A New Peer-to-Peer Topology for Video Streaming Based on Complex Network Theory

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Abstract A new wave of networks labeled Peer-to-Peer (P2P) networks attracts more researchers and rapidly becomes one of the most popular applications. In order to matching P2P logical overlay network with physical topology, the position-based topology has been proposed. The proposed topology not only focuses on non-functional characteristics such as scalability, reliability, fault-tolerance, self-organization, decentralization and fairness, but also functional characteristics are addressed as well. The experimental results show that the hybrid complex topology achieves better characteristics than other complex networks' models like small-world and scale-free models; since most of the real-life networks are both scale-free and small-world networks, it may perform well in mimicking the reality. Meanwhile, it reveals that the authors improve average distance, diameter and clustering coefficient versus Chord and CAN topologies. Finally, the authors show that the proposed topology is the most robust model, against failures and attacks for nodes and edges, versus small-world and scale-free networks.

Keywords Complex network's metrics, complex network models, peer-to-peer topology, site and bond percolation, video streaming.

1 Introduction

In recent years P2P topology formation for video streaming applications has been subject to major thinking. The motivation for the current research is two-fold. First, from a complex network perspective, metrics that govern the growth of a network, which help us to analysis topology characteristics, were considered. The second motivation of this research is considering P2P parameters for growing network in the scene of satisfying video streaming requirements.

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In many P2P networks' applications, in order to avoid bottleneck, traffic and improve overall performance of the network, surrogate servers were used in a Content Delivery Network (CDN) infrastructures. In this hierarchical structure, communication between peers is not the same as connections of surrogate servers; likewise that relationship across peers is not the same for all of them; some has close to each other in comparison with those others. Some peers are also more active, help and serve more peers but the others just benefit from others. Therefore, relationships should be segregated and this idea in social network viewpoint reminds network's motifs and communities to us.

Network motifs were introduced in 2002[1] as a statistical measure for investigating complex networks. Motifs are small k-sub graph, with k usually being 3 or 4. The main aim of network motifs is to close the gap between local and global knowledge of large networks. Two levels bring up in P2P networks topology based on communication for streaming video: Peers level and CDN level. We decide to render proper topology for P2P networks that if peers follow that structure, they will gain more benefits as lower delay, bandwidth consumption, scalability, efficiency, fault-tolerance, reliability, and so on.

To the best of our knowledge, this work is one of the first efforts to propose topology for P2P networks based on an extensive analysis of complex networks parameters that affect the utility of the network. Our contributions can be summarized as following: (i) Collecting precious requirements of P2P networks. (ii) Considering which measures and metrics of complex networks theories are suitable for P2P networks performance. (iii) Proposing final suitable topology based on previous discussions. (iv) Determining which selected metrics satisfying which P2P requirements in proposed topology. (v) Comparing the proposed topology with complex networks models and previous P2P topologies. (vi) Analysis our proposed topology from the viewpoint of Site Percolation, Bond Percolation, Assortativity and reciprocity for video streaming applications.

The rest of this paper is organized as follows. In Section 2, we explain the history of topologies which reformed based on complex network models. In Section 3, the valuable requirements which are important in P2P networks is discussed. Some worthy complex network metrics that should be considered in P2P networks is described based on their priority in Section 4 and this section is followed by matching P2P requirements and these metrics. In Section 5, the proposed topology is presented and its characteristics are described as well. Simulation results for comparing our proposed topology with the previous P2P topologies and complex networks models has been shown in Section 6, and finally, we close this paper in Section 7 with conclusions and future works.

2 Literature Review

Peer-to-Peer topologies are categorized into two parts: centralized systems (ex. Napster) and decentralized one. Decentralized systems are also divided into three parts: Structural P2P overlay network (ex. CAN, Chord), unstructured (ex. Gnutella, KaZaa), and hybrid models. As far as we know, all proposed model for P2P networks which are based on complex network properties are only either based on small-world models[2−8] or scale-free models[9−14]. Previous models have some limitations which are listed as following: 1) Small-world networks scalability is challenging problem and also real world networks are rarely grown as small-world models. 2) In scale-free networks some nodes endure more burden than others, so load-balancing is not maintained and against malicious attacks these nodes are vulnerable and network be partitioned soon. In order to overcome the shortcoming of previous works, hybrid models should be utilized.

Besides, some topological properties are evaluated based on complex networks theory in many literatures: For instance, fault-tolerance[15−17], robustness[18], reliability in routing[19], peer coverage in network[20], searching[21], locating content[22], determining priority of users[23] and handling model attributes[24−26]. Based on complex network models, P2P video streaming topologies are also conformed[27] as tree structure but some problems are highlighted in this paper too: For instance, nodes in the leaf position don't consume their bandwidth very well, longest path between root server and nodes in leave position leads to higher delay and only two metrics of complex networks (degree centrality & shortest path length) are considered which are not enough.

3 Remarkable Requirements for P2P Networks

Recall from Introduction Section that two levels are considered in P2P topologies: Peers level and CDN level. The following key requirements are addressed for Peers level[28] according to their preferences to obtain appropriate topology in this level:

Scalability Very large numbers of participating peers can add to network without any significant performance degradation.

Efficiency Routing should incur a minimum number of overlay hops (with minimum physical distance) and maintaining the overlay should be kept minimal too[28].

Fault Tolerance Participating nodes in P2P networks can be added or removed as members can join or leave social network. Network's links may also fail at any time; still all resources should be accessible from all peers. In any malicious attack or undesirable failures which cease operations, the overlay network should still provide an acceptable service.

Reliability Any single point of failure should be emitted.

Self-organization In the presence of the churn and frequent changes, the overlay network requires certain degree of self-organization towards stable configurations.

Decentralized Lack of centralized control in the overlay network for any peer.

In CDN level, surrogate servers have same requirements with different priority and definition which are listed as below:

Efficiency Shortest path length should be kept among the servers to interact with each other efficiently.

Reliability Avoiding bottleneck on each server (proof of development of CDN level).

Self-organization Each server is automatically turned on/off based on the burden on its neighbor servers.

Decentralized Whether server should be turned on or not is independently decided. It is important to say that whenever two servers which have common neighbor want to be turn on in order to reduce the burden of their common neighbor should care that they don't be turn on simultaneously; maybe its sufficient that one of them be turned on (behaving as critical region).

Fault-Tolerance Servers have back-up for themselves.

Scalability In any time our requests grows more, servers can response them.

4 Noticeable Parameters in Complex Networks for P2P Topology

Remarkable metrics[29] of social networks with their definition are presented in Table 1. Some of these measures are considerable in Peer levels according to their requirements (such as number 2, 4, and 10) and some of them (like number 5 and 9) are remarkable in CDN level and the others (numbers 1, 3, 6, 7, 8) should be notified in both level. In proof of why these measures are selected for each level, metrics should be analyzed carefully in detail as following.

In a nutshell, the six prenominates requirements based on their concepts and definitions (Section 3) are handled by investigated metrics and they are summarized in Table 2 & Table 3 for Peer-level and CDN-level respectively. Our points are clarified by way of illustration and interpretation: 1) Degree Centrality and its extension Katz Centrality guarantee connectivity which is the fundamental issue for scalability and whenever at the Peer-level, density is more than predefined threshold then at the CDN-level, associated server will be turned on. Therefore, network can continue to service growing requests in Peer-level and scalability will be ascertained as well. 2) Efficiency is satisfied by Closeness Centrality because videos should be routed in minimum hops and also Clustering Coefficient should be considered for emitting bottlenecks and finding alternative paths. As an example, servers for copying video frames which are missed in them should access to other servers in short distances and also peers must reach to video frames of other peers as this way so Closeness Centrality metric is significant for both of them. 3) Structural Balance leads to keeping CDN topology fault-tolerance because network burden has been distributed fairly among the servers. In addition, videos in each server has backup on one or more other servers. This property is maintained among peers by caring about Assortativity and Eigenvector Centrality; since in the malicious attacks and failures, alternative nodes for reaching videos are specified by looking after these measures. It's noteworthy that Eigenvector Centrality is considered in situation that nodes have distinctive hierarchical structure; therefore it will be handled only in Peer-level. 4) In order to avoid bottleneck in servers and single point of failures in hierarchical structure of peers, Betweeness Centrality is a common metric to mark. As mentioned before, authorities have favorable video frames which is used by peers in Peer-level for gaining desire videos whiles Hubs have helpful information in finding suitable frames of videos that is the aim of CDN level; Therefore, whereas Hubs and Authority are equivalent metrics with different functions, they should be evaluated according to their roles in CDN and Peer level respectively. 5) Assortativity and Clustering Coefficient help us to expedite finding locator nodes in P2P topology for having self-organized structure and reaching stable state. 6) Servers independently determine their status and make decision to be turned on or off; besides peers according to their Degree and Betweeness metrics set their density parameter to announce servers.

Table 1 Metrics and measures of Complex networks with their definition

No	Complex Network's Metrics	Definition	Mathematical Formula &Their Notations
1	Degree Centrality	Number of Connectedness.	$D_i = \sum_{j=1}^{n} A_{ij}$ A_{ij} : Matrix of Adjacency
2	Eigenvector Centrality	It's significant that who you know instead of what you know: How central you are depends on how central your neighbors are.	$x'_i = \sum_j A_{ij} x_j$ x_i: Centrality of each vertex
3	Katz Centrality	It's extension of Eigenvector Centrality.	$x_i = \alpha \sum_j A_{ij} x_j + \beta$ α, β: Positive Constant
4	Authorities	Authorities are nodes that contain useful information on a topic of interest.	$x_i = \alpha \sum_j A_{ij} y_j$
5	Hubs	Hubs are nodes that tell us where the best authorities are to be found.	$y_i = \beta \sum_j A_{ji} x_j$
6	Closeness Centrality	Ease of reaching other nodes: Closeness is based on the length of the average shortest path between a node and all other nodes in the network.	$l_i = \frac{1}{n-1} \sum_{j(\neq i)} d_{ij}$ $C_i = \frac{1}{l_i} = \frac{n}{\sum_j d_{ij}}$ d_{ij}: shortest path between i&j n: number of nodes
7	Betweeness Centrality	Role as an intermediary or Connector.	$x_i = \sum_{st} \frac{{n_{st}}^i}{g_{st}}$ ${n_{st}}^i$:#of shortest path pass i from source to destination g_{st}: total # of shortest path from source to destination
8	Clustering Coefficient Transitivity	What's probability that my friends friends to be my friends.	$C = \frac{(\text{numberoftriangles})*3}{(\text{numberofconnectedtriples})}$
9	Structural Balance	Nodes in one region should attain equal service from their service provider.	$\cdots$
10	Homophiles Assortative	Important nodes connect to other important ones.	$\sum_{\text{edges}(i,j)} \delta(c_i, c_j) = \frac{1}{2} \sum_{ij} A_{ij} \delta(c_i, c_j)$ c_i: Type of vertex i c_j: Type of vertex j

Table 2 Matching of Complex network's measures and metrics with Peer's requirements

No	P2P Requirements	Complex Network's Metrics
1	Scalability	Degree Centrality, Katz Centrality
2	Efficiency	Closeness Centrality, Clustering Coefficient
3	Fault-Tolerance	Assortativity, Eigenvector Centrality
4	Reliability	Betweeness Centrality, Authority
5	Self-organization	Assortativity, Clustering Coefficient
6	Decentralization	Betweeness Centrality, Degree Centrality

Table 3 Matching of Complex network's measures and metrics with Server's requirements

No	Servers Requirements	Complex Network's Metrics
1	Efficiency	Closeness Centrality, Clustering Coefficient
2	Reliability	Betweeness Centrality, Hubs
3	Self-organization	Hubs, Clustering Coefficient
4	Decentralization	Betweeness Centrality, Degree Centrality
5	Fault-Tolerance	Structural Balance
6	Scalability	Degree Centrality, Katz Centrality

As mentioned before, servers must recognize the dense regions and turned on automatically in those areas and it is compatible with this point that in some areas more peers decide to download the same video whereas that video file is not advocated in other zones. Based on these analysis, in the next Section we proposed a new P2P topology and by using theoretical analysis of characterizations, we certified that how does the model match P2P requirements.

5 Proposed Topology

In this section, we describe the basic outline of our distributed approach and how it engages network motifs in local decision rules for constructing robust streaming topologies. In the first step of constructing topology, we start with 3-clique which is the smallest sub-graph in networks as motif. These first three nodes (servers in CDN level) should be far from each other as much. In the second step, new peer is added and connected to its three close neighbors. Therefore by adding this peer, three regions will be appeared for the subsequent peers. In the next step, new peer based on its position perch on one of these three areas and will produce three zones as well. This cycle will continue until all peers append to the topology. This process reminds us Random Apollonian Networks (RANs) in mathematical models (Figure 1) and Peer-level topology formed as this hierarchical way.

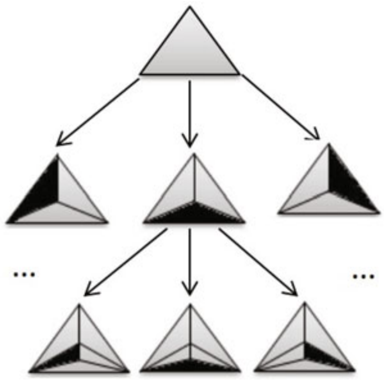

Figure 1 Topology formation based on geographic position of peers

In CDN-level, in addition to three far servers added at first, other servers based on the density of peer-level are turned on in that area (Figure 2). Since servers in CDN-level should be closer to each other in proportion to peers in Peer-level, we connected them as Apollonian Network structure and as this way structural balance in this level is guaranteed. The following pseudo code is an outline of our P2P topology formation at $T_{\max}$ step which is applied here:

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1. Let G_0 be a first 3-clique embedded on 3 far distance geographical area.
2. For Step 1 to $T_{\max}$:
   (a) Select a triangle (i, j, k) of the graph G_{t-1} according to peer position.
   (b) Insert the vertex $t + 3$ inside the selected 3-clique (e.g., place new peer proportional to its geographic position in elected 3-clique)
   (c) Link new peer to its neighbors, e.g., the three edges $(i, t + 3), (j, t + 3), (k, t + 3)$
3. It's the final step for development of peers; during their formations, servers in CDN level which are shaped in Apollonian Network structure will be turned on / off according to the burden of their neighbor's servers.

It is notable that this structure satisfies peers requirements: Peers continuously add to topology, the time will arrive that some regions are denser while the other zones are sparse. In this condition, server nodes in CDN level decide whether to be turned on (in dense areas) or turn off (in sparse areas). As in the dense areas, servers at CDN level accordingly will be turned on; therefore the graceful degradation can be seen by growing nodes (Scalability in Peer-level). By turning the server on in the dense region, the burden of neighbor's server nodes will be reduced as well; Figure 2 is depicted growing nodes after 1000 steps.

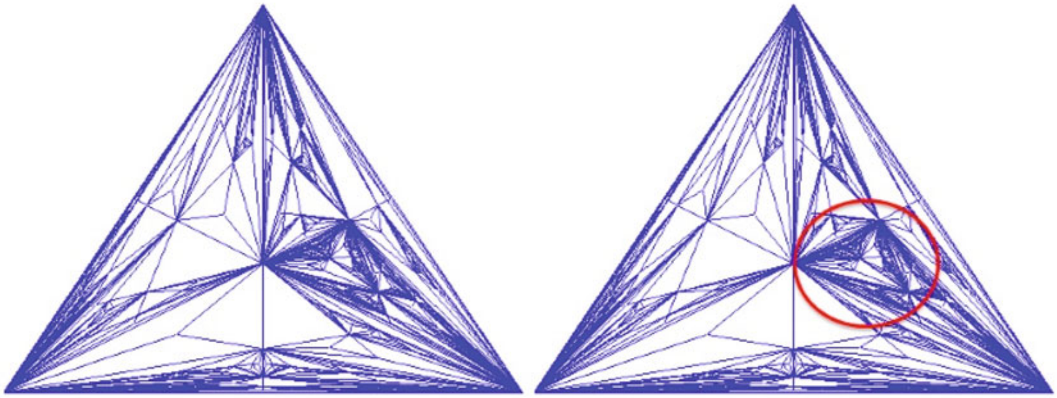

Figure 2 The snapshot of peer-level topology after adding 1000 peers on the left, and delineated its dense area on the right

The model exhibits small world properties of scale free degree sequence, large clustering coefficient and small diameter and since most real-life networks are both scale-free and small-world networks, our two-layer hybrid model may perform well in mimicking the reality. Here we focus on some properties of the Peer-level topology: The average degree of all its nodes equals 6 and it has a power-law degree distribution $p(k) \sim k^{-3}$. It has been proved that the increasing tendency of average path length of Peer topology is a little slower than the logarithm of the number of peers (Efficiency in Peer-level)[30]. By means of theoretic calculations the clustering coefficient of peer topology with large order N is obtained as 0.74 and has been proved that the increasing tendency of average shortest path is a little slower than $\ln(N)$[31]. Since servers in CDN-level has not any limitation on their degree like peers (for bandwidth constraint), the first level of peers in hierarchical structure of Peer-level which is shown in Figure 3[32] and their children are connected to server in that region. Therefore, if any peer leaves the network, other peers have alternative paths to access to the server and we don't have any single point of failure in the network (Reliability in Peer-level); as peer leaves the network, among its children, the peer which have the highest Betweenness is replaced for it and connect to the server in that area, thus network is self-organized (Fault-Tolerance in Peer-level) and the system dynamics, in particular the churn which is the most critical factor that affects the overall performance, is handled. Since peers can join and leave the network independently, our proposed topology is decentralized too.

We assume almost the same topology with alternative relation between server nodes in CDN-level; Server nodes are joined to the network with moderate style. Thus we have Apollonian Network (AN) which is the balanced version of RANs, and structural balanced property is maintained in topology (Reliability in CDN-level). Apollonian Networks are known as simultaneously scale-free, small-world, Euclidean, space filling, and with matching graphs[33]. Degree distribution of AN is $P(k) = \frac{2}{3}(\frac{3}{k})^{(\frac{\ln 3}{\ln 2})}, k = 3, 3*2, 3*2^2, \cdots, 3*2^{(t-1)}$[34] and it indicates that it can be regarded as a scale-free network with degree exponent $\gamma = \frac{\ln 3}{\ln 2}$. Another property that characterizing a small-world network is the clustering coefficient which is found to be 0.828

in the limit of large N (number of nodes) and average shortest path length between any two vertices grows slower than any positive power of the system size N and is equal to $l \propto (\ln N)^{\beta}$ with $\beta \approx \frac{3}{4}$ (Efficiency in CDN-level); they have intermediate behavior between small ($l \propto \ln N$) and ultra-small ($l \propto \ln \ln N$) networks[35].

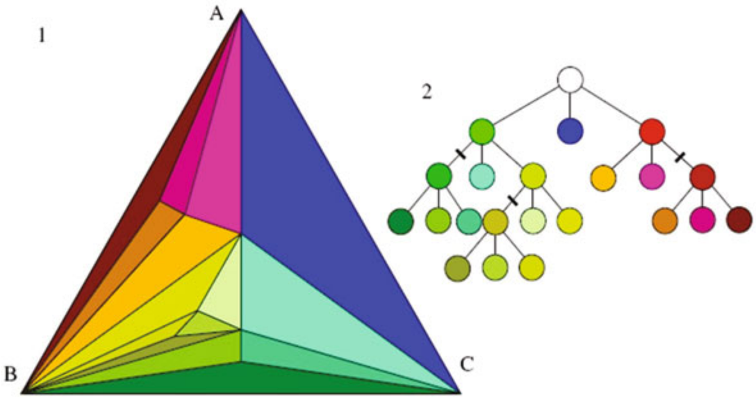

Figure 3 1) Hierarchical structure of Random Apollonian Networks; 2) Its associated ternary tree

Since servers in CDN-level are automatically turned on/off based on the density of peers and their decision are independent from each other, they are self-organized and decentralized too.

In brief, our proposed model is a two layer hierarchical topology; the first layer is assigned to servers with Apollonian Network structure (CDN-Level) and the second layer is designed for peers with Modified Random Apollonian Network (Peer-level) form. Besides, our proposed topology adopted itself with situation and burden of the network dynamically.

6 Comparison with Other P2P Topology

For evaluating our model, we investigate the quality properties from two different perspectives: At the first step, as complex network point of view, it will be compared with related complex network models; at the second part, from the viewpoint of P2P topological property, the proposed topology will be compared with two famous P2P network model.

In order to compare of our proposed topology with complex networks models, Barabasi-Albert model for scale-free networks and Watts and Strogatz's model for small-world networks were selected as well-known models. Our topology implemented in Matlab and evaluated by Boost Graph Library in it. For small-world networks and scale-free models, we use their available codes in Netlogo and append on them some additional part for calculating desire metrics. Table 4 provides a brief overview of the main results of our simulation.

The experimental results show that our topology reduces the Average Path Length about 23 percent and 16 percent respect to small-world and scale-free networks respectively. This reduction is appeared in Diameter too whiles its' Clustering Coefficient increments near 67 and 74 percent in comparison to small-world and scale-free models respectively.

Table 4 Comparison of our proposed topology with small-world and scale-free networks

Model	#Nodes	#Edges	Avg.Degree (Min/Max)	Avg. Distance	Diameter	Clustering Coefficient
Scale-free	1024	3066	5.98 (1 / 74)	3.893	7	0.0071
Small-World	1024	3066	5.98 (4 / 11)	4.26	8	0.074
Proposed Topology	1024	3066	5.98 (3 / 88)	3.26	6	0.7384

Table 5 Comparison of our proposed topology with CAN and Chord topologies

Model	#Nodes	#Edges	Avg.Degree (Min/Max)	Avg. Distance	Diameter	Clustering Coefficient
CAN	1024	9524	18.60 (4 / 45)	4.85	10	0.50
Chord	1024	9728	19 (19 / 19)	3.45	5	0.16
Proposed Topology	1024	9621	19.41 (3/118)	2.60	4	0.63

P2P overlay networks are generally classified into two categories: 1) Structural P2P networks such as CAN, Chord, Pastry, Tapestry, Kademlia and Viceroy and 2) Unstructured P2P networks as an example of Freenet, Gnutella, KaZaA, Bit-Torrent, and Overnet[36]. Un-Structural networks face with an inherent scalability problem. Some topologies as Gnutella, KaZaA, and Overnet, the more real-world popular examples of their respective network types, follow scale-free models[37] while Freenet pursues small-world models[4]. Since our topology was compared with small-world and scale-free models, we choose CAN and Chord topologies among overlay networks which have received specific attention from both developers and researchers[38], so we will compare our topology with them as sample of Structural P2P networks. As Table 5 shows, not only the Average Path Length was decreased considerably, but also Clustering Coefficient was sequentially increased 47 and 13 percent in compared with Chord and CAN topologies respectively.

In order to compare our proposed topology with scale-free and small-world models as vulnerability perspective, we can categorize attacks and failures in four type procedures from a complex network standpoint: 1) Preferential Site Percolation which remove nodes with highest degree until the network is partitioned; 2) Random Site Percolation which randomly eliminate nodes one by one until the network becomes unconnected; 3) Preferential Bond Percolation that edges with highest betweenness will be deleted till the network takes apart; and finally 4) Random Bond Percolation which has repeated to omit edges randomly until the network is partitioned into components.

The results of running these four procedures on Barabasi-Albert, Watts and Strogatz's and our proposed topology are summarized in Table 6. Each number in this table shows that in how many steps the network endure to be partitioned (the greater-the better); it has been shown that scale-free models versus small-world models are more sensitive to malicious attacks on nodes while it is more robust to malicious attack on edges and this issue is contrary for small-world models. Our simultaneously scale-free, small-world hybrid model not only in both malicious attack domains is the most robust model, but also it have endured node's and edge's failures much more better than the others.

Table 6 Comparison of proposed topology with CN models as vulnerability point of view

Attack or Failure Type	Scale-free Model	Small-world Model	Proposed Topology
Preferential Site Percolation	5	21	30
Random Site Percolation	33	26	37
Preferential Bond Percolation	70	40	88
Random Bond Percolation	33	91	135

According to Newman[39], Assortative (or dissortative) Mixing is a graph theoretical quantity which is evaluated by the Pearson Coefficient r and is calculated as follows:

$$r = \frac{\sum_i j_i k_i - M^{-1} \sum_i j_i \sum_{i'} k_{i'}}{\sqrt{[\sum_i {j_i}^2 - M^{-1}(\sum_i j_i)^2][\sum_i {k_i}^2 - M^{-1}(\sum_i k_i)^2]}}, \tag{1}$$

where j_i and k_i are the excess in-degree and out-degree of the vertices that the ith edge into and out of, respectively, and M is the total number of edges in the graph. Positive values for r indicate that nodes with high degrees tend to be connected to other nodes with high degrees (Assortativity); on the other hand, negative values exhibits a dissortative mixing and nodes with high degrees tend to be connected to nodes with low degrees. The proposed model exhibits a dissortative mixing with $r = -0.131$ where high degree nodes preferentially connect with low degree ones and these values are $r = -0.087$ and $r = 0.0068$ for Scale-free and small-world models respectively. This issue is one of the reasons that our model is the most robust model in comparison with the two other ones. The last metric that considered here is link reciprocity ρ which is defined as the correlation coefficient between the matrix entries[40]:

$$\rho = \frac{\sum_{i \neq j}(a_{ij} - \overline{a})(a_{ji} - \overline{a})}{\sum_{i \neq j}(a_{ij} - \overline{a})^2}, \tag{2}$$

where the average value $\overline{a} = \sum_{i \neq j} a_{ij}/N(N-1)$ and N is the number of peers in the graph. The reciprocity coefficient tells whether the number of mutual links in the network is more or less than that of a random network. If the value of ρ is higher than 0, the network is reciprocal;

otherwise, anti-reciprocal. This value for our proposed scheme is 0.010050, which means that the network is somehow reciprocal than a randomized graph. In contrast, based on [40], the reciprocity coefficients of the World Wide Web and of Wikipedia have been found to be 0.5161 and 0.32 respectively. In terms of networks created essentially by textual communication, the reciprocity coefficient is 0.231 for e-mail, 0.28 for Slashdot, 0.58 for Twitter, and 0.765 for guestbook communication in Cyworld.

Thus, among all these networks the quantitative link reciprocity of our video streaming P2P topology is the smallest. By the way, this weakly reciprocal communication is very beneficial specially in video streaming because it avoids that peers has received redundant videos.

7 Conclusions & Future Research

This study has proposed a novel P2P topology by matching P2P requirements with social networks metrics. We have shown that our mechanism not only has resolved the scalability problem of structural networks but also has achieved much better Clustering Coefficient with reducing average path length. Meanwhile, we overcome the challenges of pervious social networks models such as small-world networks and scale-free ones by using hybrid model. To this end, we have combined their features and enhanced clustering coefficient and average path length considerably. Besides we have shown that our hybrid topology behaves much better versus small-world and scale-free networks in attacks and failures point of view. Finally, our position-based topology, coincide P2P logical overlay network with physical topology as well.

Our initial work has raised a number of interesting questions which we hope to pursue in future work. The first question is that when the new server should be turned on and for how many peers a new server can reduce the burden of its neighbor's servers? In the other word what's the appropriate density for turning the new server on. Another line of our future efforts will deal with caching videos in servers in order to reduce the delay of peers and improve the bandwidth usage. At the end, future research could help in providing a new strategy for caching videos according to their predicted popularity in way that quality metrics will be satisfied.

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