locality properties.

In general P2P streaming platforms apply either content pushing over multicast tree or receiver driven content pulling over a mesh overlay. mTreeBone [18] has proposed a hybrid approach where more stable nodes constitute the internal nodes of the tree and more dynamic nodes are placed at the leaf level. the leaf node also participate in a mesh, and the stream is delivered using a combination of pushing and pulling. Our approach of using stable node to construct the tree backbone is similar to mTreeBone. However, the locality based clustering was not considered in mTreeBone.

Making the overlay localized runs the risk of partitioning the network. In DAGStream [9] a DAG of nodes are created instead of a tree and content is delivered by receiver driven pulling. Presence of multiple parents allow the system to work in presence of node failure or departure. AnySee [10] maintains a set of backup paths for each active path over which it streams the data. When stream in the active path is disrupted, one of the backup path is selected and assumed as active path. However, switching the whole path takes much longer time than switching a single hop as done in CliqueStream.

Zigzag [15] maintains a head and an associate head for each cluster. An associate-head receives the stream from the head of a foreign cluster and disseminates it inside the cluster. The head controls the resources within a cluster and can quickly elect a new associate-head in case current one fails. Failure of the head is tolerated by selecting alternative foreign head by the downstream associate-head. Unlike hierarchical clustering in Zigzag, CliqueStream creates disjoint clusters of nodes at the same level. CliqueStream maintains backup relay node for each relaying stable node. The recovery procedure is initiated by the backup node of the same clique and it is contained locally.

6. Conclusion

In this paper we have exploited the features of a clustered distributed hash table overlay to create network efficient topology for video streaming. Our analysis show that the clustered topology provides good locality properties such as low stretch and low communication load compared to random topologies commonly used in existing system. Also, we have introduced fast and localized failure recovery mechanism to make the streaming plaform robust against node dynamics. Relatively more stable nodes are used as internal nodes of the streaming tree so that their failure probability is minimal. Moreover, backup relay nodes are used to allow fast recovery. The localized clustering of the nodes allows efficient election mechanism for the relay nodes and backup relay nodes.

To avoid the small disruptions in the streams that occur due to failure of tree nodes, use of multiple description coding and streaming different descriptions over different trees may be a good solution. How multiple node-disjoint trees can be constructed in the clustered peer-to-peer overlay, remains to be an open problem to solve.

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