Understanding the Topologies of BitTorrent Networks: A Measurement View

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Abstract—**BitTorrent (BT) is one of the most popular Peer-to-Peer (P2P) network applications. Most characteristics (except the topology) of BT network have been examined extensively by measurement approaches. In this work, we deploy a measurement system to study the performance-related properties of BT topologies. We also use our measurement system to verify some previous simulation and experiment results obtained by other researchers. Different from previous results, we observe that a BT swarm has short distance, low clustering coefficient and Gaussian-like degree-frequency distribution. This indicates that a BT swarm is very close to a random network rather than a scale-free network or a small world. We observe that the diameter of a BT network at the initial stage is small even when 95% of peers use the peer exchange extension but the networks are not fully connected at the steady stages.**

Keywords— BitTorrent; topology; measurement; performance

I. INTRODUCTION

During the last decade, BitTorrent (BT) has been widely used in file-sharing for its efficiency and robustness. Researchers and developers have been working to improve its performance, and lots of measurement studies have been performed on the swarm evolution [1], popularity [2], and availability [3], etc. Despite it is import to better understand BT networks and analyze BT performance, however, little is known about the topology characteristics of real BT networks.

Unlike other P2P systems, BT does not provide a global topology discovering mechanism. Both trackers and peers do not have the knowledge about all peers and their connections. Fortunately, the BT peer exchange extension (PEX) [4], which allows peers to exchange the information of newly connected and disconnected peers periodically, provides an opportunity to learn the connectivity between pees. Therefore we design a measurement system to collect the peers from trackers and connections from PEX to form topologies of BT networks.

In this paper, we analyze some topology properties of BT overlay by measurement results of real world. Our goal is to provide a measurement view of existing BT topologies and verify the previous results of theoretical analysis [5], simulations [6] and controlled experiments [7]. We examine the peer degree distribution, peer distance and clustering coefficient in different swarm evolution stages. We also try to explain the potential influential factors of some results and its effects on BT performance from the protocol design and client implementation perspectives.

Our main findings can be summarized as follows:

(1) We observe that there is no large amount of low-degree peers to form a power-law distribution. Especially in the steady stage, the peer degree distribution of large-scale swarm follows a Gaussian distribution. This result suggests BT network is more likely random other than scale-free, which is different from previous results.

(2) The connection limitation of BT clients limit the connection number of many peers in the initial stage but affect less in the steady stage. More than 70% of peers have the degrees less than 50 in the steady stage.

(3) In the steady stage, the peer distances between most peers are small (larger than the initial stage), and the clustering coefficient of network is low (lower than the initial stage), further confirming the BT is more likely a random network and suggesting that the BT is not a small world. Especially, the networks are not fully connected at the steady stages.

(4) Different from [7], we find out that the diameter of BT networks in the initial stage are still very small (<6) although more than 95% of peers applying PEX in existing BT networks.

The rest of this paper is organized as follows. We introduce some related work in section II and present our measurement methodology in section III. In section IV, we analyze the measurement results and study the properties of BT topologies. We conclude this paper in section V.

II. RELATED WORK

There are many measurement studies on characterizing the overlay topologies of P2P networks [8] [9] except BitTorrent. Despite some work [10]-[12] focus on the locality distribution of BT, however, only a small number of papers [5]-[7], [13] examine the properties of BT topologies extensively. Out of these, only [10] uses the measurement approach.

Al-Hamra *et al.* [6] analyze how the overlay properties impact BT efficiency by extensive simulations. They show that the BT overlay is robust but not a random graph. They also find that the BT PEX generates large-diameter chain-like overlays in the initial swarm stages. However, Wu *et al.* [4] do not observe the chain-like topology in their PlanetLab [14] experiments. Dale *et al.* [7] study the topology properties by deploying experimental swarms with a modified BT client on more than 400 PlanetLab nodes. Their results show that the network of peers that are unchoked by others is scale-free. They find out that there are no clear evidences of persistent clustering and presences of small word. However, in real world, due to the Network Address Translations (NATs) and firewalls, the connectivity between peers is much worse than that of PlanetLab nodes, which may lead different peer degree distribution. Besides, the swarm size and diversity of BT clients may also affect the peer connections. Zhong *et al.* [5] analyze the topological properties by a directed weighted graph model. They find that the node strength of BT network follows a power-law distribution. When the seeder proportion increases, a BT network tends to be less clustered. The average shortest path length grows as network size expands.

Fauzie's work [13] is the closest one to ours. Fauzie *et al.* collect the information of peers and connections by a modified rasterbar libtorrent client [15]. They join 35 TV series torrents and take the snapshots with 3-minutes duration for about 8 days. They find out that the degree distribution is a power-law with exponential cutoff and the clustering is not obviously. However, we argue that the 3 minutes duration may not be sufficient to find all peers of hot torrents due to the discovering ability of the BT client.

Different from [5]-[7], in this paper, we study the topology characteristics of real BT networks by measurement rather than theoretical analyses [5], simulations [6] or experiments [7]. Unlike [13], we design a measurement system that uses both active and passive approaches to get comprehensive temporal topologies of BT networks in a short time. Furthermore, we provide more detail analysis on the topology characteristics (e.g. peer degree distribution and clustering) than Fauzie *et al.* [13]. In addition, we focus on these characteristics in different swarm stages and give some potential explanations to our results.

III. Topology Measurement

A. Design of Our Measurement System

We design a measurement system to capture snapshots of BT swarms, shown in Fig. 1. A *snapshot* is a temporal situation of a BT swarm observed at a particular moment, and it includes peers, the status of each peer (e.g., its download percentage) and connections among peers. We crawl peers from tracker and collect connection information by exchanging PEX messages with peers. We use both active and passive approaches to fast capture snapshots. The dynamic and large scales of BT networks are major challenges.

The active measurement of each snapshot consists of a *peer finding* stage and a *peer detecting* stage. In the peer finding stage, the system requests peer lists from trackers extracted from the torrents, and then connects with these peers to find more peers from PEX messages. Repeat this process until the stop condition is met. In the peer detecting stage, the system connects to all the peers (found in the first stage), exchanges BT messages, and records the BITFIELD (from BITFIELD

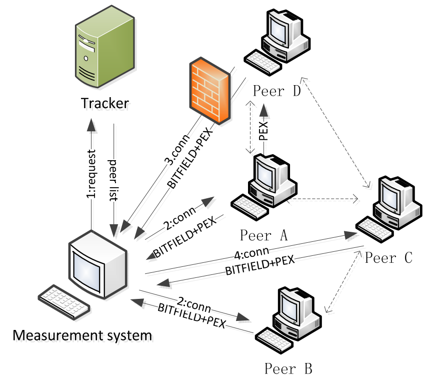

Fig. 1: Illustration of our approach

message) and neighbors (from PEX messages) of each connected peer. To save the bandwidth, the system does not download any file data.

We apply a passive approach to get PEX and BITFIELD of the unreachable peers (e.g. behind firewalls or NATs). The system listens and responds to requests from these peers and logs their BITFIELD and neighbors. The system keeps connections with all connected peers to track their status. In our post-processing, the logs are split according to the start time and end time of each snapshot.

Due to the large scale and dynamic of swarms, it is nearly impossible to capture all the peers of the swarm in a snapshot. To reduce the measurement time, we deploy several detection nodes and send requests to multiple trackers and peers at the same time. We use 10 nodes in parallel when deployment to reduce the impact on BT swarms. We calculate the stop condition of the measurement in a similar way as in [16]. Assume each tracker returns a subset of k peers randomly chosen from N peers, among which there are $\Delta(m)$ newly discovered peers (identified by IP address and listen port) at the m-th request. The coverage ratio is calculated by (1).

$$P(m-1) = 1 - \frac{\Delta(m)}{k} \tag{1}$$

In deployment, the system detects until $\Delta(m) < 3$ (k=60) for $C=20$ consecutive times, where the threshold C is used to avoid the error of a single measurement. Therefore, the peer coverage ratio is more than 95%. Based on the results in [16], for a swarm of N=5000 peers, we need at most 74+20=94 times of requests, which is about 10 request sent from each nodes. We request to the trackers every 5s. Hence, it takes less than 1 minute (10×5s=50s) to crawl a 5000-peer swarm.

We discover that most of popular BT clients (e.g. µTorrent) return all their connected peers in the first PEX message. By exchanging one PEX message with each connected peer, we can get all the connections of them. Each message takes less than 1 minute. We keep the connections with peers during the detecting stages and every minute peers send a PEX message containing the newly connected and disconnected peers. The connection set of a peer at the end of a snapshot is its initial connections plus its newly connected peers and then minus its disconnected peers. In the implementation of our measurement system, the peer detecting stage lasts less than 130s.

TABLE I. INFORMATION OF TORRENTS USED IN THIS PAPER

Description	Torrent 1	Torrent 2	Torrent 3	Torrent 4	Torrent 5
Created Time	2011-12-24 15:46:35	2011-11-09 8:47:45	2011-12-24 3:52:54	2011-12-20 22:58:57	2011-12-22 19:16:42
Start time	2011-12-25 11:30:27	2011-12-13 19:38:05	2011-12-24 09:41:52	2011-12-21 11:40:32	2011-12-23 22:56:00
File type	TV show	Game	Movie	Music	Movie
File Size	801MB	12.8GB	1.77GB	118MB	1.12GB
Swarm/Connected[1]	35004/9272	27483/6745	4980/1630	1379/675	392/128
Swarm/Connected[2]	31593/8832	24954/5083	4150/1259	1096/415	378/102

1. Average swarm population and connected peers observed during the 1st 50 snapshots at the initial measurement
2. Average swarm population and connected peers observed during the 1st 50 snapshots at 4th day of measurement

B. Deployment and Measurement Results

We randomly chose 106 torrents from the well-known BT torrent search engine TorrentZ [17]. Each torrent had more than 300 peers when the measurement started. We deployed our system on 2 servers. Each server had 10 measurement nodes. The system continuously captured the snapshots of each swarm from 2011-12-13 to 2012-01-31, and each snapshot took about 3 minutes on average. About 30 torrents were measured in only a few hours after they were published to the website, and most of their swarm evolutions were caught.

In each snapshot, the percentage of peers that our system could connect to is about 30% ~ 50%, and the percentage of peers that we observed from PEX message is about 85% ~ 90%. There are about 10% ~ 15% peers that we can observe from trackers but we could not connect them or observe from PEX. In addition, there are less than 1% peers that we observed from passive measurement but we did not observe from the active measurement, some of which may be trackerless peers.

C. Influence Factors of the Coverage

There are some factors that affect the coverage ratio of measurement results. First, we cannot get the peer lists of the seeders behind firewalls and NATs. Second, some BT clients (e.g. µTorrent) do not send PEX messages if they connect less than 3 peers. Third, we cannot establish connections with peers whose number of connections has reached the limit. The status of these peers and their connections cannot be discovered by our measurement system, and therefore are missing from the snapshots.

IV. TOPOLOGY ANALYSIS

In this section, we analyze the BT topology properties based on our measurement results. We select 5 torrents of different scales to demonstrate our analyzing results, as shown in Table I. Other torrents have similar characteristics.

A. Peer Degree Distribution

The degree of a peer v is the number of peers to which it connects in each snapshot, referred as $deg(v)$. The distribution of peer degree reflects the topology characteristics and the robustness of a BT network. A previous experiment study by Dale *et al.* [7] shows that the BT peer degree do not follow a power-law distribution. To study the peer degree distribution in our measurement results, we plot the degree-frequency distribution of reachable peers of the steady-stage snapshots (the 4th day after measurement startup), shown as Fig. 2 ~ Fig. 6. The x-axis is the degree of peers and the y-axis is the percentage of peers with that degree. It can be seen that only a few peers have very large (or very small) number of connections; most peers have a moderate degree (usually, close to but less than 50). Therefore, most of peers are resilient to the departure of its neighbors for it can continue downloading from other connected peers, suggesting the robust of the BT swarms.

Potential reasons of BT peer degree exhibiting such a distribution may lie in: 1) Due to the limitation of BT clients and network connectivity, a peer cannot establish connections with all peers it knows. Hence, the degree cannot be too large. 2) Trackers, DHT and PEX increase the opportunity of peers finding each other and BT clients may try to setup more connections to increase the download speed. 3) Some clients (e.g., µTorrent) do not return PEX if the number of connected peer is less than 3. Hence, the actual number of low-degree peers is more than the number measured by our system.

We notice that trackers randomly choose a subset of peers from the peer list, and peers randomly choose other peers to connect. This may make the BT swarm form a random network. Therefore, to examine this, we use Gaussian distribution (2) to fit the degree-frequency of each snapshot.

$$f(x) = \frac{A}{\sqrt{2\pi\sigma}} \exp\{-\frac{(x-\mu)^2}{2\sigma^2}\} \tag{2}$$

Results show that in the steady stage, the degree-frequency distribution of a large-scale swarm (torrent 1~4 in Fig. 2~5) follows a Gaussian distribution with the correlation coefficient R larger than 0.9. R is around 0.5 for small-scale swarms (e.g., torrent 5 in Fig. 6). This indicates that the BT network is very close to a random network rather than a scale-free network, especially for the large-scale swarms. This result is different from the simulation result of Al-Hamra *et al.* [6], which shows that the BT network is not random. Our result is also different from Fauzie *et al.* [13], which suggests a power-law distribution with exponential cutoff is more proper model. The random characteristic of a BT network may be attributed to the random peer selection policy used by the trackers and the peers. Compared with a scale-free network, in BT, the leaving of a peer affects little to the downloading status of the whole network because peers can download from remaining peers. We also examine the peer degree distribution at the initial stage, one result is plotted in Fig. 7 (torrent 3, a medium scale swarm). We observe that although the degree-frequency distribution exhibits a Gaussian-like distribution, the R is small. (smaller than the steady stages, R=0.759 vs. R=0.97), which is similar to the result of Al-Hamra *et al.* [6].

We notice that for the peer-degrees between 45 and 50, the percentage of peer is high, and there is a spike around the degree of 50. Then the percentage drops dramatically at the

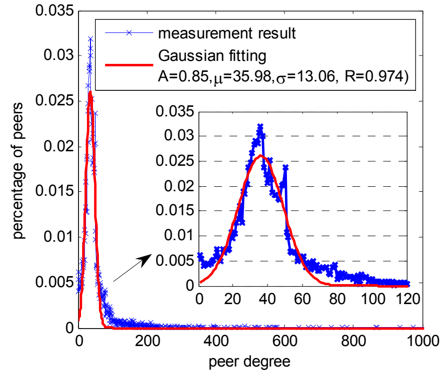

Fig. 2: Degree-frequency distribution of torrent #1

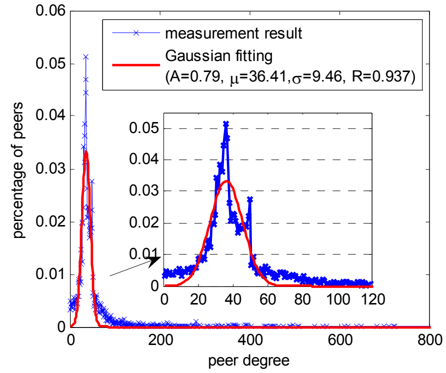

Fig. 3: Degree-frequency distribution of torrent #2

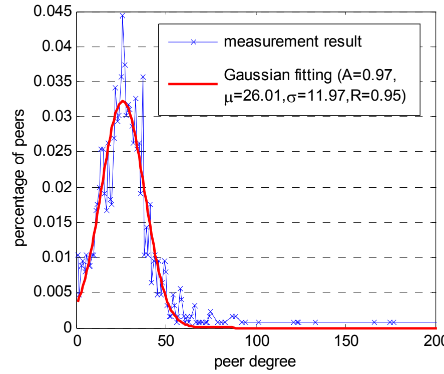

Fig. 4: Degree-frequency distribution of torrent #3 (The 117th round on 2011-12-28)

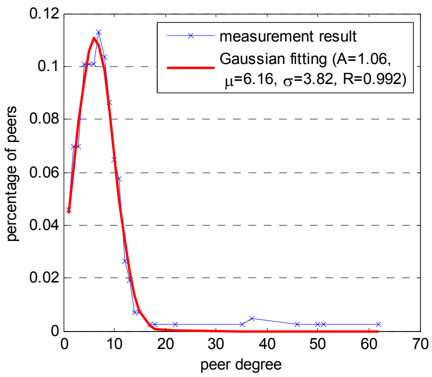

Fig. 5: Degree-frequency distribution of torrent #4

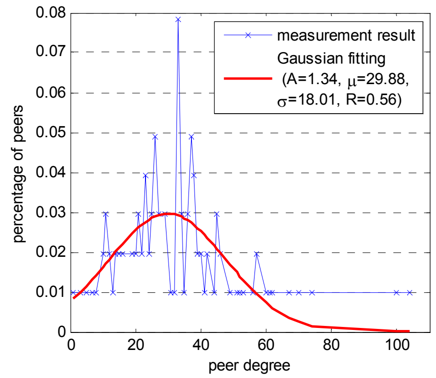

Fig. 6: Degree-frequency distribution of torrent #5

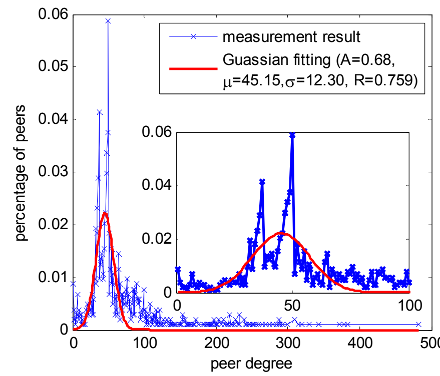

Fig. 7: Degree-frequency distribution of torrent #3 (The 41st round on 2011-12-24)

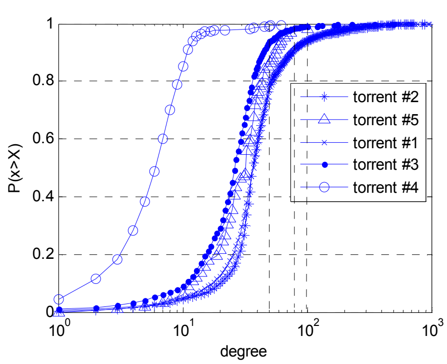

Fig. 8: CDF of the number of peers with the degrees

degree of 51. This is more obvious in the initial stage. We believe that the most important reason of this phenomenon is the connection limitation of BT clients. For most BT clients, by default the maximum number of connected peers per torrent is set to 50, which limits the number of connections with peers that have high bandwidth. On the other hand, peers reaching their connections' limits may actively free some idle or low-speed connections and try to connect to new peers. Moreover, some clients will reserve some connections for the incoming peers. We confirm these speculations on µTorrent, which has a default connection limit is 50. Even when we change this limit, it only actively connects to 76% of the limit simultaneously, with the remaining 24% reserved for incoming connections. µTorrent will drop the inactive connections after 5 minutes timeout and attempt new connections.

In Fig. 8, we plot the CDF of the number of peers with respect to their degrees at steady stage. It shows that there are more than 70% of peers whose degrees are less than 50; 90% of peers have a degree are less than 60, and less than 5% of peers have degree larger than 100. The results suggest that in the steady state, for most peers, the dominant factor of peer degree is not the connection limit of BT clients.

B. Distance between Peers

Many existing P2P networks (e.g. Gnutella) have been proved to be a small-world [8], in which, the mean distance between nodes is small and nodes are highly clustered. Legout *et al.* [18] observe node clustering in the early stages of swarms based on PlanetLab experiment. However, Dale *et al.* [7] find no clear evidence of clustering in their experiments. Moreover, Al-Hamra *et al.* [6] show that PEX may generate a chain-like overlay with a large diameter. However, we believe that PEX helps peers know each other with a short distance. Therefore, we study the peer distance in this section and clustering coefficient in subsection *C* to check whether the topologies of real BT network exhibit the small-world characteristics or not.

In a BT snapshot, there are three types of peers: those directly connected with us (referred to as $\boldsymbol{P_c}$), those not connected with us, but known to us because they are directly connected to peers in $\boldsymbol{P_c}$ (referred as $\boldsymbol{P_k}$), and those we observed from trackers but not connected to peers in $\boldsymbol{P_c}$ (referred as $\boldsymbol{P_n}$). Each topology can be represented by an undirected graph $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$, in which vertices $\boldsymbol{V} = \boldsymbol{P_c} \cup \boldsymbol{P_k} \cup \boldsymbol{P_n}$ denotes the peers and edges $\boldsymbol{E}$ denotes the connections, i.e. $(u, v) \in \boldsymbol{E}$ if and only

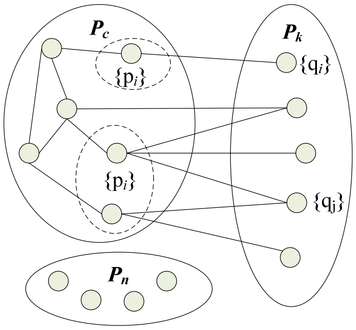

Fig. 9: Illustration of the connectivity graph of a snapshot

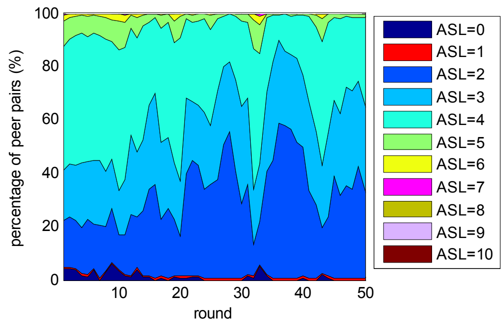

Fig. 10: Percentage of peer pairs with different *ASL*s in ***Pc*** of torrent #3 (50 rounds on 2011-12-28)

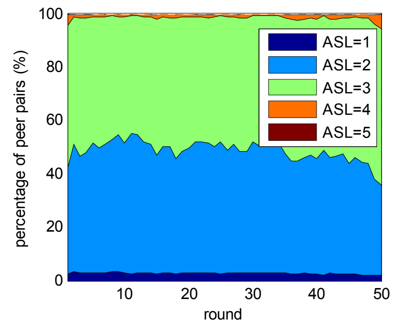

Fig. 11: Percentage of peer pairs with different *ASL*s in ***Pc*** of torrent #3 (50 rounds on 2011-12-24)

if peers u and v are connected to each other. Fig. 9 gives an illustration of such a graph. An edge is also referred as a path, and the distance between each pair of peers is the shortest path length between them. If there are two peers with no path between them, the network is not fully connected. The diameter of a network is the maximum length of the shortest path between peers.

Although we cannot know the complete topology of a BT swarm due to the limitations of measurement, we can use our measurement results and obtain an approximate value of the shortest path length between peers u and v, donated as $ASL(u,v)$. Take the graph in Fig. 9 as an example. First, for peers p_i, $p_j \in \boldsymbol{P_c}$, we simply use the known portion of $\boldsymbol{P_c}$'s topology ($\boldsymbol{G_c}$, consisting of all peers in $\boldsymbol{P_c}$ and the connections among them), and directly compute the shortest path length between p_i, p_j as the $ASL(p_i, p_j)$. Second, $\boldsymbol{P_k}$'s topology is unknown, but we can approximate the shortest path length between peers q_i, $q_j \in \boldsymbol{P_k}$ according to their connectivity with peers in $\boldsymbol{P_c}$. For example, if q_i and q_j are connected to peers in $\{p_i\} \subseteq \boldsymbol{P_c}$ and $\{p_j\} \subseteq \boldsymbol{P_c}$ respectively, we have:

$$ASL(q_i, q_j) \le \min_{p_i \in \{p_i\}, p_j \in \{p_j\}} ASL(p_i, p_j) + 2 \tag{3}$$

Third, for peers $p_i \in \boldsymbol{P_c}$ and $q_j \in \boldsymbol{P_k}$, if q_j is connected to peers in $\{p_j\} \subseteq \boldsymbol{P_c}$, similarly we have:

$$ASL(p_i, q_j) \le \min_{p_j \in \{p_j\}} ASL(p_i, p_j) + 1 \tag{4}$$

We cannot get the shortest path length between peers in $\boldsymbol{P_n}$ because we know nothing about their topologies. However, according to our measurement results, $\boldsymbol{P_c}$ and $\boldsymbol{P_k}$ cover about 90% of the peers and 50% - 75% of the connections. Hence, our measurement can reflect the connectivity of BT network to a good extent.

According to (3) and (4), we only need to calculate the *ASL* of each pair of peers in $\boldsymbol{G_c}$, in which the connections are *definite* (connected or unconnected). In Fig. 10, we plot 50 steady-stage snapshots of the torrent 3 as an example. We find out that the $\boldsymbol{G_c}$ of most snapshots are unconnected, with a few pairs of peers (<10%) where there is no path between them (*ASL*=0 in Fig. 10). The *ASL* of other peer pairs are less than 10. Particularly, the *ASL*s of more than 80% of the pairs are less than 4, which is consistent with the simulation result of Al-Hamra [6]. The short distances demonstrate that a leecher is able to find out any other peers (especially seeders) by exchanging peer lists for several times, suggesting the PEX is efficient of peer discovering. In addition, the partition of topologies suggests that the trackers and DHT are necessary because they provide an extensive peer indexing policy to help peers in different partition find each other.

According to similar analysis in (3) and (4), the number of peer pairs whose *ASL*=0 and the *ASL*s of peer pairs in $\boldsymbol{P_c}$ may be smaller than our calculation. By examining the download percentage of the peers in $\boldsymbol{P_c}$, we find that most of the peers are seeders, so there is no direct path between them as they do not connect with each other to download pieces, and this may be the reason why the graphs are split.

Wu *et al.* [4] observe that more than 95% BT peers use the PEX protocol. We plot the *ASL*s of torrent 3 in its early swarm stage to examine whether the PEX generates the large-diameter chain-like topologies in real world as in Al-Hamra *et al.*'s simulation result [6]. The result (shown as Fig. 11) actually differs from [6] because the network diameter of the initial stage is very short (less than 5+2=7). In addition, the result shows that the topology in its initial stage is a connected graph and, especially, 90% of peer pair has a shortest path with length less than 3, meaning that the connectivity in the early stage is better than that in the steady stage. The results indicate that in the early swarm stage, a tracker can reduce its load by reducing the frequency of client requests.

C. *Clustering Coefficient*

Clustering coefficient is a measure of degree to which nodes in a graph tend to cluster together, defined as (5), where T_e is the number of connections between neighbors of peer v. The clustering coefficient is usually large in a scale-free graph while small in a random graph. The clustering coefficient for the entire network is calculated by equation (6).

$$C_v = \frac{2 \times T_e}{\deg(v)(\deg(v) - 1)} \tag{5}$$

$$C = \frac{1}{N} \sum_{i=1}^{N} C_v \tag{6}$$

In Fig. 12, we plot the network clustering coefficient of 50 snapshots of torrent 3 in its early stage and steady stage of its swarm evolution. The results show that the network clustering coefficient is small (<0.15) in the steady stage. This observation is consistent with Dale *et al.* [7] and Fauzie *et al.*

[13], and further proves that the BT topologies are more likely random graphs. In addition, similar with Dale *et a*l., we also notice that in the real network, the clustering coefficient of the initial stage exhibits a declining tread as the swarm evolves and it is larger than that in the steady stage. This may also be caused by the increased proportion of seeder who can provide more uploading connections than the leechers. We do find a larger proportion of seeders in the steady stage compared to the initial stage. Our measurement result is also consistent with Zhong *et al.* [5] which show that the BT networks tend to be less clustered when the seeder proportion increases. A high clustering coefficient in the initial stage implies that peers collaborate in sharing files while a low clustering coefficient in the steady stage suggest that seeders may contribute more.

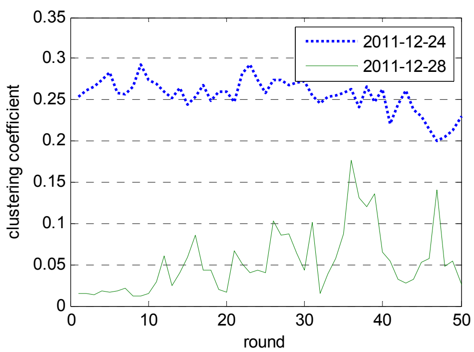

Fig. 12: Comparison of clustering coefficient of torrent #3, 50 rounds in initial stage (2011-12-24) and the steady stage (2011-12-28)

Summing up subsection *B* and *C*, in the steady stage, the BT networks are not fully connected and the clustering coefficient is much low, indicating that the BT networks are not small-world and further specifying the BT swarms are more likely random graphs.

V. CONCLUSION

In this paper, we presented a measurement study on the topology characteristics of real BT networks. We designed a hybrid BT measurement system with a combination of active and passive approaches. We explored the BT peer exchange (PEX) protocol to collect the connections information among peers. Our measurement results cover more than 95% of peers and 51% ~ 75% connections of each snapshot. We analyzed the peer degree distribution, peer distance and network clustering coefficient. We also gave explanations to some measurement results. In the future, we will study the peer locality distribution from snapshot views and characterize the dynamic of BT networks.

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