A Measurement Study on Signaling in Gnutella Overlay Networks

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Abstract. In this paper we present a measurement study on signaling in Gnutella overlay networks. Both signaling load and the scale of variability in the existence of p2p overlay connections are investigated. The purpose of the study is to identify and understand characteristic scales of variability and stability of peer-to-peer overlay networks. The identified, typical scales should ultimately provide a basis for a dynamic management of peer-to-peer services. Unmanaged peer-to-peer service have often enough incubated a prohibitively large signaling traffic load.

1 Introduction

At first, the Internet was hailed for its capability of providing world-wide remote access to networked resources and its simple and powerful protocols for exchanging data, like SMTP, NNTP, FTP, or Telnet. The second generation Internet was marked by the introduction of the World Wide Web. It effectively and efficiently interconnected distributed information sources by using hyperlinks. The architecture of the Second Generation Internet, however, retained the traditional client/server concept. A relatively small number of fixed servers provide the vast majority of information and resources. A static placement of heavily used servers allows for traffic aggregation techniques to be applied.

The next, or Third Generation, Internet (TGI) could be dominated by loosely connected applications which would be located at network edges. TGI services are expected to be highly dynamic. Variable connectivity, variable addresses, and mobility are considered as the norm. Nodes will be highly autonomous and nodes participating in a group relationship will be characterized by symmetric roles. A node can have the role of a client, a server, or a router, all at the same time. In addition, future high-speed wire-line and wireless access technologies will provide instant high-bandwidth connectivity. These features may lead to dispersion of traffic sources throughout the network and may cause difficulties in controlling traffic flows on relatively small time scales. More traditional traffic engineering techniques, such as Traffic Load Flow Optimization or Multi-Hour dimensioning (see Annex 6 of [1]) may prove inadequate. It is anticipated that new planning and management principles are needed to address topics like reliability, security, or self-organized load-balancing. To compound matters, new methods will have to be robust with respect to dynamic environments.

In this paper we examine the dynamics of the Gnutella filesharing service as a typical representative of peer-to-peer (p2p) services. Both signalling overhead and the scale of variability in the existence of p2p overlay connections are investigated. The variability is characterized by two factors: a) the number of simultaneous overlay connections maintained by a peer and b) the duration of maintaining these connections. We present a first simple statistical model of the process of maintaining overlay connections and provide estimates on some model parameters.

The reminder of this paper is organized as follows. Section 2 briefly outlines the main features of a Gnutella filesharing service. Section 3 then describes the set-up of our measurement environment, discusses the measurement results, and presents a first statistical model of the variability of Gnutella overlays. Section 4 discusses the anticipated impact of TGI services on traffic engineering in future networks. Section 5 is the related work section. Section 6, finally, summarizes the paper.

2 The Gnutella Filesharing Service

The Gnutella service is a fully distributed, information sharing technology. It is based on a peer-to-peer model [2] and applies a distributed, open group membership and search protocol [3] [4]. The Gnutella service forms an application-specific overlay of Internet accessible hosts running Gnutella-speaking applications like `LimeWire` [5] or `Gnut` [6]. The Gnutella hosts may have multiple, simultaneous roles. As a client they provide user interfaces for issuing queries, viewing search results, and initiation of downloads. In server mode they accept in parallel queries from other nodes, check for matches against their local data set, respond with results, and manage the file transmission. In Gnutella context, a node is called a *servent (SERver + cliENT)*. The servents are also responsible for routing the *signaling traffic*. This traffic spreads information used to preserve network integrity and is needed to locate information. File downloads are performed outside of the overlay by a direct peer-to-peer connection between servents using HTTP protocol. Since the overlay is reserved for transmitting Gnutella control information it can be denoted as a *signaling overlay*.

The Gnutella protocol defines two categories of signaling messages: *A) Overlay Membership:* To discover additional hosts on the Gnutella network, servents use a "Ping/Pong" protocol. A servent issues a "Ping" message[1] to actively probe the network. A servent receiving a "Ping" is supposed to respond with a "Pong" message, containing the IP address and the amount of data it is sharing on the network. A "Ping" message can be answered with multiple "Pong" messages from multiple servents.

[1] The Gnutella "Ping" message should not be mistaken for the ICMP echo request message often colloquially also denoted as "Ping".

B) Searching Information: A piece of information is located in Gntutella via "Query" and "QueryHit" messages. A "Query" contains mainly the search criteria. A servent receiving a "Query" descriptor responds with a "QueryHit" message if a local match is found. A "QueryHit" message contains information to identify the replying servent in the IP address space as well as in the Gnutella domain. In addition, it contains file information such as local identifier, file size and file name.

Once a servent receives a "QueryHit" response, a user may trigger a download. A HTTP connection containing a GET request is directly established between the servents.

In order to join the Gnutella signaling overlay, a new servent connects (i.e. opens a TCP connection) to one of numerous well-known hosts that are always available, e.g. `router.limewire.com`. After having been connected successfully, servents send messages to interact with each other. The membership in the Gnutella overlay is granted to any servents sending the correct greeting string. Gnutella servents know only about servents which are directly connected to them. Other nodes are invisible unless they announce themselves. A node may maintain multiple simultaneous connections to other servents in the overlay. The maximal number of simultaneous connections can usually be configured by the user.

Signaling messages are routed in the overlay by using two simple principles: *a)* they are *broadcasted* to all neighbors, i.e. sent to all nodes with which the sender has open TCP connections, and *b)* responses are *back-propagated* in the overlay along the path taken by the triggering message.

An important feature of the Gnutella p2p filesharing services is that peers may join or leave the signaling overlay arbitrarily. To preserve network integrity, servents have to maintain multiple simultaneous connections. New overlay connections have to be initiated as soon as old ones terminate. Peers acquire new candidates for its overlay connections by sending periodically "Ping" messages to neighbors and inspecting "Pong" responses. Nodes base their decision where to connect to in the network on their local information. The Gnutella protocol doesn't provide any support for a coordinated organization of the signaling overlay. The Gnutella service forms an randomly structured overlay network.

3 Overlay Measurements

While qualitative justification is straightforward, little is known of quantitative results on the scale of dynamics in overlays and p2p applications. In particular, time scale and variability of the number of virtual overlay connection have to be characterized.

3.1 Measurement Set-Up

To analyze the signaling traffic in the Gnutella overlay, we modified a publicly available Gnutella command line application `Gnut` [6] to record all signaling

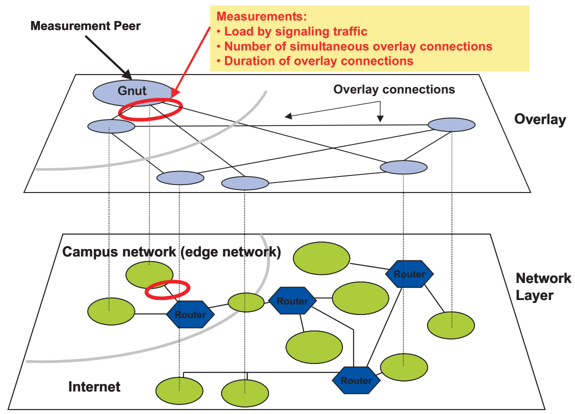


Fig. 1. Overlay measurements

packets with time stamp, payload size, and IP address where a packet was sent to or received from. The `Gnut` application was executed on an Linux-based PC. The PC was located inside the campus network of the University of Würzburg and was connected to the departmental network via FastEthernet. The measurement campaign was carried out in March 2002. The measurement duration was 60h. Figure 1 shows the position of the measurements in a simplified manner. The measurements have been performed on the edge network connection of the peer at overlay level.

3.2 Traffic Load

Figure 2 shows the sum of all signaling traffic load observed by the measurement peer. The depicted load is the total load of all simultaneous overlay connections. Figure 2 depicts solely traffic load generated by Gnutella search requests ("Query"), search replies ("QueryHit"), host queries ("Pings"), and host announcements ("Pongs"). No download traffic has contributed to the load shown in Figure 2. The load is averaged on 10sec intervals.

The observed average of signaling load was 0.274Mbps in the 10sec-intervals. The maximum was 50.9Mbps. Figure 2 has been prune to the range of 10Mbps in order to focus on the most relevant part of the graph. The figure depicts also the 95% percentile of the load, which is 1.03Mbps. In total, more than 7.06Gbyte of signaling traffic has been transmitted through the measurement peer during the 60h. That data volume, which is equivalent to ten Video-CDs with 700Mbyte each and without any immediate benefit to the user. The high overhead is due to the use of broadcast mechanisms in the Gnutella protocol. The Gnutella overlay network is flooded with signaling information. Moreover, the better the peer's connection to the overlay, the faster messages are forwarded to it. A control of the traffic load is difficult. With the exception of a TTL (Time-To-Life) field, the Gnutella protocol doesn't contain any mechanisms to control the signaling. Traffic control has to be implemented locally and independently on each peer.

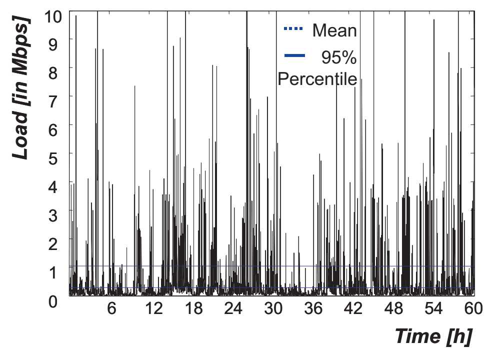


Fig. 2. Sum of signaling traffic load

3.3 Overlay Variability

The variability in the p2p overlay can be characterized by two factors: *a)* the number of simultaneous overlay relations maintained by a peer and *b)* the duration of maintaining these relations. The term "relation duration" as used in this paper denotes the time between the first and the last instance of information exchange between the measurement peer and a particular other peer. A peer is identified by its IP address and the TCP port number used by the Gnutella application running on this peer. A peer-to-peer relation may therefore last several physical connections between some peers. The term "connection", however, is not fully appropriate in the context of p2p services. Many signaling messages may be exchanged between some peers, while the same peers may repeatedly join or leave the overlay.

Number of simultaneous overlay relations: A peer tries to maintain a given number of relations. The number can be configured by the user and has been fixed here at 20 relations for the measurement peer. If, for instance, a peer maintains less relations than configured, it picks out an arbitrary host announcement and tries to establish a new relation to this host.

Figure 3 depicts the number of simultaneous p2p relations maintained by the measurement peer during the measurement period. Although the peer was configured to keep up with 20 relations, it maintained only an average of 9.86 relations. Most importantly, however, the connectivity process reveals a very high variability and is far from being constant.[2]

If the connectivity of a peer is high, i.e., a peer maintains high number of simultaneous overlay relations, many signaling messages will be forwarded to it. If bandwidth is not sufficiently available an overload situation is caused in the physical network. If the connectivity of a peer is low, i.e., a peer maintains a small number of relations, then a peer might not receive enough signaling information

[2] Figure 3 shows also that the measurement peer occasionally maintained more than 20 connections. This is an implementation feature of the `Gnut` client.

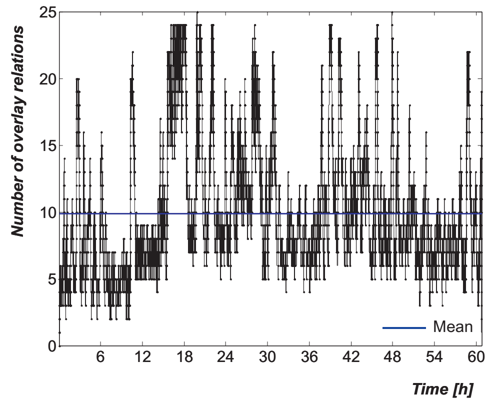


Fig. 3. Number of simultaneous overlay relations

to discover new hosts and new resources. In an extreme case, a peer might drop out of the overlay network and has to be re-connected to a well-known peer. That may cause a severe disruption of the service. This characteristic suggests the existence of an optimal level of connectivity. But rather than consistently maintaining an optimal level of connectivity, connectivity fluctuates widely in unmanaged p2p environments.

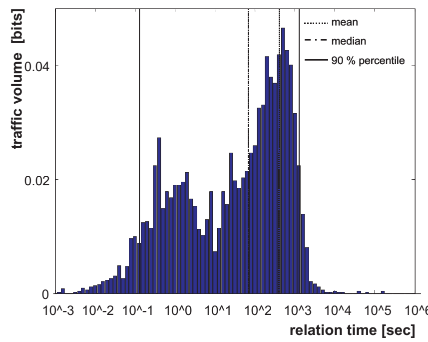
The high variability in number of simultaneous overlay relations indicates that management might be needed in order to maintain the optimal point of operation for a peer under given performance and reliability constrains.

Distribution of the relation time: The distribution of the relation times of peers is the second factor in the variability of the overlay.

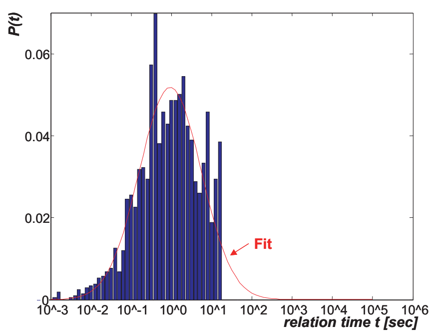
The measurement peer has exchanged signaling messages with 5320 distinct peers and has monitored the duration of the relation times. Figure 4 a) depicts the histogram of the relation durations observed by the measurement peer. The mean relation holding time is $4.05 \cdot 10^2$sec. The histogram shows also the 90%-percentile, which is between $1.28 \cdot 10^{-1}$sec and $1.28 \cdot 10^3$sec and which reaches over four orders of magnitudes in the time scale. The median is at $6.88 \cdot 10^1$sec. In addition, Figure 4 a) reveals clearly a distribution with two modes. The separating minimum is located at about 10sec. The characteristic indicates that the p2p relation is governed by multiple states.

From user's point of view, the participation in a p2p overlay is fruitful when peers receive sufficient content information. That way, peers might use and contribute resources to the p2p community in a valuable way. Hence the volume of *incoming signaling traffic* was examined in greater detail. The traffic was correlated with the relation times.

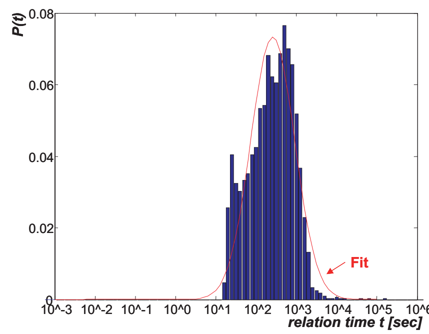
Figure 5 and Figure 6 show the correlation of the relation times for the complete amount of incoming signaling data transmitted during existence of a p2p relation. Each point in the diagrams stand for a single relation. The abscissa



(a) all relations



(b) first category ($< 1.95 \cdot 10^1$sec or $< 9.12 \cdot 10^3$bits)



(c) second category ($\geq 1.95 \cdot 10^1$sec and $\geq 9.12 \cdot 10^3$bits)

Fig. 4. Relation times observed by the measurement peer

axis denotes the relation duration and the ordinate represents the transmitted amount of signaling data in this relation.

Figure 5 depicts the 90% percentile for the relation duration (vertical lines) and the traffic volume (horizontal lines). The average and the median are indicated by dotted and dashed lines. The figure allows the identification of two discriminating values which correspond to the lower bound of the percentile. For the relation times a separating value of $3.90 \cdot 10^{-1}$sec and for the signaling traffic volume a total of $1.54 \cdot 10^4$ bits are indicated. The lower bounds of the 90% percentile on the time axis and the 90% percentile on volume axis describe the range of beneficial overlay relation. During this relations either sufficient host or search information is exchanged between peers. The separating values become even more evident when the correlation is performed for the individual Gnutella protocol entities. Figure 6(a) depicts the correlation for "Query" packets, i.e.,

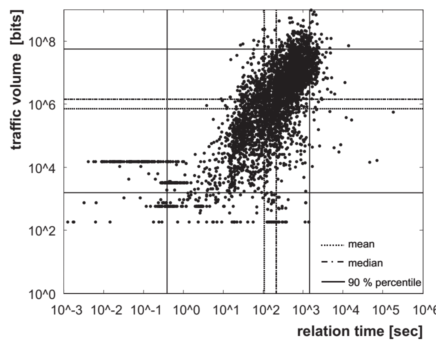


Fig. 5. Correlation of relation times and amount of incoming signaling data: all information (content and host)

for file search requests only. The lower bounds of the 90% percentiles for relation duration and signaling volume are at $1.95 \cdot 10^1$sec and $9.12 \cdot 10^3$ bits. A similar behavior is also visible for "QueryHit" packets, cf. Figure 6(b).

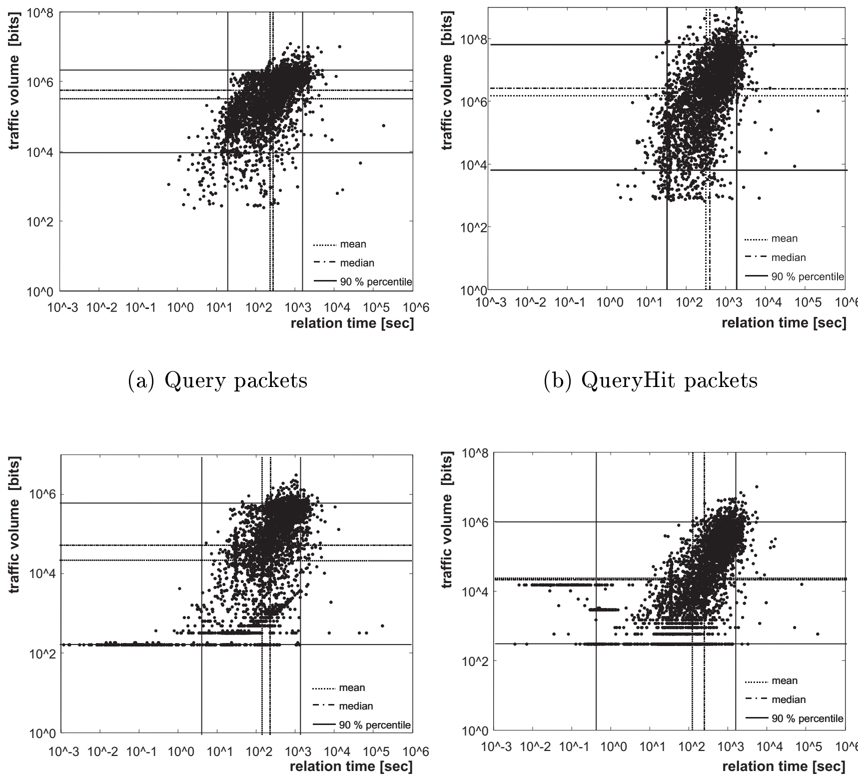
In contrast to the behavior of "Query" and "QueryHit" packets, the correlation analysis for "Ping" packets, i.e., host query packets, shows that a considerable number p2p relations exist which have a duration of less than 10sec. In this case the transmitted amount of signaling information is small, see Figure 6(c), and typically less than 10^4 bits. This is also the case for "Pong" packets, i.e. host announcement information, see Figure 6(d).

3.4 Statistical Model

Based on the correlation analysis the histogram of relation times was re-assessed. The p2p relation times are filtered and divided into two disjoint categories. The categories are determined by the lower bounds of the 90% percentiles of the relation times and traffic volume for queries (see Figure 6(a)). The first category contains overlay relations which last less then $1.95 \cdot 10^1$sec and have less than $9.12 \cdot 10^3$ bits signaling volume, see Figure 4(b), and contains 39.0% of the relations (2077 relations out of the total of 5320). The second category has relation times greater than $1.95 \cdot 10^1$sec and traffic volume of more than $9.12 \cdot 10^3$ bits, see Figure 4(c). The category comprises 61.0% of the relations (3243 out of 5320). In both categories the shape of the histogram of relation times may be approximated by a normal probability distribution. Since the abscissa axis in Figure 4 is of logarithmic scale, it is indicated that relation duration in the two classes are distributed according to *log-normal* distribution function:

$$f(x) = \frac{1}{x\sqrt{2\pi\sigma^2}} e^{\frac{-(\ln x - \mu)^2}{2\sigma^2}}. \tag{1}$$

The fitted distributions are added to the histograms of Figures 4(b) and 4(c). Visual inspection of these figures shows that the fit is remarkably well.



(a) Query packets

(b) QueryHit packets

(c) Ping packets

(d) Pong packets

Fig. 6. Correlation of individual signaling packet types

This indicates in this case that the log-normal distribution appears as a valid statistical model for states which conduct the set-up of overlay relations. Table 1 provides the values (measured and fitted) for the mean and the variance of the relation durations in the two categories.

Significance for P2P Overlays: The correlation analysis leads to a two-state model for Gnutella p2p overlay relations. In the first state, which is called the "short" state, a peer establishes only short-lived connections to other peers. The involved peers exchange some signaling information, typically only host information, and the relation is terminated immediately. In the other state a peer establishes a long-duration relation and exchanges continuously signaling messages, mostly search requests. From the perspective of a user, this state can

	Mean		Variance	
Category / State	Measurement	Fit	Measurement	Fit
1 / "short"	3.01 sec	1.85 sec	$1.98 \cdot 10^1$ sec^2	9.99 sec^2
2 / "stable"	$5.93 \cdot 10^2$ sec	$3.63 \cdot 10^2$ sec	$1.24 \cdot 10^7$ sec^2	$1.29 \cdot 10^5$ sec^2

Table 1. Measured and fitted parameters for relation duration

be called "stable" state, since it permits uninterrupted operation of the p2p service.

The characteristic of log-normal distributed p2p relations indicates that the majority of peers in the stable phase reside in the system for the same average amount of time. A significant number of peers, however, may stay longer than the average. This result supports the view that few peers are more powerful and durable than other peers [7].

4 Possible Impact of Scale of Dynamics on Traffic Management

The observed scales in Gnutella signaling overlay, i.e., signaling volume, number of simultaneous relations, and duration, indicate that traffic management and traffic engineering for future generation Internet will require new approaches. Future applications allow for a permanent coming and going of service requests, resources offerings, and service consumption. In this way they permit an easy forming and dissolving of groups. Reed's findings on *Group Forming Networks (GFN)* [8] demonstrate that the value of GFN networks, which is defined as the number of possible communication relationships, scales exponentially with the number N of participants. Abbreviated, the number of non-trivial subsets that can be formed from a set of N members is $2^N - N - 1$, which grows as 2^N. Even when its participants transmit with probability significantly smaller than one, that relationship still indicates that signaling traffic will grow dramatically. As the measurements on p2p services reveal , that characteristics is already visible in today's networks. Application, protocol, and network design for tomorrow's Internet has to provide mechanisms to reduce the effect.

The group communication support by future applications will additionally lead to the dispersion of traffic sources throughout the network and may also cause difficulties in estimating traffic flows on small time scales. The *scale of dynamics* of future application-specific service overlays might be in the range of the variability of today's p2p overlays. As the measurements of the variability of the Gnutella overlay have shown, cf. Section 3.3, this will be on a time-scale in the order of 10s of minutes. This characteristic prevents the future use today's traffic engineering techniques, such as Traffic Load Flow Optimization or Multi-Hour dimensioning (see Annex 6 of [1]).

The new services offered by future Internet will be built on node autonomy and on symmetric roles of networked nodes. The applications specific overlays may contest for network capacities [9]. In contrast, current IP Quality-of-Service (QoS) design favours the differentiation of traffic, e.g., by explicit use of ToS

(Type-of-Service) bits to select QoS, and avoids congestion. To provide attractive overlay services, future services will have to include self-organization mechanisms on application layer. The mechanisms should be able to observe overlay load and be adaptive on small timescales.

An absence of any traffic engineering, as currently observed with many p2p overlays, will lead to a reduction of the service quality of these services. The service performs well for users with high bandwidth access, i.e., they perceive high throughput for downloads. On the down side, a large amount of signaling traffic is also forwarded to these peers and has to be handled. Considerable bandwidth is consumed without getting immediate benefit. It is anticipated that a management architecture will be needed that can handle specific granularities in time as well as in space to enable dynamic and adaptive operation of future virtual overlay networks.

5 Related Work

Various measurement studies of Gnutella have been performed recently. The first analysis was carried out by E. Adar et al. [7]. Their measurements have shown that there is a strong asymmetry between content providers and content consumers. Nearly 70% of the Gnutella users share no files, and nearly 50% of all responses are returned by the top 1% of sharing hosts. The main results of the measurement done by S. Saroiu et al. [10] was the characterization of end-user hosts participating in Gnutella. The characterization provided numbers and distributions for bottleneck bandwidth, IP-level latencies, how often hosts connect and disconnect from the overlay, and the degree of cooperation between the peers. Jovanovic et al. [11] investigated the connectivity and the degree of cooperation between peers. Their results evidence that degree distribution of the Gnutella network topology follows a *Power-law*. Similar measurements were accomplished by M. Ripeanu et al. [4]. These measurements acknowledged that Power-law in the degree distribution was present in an early stage of the Gnutella overlay, however this characteristics has declined recently. A recent measurement study was performed by J. Vaucher et al. [12]. Their measurements and experiments have shown that the composition of the community changes quite rapidly.

The measurements presented in this paper complement the ones reported in previous publications. The focus of the investigations discussed here, is on the variability in the overlay of the Gnutella service. This aspect was not yet properly addressed in previous research, but is expected to have significant impact on traffic engineering in future networks.

6 Conclusions

In this paper we have presented a measurement study on signaling in Gnutella overlay networks. Both signaling load and the scale of variability in the existence of p2p overlay connections have been investigated. The variability was characterized by two factors: a) the number of simultaneous overlay connections maintained by a peer and b) the duration of maintaining these connections. We presented a first simple statistical model of the process of maintaining overlay connections and provided estimates on some model parameters. It has been validated by measurements that P2P services are prone to highly variable connectivity patterns and traffic load profiles.

Today's peer-to-peer networks exhibit signaling characteristics that are anticipated to be typical for the future services of the Third Generation Internet. We expect a new management architecture to be needed for TGI that can handle specific granularities in time as well as in space to enable dynamic and adaptive operation of future virtual overlay networks. Highly flexible resource and network management methods are required. The upcoming challenges caused by introducing new networking services on demand with significantly reduced provisioning cycles brings that even more into focus.

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