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▶ To cite this version:

Anwar Al Hamra, Arnaud Legout, Chadi Barakat. Understanding the Properties of the BitTorrent Overlay. [Technical Report] 2007, pp.18. inria-00162088

Understanding the Properties of the BitTorrent Overlay

Anwar Al-Hamra, Arnaud Legout, and Chadi Barakat

INRIA

Sophia Antipolis, France

Email: {anwar.al_hamra, arnaud.legout, chadi.barakat}@sophia.inria.fr

Technical Report

Abstract—In this paper, we conduct extensive simulations to understand the properties of the overlay generated by BitTorrent. We start by analyzing how the overlay properties impact the efficiency of BitTorrent. We focus on the average peer set size (i.e., average number of neighbors), the time for a peer to reach its maximum peer set size, and the diameter of the overlay. In particular, we show that the later a peer arrives in a torrent, the longer it takes to reach its maximum peer set size. Then, we evaluate the impact of the maximum peer set size, the maximum number of outgoing connections per peer, and the number of NATed peers on the overlay properties. We show that BitTorrent generates a robust overlay, but that this overlay is not a random graph. In particular, the connectivity of a peer to its neighbors depends on its arriving order in the torrent. We also show that a large number of NATed peers significantly compromise the robustness of the overlay to attacks. Finally, we evaluate the impact of *peer exchange* on the overlay properties, and we show that it generates a chain-like overlay with a large diameter, which will adversely impact the efficiency of large torrents.

I. INTRODUCTION

Recently, Peer-to-Peer (P2P) networks have emerged as an attractive architecture for content sharing over the Internet. By leveraging the available resources at the peers, P2P networks have the potential to scale to a large number of peers. Nowadays, P2P networks support a variety of applications, for instance, file sharing (e.g., BitTorrent, Emule), audio conferencing (e.g., Skype), or video conferencing (e.g., End System Multicast [1]). Among all existing P2P applications, file sharing is still the most popular one. A study in 2004 by the *Digital Music Weblog* magazine [2] states that P2P file sharing is responsible for $70 - 80\%$ of the overall European Internet traffic. And among the many P2P file sharing protocols, BitTorrent [3] is the most popular one. Alone, BitTorrent generates more than half of the P2P traffic [4].

Invented by Bram Cohen, BitTorrent [5] targets distributing efficiently large files, split into multiple pieces, in case of a massive and sudden demand. The popularity of BitTorrent comes from its efficiency ensured by its peer and piece selection strategies. The peer selection strategy aims at enforcing the cooperation between peers while the piece selection strategy tends to maximize the variety of pieces available among those peers. The great success of BitTorrent has attracted the curiosity of the research community and several papers have appeared on this subject. Thanks to this research effort, we now have a better idea on the strengths and weaknesses of the

protocol [6], [7], [8], [9]. We also have a clear idea on the peers' behavior (i.e., arrival and departure processes), and on the quality of service they experience [10], [11], [12]. But so far, little effort has been spent to understand the properties of the distribution overlay generated by BitTorrent. As already showed by Urvoy et al. [13], the time to distribute a file in BitTorrent is directly influenced by the overlay topology. For example, it is reasonable to believe that BitTorrent performs better on a full mesh overlay than on a chain one. In addition, as compared to a chain, a full mesh overlay makes BitTorrent more robust to peers' departures and overlay partitions.

We conduct in this paper extensive simulations to isolate the main properties of the overlay generated by BitTorrent. Our contributions are summarized as follows.

- We first evaluate the impact of the overlay properties on the BitTorrent efficiency. We show that a large peer set increases the efficiency of BitTorrent, and that a small diameter is a necessary, but not sufficient, condition for this efficiency. We also show that the time for a peer to reach its maximum peer set size depends on the size of the torrent it joins. The larger the torrent when a peer joins it, the longer the time for this peer to reach its maximum peer set size.
- We then study the properties of the overlay generated by BitTorrent. We show that BitTorrent generates a graph with with a small diameter. However, this graph is not random and the average peer set size is significantly lower than the maximum possible peer set size. We also show that this overlay is robust to attacks and to churn.
- We show that the properties of the overlay are not significantly impacted by the torrent size, and that a peer set size of 80 is a sensible choice. However, a larger peer set size increases the efficiency of the protocol at the expense of a higher overhead on each peer. We also explain why a maximum number of outgoing connections set to half the maximum peer set size is a good choice, and we show that a large fraction of NATed peers decreases significantly the robustness of the overlay to attacks.
- Finally, we evaluate the impact of *peer exchange* on the overlay properties. Whereas peer exchange allows peers to reach fast their maximum peer set size, it builds a chain-like overlay with a large diameter.

The closest work to ours is the one done by Urvoy et al. [13]. The authors focus on two parameters, the maximum peer set size and the maximum number of outgoing connections. As a result, they show that these two parameters influence the distribution speed of the content and the properties of the overlay.

In this paper, we go further and we provide an analysis that highlights the relation between the overlay properties and the performance of BitTorrent. We also present an in-depth study that characterizes the properties of the BitTorrent overlay. Finally, we show how the overlay properties change as we vary the different system parameters. These parameters include, in addition to the maximum peer set size and maximum number of outgoing connections, the torrent size (i.e., number of peers), the percentage of NATed peers, and the peer exchange extension protocol.

The rest of this paper is organized as follows. In Section II we give a brief overview of BitTorrent. In Section III we describe our methodology and we give results in Sections IV and V. In Section VI we discuss the impact of peer exchange on the overlay and we conclude the work with Section VII.

II. OVERVIEW OF BITTORRENT

BitTorrent is a P2P file distribution protocol with a focus on scalable and efficient content replication. In particular, BitTorrent capitalizes on the upload capacity of each peer in order to increase the global system capacity as the number of peers increases. This section introduces the terminology used in this paper and gives a short overview of BitTorrent.

A. Terminology

The terminology used in the BitTorrent community is not standardized. For the sake of clarity, we define here the terms used throughout this paper.

Torrent: A torrent is a set of peers cooperating to share the same content using the BitTorrent protocol.

Tracker: The tracker is a central component that stores the IP addresses of all peers in the torrent. The tracker is used as a rendez-vous point in order to allow new peers to discover existing ones. The tracker also maintains statistics on the torrent. Each peer periodically (typically every 30 minutes) report, for instance, the amount of bytes it has uploaded and downloaded since it joined the torrent.

Leecher and Seed. A peer can be in one of two states: the *leecher* state, when it is still downloading pieces of the content, and the *seed* state, when it has all the pieces and is sharing them with others.

Peer Set: Each peer maintains a list of other peers to which it has open TCP connections. We call this list the peer set. This is also known as the neighbor set.

Neighbor: A neighbor of peer P is a peer in P's peer set.

Maximum Peer Set Size: Each peer cannot have a peer set larger than the maximum peer set size. This is a configuration parameter of the protocol.

Average Peer Set Size: The average peer set size is the sum of the peer set size of each peer in the torrent divided by the number of peers in that torrent.

Maximum Number of Outgoing Connections: Each peer has a limitation on the number of outgoing connections it can establish. This is a configuration parameter of the protocol.

Pieces and Blocks: A file transferred using BitTorrent is split into pieces, and each piece is split into multiple blocks. Blocks are the transmission unit in the network, and peers can only share complete pieces with others. A typical piece size is equal to 512 kBytes, and the block size is equal to 16 kBytes.

Official BitTorrent Client: The official BitTorrent client [5], also known as *Mainline* client, was initially developed by Bram Cohen and is now maintained by the company he founded.

B. BitTorrent Overview

Prior to distribution, the content is divided into multiple pieces, and each piece into multiple blocks. A *metainfo file* is then created by the content provider. This metainfo file, also called a torrent file, contains all the information necessary to download the content and includes the number of pieces, SHA-1 hashes for all the pieces that are used to verify the integrity of the received data, and the IP address and port number of the tracker.

To join a torrent, a peer P retrieves the metainfo file out of band, usually from a well-known website, and contacts the tracker that responds with an initial peer set of randomly selected peers, possibly including both seeds and leechers. This initial peer set is augmented later by peers connecting directly to this new peer. Such peers are aware of the new peer by receiving its IP address from the tracker. If ever the peer set size of a peer falls below a given threshold, it re-contacts the tracker to obtain additional peers.

Once P has received its initial peer set from the tracker, it starts contacting peers in this set and requesting different pieces of the content. BitTorrent uses specific peer and piece selection strategies to decide with which peers to reciprocate pieces, and which pieces to ask to those peers. The piece selection strategy is called the local rarest first algorithm, and the peer selection strategy is called the choking algorithm. We describe briefly those strategies in the following.

Local rarest first algorithm: Each peer maintains a list of the number of copies of each piece that peers in its peer set have. It uses this information to define a rarest pieces set, which contains the indices of all the pieces with the least number of copies. This set is updated every time a neighbor in the peer set acquires a new piece, and each time a peer joins or leaves the peer set. The rarest pieces set is consulted for the selection of the next piece to download.

Choking algorithm: A peer uses the choking algorithm to decide which peers to exchange data with. The choking algorithm is different when the peer is a leecher or a seed. We only describe here the choking algorithm for leechers. The algorithm gives preference to those peers who upload data at high rates. Once per *rechoke period*, typically set to ten seconds, a peer re-calculates the data receiving rates from all peers in its peer set. It then selects the fastest ones, a fixed number of them, and uploads only to those for the duration of the period. We say that a peer unchokes the fastest uploaders

via a *regular unchoke*, and chokes all the rest. In addition, it unchokes a randomly selected peer via an *optimistic unchoke*. The rational is to discover the capacity of new peers, and to give a chance to peers with no piece to start reciprocating. Peers that do not contribute should not be able to attain high download rates, since such peers will be choked by others. Thus, free-riders, i.e., peers that never upload, are penalized. The algorithm does not prevent all free-riding [14], [8], but it performs well in a variety of circumstances [7]. Interested readers can refer to Sections 2.3.1 and 2.3.2 in [6] for a detailed description of the choking algorithm for leechers and seeds.

III. SIMULATION METHODOLOGY

To evaluate the properties of the overlay distribution, we have developed a simulator that captures the evolution of the overlay over time, as peers join and leave. We present here the methodology used and in particular the use of simulations over experiments in Section III-C.

A. Parameters Used in the Simulations

BitTorrent has the following parameters to adjust the overlay topology: (1) the maximum peer set size, (2) the maximum number of outgoing connections, (3) the minimum number of neighbors before re-contacting the tracker, and (4) the number of peers returned by the tracker. The default value of those four parameters can be different depending on the version of BitTorrent. For example, the maximum peer set size was recently changed in the mainline client [5] from 80 to 200. Our study shows how these parameters influence the properties of the overlay and the efficiency of BitTorrent.

Another parameter that can have an impact on the overlay properties is the percentage of NATed peers. We will evaluate how this parameter influences the overlay properties. Note that a NATed peer refers to a peer behind a NAT or a firewall.

B. Simulation Details

Our Simulator, that we made public [15], was developed in MATLAB. We have simulated the tracker protocol as it is implemented in the BitTorrent mainline client 4.0.2. In the following, we give the details of our simulator. First of all, the tracker keeps two lists of peers, L_{nated} for NATed peers and $L_{not-nated}$ for non NATed ones. Assume that the percentage of NATed peers in the torrent is $X\%$. Thus, when a new peer P_i joins the torrent, it is considered NATed with a probability of $X\%$. Then, P_i contacts the tracker, which in turn returns the IP addresses of up to σ (e.g., 50) non NATed existing peers (if there are any). These σ IP addresses are selected at random from the $L_{not-nated}$ list. Then, the tracker adds P_i to L_{nated} if P_i is NATed or to $L_{not-nated}$ otherwise.

When P_i receives the list of peers from the tracker, it stores them in a list called $L_{tracker}^{P_i}$. Then, P_i starts initiating connections to those peers sequentially. When P_i initiates a connection to peer P_j, P_i removes P_j from $L_{tracker}^{P_i}$. When a peer P_j receives a connection request from peer P_i, P_j will accept this connection only if its peer set size is less than the maximum peer set size. In this case, P_i adds P_j to its list of neighbors $L_{neighbors}^{P_i}$. P_j also adds P_i to $L_{neighbors}^{P_j}$. Note that, in practice, peer P_i would initiate TCP connections to the peers in its $L_{tracker}^{P_i}$. In our simulator, establishing a connection between peers P_i and P_j results in adding P_i to the list of neighbors of P_j $L_{neighbors}^{P_j}$ and also adding P_j to the list of neighbors of P_i $L_{neighbors}^{P_i}$. This is reasonable because our goal is to reproduce the topology properties of the overlay and no data exchange is simulated over the links between peers.

After the connection has been accepted or refused by P_j, P_i initiates a new connections to the next peer in $L_{tracker}^{P_i}$. Peer P_i keeps on contacting the peers it discovered from the tracker until (1) it reaches its maximum number of outgoing connections, or (2) $L_{tracker}^{P_i}$ becomes empty.

Assume that P_i and P_j are neighbors. When P_j leaves the torrent, P_i removes P_j from its list of neighbors $L_{neighbors}^{P_i}$. The tracker also removes P_j from L_{nated} or $L_{not-nated}$ depending on whether P_j was NATed or not. In addition, P_i will try to replace the neighbor it lost. For this purpose, P_i checks whether the number of connections it has initiated to its actual neighbors is less than the maximum number of outgoing connections. If this is the case, P_i checks whether it still knows about other peers in the torrent, i.e., if $L_{tracker}^{P_i}$ is not empty. If this is the case, it contacts them sequentially until either (1) one of them accepts the initiated connection or (2) $L_{tracker}^{P_i}$ becomes empty.

Whenever the peer set size of P_i falls below a given threshold (typically 20), it recontacts the tracker and asks for more peers. We set the minimum interval time between two requests to the tracker to 300 simulated seconds.

Finally, each peer contacts the tracker once every 30 minutes to indicate that it is still present in the network. If no report is received from a peer within $30 - 45$ minutes, the tracker considers that the peer has left and deletes it from L_{nated} or $L_{not-nated}$.

Our simulator mimics the real overlay topology construction in BitTorrent and therefore, we believe that our conclusions will hold true for real torrents.

C. Simulations vs. Experiments

There are three reasons that motivated us to perform simulations and not experiments. First, in BitTorrent, we cannot use solutions that rely on a crawler to infer the topology properties as already done in the context of Gnutella [16]. The reasons is that BitTorrent does not offer distributed mechanisms for peers discovery or data lookup. Thus, there is no way to make a BitTorrent peer give information about its neighbors.

Second, we cannot take advantage of existing traces collected at various trackers. The reason is that a peer never sends information to the tracker concerning its connectivity with other peers, e.g., its list or number of neighbor.

Third, we can experimentally create our own controlled torrents. However, in order to give significant results, we need torrents of moderate size with more than 1000 peers, which is not easy to obtain. In addition, as we have much less flexibility with real experiments, and as we are only concerned by the
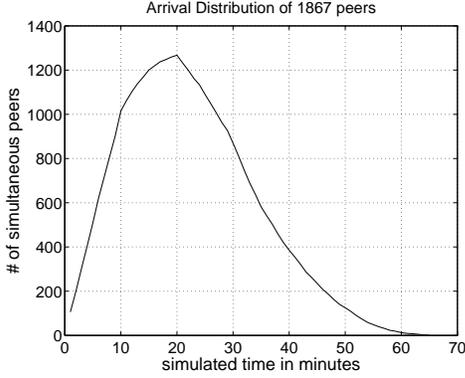
Fig. 1. The evolution of our torrent size over time. The overall number of peers that join this torrent from the beginning to the end is equal to 1867, and the maximum number of simultaneous peers is about 1250. *The rate at which peers join the torrent decreases exponentially with time.*

overlay construction (except in Section IV-A) which is far easier to simulate than the data exchange protocol, we decided to run simulations instead of experiments. We validate our simulator on a small torrent of 420 peers in Section V-B.

D. Arrival Distribution of Peers

We assume that peers' arrivals follow an exponential distribution, i.e., the rate at which peers join the torrent decreases exponentially with time. More precisely, we split the simulated time into slots. Each slot represents 10 minutes of simulated time. The first slot of time refers to the first 10 simulated minutes. More formally, slot i is defined as the simulated time elapsed between the moment $t = (i-1) \cdot 10$ minutes and the moment $t = i \cdot 10$ minutes. Then, within each slot of time i, the number of new peers that join the torrent is computed as

$$
\begin{aligned}
arrivals\ at\ slot\ i &= 1000 \cdot \exp^{-0.7 \cdot (i-1)} \ \ if\ i \le 4 \quad (1) \\
&= 0 \ if\ i > 4
\end{aligned}
$$

Each peer stays on-line for a random amount of time uniformly distributed between 10 and 20 simulated minutes. Under this assumption on the arrival process, 1000 peers will arrive during the first 10 minutes of the simulations, 497 peers during the second 10 minutes, 247 peers during the third 10 minutes, 123 peers during the fourth 10 minutes. Note that no peer will arrive after the first 40 minutes of the simulation. As a result, we have more arrivals than departures during the first two time slots. In contrast, starting from the third time slot, the departure rate becomes higher than the arrival rate. The torrent size that results from these arrivals and from the lifetime distribution described above corresponds to a typical torrent size evolution [10], [11]. The overall number of peers that join this torrent from the beginning to the end is equal to 1867, and the maximum number of simultaneous peers is about 1250.

Even if this torrent is of moderate size, we will show later that it allows us to gain important insights on the properties of the overlay. Moreover, we will explain how we can extrapolate our results to larger torrents. Note that, the lifetime of our torrent is of 70 simulated minutes and the average lifetime of

a peer is 15 minutes. One may wonder whether this is realistic as BitTorrent is mostly used to download large files. Typically, the lifetime of a BitTorrent's peer is of several hours and the torrent's lifetime ranges from several hours to several months. However, we are interested only in the construction of the overlay and not in the data exchange. Thus, we only need to see how the overlay adapts dynamically to the arrival and departure of peers, which is ensured by the arrival distribution we consider. As a result, considering torrents and peers with larger lifetimes will not give any new insights. It will only increase the run time of the simulations.

E. Metrics

We consider 4 different metrics to evaluate the overlay properties in this paper. Those metrics are discussed below.

Average peer set size: The peer set size is critical to the efficiency of BitTorrent. Indeed, the peer set size impacts the piece and peer selection strategies, which are at the core of the BitTorrent efficiency.

The piece selection strategy aims at creating a high diversity of pieces among peers. The rational is to guarantee that each peer can always find a piece it needs at any other peer. This way, the peer selection strategy can choose any peer in order to maximize the efficiency of the system, without being biased by the piece availability on those peers. However, this piece selection strategy is based on a version of rarest first with local knowledge. Whereas with global rarest first each peer replicates pieces that are globally the rarest, with local rarest first each peer replicates pieces that are the rarest in its peer set. Therefore, the peer set size is critical to the efficiency of local rarest first. The larger the peer set, the closer local rarest first will be to global rarest first.

The peer selection strategy aims at encouraging high peer reciprocation by favoring peers who contribute. Recently, Legout et al. [7] showed that peers tend to unchoke more frequently other peers with similar upload speeds, since those are the peers that can reciprocate with high enough rates. Thus, the larger the peer set, the higher the probability that a peer will find peers with similar upload capacity and the more efficient the choking algorithm. We confirm this analysis with simulations in Section IV-A.

Speed to converge to the maximum peer set: As we will show later, a large peer set helps the peer to progress fast in the download of the file. Thus, it is important to investigate how long a peer takes in order to reach its maximum peer set size.

Diameter of the overlay distribution: A short diameter is essential to provide a fast distribution of pieces. In Section IV-C, we develop a simple analysis to support this claim.

Robustness of the overlay to attacks and high churn rate: P2P networks represent a dynamic environment where peers can join and leave the torrent at any time. As a result, it is important to know whether the overlay generated by BitTorrent is robust to high churn rate. In addition, P2P overlays may be subject to attacks that target to partition the overlay. In Section V, we explain how we simulate churn rates and attacks.

IV. IMPACT OF THE OVERLAY ON BITTORRENT'S EFFICIENCY

In this section, we investigate the impact of the overlay structure on the efficiency of BitTorrent. First, we evaluate the impact of the peer set size on BitTorrent efficiency. Second, we analyze the convergence speed of peers toward their maximum peer set size. Finally, we develop a simple model that highlights the relation between the diameter and the distribution speed of pieces. Note that the robustness of the overlay will be studied in Section V through simulations.

A. Impact of the Average Peer Set Size

In this section, we simulate the exchange of pieces in BitTorrent in order to understand the influence of the average peer set size on the efficiency of the protocol. Our simulator runs in rounds where each round corresponds to 10 simulated seconds, which is the typical duration between two calls of the choking algorithm in BitTorrent. Every 10 seconds, we scan all peers one after the other. For each peer, we apply the choking algorithm to identify the set of peers it is actively exchanging data with. Then, we apply the piece selection strategy to discover which pieces to upload to each peer chosen by the choking algorithm. The choking algorithm is implemented as explained in Section 2.3.2 in [6]. We consider that bottlenecks are at the access links of the peers. We do not consider network congestion, propagation delays, and network failures.

We generate three overlays each with 1000 peers and a diameter of 2. They only differ in their peer set size. The first overlay has a peer set size of 50, the second one has a peer set size of 100, and the third one has a peer set of 150. We now explain how to construct an overlay with 1000 peers, with a diameter of 2 and a peer set size of 50. The same methodology is used to construct the two other overlays. We apply this algorithm for each peer sequentially starting with P_1. For each peer P_i, we connect it to other peers randomly selected from the set of peers $\{P_1, \ldots, P_{1000}\}$. The following two conditions should never be violated. First, no peer is allowed to have more than 50 neighbors. Second, a peer cannot be its own neighbor. Note that there is no guarantee that each node will have exactly 50 neighbors. Yet, our results show that very few peers have less than 50 neighbors. Then, we select one source at random to distribute a file of 100MB, which is split into 100 pieces. We assume that all peers join the torrent at its beginning and stay until the end of the simulation. Each peer has a download capacity of 1 Mbit/s, and the upload capacity is randomly selected, with a uniform distribution, between 160 kbit/s and 350 kbit/s. This homogeneous download capacity of peers is reasonable as the replication speed of pieces is usually limited by the upload capacity of peers. Our goal is to study the evolution of the total number of pieces received by each peer in the torrent.

Our results confirm previous ones showed by Urvoy et al. [13] and show that BitTorrent replicates pieces faster with a larger peer set. Indeed, Fig. 2 shows that, as we increase the peer set size from 50 to 100 (respectively from 100 to 150), the replication speed of pieces improves by 12% (respectively by 5%).
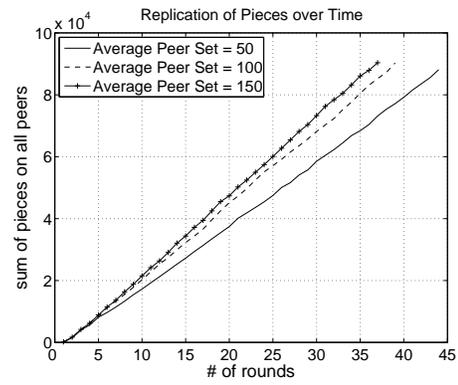

Fig. 2. Impact of the peer set size on the BitTorrent efficiency. These results are the average over ten independent runs. *The larger the peer set size, the faster the replication of pieces.*

In summary, a larger peer set improves the speed of piece replication. However, this is at the expense of an additional load on each peer that has to maintain a larger number of TCP connections and has to handle an additional signaling overhead per connection. Keep in mind that, in the following, and while evaluating the overlay properties, there will be no data exchange between peers. We now only focus on the evolution of the overlay as peers join and leave the torrent.

B. Analysis of the Convergence Speed

A BitTorrent client usually needs time to reach its maximum peer set size. In this section, we show that this is a structural problem in BitTorrent and that the convergence speed depends on the torrent size and on the arrival rate of peers. We consider in our analysis a maximum peer set size of 80, a maximum number of outgoing connections of 40, and 50 peers returned by the tracker. We have chosen fixed values for the sake of clarity, and it is straight forward to extend our analysis to other parameter sets.

When a new peer P_i joins the torrent, it receives from the tracker the IP addresses of 50 peers chosen at random among all peers in the torrent. Then, P_i connects to at most 40 out of these 50 peers. To complete its peer set and have 80 neighbors, P_i keeps on cumulating new connections received from the peers that arrive after it. One can easily derive on average how long a peer needs to wait until it completes its peer set.

We assume that the number of peers in the torrent is N_s when P_i arrives. We also assume that P_i has succeeded to initiate 40 outgoing connections and still misses 40 incoming connections in order to reach its maximum peer set of 80 connections. Therefore, the probability that peer P_i receives a new connection from a new peer P_j joining the torrent is $\frac{40}{N_s}$. Thus, the number of peers K that should arrive after peer P_i in order for this peer to cumulate 40 incoming connections is on average given by:

$$1 = \sum_{n=N_s+1}^{N_s+K} \frac{1}{n} \qquad (2)$$

Fig. 3 shows K as a function of N_s as obtained from Eq. (2). We see that the time for a peer to reach its maximum peer set
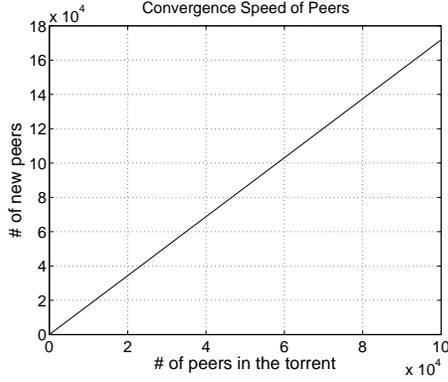
Fig. 3. Convergence speed of peers toward their maximum peer set size. *The number of peers that should arrive after peer P_i so that P_i receives 40 incoming connections depends linearly on the size of the torrent when P_i has joined the torrent.*
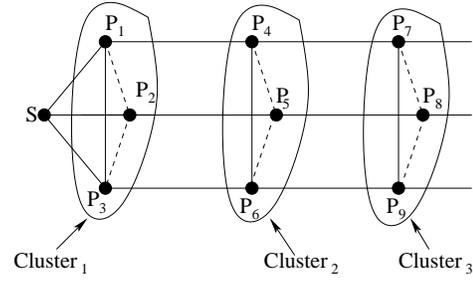

Fig. 4. An example of a chain-like overlay. For clarity, we consider only 3 chains that expand in parallel. At each level in this overlay, we have a cluster that includes three peers fully interconnected with each other. *The distribution time of the file increases linearly with the number of clusters in the overlay.*

size increases linearly with the torrent size N_s. For example, peer P_{100} should wait the arrival of 173 peers after it in order to receive 40 incoming connections, peer P_{1000} should wait for 1720 peers and peer peer P_{10000} for 17184 peers.

This linear dependency can be further shown through the following approximation obtained from Eq. 3:

$$K \sim (e - 1) \cdot N_a \tag{3}$$

The error generated by this approximation is low even for very small torrent sizes. For example, we obtain an error of 0.6% for a torrent of 100 peers and an error of 0.09% for a torrent of 1000 peers.

In summary, the larger the torrent when a peer joins it, the longer this peer will wait to reach its maximum peer set size.

C. Impact of the Diameter of the Distribution Overlay

Yang et al. [17] shows that the service capacity of P2P protocols scales exponentially with the number of peers in the torrent. In this section, we apply their analysis to show the impact of the diameter on the capacity of service of P2P protocols.

We consider a torrent with $N = 2^k$ peers. We assume that all peers have the same upload and download capacity b. Moreover, we assume that all peers join the system at time $t = 0$ and stay until the file is distributed to all peers. The unit of time is $T = \frac{C_s}{b}$, where C_s is the content size. Each peer downloads the content from a single peer at a time. A peer can start uploading when it receives entirely the content. Then, it can upload to a single peer at a time. We finally assume that the file is initially available only at the source S.

At time $t = 0$, S starts serving the file to peer P_1. At time $t = T$, P_1 receives completely the file and starts serving it to peer P_2. At the same time, S schedules a new copy of the file to peer P_3. After $l.T$ units of time, 2^l peers have entirely the file. As a result, the number of sources, thus the capacity of service, scales exponentially with time. However, this means that, at any time $i \cdot T$, the 2^i sources of the file should find 2^i other peers that have not yet received the content. In other words, each of the 2^i sources must have a direct connection in the overlay to a different peer that does not have yet the

content. Whereas it is likely that such a condition is verified most of the time for an overlay with a small diameter, it is not clear what happens when the diameter is large.

Now, we evaluate how the capacity of service scales on the chain-like overlay shown in Fig. 4. The overlay includes multiple levels. At each level, we have a cluster that includes 2^m peers. Each peer is connected to all peers in its cluster. In addition, it maintains one connection to the two clusters that surround its own cluster. The source is connected only to the peers in the first cluster. For this overlay, at time $t = 0$, the source serves the file to peer P_1 in the first cluster. At time $t = T$, after receiving the entire file, P_1 starts serving it to the peer it knows in the second cluster while S schedules a new copy of the file to peer P_2, in the first cluster. At time $t = 2.T$, P_1 does not know any other peer in the second cluster and therefore, it will serve the file to a new peer in its own cluster. We can easily verify that the intra-cluster capacity of service, i.e., the capacity of service inside a cluster once it has at least once source of the content, increases exponentially with time. However, the inter-cluster capacity of service, i.e., the time for each cluster to have at least one source of the content, increases linearly with time. In other words, once the file is served by the source S, it needs $p.T$ units of time to reach the cluster P. Thus, for a chain with $N_{clusters}$ of size 2^m each, the service time of the file is $(N_{clusters} + m).T$, where $N_{clusters}.T$ units of time are needed to reach the Nth cluster in the overlay and $m.T$ units of time are needed to duplicate the file over the 2^m peers inside the last cluster. As a result, a chain-like overlay fails to keep peers busy all the time and, consequently, the distribution time of the file increases linearly with the number of clusters in the system.

In summary, a short diameter is necessary to have a capacity of service that scales exponentially with time. However, this condition is not sufficient. For instance, a star overlay where all peers are connected to the same peer in the center has a diameter of 2. In this topology, the peer at the center of the star is a bottleneck, which leads to a poor capacity of service. Therefore, when analyzing the properties of an overlay, the diameter should be interpreted along with the shape of the overlay before making any conclusion.
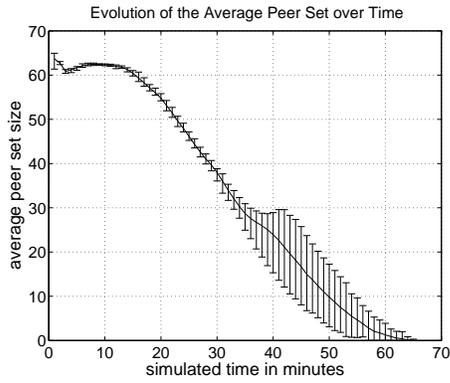
Fig. 5. The average peer set size over time for the initial scenario, averaged over ten independent runs. At a given time t, the average peer set size is the sum of the peer set size at time t of each peer in the torrent divided by the number of peers in that torrent. The error bars indicate the minimum and maximum. *The average peer set size is lower than the maximum peer set size.*
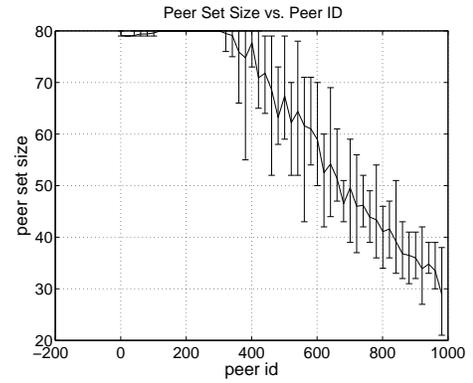

Fig. 6. The peer set size as a function of the peer id at time $t = 10$ minutes, averaged over ten independent runs. The error bars indicate the minimum and maximum. Peers are ordered according to their arriving time, the smaller the index the earlier the arrival time. *The later a peer joins the torrent, the smaller its peer set size.*

V. CHARACTERIZING THE PROPERTIES OF BITTORRENT'S OVERLAY

In Section IV we have evaluated the impact of the overlay properties on BitTorrent efficiency. In this section, we conduct extensive simulations in order to study the properties of the overlay generated by BitTorrent. We first describe the properties of the overlay for a default set of parameters. Then, we vary some of them in order to identify their impact on the overlay properties. For each simulation, we evaluate the overlay properties according to the four metrics introduced in Section III-E.

A. Initial Scenario

For this initial scenario, we consider a set of parameters used by default in several BitTorrent clients (e.g., mainline 4.x.y [5]). We set the maximum peer set size to 80, the maximum number of outgoing connections to 40, the number of peers returned by the tracker to 50, and the minimum number of peers to 20. We also consider a torrent with 1867 peers, as described in Section III-D, and we assume that no peer is NATed. We study the case of NATed peers in Section V-F.

Average peer set size: As we can see in Fig. 5, BitTorrent generates an average peer set size that is low compared to the maximum peer set size targeted. For example, the average peer set size does not exceed 65 while the maximum peer set size is set to 80. To explain this low average peer set size we focus on the convergence speed.

Convergence speed: In Section IV-B, we have seen that the time for a peer to reach its maximum peer set size depends on the torrent size at the moment of its arrival and on the arrival rate of new peers. In Fig. 6, we depict the distribution of the peer set size after 10 simulated minutes over the first 1000 peers in the torrent. As we can see, the later a peer joins the torrent, the smaller its peer set size. More precisely, the peers that join the torrent earlier reach their maximum peer set size. In contrast, the peers that arrive later do not cumulate enough incoming connections to saturate their peer set, and therefore, their peer set size is around the maximum number of outgoing connections of 40. As a result, the average peer set size is only
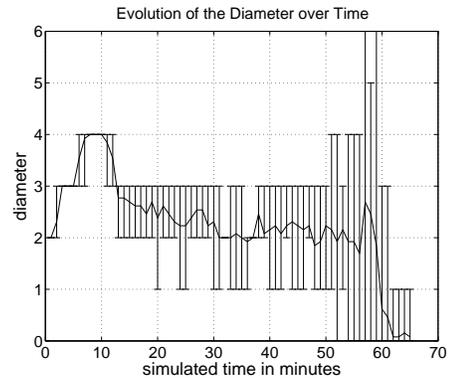

Fig. 7. The diameter of the overlay over time for the initial scenario, averaged over ten independent runs. The error bars indicate the minimum and maximum. *The average diameter is lower than 4 during the entire simulations.*

65. In Fig. 6, one would expect peer P_{1000} to have a peer set size of 40 and not 30. In fact, among the 50 peers returned by the tracker at random, only 30 had a peer set size lower than 80. This is also the reason behind the oscillations in this figure.

Diameter of the overlay: BitTorrent generates an overlay with a short diameter. As we can observe in Fig. 7, the average diameter of the overlay is between 2 and 4 most of the time[1]. However, at the end time of the torrent, the overlay may get partitioned. If we look closely at the right part of Fig. 7, we notice that the minimum value of the diameter goes to zero, a value we use to indicate partitions. Actually, after a massive departure of peers, we may obtain many small partitions each of tens of peers. The partitions are due to the minimum number of neighbors δ a peer should reach before recontacting the tracker for new peers. Indeed, to minimize the interaction between peers and the tracker, a peer asks the tracker for more peers only if its number of neighbors falls below δ. Therefore, as long as the peer set size is larger than δ, to recover from

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[1]In this paper, we compute the diameter of the overlay as the longest shortest path between 1000 peers of the overlay selected at random. This method allows us to obtain very good approximation of the diameter and speeds up the run time of the simulator.
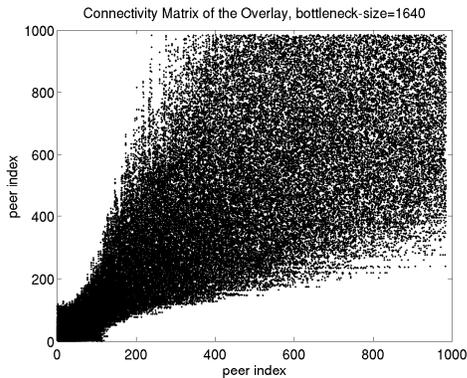
Fig. 8. The connectivity matrix of the BitTorrent's overlay after 10 minutes, for a single run. We only show the first 1000 peers. A dot at (i,j) means that i and j are neighbors. We have a bottleneck of 1640, which refers to the number of connections between the first 80 peers and the rest of the torrent. *BitTorrent does not generate a random graph.*
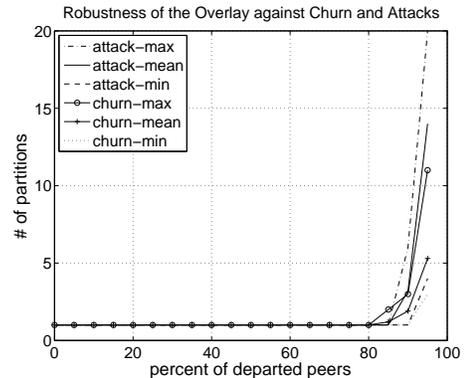

Fig. 9. The number of partitions in the overlay as a function of the percentage of departed peers, averaged over ten independent runs. In addition to the mean, we also draw the min and max of our results. *The overlay is robust to attacks and churn.*

a decrease in its peer set size, a peer has to wait for new incoming connections from newly arriving peers, which does not happen toward the end of the torrent. That is why the torrent does not merge again. To prevent such a behavior, one needs to assign a high value to δ. The value of δ is then a trade-off between having a connected overlay at the end of the torrent, and a high load at the tracker.

In our analysis in Section IV-C, we show that a short diameter is a necessary, but not sufficient, condition for an efficient distribution of the file. We draw in Fig. 8 the shape of the overlay generated by BitTorrent. We see that BitTorrent does not generate a random overlay, and that the overlay has a specific geometry. Indeed, Fig. 8 shows a clustering among peers that arrive first. For example, peer P_{25} is connected only to the first hundred peers. The reason is that when P_{25} arrives, it connects to all the 24 peers already existing in the torrent. Then, P_{25} waits for new arrivals in order to complete the 56 peers it still needs to saturate its peer set. According to Eq. (2), these missing connections can be fulfilled after the arrival of 75 peers on average, $P_{26}, \ldots, P_{100}$. Similarly, when peer P_{200} arrives, it establishes up to 40 outgoing connections. However, P_{200} needs to wait the arrival of a large number of peers in order to complete its 40 incoming connections. This explains why, as compared to P_{25}, the neighbors of P_{200} are selected from a larger set of peers (i.e., between P_{60} and P_{600}). Even though we have this clustering phenomena, the overlay does not include bottlenecks. Actually, the number of connections between the first 80 peers and the rest of the network is equal to 1640. Therefore, the BitTorrent has the potential to allow a fast expansion of the pieces.

Robustness to attacks and churn: We investigate the robustness of the overlay to a massive departure of peers, which can be due to an attack or a high churn rate. We now consider how we simulate the attack scenario. First, we consider the overlay topology shown in Fig. 8, which represents a snapshot of the topology at time $t = 10$. Then, we force the most connected peers to leave. For example, assume that we want to evaluate the robustness of the overlay to attacks after the departure of 30% of the peers. In this case,

we identify the 30% most connected peers in the overlay and we disconnect them from the overlay. Forcing a peer to leave means that we remove all connections between this peer and the rest of the torrent. Once these peers are disconnected, we check whether the overlay becomes partitioned, i.e., includes more than one partition. By varying the percentage of peers that we force to leave, we are able to explore the robustness limits of the BitTorrent overlay.

To simulate a churn rate, we proceed similarly as for the case of an attack. The only difference is that, the peers that we force to leave are selected randomly instead of the most connected ones.

Fig. 9 shows that BitTorrent's overlay is robust to attacks and churn. Indeed, the overlay stays connected, i.e., there is a single partition, when up to 80% of the peers leave due to an attack or to churn rate. When more than 85% of the peers leave the torrent, partitions appear. However, there is one major partition that includes most of the peers and a few others with one peer each.

For example, when 95% of the peers leave the torrent due to an attack, the result of 1 run produced 18 partitions. More precisely, we had 1 partition that included 23 peers, 2 partitions that included each 7 peers, 2 other partitions with 2 peers each, and 13 partitions with 1 single peer each. Similarly, when 95% of the peers leave the torrent due to a high churn rate, the overlay was split into 4 partitions, 1 partition with 43 peers, 1 partition with 5 peers, and 2 partitions with 1 peer each.

In summary, we have seen that the average peer set size is significantly lower than the maximum peer set size, and the peer set size of a peer depends on its arriving time in the torrent. In addition, BitTorrent generates an overlay with a short diameter, but this overlay is not a random graph. However, the overlay is robust to attacks and churn.

B. Validation with Experiments

To validate our simulation results, we have run real experiments using the mainline client 4.0.2 and its tracker implementation that we described in details in Section III-B. In Fig. 10(a) and Fig. 10(b) we draw the connectivity matrix of the overlay as obtained from experiments and simulations

Matrix Connectivity of the Overlay with 420 Peers - Experimental result

(a) Experimental results

Connectivity Matrix of the Overlay with 420 Peers - Simulation Result
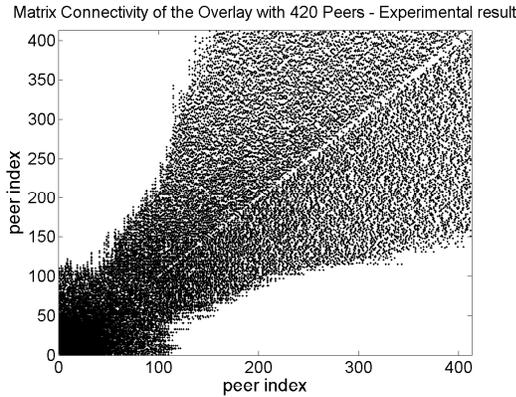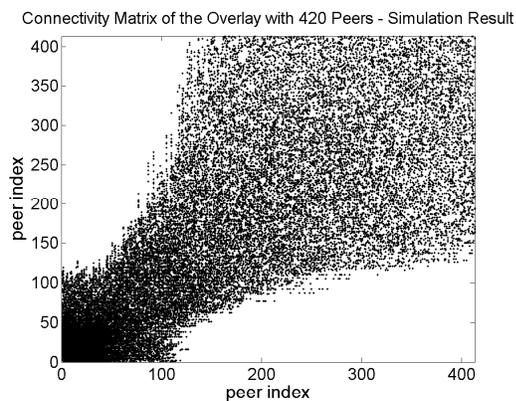
(b) Simulation results

Fig. 10. The connectivity matrix of the BitTorrent's overlay after the arrival of 420 peers, for a single run as obtained from real experiments and simulations. A dot at (i,j) means that i and j are neighbors. *Real experiments and simulations show similar properties of the overlay.*

Fig. 11. The average peer set size over time for different torrent sizes, averaged over ten independent runs. *The average peer set size is independent of the torrent size.*
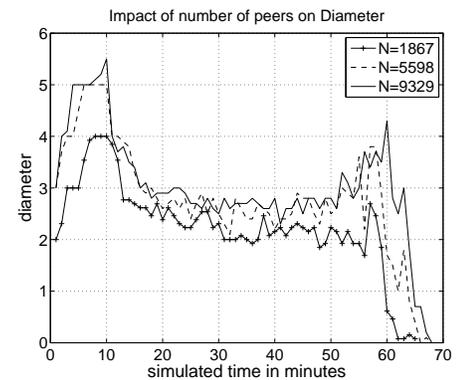
Fig. 12. The diameter over time for different torrent sizes, averaged over ten independent runs. *The diameter increases slowly with the torrent size.*

respectively. The connectivity matrix is computed after the arrival of 420 peers to the network. As we can see from these two figures, the real experiments and the simulations show similar properties of the overlay. As a result, our simulator produces accurate results, and as compared to real experiments, it offers much more flexibility and allows us to consider larger torrents. Therefore, in the following, we will give results only for simulations.

In the next sections, we will investigate how these results are influenced by (1) the size of the torrent, (2) the maximum peer set size, (3) the maximum number of outgoing connections, and (4) the percentage of NATed peers. We will also discuss in Section VI how peer exchange impacts those results.

C. Varying the Number of Peers

The torrent for the initial scenario is of moderate size. Indeed, it consists of 1867 peers and of a maximum of 1200 simultaneous peers. To validate how the results of Section V-A are impacted by larger torrents, we have considered two other

torrent sizes: 5598 and 9329 peers. For the largest torrent, the maximum number of simultaneous peers is 6282.

Average peer set size: The average peer set size does not depends on the torrent size. Indeed, Fig. 11 shows that the average peer set size is roughly the same for the three torrent sizes. For example, after 10 minutes, when the number of simultaneous peers is 1200 for the smallest torrent and 6282 for the largest torrent, the average peer set size is the same for the three torrents. The evolution of the peer set size for the three torrents is similar to the once presented in Fig. 6. The peer set size decreases from 80 for the peers that join the torrent early to around 40 for the peers that arrive toward the end.

Convergence speed: According to section IV-B, the convergence speed of the peer set decreases when the torrent size increases as shown in Fig. 3.

Diameter of the overlay: The diameter of the overlay increases slowly with the torrent size. As we can observe in Fig. 12, after 10 minutes, the diameter of the overlay is 4 for the smallest torrent and 5.5 for the largest torrent. The connectivity matrix presents the same characteristics as in Fig. 8 for the three torrents.

Robustness to attacks and churn: Fig. 13 shows that the robustness of the overlay is independent of the torrent size. In particular, the three overlays stay connected for up to 85%

Fig. 13. The robustness of the overlay under churn and attacks, averaged over ten different experiments. *The overlay shows similar robustness for the different torrent sizes.*

Fig. 14. The average peer set size as a function of the maximum peer set size, averaged over ten independent runs. The error bars indicate the minimum and maximum. *The average peer set size is a linear function of the maximum peer set size.*
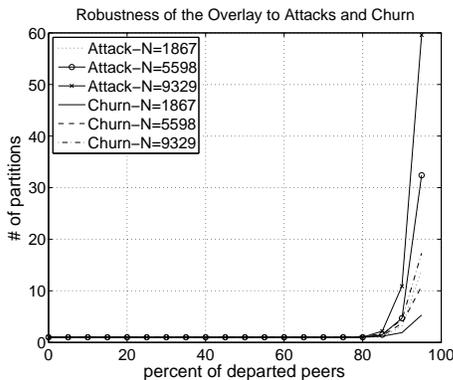
of peer departures. Then, the overlay is partitioned with a single large partition and several partitions with a few peers. To show the similarity at the robustness level for the different torrent sizes, we now analyze the number of partitions that we obtain with the attack scenario after the departure of 90% of the most connected peers. Our results show that the torrent of 1867 peers becomes partitioned into 4 partitions with one partition of 96 peers and three others of one single peer each. Similarly, the torrent of 5598 peers becomes partitioned into 5 partitions with one partition of 294 peers and four others of one single peer each. Finally, the torrent of 9329 peers becomes partitioned into 9 partitions with one partition of 498 peers, another partition of two peers, and seven other partitions of one peer each. We found the same tendency for the churn scenario.

In summary, we have investigated the impact of the torrent size on the properties of the overlay formed by BitTorrent. We have found that the results obtained for the initial scenario still hold for larger torrents. Therefore, and in order to reduce significantly the run time of these simulations, in the following, we will focus on a torrent with 1867 peers.

D. Impact of the Maximum Peer Set Size

The maximum peer set size is usually set to 80. However, some clients choose higher values of this parameter, e.g., mainline 5.x [5] has a maximum peer set size set to 200. In this section, we evaluate the impact of this parameter on the properties of the overlay.

We run simulations with a maximum peer set size Δ varying from 20 to 200. For each value of Δ, we set the maximum number of outgoing connections O_{max} to $\frac{\Delta}{2}$, the number of peers returned by the tracker to $\frac{\Delta + O_{max}}{2}$, and the minimum number of neighbors δ to 20. Then, we evaluate the overlay after 10 simulated minutes, because it is the time at which the number of simultaneous peers in the torrent reaches its upper bound of 1200 peers.

Note that there is no specific rule to set the value of the number of peers returned by the tracker σ when we change the maximum peer set size Δ and maximum number of outgoing connections O_{max}. Intuitively, σ should be larger than O_{max}.
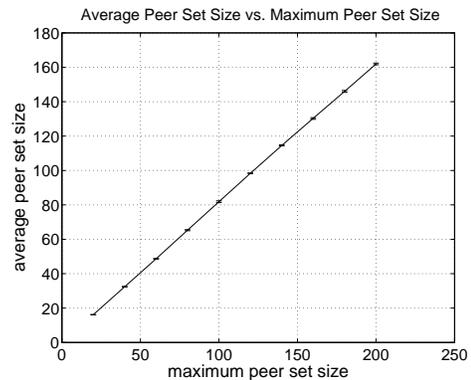
The reason is that each peer P_i seeks to initiate O_{max} connections, which is only possible if the tracker provides P_i with the addresses of at least O_{max} other peers in the torrent. Yet, the value of σ should not be much larger than O_{max} in order not to increase the load on the tracker. We tried several values of σ between O_{max} and Δ, but we obtained similar results. Therefore, we decided to set σ to $\frac{\Delta + O_{max}}{2}$.

Average peer set size: The average peer set size increases linearly with the maximum peer set size Δ. Indeed, Fig. 14 shows that the average peer set size is roughly equal to $\frac{2 \cdot \Delta}{3}$. For instance, for a maximum peer set size of 100, the average peer set size is 65.

We found this linear trend in all our simulations, but the slope depends on the instant at which we perform the measurements.

Convergence speed: We extend the analysis in Section IV-B by considering a variable maximum peer set size Δ and a maximum number of outgoing connections O_{max}. We rewrite Eq. (2) as follows:

$$
\begin{aligned}
\Delta - O_{max} &= \sum_{n=N_s+1}^{N_s+K} \frac{O_{max}}{n} \\
\frac{\Delta}{O_{max}} &= 1 + \sum_{n=N_s+1}^{N_s+K} \frac{1}{n} \quad\quad (4)
\end{aligned}
$$

where $\Delta - O_{max}$ is the number of missing connections, i.e., the number of incoming connections the peer is still waiting for, assuming that the peer has succeeded to initiate O_{max} outgoing connections. $\frac{O_{max}}{n}$ is the probability that a peer receives a new incoming connection from a new peer given the number of peers n in the torrent. Recall that N_s represents the torrent size at the moment of the arrival of peer P_i, and K is the average number of peers that should arrive after peer P_i in order for this peer to complete its $\Delta - O_{max}$ missing connections. We assume that no peer leaves the system. When $O_{max} = \frac{\Delta}{2}$ Eq. (4) is equivalent to $1 = \sum_{n=N_s+1}^{N_s+K} \frac{1}{n}$, which is Eq. (2). Therefore, when $O_{max} = \frac{\Delta}{2}$, the convergence speed is independent of the value of Δ.

Diameter of the overlay: The diameter of the overlay decreases slowly with the maximum peer set size Δ as shown

Fig. 15. The diameter of the overlay as a function of the maximum peer set size, averaged over ten independent runs. The error bars indicate the minimum and maximum. *The diameter decreases slowly after a peer set size of* 100.

Fig. 17. The connectivity matrix of the overlay after forcing 45% of the most connected peers to leave the torrent, for a single run. A dot at (i,j) means that i and j are neighbors. *The first peers are disconnected from the rest of torrent.*

Fig. 16. The robustness of the overlay under churn and attacks, averaged over ten different experiments. *The robustness of the overlay increases with the maximum peer set size.*

in Fig. 15. The diameter is 6.5 when Δ is 20, 5.5 when Δ is 40, 4.5 when Δ is 80, and 3 when Δ is 200. However, in contrast to the average peer set size, there is no clear trend that can be used to predict the diameter as a function of the maximum peer set size.

Robustness to attacks and churn: The robustness of the overlay increases with the maximum peer set size Δ as shown in Fig 16. For example, when we set Δ to 40, 80, and 200, the overlay is not partitioned for up to respectively 65%, 80%, and 95% of peers that leave. There is no discernible distinction between leaves due to churn or attacks.

However, if we carefully look at Fig. 16, we can see that the attack scenario produces partitions when the percentage of departed peers is at 45%. To understand this behavior, we plot in Fig. 17 the connectivity matrix of the overlay after attacking 45% of the peers. Fig. 17 shows that there are around 12 peers that are disconnected from the rest of the torrent.

From our previous results, we know that the peers that arrive at the beginning of the torrent are the most connected ones and highly connected among each other (see Fig. 8). In addition, these first peers are the most concerned ones by the attack. Recall that the attack scenario forces the most connected peers to leave the torrent. Thus, with a 45% of departed peers, only very few of those first peers will remain present in the torrent after the attack. These few peers will have a very few

neighbors and will become disconnected from other peers. However, if we consider a percentage of departed peers of 50% instead of 45%, more peers will leave the torrent and those 12 peers will disappear. This means that the torrent will be connected again. In contrast, if we consider a percentage of departed peers of 40% instead of 45%, there will be more peers present in the torrent after the attack, which helps the torrent to remain connected.

In summary, the maximum peer set size does not have a major impact on the properties of the overlay, as long as the maximum peer set size is large enough to have a small diameter. In our simulations, we do not see a major difference in the overlay properties between a maximum peer set size of 80 and 200. However, as the maximum peer set size increases linearly the average peer set size, it also increases the speed of replication of the pieces (according to Section IV-A). Therefore, the main reason to increase the maximum peer set size is to improve the speed of replication. But, there is a tradeoff, as a larger maximum peer set size increases the load on each client due to the larger number of TCP connections to maintain and due to the signaling overhead per connection.

E. Impact of the Maximum Number of Outgoing Connections

The maximum number of outgoing connections O_{max} is critical to the properties of the overlay. Indeed, when O_{max} is close to the maximum peer set size Δ, the peer set size will converge fast to Δ, but new peers will find few peers with available incoming connections, hence a larger diameter.

In this section, we evaluate the impact of O_{max} on the overlay properties. For the simulations, we set Δ to 80, the minimum number of neighbors to 20, and we vary O_{max} from 5 to 80 with a step of 5. For each value of Δ and O_{max}, the number of peers returned by the tracker is equal to $\frac{\Delta + O_{max}}{2}$.

Average peer set size: Fig. 18 shows the evolution of the average peer set size as a function of the maximum number of outgoing connections. We see that the average peer set size increases fast with O_{max} when O_{max} is smaller than $\frac{\Delta}{2}$, and it increases slowly with O_{max} when O_{max} is larger than $\frac{\Delta}{2}$. We notice that, a small O_{max} leads to a small average peer
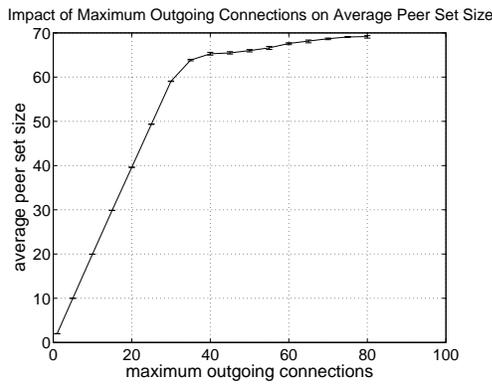
Fig. 18. The average peer set size as a function of the maximum number of outgoing connections, averaged over ten independent runs. The error bars indicate the minimum and maximum. *The average peer set size increases slowly when the number of maximum number of outgoing connections is larger than $\frac{\Delta}{2}$.*
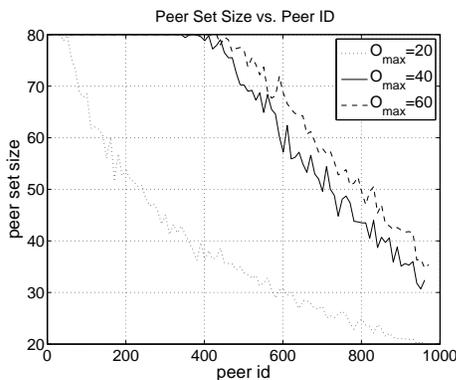

Fig. 19. The peer set size vs. the peer id, at time $t = 10$ minutes, averaged over ten independent simulations. *The peer set size increases slowly when the number of maximum number of outgoing connections is larger than $\frac{\Delta}{2}$.*

set size. For example, when O_{max} is equal to 5, the average peer set size is around 10.

Convergence speed: In Fig. 19 we plot the peer set size of each peer at time $t = 10$ minutes as a function of the peer id for three values of the maximum number of outgoing connections. These outdegree distributions of peers reflect the convergence speed of peers towards their maximum peer set size. As we can see from Fig. 19, the peer set size of the different peers improves with O_{max} when O_{max} is smaller than $\frac{\Delta}{2}$, and it increases slowly with O_{max} when O_{max} is larger than $\frac{\Delta}{2}$. For example, after the arrival of the first 1000 peers $P_1, \ldots, P_{1000}$, peer P_{500} has a peer set size of 34 when O_{max} is at 20 and a peer set size of 70 when O_{max} is at 40. However, when we increase O_{max} from 40 to 60, the peer set size of P_{500} increases from 70 to 76 only. This result means that, when we increase O_{max} beyond $\frac{\Delta}{2}$, the convergence speed of a peer towards its maximum peer set increases slowly. We explain this conclusion as follows. According to Eq. (4), when O_{max} increases, K decreases, where K is the number of peers that should arrive after a peer P_i, so that P_i reaches its maximum peer set size. Indeed, when O_{max} increases, the probability that a peer receives incoming connections from new peers increases too. However, to derive
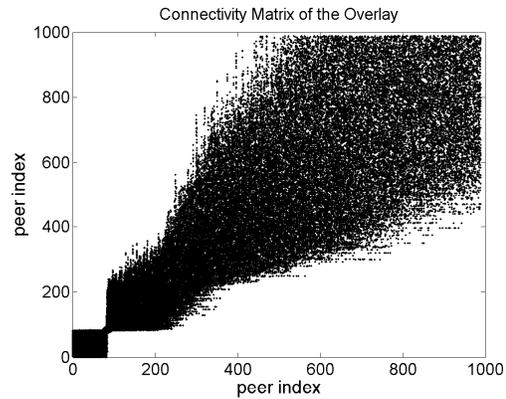
(a) maximum number of outgoing connections of 70
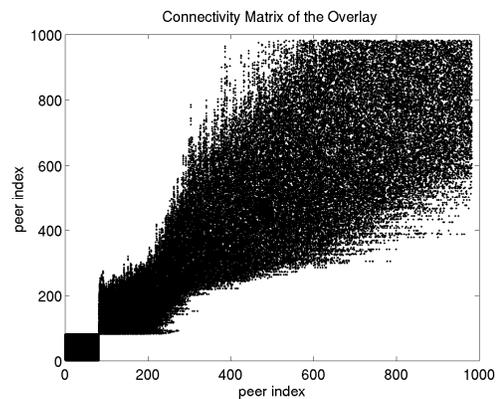
(b) maximum number of outgoing connections of 80

Fig. 20. The connectivity matrix of the BitTorrent overlay after 10 minutes for a maximum number of outgoing connections of 70 and 80, for a single run. A dot at (i,j) means that i and j are neighbors. *When we increase O_{max} beyond $\frac{\Delta}{2}$, the connectivity matrix becomes more narrow around peer index 80.*

Eq. (4), we assumed that a peer succeeds to establish all its allowed O_{max} outgoing connections and that the number of connections it misses is $\Delta - O_{max}$. This is the most optimistic case, and it is not true when O_{max} is larger than $\frac{\Delta}{2}$. Indeed, in that case, peers that arrive at the beginning of the torrent are able to establish a lot of connections among themselves and reach fast their maximum peer set size. However, those peers leave few rooms for incoming connections, as O_{max} is close to the maximum peer set size Δ. Therefore, peers that join later the torrent will not be able to establish O_{max} outgoing connections, which results in a larger number than $\Delta - O_{max}$ of missing connections. As a consequence, the increase in the probability that a peer is selected by new arriving peers is compensated by the increase in the number of missing connections.

Diameter of the overlay: Taking a maximum number of outgoing connections O_{max} larger than $\frac{\Delta}{2}$ increases the diameter of the overlay. As we can see in Fig. 21, for O_{max} equal to 40 (respectively 70), the diameter of the overlay is
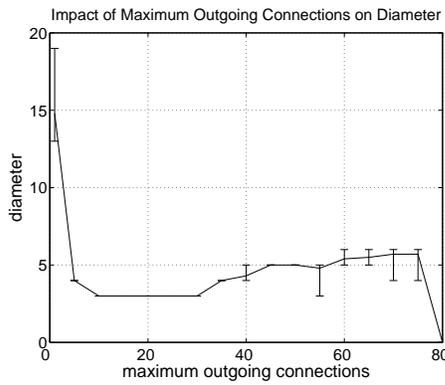
Fig. 21. The diameter of the overlay as a function of the maximum number of outgoing connections, averaged over ten independent runs. The error bars indicate the minimum and maximum. *Taking a maximum number of outgoing connections O_{max} larger than $\frac{\Delta}{2}$ increases the diameter of the overlay.*
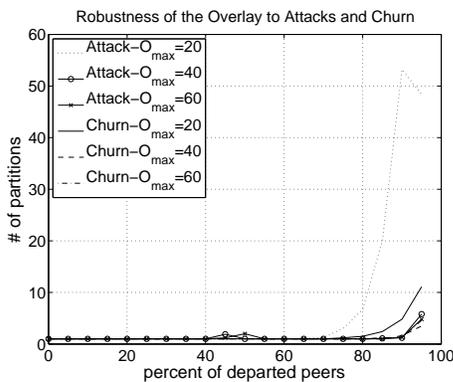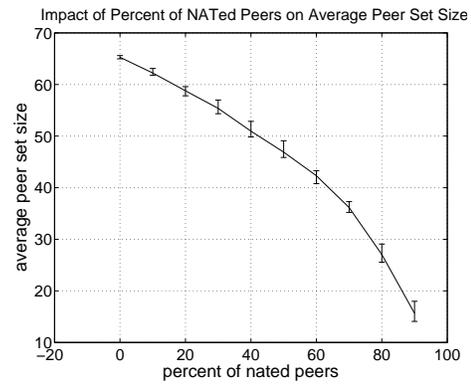

Fig. 23. The average peer set size vs. the percentage of NATed peers, averaged over 10 independent runs. The error bars indicate the minimum and maximum. *The average peer set decreases linearly with the percentage of NATed peers.*

most connected peers to leave the network, a O_{max} of 20 will produce a lot of partitions with a very few peers each. Thus, increasing the number of departing peers removes those "one single peer partitions".

Note that, when O_{max} is set to 40 (respectively to 60), the attack scenario produces partitions when the percentage of departed peers is at 45% (respectively 50%). The reason is that, among the most connected peers, the remaining peers are very few to stay connected with the rest of the torrent.

In summary, setting the maximum number of outgoing connections O_{max} to $\frac{\Delta}{2}$ is a good tradeoff between the average peer set size and the diameter of the overlay.

Fig. 22. The robustness of the overlay under churn and attacks, averaged over ten different experiments. *The robustness of the overlay increases slightly with the maximum peer set size.*

F. Impact of the Number of NATed Peers

In this section, we discuss the impact of the percentage of NATed peers on the overlay properties. When a peer is behind a NAT, it cannot receive incoming connections from other peers in the torrent. However, it can initiate outgoing connections to non NATed ones. For the simulations, we set the maximum peer set size to 80, the maximum number of outgoing connections to 40, the minimum number of neighbors δ to 20, and the number of returned peers by the tracker to 50. Then, we vary the percentage of NATed peers from 0% to 90% with steps of 10.

Average peer set size: BitTorrent mitigates very efficiently the impact of the NATed peers on the overlay. For example, we see in Fig. 23 that as we increase the percentage of NATed peers from 0 to 30%, the average peer set size is reduced from 65 to 55. Indeed, the average peer set size decreases slowly with the percentage of NATed peers. However, the slope of the curve becomes much sharper when the percentage of NATed peers exceeds 60%.

Convergence speed: The convergence speed that we derive in Eq. (2) holds for non NATed peers. When a peer is NATed, it will establish at most O_{max} outgoing connections, which is the higher bound for its maximum peer set size.

Diameter of the overlay: NATed peers do not make the diameter significantly larger. For example, as shown in Fig. 24, when 10% (respectively 80% of the peers are NATed, the average value of the diameter is at 4.5 (respectively 5.5).

equal to 4 (respectively 5.5). When O_{max} is equal to Δ, i.e., 80, the overlay is partitioned. If we focus on the connectivity matrix of the overlay, we observe how the overlay gets partitioned into two partitions. Indeed, Fig. 20(a) shows that when O_{max} is equal to 70, the connectivity matrix becomes narrow around peer index 80. This results in the first 80 peers in the torrent being highly connected among themselves with 3115 connections, and poorly connected with the rest of the torrent with 170 connections. When O_{max} is equal to 80, the first 80 peers become disconnected from the rest of the torrent. This might be a major issue if the source of the torrent is among those 80 peers, which is the regular case.

Robustness to attacks and churn: Fig. 22 draws the robustness of the overlay with a maximum number of outgoing connections O_{max} set to 20, 40, and 60. We observe that large values of O_{max} make the overlay slightly more robust to attacks and churn. For example, in case of an attack, when setting O_{max} to 20, the partitions appear after the departure of 60% of the peers. In contrast, when setting O_{max} to 40 or 60, the partitions appear after the departure of 85% of the peers.

In Fig. 22, we can also show that, when we set O_{max} of 20, the number of partitions decreases at the end of the curve. The reason is that, when we force 90% or more of the
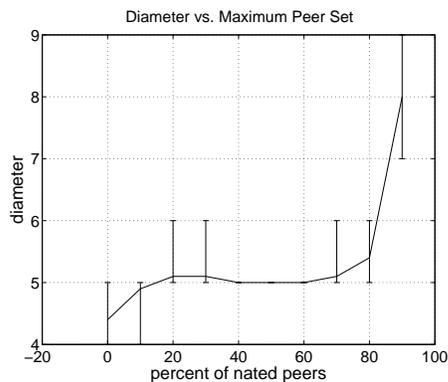
Fig. 24. The diameter of the overlay vs. the percentage of NATed peers, averaged over 10 independent runs. The error bars indicate the minimum and maximum. *The diameter increases slowly with the number of NATed peers.*
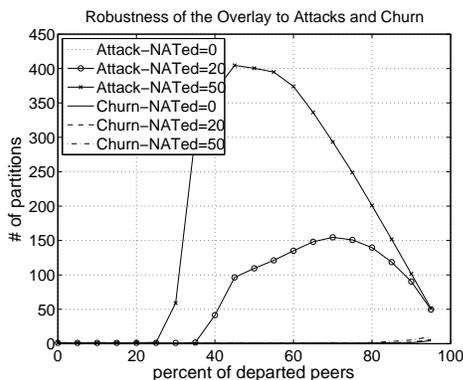
Fig. 25. Robustness of the overlay with different percentage of NATed peers. *The robustness to churn does not depend on the percentage of NATed peers, but the overlay is not robust to attacks when there are NATed peers.*

However, in extreme cases where 90% of the peers are NATed, the diameter can reach 9.

Note that, NATed peers may cause partitions. For example, assume that peer P_i is NATed. It may happen that, out of the peers returned by the tracker to P_i, no one has room for more connections. As a result, P_i will not be able to establish any outgoing connections. In addition, and because it is NATed, P_i cannot receive connections from other peers. As a result, peer P_i will be isolated alone (disconnected from the rest of the torrent) until it contacts the tracker again and discovers more peers. This behavior becomes more common as the percentage of NATed peers increases.

Robustness to attacks and churn: The robustness of the overlay to high churn rates does not depend on the presence of NATed peers. Indeed, Fig. 25 shows that the overlay stays connected when up to 80% of peers leave the torrent. However, the overlay is not robust to attacks when there is a large number of NATed peers. Indeed, Fig. 25 shows that when there are 50% of NATed peers, the overlay starts to be partitioned when 25% of the peers leave due to an attack. We see that the number of partitions decreases for a large percentage of departing peers, because as there are many small partitions, increasing the number of departing peers removes those partitions.

In summary, NATed peers decrease significantly the robust-ness of the overlay to attacks.

VI. IMPACT OF PEER EXCHANGE ON THE OVERLAY

We have seen that BitTorrent generates overlays with a short diameter that are robust to churn and attacks. However, the time for a peer to reach its maximum peer set size depends on the torrent size and peer arrival rate. One way to reach faster the maximum peer set size is to increase the number of requests to the tracker in order to discover more peers and establish more connections. However, such requests increase the load on the tracker, whereas the tracker is known to have scarce resources [18], [19].

In Mai 2005, Azureus 2.3.0.0 [20] introduced a new feature, namely *peer exchange* (PEX), where neighbors periodically exchange their list of neighbors. For example, assume that peers P_i and P_j are neighbors. Then, every minute, P_i sends its list of neighbors to P_j and vice versa. As a result, each peer knows its neighbors and the neighbors of its neighbors. The intuition behind PEX is that peers will be able to discover fast a lot of peers and consequently achieve a larger peer set size.

Note that the results that we have given in previous sections are for the case of BitTorrent without PEX, e.g., the official BitTorrent client [5]. In this section, we extend our work and analyze how PEX impacts the overlay topology of BitTorrent. PEX is becoming very popular and, in addition to Azureus, it is now implemented in several other P2P clients including KTorrent, libtorrent, μTorrent, or BitComet, but with incompatible implementations. To the best of our knowledge, the impact of PEX has never been discussed previously.

A. Simulating PEX

To evaluate the impact of PEX on the overlay topology, we added this feature to our simulator exactly as it is implemented in Azureus. Concerning the communications between peers and the tracker, all what we described in Section III-B is still valid. That is, the tracker keeps two lists, L_{nated} and $L_{not-nated}$ peers. And, when a peer P_i joins the torrent, it gets from the tracker up to σ peers randomly selected from $L_{not-nated}$. Then, P_i stores those IP addresses in its $L_{tracker}^{P_i}$ list and initiates sequentially up to O_{max} connections to those peers. Moreover, P_i will be added at the tracker to either L_{nated} or $L_{not-nated}$.

We now explain the modifications that we made in our simulator. Assume that, at time $t = 0$, a connection has been established between two peers P_i and P_j. Just after, P_i sends its list of neighbors to P_j and vice versa. Then, every 1 simulated minute, P_i and P_j repeat this exchange process.

Assume now that, after performing PEX with its neighbor P_j, P_i discovers peer P_k. Then, P_i checks whether (1) it already has a connection with P_k or (2) it already knows P_k from the tracker. If none of these two conditions holds true, then P_i adds P_k to the list $L_{pex}^{P_i}$ of peers it discovered through PEX. Note that, P_i may receive the IP address of P_k from many neighbors. In this case, P_k will appear only once in $L_{pex}^{P_i}$.
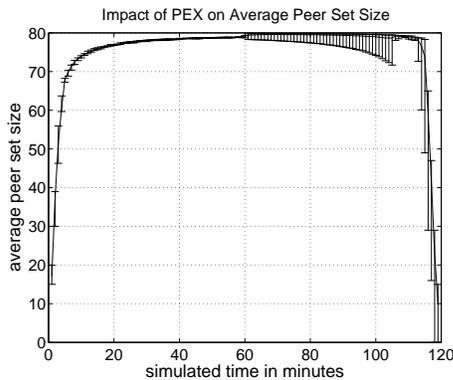
Fig. 26. Evolution of the outdegree of peers with time with PEX, averaged over ten independent runs. The error bars indicate the minimum and maximum. *PEX produces an average peer set size that is very close to the maximum peer set size.*
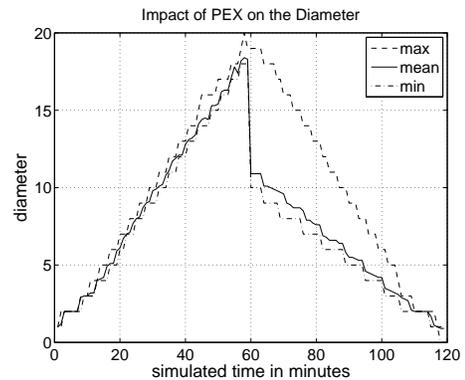

Fig. 27. Evolution of the overlay diameter with time with PEX, averaged over ten independent runs. We plot the mean, max, and min values. *PEX generates overlays with very large diameter.*

Note that, when establishing connections, peers discovered from the tracker are given more priority. For example, assume that peer P_i decides to initiate a new connection, which can be due to the departure of one of its neighbors or after discovering new peers. In this case, P_i contacts first the peers it has discovered from the tracker. If none of those peers accepts the connection request, P_i contacts the peers that it discovered through PEX.
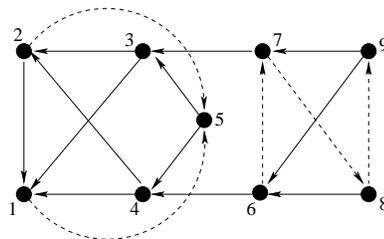

Fig. 28. The topology evolution with PEX with 9 peers. Connections established with the tracker information are shown with solid lines, and connection established with PEX are shown with dashed lines.

B. Analysis of PEX

We implement PEX in our simulator and run simulations with the following parameters. We set the maximum peer set size to 80, the maximum number of outgoing connections to 40, the minimum number of neighbors to 20, and the number of peers returned by the tracker to 50. However, due to the gossiping messages between peers, the PEX feature makes our simulator very slow. In order to save time, we run simulations for a torrent of 1000 peers that arrive to the torrent within the first 60 simulated minutes according to Eq. 1. The departure of peers is scheduled during the next simulated 60 minutes, and it follows a random uniform distribution. For example, if peer A arrives at time $t = 30$, it will leave the network at a random time uniformly selected between $t = 60$ and $t = 120$. Still, this torrent allows us to understand how the overlay is constructed with PEX and how it evolves as peers join and leave.

Average peer set size: PEX meets its intended goal and permits peers to be at their maximum peer set size most of the time as shown in Fig. 26. Moreover, PEX prevents the average peer set size from decreasing in case of a massive departure of peers. Indeed, when a peer loses a connection due to the departure of a neighbor, it can replace it by a new connection to one of its neighbors' neighbors. As a result, the average peer set size stays at its maximum value of 80 as long as there are 80 peers in the torrent.

Convergence speed: Each peer reaches its maximum peer set size within a few gossiping period (that we set to one minute in our simulations).

Diameter of the overlay: The increase in the average peer set size comes at the expense of a larger diameter. As we see in Fig. 27, the maximum value of the diameter reaches 20 when the number of peers in the torrent is 1000.

To explain why PEX produces such a long diameter, we plot in Fig. 28 the evolution of a torrent with 9 peers ($P_1, \ldots, P_9$) that arrive sequentially, one every 1 unit of time. In this example, we set the maximum peer set size to 4, the maximum number of outgoing connections to 2, and the number of peers returned by the tracker to 2. At time $t = 0$, there is only peer P_1. At time $t = 2$, P_2 joins the torrent and connects to P_1. At time $t = 3$, P_3 arrives and connects to P_1 and P_2. Then, P_4 arrives and connects to two existing peers selected at random, say P_1 and P_2. At the end of time $t = 3$, PEX has not yet been used. At time $t = 4$, P_5 arrives and connects to P_3 and P_4, which in turn tell P_1 and P_2 about this new neighbor. At this time, P_1 and P_2 each has a room for one more outgoing connection and both connect to P_5. Thus, at time $t = 4$, only peers P_3 and P_4 can accept new incoming connections, i.e., P_1, P_2, and P_5 have already reached the maximum number of connections. At time $t = 5$, peer P_6 joins the torrent and gets from the tracker the addresses of P_1 and P_4. However, P_6 can only initiate a connection to P_4, as P_5 has already reached its maximum peer set size. Peer P_7 arrives at time $t = 6$, gets the addresses of P_3 and P_5 and initiates one connection to P_3. Then, P_8 joins the torrent at time $t = 7$, obtains the addresses of P_2 and P_6 and initiates only one connection to P_6. At time $t = 8$, peer P_9 arrives and gets the addresses of P_6 and P_7. Given that these two peers have not reached their maximum peer set size, P_9 succeeds to connect to both of them. Afterward, P_6 tells its neighbor P_8 about P_9, thus a
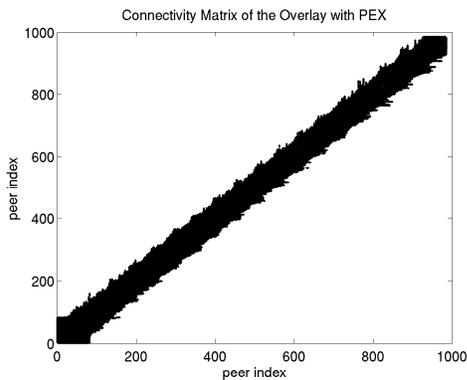
Fig. 29. The connectivity matrix of the overlay distribution with PEX after 59 minutes, for a single run. A dot at (i,j) means that i and j are neighbors. At $t = 59$, almost all the 1000 peers have joined the network and no peer has left yet. *We observe a chain-like overlay.*

new connection is initiated from P_8 to P_9. Then, P_9 tells P_7 about P_8 and a new connection is initiated from P_7 to P_8.

As we can see, PEX tries to maximize the number of outgoing connections at each peer. Peers keep on gossiping and whenever they discover new peers, they establish new connections if they still have room for. However, the disadvantage is that peers that arrive at the beginning establish a lot of connections among each other and leave only a few free connections for the peers that arrive afterward. In the example that we consider here, $P_1, \ldots, P_5$ are highly interconnected and they leave only two connections for next peers. Similarly, when peers $P_6, \ldots, P_9$ arrive, they connect to the overlay at peers P_3 and P_4 and then interconnect strongly with each other.

As a result, PEX leads to a clustering phenomena, where each cluster contains approximately a number of peers close to the maximum peer set size. Each cluster exhibits a high intra-cluster connectivity and a poor inter-cluster connectivity with the cluster that arrives just before and to the one that arrives just after. To confirm our analysis, we draw in Fig. 29 a snapshot of the connectivity matrix of the overlay distribution after 60 minutes when the first 1000 peers have arrived in the torrent. The clustering phenomena appears clearly in the figure, which explains the large diameter of the overlay. As we explained in Section IV-C, such a chain-like overlay constraints the distribution time in the system to be a linear function of the number of clusters. As compared to the overlay generate by the tracker only, this chain-like overlay becomes less efficient when the number of clusters becomes larger than the number of pieces. Typical files distributed using BitTorrent includes an average of 1000 pieces. In this case, this chain-like overlay will become inefficient when the number of clusters is larger than 1000, i.e., the number of peers is larger than 800.000 peers. Current torrents are much smaller and they rarely exceed 100.000 peers and therefore, no one has noticed yet the negative impact of the PEX on the download time of files.

Let us now go back to Fig. 27. If we carefully look at this figure, at time $t = 60$ minutes, the average value of the diameter drops from 18 to 11. Actually, at $t = 60$ minutes,
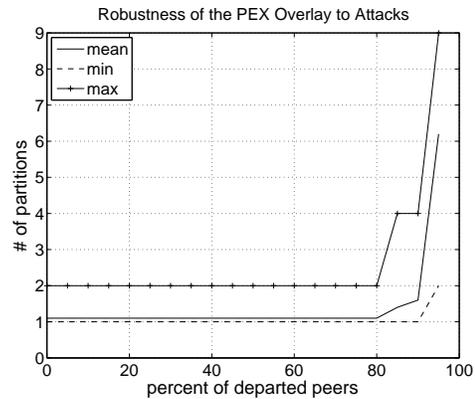
(a) Impact of attack on the PEX overlay
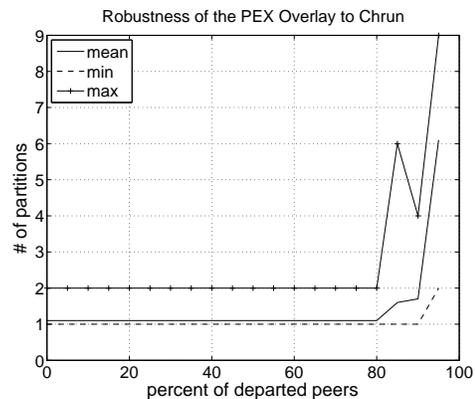
(b) Impact of churn on the PEX overlay

Fig. 30. Robustness of the chain-like overlay generated by PEX. *The PEX overlay can be easily partitioned by simply attacking a peer, its neighbors, and its neighbors of neighbors.*

peers start leaving the torrent. At the same time, the last peers to join the torrent also arrive at $t = 60$ minutes. Those departed peers will allow the arriving ones to connect at different levels of the chain and not only at the tail, which consequently reduces the diameter of the overlay.

To better explain this behavior, consider the overlay shown in Fig. 29. In this chain-like overlay, all peers are at their maximum peer set size except those that are at the tail. Assume now that peers $P_1, \ldots, P_{15}$, leave the torrent. Assume that, at the same time, $P_{985}, \ldots, P_{1000}$, join the torrent. In this case, the departed peers $P_1, \ldots, P_{15}$, will leave rooms for incoming connections inside the first cluster, i.e., at the head of the chain. Thus, the arriving peers $P_{985}, \ldots, P_{1000}$, will be able to establish connections to the tail as well as the head of the chain. As a result, the head and tail of the chain become connected and the diameter of the overlay drops by half. Still, the diameter remains very high when compared to an overlay generated only by the tracker.

Robustness to attacks and churn: Surprisingly, the overlay produced with PEX is robust to churn rate and to the attack that targets the most connect peers. As shown in Fig. 30(a)

and Fig. 30(b), the overlay stays connected with up to 80% of the peers leaving the torrent.

As we can see in Fig. 30(a), up to 80% of departed peers, the attack scenario produces a maximum number of partitions of 2. Actually, out of the ten runs that we performed, we obtained partitions with only 1 run. In particular, we obtained one major partition and a second one with only 1 peer. For example, for 80% of departed rate, we obtained 1 partition that includes 167 peers and a second partition with only 1 peer. Same conclusions apply on the churn scenario.

Even though PEX shows good robustness to the attack that we have been using so far, this chain-like overlay can be easily partitioned by using more sophisticated attacks that target a peer, its neighbors, and its neighbors of neighbors.

In summary, even if PEX significantly decreases the time for a peer to reach its maximum peer set size, it creates a chain-like overlay that is not robust against partitions and whose diameter is large. This large diameter will lead to a long download time of files when the number of simultaneous peers is large. We plan to evaluate how much this overlay impacts the efficiency of the transfer when compared to an overlay created only by the tracker.

VII. Discussion

A. Summary of our Contributions

We have conducted a large set of simulations to investigate the properties of the overlay formed by BitTorrent. Below is a list of our main contributions.

- First, we have analyzed the relation between the overlay properties and the performance of BitTorrent. In particular, we have shown that a large peer set size increases the efficiency of BitTorrent, and that a small diameter is a necessary, but not sufficient, condition for this efficiency.
- Second, we have shown for the first time that the overlay generated by BitTorrent is not a random graph, as it is commonly believed. The connectivity of a peer with neighbors in the torrent is highly biased by its arriving order in the torrent. Whereas it is beyond the scope of this study to evaluate the robustness of the overlay structure to elaborated attacks, i.e., attacks that do not only focus on the most connected peers, it is an interesting area for future research. In particular, it is critical to understand such issues when a public service is to be built on top of BitTorrent.
- Third, we have evaluated the impact of the maximum peer set size and of the maximum number of outgoing connections. Whereas there are several magic numbers in BitTorrent, we have identified that the maximum peer set size is a tradeoff between efficiency and peers overhead, and we have explained why the maximum number of outgoing connections must be set to half of the maximum peer set size.
- Finally, we have identified two potentially significant problems in the overlay, which deserve further investigations. We have shown that a large number of NATed peers decrease significantly the robustness of the overlay to attacks, and we have shown that peer exchange creates a chain-like overlay that might adversely impact the efficiency of BitTorrent.

In conclusion, we expect this study to shed light on the impact of the overlay structure on BitTorrent efficiency, and to foster further researches in that direction.

B. Future Work

Our future work will progress along two avenues.

- Mitigate the impact of NATed peers on the robustness of the overlay. Actually, with its current implementation, BitTorrent produces an overlay where non-NATed peers have a higher connectivity than NATed ones. As a result, one can create partitions by attacking the non-NATed peers, which are the most connected ones. One possible solution to this problem is to allow NATed peers to initiate more connections than non-NATed ones. For example, one can imagine that the tracker reports the number of NATed peers to new peers so that they can weight their maximum number of outgoing connections. Our goal is to still have a highly connected graph, but without peers with significantly more connections. The intuition behind this solution is that the robustness of the overlay would improve. This solution, and in particular how to weight the maximum number of outgoing connections, will be subject to further investigation.
- Extend peer exchange in order to still converge fast to the maximum peer set size while maintaining a low diameter overlay. Indeed, with the current implementation of peer exchange, peers converge fast to their maximum peer set size, but only peers that are at the tail of the overlay chain have rooms for incoming connections. As a result, new arriving peers can only connect to the tail of the overlay chain. We are investigating possible solutions to this problem whose main goal is to add randomness in the overlay generated with peer exchange.

  One solution is to allow peers coming from the tracker to preempt connections of peers discovered with peer exchange. For example, assume that peer P_i has reached its maximum peer set size and amongst its neighbors, there is P_j that it discovered with peer exchange. Assume now that P_k joins the torrent and receives the IP address of P_i from the tracker. If P_k initiates a connection to P_i, P_i will accept this connection and drop its connection to P_j.

  Another solution is to add randomness during the construction of the overlay. For instance, instead of collecting a list of neighbors of its neighbors, which creates locality in the graph construction, a peer P_i can ask neighbors to randomly selected peers. The rational is to discover and create connections to peers that are far from P_i in the overlay. The choice of the random function to discover those peers is critical and currently under investigation.

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