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RESOURCE OPTIMIZATION IN OPTICAL NETWORKS AND PEER-TO-PEER TRAFFIC IDENTIFICATION IN IP NETWORKS

Collection of Ph. D. Theses

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1. Introduction

My theses cover two different areas of telecommunication, namely *configuration and resource optimization of optical networks*, and *traffic identification and analysis of Peer-to-peer (P2P) applications in IP networks*. These two blockbuster technologies – together with the progression of *multimedia applications and services* – have played an important role in the development of Internet and computer networks in recent years. They are, however, forces acting against each other.

1.1. Peer-to-Peer Traffic Identification and Analysis

The main characteristic of a P2P system is that it is not built around the server and client concept but on the cooperation of equal peers. This principle involves the adapting nature of P2P systems as individual peers join or leave the network.

P2P applications generate the major part of Internet traffic and likely also a significant part of the unidentifiable traffic, overtaking the traffic share of the World Wide Web [1][2]. Therefore P2P traffic is one of the main factors responsible for an unprecedented demand for bandwidth in telecommunication networks.

The other phenomenon that has increased the network load significantly is the appearance of high quality multimedia content (primarily high definition video). There are two promising ways to distribute multimedia traffic: *multicast* and *P2P delivery*. However, these options do not necessarily rule out each other. Multicast delivery [3], if it is happening in a lower network layer, is undoubtedly the most economical way of delivering high bandwidth multimedia content. On the other hand, P2P distribution can be very convenient (it can be easily implemented in the application layer). Even though it lavishes bandwidth, it is especially popular on the Internet.

The most common use of the P2P principle is *file-sharing* [4] (photos, movies, music files, applications, etc.), including often *illegal content*. Thus it causes a huge loss for the authors and publishers, who aim to prohibit this kind of usage. After the first popular P2P based multimedia file sharing systems (Napster) was developed, numerous others have followed (BitTorrent [5], Gnutella [6], eDonkey, etc.).

P2P technology is also intensely used for providing *communication services*, like “presence service”, chat, Internet telephony (Voice over IP, VoIP, in the same or even in better quality than traditional telephone networks), video conferencing, and file transfer. Popular applications include Skype, Windows Live Messenger, Google Talk, and many others. Some of these services offer a real alternative to traditional telephony services because they are much cheaper or even free of charge.

P2P applications cause headache for landline and mobile network operators for several reasons:

- File-sharing traffic consumes the biggest portion of bandwidth in both transport and access networks; "heavy P2P users" especially consume high bandwidth.
- P2P traffic is often associated with illegal file sharing. There is a huge pressure on operators to stand up against illegal content in their network.
- P2P VoIP applications endanger the privileges of traditional telephone service providers, especially mobile service providers. Mobile operators usually calculate the call and data transfer rates on a per-minute and per-megabyte basis, respectively. It is important to know the quantity of VoIP calls (including Skype [7] as the most popular application) and the related amount of data for pricing purposes. This way they can determine a tradeoff between the call based pricing and the transferred data based pricing.

For all these reasons some operators try to regulate, control, or even prohibit the usage of P2P applications in their networks. As an aftermath, recent popular P2P applications try to hide their presence and disguise their generated traffic resulting in the *problematic issue of traffic identification* (see *Section 8.1 of the Dissertation* for an overview).

The accurate P2P traffic identification is indispensable in traffic *filtering*, *blocking*, *shaping*, *measurement*, and *analysis*.

1.2. Optical Networks

P2P networking and rich multimedia content has caused an explosion in the Internet traffic from the demand side. This increased load has to be handled from the network provider's side. The only way to cope with such a rapid development and to solve the capacity issue (especially on a long term) is the application of *optical technology* [8][9].

Multi-wavelength technology appeared as the solution for the bandwidth hungry applications and *WDM (Wavelength Division Multiplexing*, [10]) has been introduced to increase the transmission capacity of existing optical links.

In early, single hop WDM based All Optical Networks (AON) wavelength connections were handled in the optical domain without any electronic conversion during the transmission [11][12].

The WDM networks have successfully solved the capacity issues, but the continuously changing traffic still causes a serious problem for the operators. Emerging demands often cannot be satisfied without modifying the network design (which is quite costly and difficult), so operators try to avoid this situation whenever possible. This is especially true on lower aggregation levels, where the traffic is more variable. There is a strong need for a system that can deliver the same capacity as WDM, with the design and provisioning flexibility of SONET/SDH [13]. The solution must ensure flexibility for dynamically changing future demands.

Although provisioning of continuously changing *(dynamic) traffic demands* is more problematic than the static configuration, dynamic networks have recently attracted more attention, especially on the field of research.

Reconfigurable optical networks (e.g., [14]) offer the possibility to quickly adapt to changing traffic demands with no advanced engineering or planning and without disrupting existing services. In the past, reconfigurable optical networking technology was too expensive or delicate to be widely deployed. With recently matured silicon-based integrated Planar Lightwave Circuit components, *reconfigurable optical add/drop multiplexers* (ROADMs) are now being installed by many operators. The ROADM technology means a real breakthrough in WDM networks by providing the flexibility and functionality required in present complex networking environments. ROADMs allow service providers to reconfigure add and drop capacity at a node remotely, reducing operating expenses by eliminating the time and complexity involved in manual reconfiguration.

ROADM by itself is not enough. Increased data management capabilities on individual wavelengths are also needed to exploit the benefits of ROADM in metro and backbone WDM networks. The real innovation lies in the system engineering related to the ROADM function addressing *per-wavelength power measurement and management*, and per-wavelength fault isolation, which are offered by almost every optical system vendor in commercial products ([15]-[18]).

The next step towards a fully reconfigurable WDM optical network is the deployment of tunable Small Form-factor Pluggable (SFP) modules, where the wavelength allocation is modified according to traffic changes.

The tunable dispersion compensation elements (which are now ready-made products [19] [20]) mean another innovation.

Considering physical effects in the provisioning, configuration and routing of optical networks is also a popular research area [21].

The evolution of optical networks seems to tend towards a *fully reconfigurable network* where the control and the management plane (CP and MP) have new functions, such as determining the signal quality, tuning the wavelength frequency, setting dispersion compensation units, and – by using variable optical attenuators – setting the channel powers. Traditional functions, such as Routing and Wavelength Assignment (RWA), will naturally remain the main function of the CP and MP.

Currently, optical networking is more dominant in transport and backbone networks. However, a clear process of bringing the optical termination closer and closer to the end-user (*Fiber to the Curb/Building/Home*, FTTC/FTTB/FTTH) can be seen. In the near future, many broadband customers will have direct optical access. Optical connection does not only serve as a high-speed Internet access, but it also allows the receiving of *High Definition TV (HDTV) channels*, replacing the traditional cable TV services. Optical access can satisfy both needs at the same time by providing high bandwidth and by having much spare bandwidth for potential further utilization.

As mentioned earlier, multicast delivery (*optical multicast*) can play a significant role in distributing video channels in both transport and access optical networks to lower resource usage and cost [26][27].

2. Research Objectives

My objective was to create new models, methods, algorithm, strategies, and scenarios for optimization of multi-layer optical networks to provide better performance, higher throughput and cheaper network (CAPEX) and operational costs (OPEX).

In the area of IP traffic identification and analysis my objective was to construct reliable traffic identification methods which support the following traffic analysis. Based on the analysis, it is possible to create new traffic models and to investigate user behavior.

3. Research Methodology

The two areas in my theses use different research methodology. Resource optimization in optical networks assumes a specific model of the whole network in the background. I chose *wavelength graph model* [28] to represent the physical network – including switching devices, physical links, optical fibers and wavelengths – by a logical network. The WL graph is derived from the physical network considering the topology and switching capabilities of physical devices, such as:

- full or limited, electronic or optical WL conversion capability
- optical or electronic lightpath branching
- grooming (multiplexing) capability (with limited number of grooming ports)

WL graph modeling is flexible enough to consider all these properties together with different protection schemes and different types of traffic demands.

Several algorithms (Minimum Cost Network Flow, Suurballe's algorithm [29], Dijsktra's algorithm [30]) were implemented and used in the *simulations*. The proposed new algorithms and techniques were also studied through simulation to verify their efficiency. In the case of dynamic routing, *discrete event simulation* was applied. In the case of static routing, *Integer Linear Programming* (ILP, [31]) was used to formulate the NP-hard problems belonging to the general problem of network *flow theory* and to obtain optimal solution. A commercial software (ILOG CPLEX [32]) was applied to solve instances of the ILP formulations. In THESIS 1.1 *statistics* was also applied to evaluate utilization of network resources during dynamic simulations.

Traffic identification and analysis (THESIS 3) apply *measurement, modeling and statistical analysis*. In the background stands the *model* of a certain application (e.g., Skype) or a more general model of P2P applications. It is necessary to construct a model, since such applications have to be regarded as black-box applications where the internal operations and protocols are hidden.

The goal is to measure several properties of the model and try to select the most characteristic features. The second goal is to statistically characterize these features as precisely as possible. This characterization process requires high amount of *measurement* data to obtain accurate statistics.

The third goal is to create a decision mechanism built on the former characteristic properties. The decision mechanism can also exploit certain properties and assumptions of the model itself.

I applied a relational *database system* and *SQL query language* [33] to help achieve the former goals. I used a robust commercial database system

(Microsoft SQL Server 2005, [33]) which proved to be very efficient in supporting the processing of measurement data, generating statistics, applying the identification process, and traffic analysis. Therefore the whole identification and analysis process could be built on it.

Statistics was also applied to evaluate the identification results of real, large scale traffic measurements and in drawing conclusions.

4. New Results

THESIS 1: *I have proposed two separate methods for dimensioning and configuration of network resources in multilayer optical networks for unicast demands. First, I have constructed a fast, generic, statistical utilization based method for joint dimensioning of grooming capability and the number of wavelengths for dynamic demands. Second, I have given the exact Integer Linear Programming (ILP) formulation of the joint optimization problem of RWA*[1] *and determining of signal powers for static demands.*

THESIS 1.1: *I have constructed a fast, generic method for dimensioning of*

a) grooming capability per node

b) the number of wavelengths per link

c) or both a) and b) jointly

Dynamic simulation is run in every step of the iterative dimensioning process. At the end of each step, the network configuration is modified according to the histograms of link and node utilizations and a set of rules. I have shown that the configuration is quickly converging to a certain balanced state.
I have pointed out that the method does not depend on the routing algorithm, the network topology, the protection scheme, and the traffic load. I have also shown the amount of grooming ports and wavelengths that can be spared if moderate blocking is allowed. However, this sparing depends on the applied protection scheme.

Dissertation: Chapter 2
Related publications: [C10] [C11] [C12]

The proposed method determines the necessary number of grooming ports in each node and the necessary number of wavelengths on each link or optimizes both at the same time. Optimization of the grooming capability only is useful if the number of available wavelengths on the links is high, since, in this case, blocking is primarily caused by the lack of grooming capacity. On the other hand, optimization of the number of wavelengths only is useful if the grooming capability is sufficient (over-dimensioned), since the lack of wavelength capacity means the bottleneck

[1] Routing and Wavelength Assignment (RWA)

in this case. In a typical scenario, however, both grooming capability and network capacity are the subject of optimization.

The proposed iterative algorithm applies dynamic simulation in each step of the iteration, routing every time the same (pre-generated) set of dynamic traffic demands. During the simulation, statistics are collected and utilization histograms are calculated.

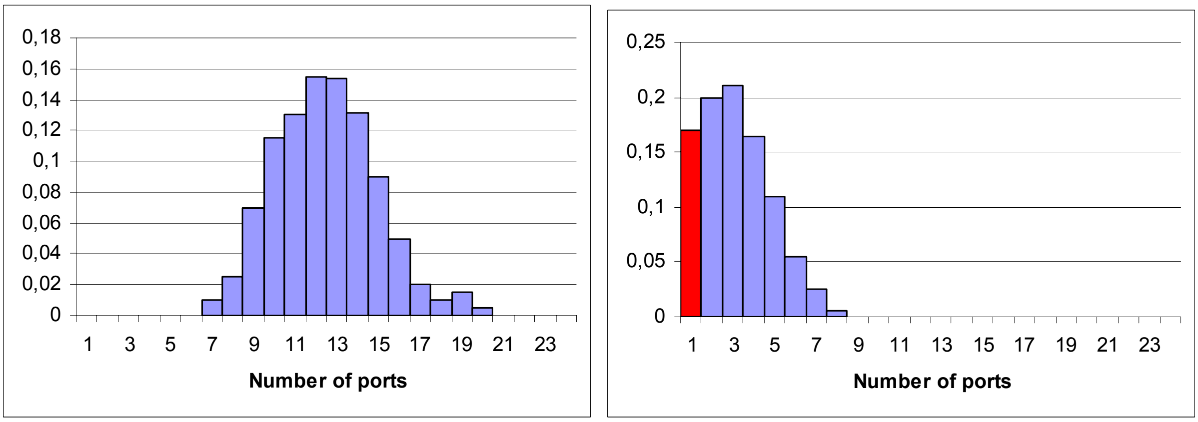

Fig. 1. The distribution of the number of free ports in a less loaded node (left) and in a heavily loaded node (right)

The value of the histogram at zero is of great importance showing the ratio of time when the node was unable to perform further wavelength conversion or grooming because it had no free O/E or E/O ports.

The network configuration is modified according to the utilization histograms and according to the following principle:

- The number of grooming ports is decreased in an "under-utilized" (per-node blocking is under a prescribed per-node blocking threshold) node and increased in an "over-utilized" node.
- The number of wavelengths on a link is modified according to the utilization of the link in a similar way.

The number of grooming ports is decreased by k in every iteration step according to the following formula (negative k means increase):

$$k := k_{\max} - 1 \text{, that } \sum_{i=0}^{i=k_{\max}} p_i \leq TH_n \text{,}$$

where p_i is the relative frequency of the event that the number of free ports was i, while TH_n is the prescribed threshold. The number of wavelengths is modified in a similar way.

If the aim is to optimize both the number of grooming ports and the number of wavelengths jointly, further decision rules are introduced to express the binding between the two types of resources.

Naturally, in real-life it is not possible to set the number of physical wavelength on a link with such a fine granularity. When the aim is, however, to design a virtual topology (e.g., a virtual private network) over a physical one, this approach is reasonable.

The number of resources in a node (or link) is modified according to local information only. Therefore the method can be regarded as a decomposition of a global resource dimensioning problem. Setting the per-node blocking threshold in each node and per-link blocking threshold in each link uniformly can result a "balanced" and fair network.

In the iteration, the network configuration eventually (in a few steps) reaches a "steady-state" (or "balanced state") when no modification takes place. Minor oscillation around the steady-state might rarely happen and can be detected and avoided by a simple stop-condition.

The extensive simulation shows that the network configuration converges to a balanced state regardless of whether it is started from an over-dimensioned or under-dimensioned configuration.

Several methods were proposed for dimensioning grooming capability of optical networks (e.g., [22], [23]). According to my knowledge, however, no other methods apply the statistical utilization approach to address the dimensioning problem.

I have made extensive simulations applying different network topologies, protection schemes (routing algorithms) and traffic loads. The simulations and results suggest that the proposed method works well in any combination of the factors listed above. Of course, the outcome is influenced by the former factors, but these are only input parameters for the method (the method itself behaves similarly).

I investigated how the per-node blocking threshold and the per-link blocking threshold affect the overall network blocking probability. I showed that the overall network probability can be tuned by the local thresholds. The results indicate that these blocking curves are similar for all protection schemes.

I also studied the necessary number of network resources to achieve a given overall network blocking ratio. I demonstrated that a significant amount of network resources and cost can be spared if moderate network blocking is allowed instead of zero blocking. The results show that, to achieve a certain blocking, the necessary number of resources differs significantly in case of different protection schemes.

THESIS 1.2: *I have given the ILP formulation of the joint optimization problem of single-layer RWA and determining of signal powers in multilayer optical networks. The method performs routing (of static demands) in the optical layer and adjusts channel powers in an optimal way while observing physical effects. The method relies on a linearized physical model and it results in global optimum.*

Dissertation: Chapter 3.3
Related publications: [J1] [J2] [C1] [C3] [P1]

I gave the exact ILP formulation of a cross-layer optimization problem, namely the joint optimization of routing (Layer 2) and setting of the appropriate signal powers (Layer 1) [21]. The proposed method routes a static set of demands and results in global optimum.

Beneficially, it is easy to implement such a technique in current optical networks, since modern switching devices allow separate adjusting of power levels for every wavelength ([15]-[18]).

Considering physical effects in routing is recently a popular research area [24][25]. To the best of my knowledge, however, this is the first method that solves the problem in an optimal way. In the past, the practice was that routes and signal levels were determined separately. Typically, after a shortest path routing, the signal levels were adjusted manually.

In the case of THESIS 1.2 (unlike in THESIS 1.3), it is assumed that the routing is performed in the optical layer only. I.e., a whole, continuous light-path is assigned to each demand from the source to the destination node. However, wavelength switching is allowed along the way.

The method observes physical effects in routing. The method relies on a linearized physical model assuming a noise limited system where other physical effects (e.g., wavelength switching) are taken into account as power-penalty. The relation between the signal power and the maximum allowed distance turned out to be linear if the power is expressed in milliwatt. To avoid non-linear effects, the total signal power introduced into a fiber is limited.

I applied wavelength graph to model the physical network and devices. The ILP formulation can be easily adapted to any kind of device model (represented in the wavelength graph).

Finally, the method is formulated by means of ILP (as a mathematical model) and the ILP instances were solved by ILOG CPLEX optimizer [32]. The method is well applicable in practice; it provides optimal solution for moderate size networks in an acceptable time. In addition, it can be the baseline for comparison with other (heuristic) algorithms.

The proposed method is protected by a patent as well [P1].

THESIS 1.3: *I have given the ILP formulation of the joint optimization problem of two-layer routing and determining of signal powers in multilayer optical networks. In addition to* THESIS 1.2*, the method performs routing (of static demands) in the optical and electronic layer jointly and supports 3R*[2] *signal regeneration, wavelength conversion and grooming as well. However, the complexity of the formulation often makes the solution problematic.*

Dissertation: Chapter 3.4
Related publications: [J1] [J2] [C1] [C3]

In comparison with THESIS 1.2, the ILP formulation of THESIS 1.2 involves the electronic layer in the routing. I.e., it performs the RWA in the electronic and in the optical layer jointly (applying peer-model). The method routes a static set of demands and results in global optimum as well.

The ILP formulation supports all features of the electronic layer: wavelength conversion, grooming, and 3R signal regeneration.

The method observes physical effects (relationship between the signal power and the maximum allowed distance of the light-path, limit on the total introduced signal power in each fiber) in routing, just like the ILP formulation of THESIS 1.2.

However, because of the different routing model, the path of a demand may consist of multiple light-paths from the source to the destination. This introduces further complexity in the routing since physical constraints are forced to be met for every light-path.

On the other hand, the enhanced routing model makes it possible to route such a demand (or an "unlucky" combination of demands) that were unsolvable without the application of multiple light-paths. The routing of even one demand can be problematic, if the distance to traverse is so long that the signal power of a single light-path would exceed the maximum allowed power in the fiber. Conspiracy of more demands may more easily create such a situation. However, by allowing more light-paths, a demand can go up to the electronic layer to perform 3R regeneration.

[2] 3R: re-amplification, re-shaping, re-timing

As a result of all of these features, a full joint optimization of routing in three layers is performed here: electronic, optical, and physical layer.

Unfortunately, the ILP formulation in THESIS 1.3 contains several complementary constraints and an additional level of ILP variables. Therefore this ILP formulation is much more complex and cannot be applied for realistic sized networks, while the former ILP formulation works for networks of moderate size as well. However, it is possible to relax the problem on the expanse of losing optimality and provide close to optimal solution in acceptable time.

Nevertheless, as the proposed method can provide optimal solution, it can be used as a baseline for comparison for other heuristic methods. The rapid growth of computational performance also helps the applicability of the method.

THESIS 2: *I have introduced a novel ILP formulation for multicast routing in multi-layer optical networks and investigated two further problems with the aid of the proposed method. I have shown the cost efficiency of optical layer multicasting over electronic layer multicasting, and how the cost of components, traffic load and grooming ratio*[3] *affect the gain. I have also shown which parameters influence the benefits of reconfiguration of dynamic multicast trees and how they influence it. I have determined the optimal length of the reconfiguration period if the cost of reconfiguration and the cost of routing are both taken into account in the total cost.*

THESIS 2 deals with static and dynamic multicast routing in multi-layer optical networks. In the recent years, the traffic load of transport networks has increased significantly due to the rapid growth of Internet and network based applications. Many types of demands, responsible for the heavy traffic load, can be regarded as multicast (point to multipoint) demand instead of ordinary unicast (point to point) demand. Applications include digital media broadcasting (e.g., IP-TV, IP-Radio) or digital media distribution and streaming. Multicast in a transport network is especially useful when the content has high bandwidth requirements, e.g., distribution of a set of high-definition TV channels from the distributor of the content to the local providers.

Despite its bandwidth saving, today the multicast service is not available to the end users by most commercial ISPs. Multicast service is an essential feature present in the core of the transport network because it is the key to the scalable implementation of the triple-play concept: TV channels are usually multicasted from a content distributor to local caches/relays near the end users.

Consequently, both static multicast and dynamic multicast scenarios are reasonable in the core network and in the access network (closer to the end user, assuming dynamic fluctuation of users), respectively.

[3] how many demands can be multiplexed into a single wavelength on average

THESIS 2.1: *I have introduced a novel ILP formulation for multicast routing in multi-layer optical networks that supports*

- *routing of a mix of static unicast and multicast demands,*
- *both optical and electronic layer branching backed by a new device model,*
- *ILP constraints on the topology of the multicast tree to reflect real-life technical constraints,*
- *and reformulation of topology and routing constraints as penalty terms in the objective function instead of constraints.*

The ILP formulation provides optimal routing of the trees (including the decision whether to use electronic or optical layer branching).

Dissertation: Chapter 4.3
Related publications: [J4] [C6]

The proposed ILP formulation can route a mix of static unicast and multicast demands in a multilayer optical network and result in global optimum.

A double layer network is assumed. The upper, electronic layer is time switching capable, while the lower, optical layer is a wavelength (space) switching capable one. The electronic layer can perform wavelength conversion and grooming.

The branching of multicast trees can be performed in the electronic or in the optical layer. The switching devices in the network may or may not have optical layer branching capabilities.

I have constructed a simple wavelength graph model for both cases to support this ILP formulation. By assigning appropriate costs to the logical edges of the device model, we can accurately determine the cost of branching in the optical layer and in the electronic.

Several technical constraints are introduced to influence certain properties of the routing. These constraints reflect real-world technical restrictions.

Since most of the existing switching devices are not able to perform neither optical nor electronic layer branching of the signal due to technical or software restrictions, it might be necessary to limit the splitting of the signal in both layers.

The all-optical branching of the signal has further implications. The power of the signal decreases by 3 dB when it is split in two. In case of splitting in more than two, the attenuation is more significant, which impairs correct detection in a receiver. The number of times the signal is split can be constrained for each sub-demand[4] because it determines the quality of the signal in the receiver.

Various constraints can be applied to influence the topology of the tree, including limit on tree size, depth limit (related to end-to-end delay), and breadth limit.

Some of the constraints can be formulated as penalty terms in the objective function. This way it is not necessary to wait until the solver determines the global optimum of the cost. Thus, the technique may provide a result faster but usually still close to the optimum.

THESIS 2.2: *By applying simulation based on the formulation proposed in* THESIS 2.1, *I have compared two scenarios; first, when the branching of the multicast trees is allowed both in the optical and in the electronic layer, and second, when branching is possible only in the electronic layer. I have shown the benefits of the first scenario over the second one as a function of*

- *the traffic load,*
- *the cost ratio of the optical and the electronic layer,*
- *the grooming ratio*

Dissertation: Chapter 4
Related publications: [J4] [C6]

I have investigated the problem of electronic and optical layer branching in case of multicast routing. I have also performed simulations for unicast routing regarding it as a reference.

Switching devices do not currently have optical branching capability. However, the cost of routing and branching in the optical layer is much cheaper than performing it in the electronic layer, since optical-electronic conversion ports are very costly. Therefore the presence of optical branching feature can be very important and cost effective.

I have shown that the gain of optical branching is a function of the traffic load, the cost ratio of switching components (e.g., grooming ports), and the grooming ratio.

In terms of the traffic load, optical branching outperforms electronic branching only if the number of nodes participating in the trees is low – compared to the total number of nodes in the network. As more and more

[4] The path between the source of the tree and a given leaf node of the tree

nodes are involved in the trees, the advantage of optical branching disappears.

Irrespectively of the grooming ratio, optical branching uses less converter ports than electronic branching. However, it does not decrease the required number of wavelengths. The simulations demonstrated that grooming can compensate for the huge drawback of unicast routing compared to multicast routing in case of tiny demands.

THESIS 2.3: *I have shown which parameters influence the benefits of reconfiguration of dynamic multicast trees and how they influence it, including*

- *the benefits of reconfiguration in case of several dynamic routing algorithms in terms of network resources,*
- *how the length of reconfiguration period, network topology, and network load affect the benefits of reconfiguration,*
- *how the presence or absence of grooming affects the benefit of reconfiguration,*
- *how quickly the optimized tree diverges from the optimal topology*

By applying a realistic cost model, I have determined the optimal length of the reconfiguration period if the cost of reconfiguration and the cost of routing are both taken into account in the total cost.

Dissertation: Chapter 5
Related publications: [J3] [J5] [C5]

In THESIS 2.3 I investigated the problem of dynamic multicast trees, where the end-nodes ("leaves") are continually changing, which causes the degradation (diverging from the optimum) of the multicast tree in terms of switching and transmission resources. This degradation can be overcome by regular reconfiguration of the tree, and a huge amount of networks resources can be released.

I examined several dynamic routing algorithms, while the optimal topology was determined by ILP of THESIS 2.1. The common in the dynamic routing algorithms is that they can route a newly arriving demand without interrupting the current active demands in the network. However, these algorithms have a higher cost in terms of required network resources. Reconfiguration by ILP provides the optimal topology, but it has several drawbacks: the consecutive configurations are very dissimilar; optimization is computationally intensive, and others. These drawbacks can be taken into account as *reconfiguration cost*, in addition to the *routing (network) cost*.

By extensive simulation, I have shown how different input factors and makings (network size, traffic load, grooming, and length of reconfiguration period) influence routing conditions (cost, resource usage) and the benefits of reconfiguration.
In summary, the results demonstrate that

- larger network size,
- higher traffic load,
- less applicability of grooming,

lead to

- a higher average routing cost,
- more networks resources (including wavelength and conversion ports),
- a quicker divergence of the tree topology from the optimal topology.

Furthermore, the results show that less frequent reconfiguration also causes higher average network costs and more resources.

Reconfiguration is more beneficial in the case of higher bandwidths, since grooming is less useful here. In the case of low bandwidths, grooming allows less frequent reconfiguration. Results for conversion units, wavelengths, and total cost are similar.

Assuming a reasonable cost model, the reconfiguration period has an optimal length if the cost of reconfiguration and the routing cost are both counted in the total cost.

THESIS 3: *I have created novel flow dynamics based identification methods to identify peer-to-peer (P2P) traffic in IP networks. The methods solve such identification problems where the conventional port based and pattern based identification methods often cannot be used.*

Since recent web based application (typically P2P application) use arbitrary, random communication ports (TCP/UDP) for transferring data, traditional port-based traffic monitoring and classification methods cannot be applied anymore. Although payload based identification methods can reach higher accuracy, reliable application patterns are often not available. In addition, payload based identification often raises legal and privacy issues and concerns. Storing packet payloads is also highly resource intensive or infeasible especially in the case of high-capacity links. Moreover, unwelcome applications (e.g., Skype or file sharing application, like BitTorrent) tend to encrypt their communication rendering the payload unrecognizable.

On the other hand, flow dynamics based identification methods use only packet headers and timing information. Storage of logged data requires less disk space, which makes offline processing feasible. Flow dynamics methods can be fast and efficient. However, their reliability must be validated.

Apart from port based and payload based attempts, a number of methods have been proposed to identify P2P traffic based on unsupervised and supervised machine learning techniques, including neural networks [36], decision trees [37], support vector machines [38], and cluster analysis [39]. The biggest disadvantage of these methods is that they do not make use of the connection (like parallelism, consecutiveness) between flows but dealing with individual flows (and their properties) only.

I realized a framework based on relational database to efficiently store, handle and process huge traffic measurements. The identification methods were implemented in the form of Transact SQL [33] scripts (in a declarative way) and stored procedures.

THESIS 3.1: *I have constructed an effective and compound heuristic method for the identification of general P2P traffic. The method relies on the recognized robust and inherent characteristics of the traffic generated by major P2P applications. The method is able to separate P2P and non-P2P traffic flows, which allows further analysis. The accuracy of the method was verified on a test dataset, and the method was applied on real-life traffic traces.*

Dissertation: Chapter 8
Related publications: [J6] [C9]

The proposed method is purely based on flow dynamics: it does not require packet payload information; only those properties are considered that can be obtained from packet headers and time stamps.

The method operates at flow level. Flow descriptors and flow level statistics are extracted from the packet dump (containing packet headers only) and contain the following fields:

- Inbound or outbound flow
- IP address and communication port of the source host
- IP address and communication port of the target host
- protocol type (to differentiate TCP and UDP communication)
- TOS (Type of Service), tunnel
- start time, end time, and duration of flows
- number of transmitted bytes, number of packets

In addition to the traditional port based technique, the method exploits strong characteristic properties of the traffic generated by major P2P applications (including file sharing applications). It focuses on the key differences between P2P and non-P2P traffic, such as:

- TCP and UDP communication in parallel,
- Random, non-fix communication port
- Multiple parallel and consecutive flows (segmented downloading)
- High flow duration, large flow size
- P2P application often use HTTP communication ports

The proposed method consists of seven heuristic steps (the order of the steps is strict) which are briefly the following:

0. Port based identification of well-known (conventional) applications.

1. Applications maintaining parallel UDP and TCP connections are P2P.
2. Separation of web and P2P traffic on HTTP communication ports (80, 443, etc.).
3. Identification based on default ports of known P2P applications.
4. Multiple flows with the same identity (IP addresses, ports, protocol type) are likely generated by P2P applications.
5. If a host (with a given IP) repeatedly chooses a certain arbitrary port for TCP/UDP connections, it is likely P2P (other server applications are already filtered out).
6. Those flows are considered P2P which have larger flow size (transmitted data) or high flow length.

Each step of the method marks a set of flows as P2P or non-P2P. Already marked flows do not take part in the identification process anymore. Following steps consider unmarked flows only, which explains why the order of the steps is important. The flow chart of the method is shown in Fig. 2.

The method was verified on a test dataset and applied on several real traffic traces.

Table 1. Validation result of the identification method

Heuristic step	Hit rate (%)
(0) Known Applications	93.01
(1) Heuristic	99.91
(2) Heuristic 2 (HTTP identification)	95.35
(3) Heuristic	99.79
(4) Heuristic	99.97
(5) Heuristic	99.51
Aggregate P2P	**99.14**
Aggregate non-P2P	**97.19**

The performance of each heuristic and the overall identification process are presented in Table 1. The hit rate of each heuristic, counted in percentage, is the ratio of the number of correctly marked flows and the total number of marked flows by the heuristic. It should be noted that the hit rate of the 6th (weakest) heuristic is not shown in the table because it marked no flows in this data set. The last two rows in the table show the rate of correctly marked P2P (non-P2P) flows and the total number of P2P (non-P2P) flows in the data set. The statistics are very convincing for all of the heuristics. The average hit rate is greater than 99%. The amount of unidentified traffic is about 0.1%. The ratio of wrongly marked P2P flows and unidentified P2P flows per the total marked P2P flows are 0.3% and 0.8%, respectively.

The novel findings of the comprehensive traffic analysis built on the hereby proposed method are presented in Section 5.2.

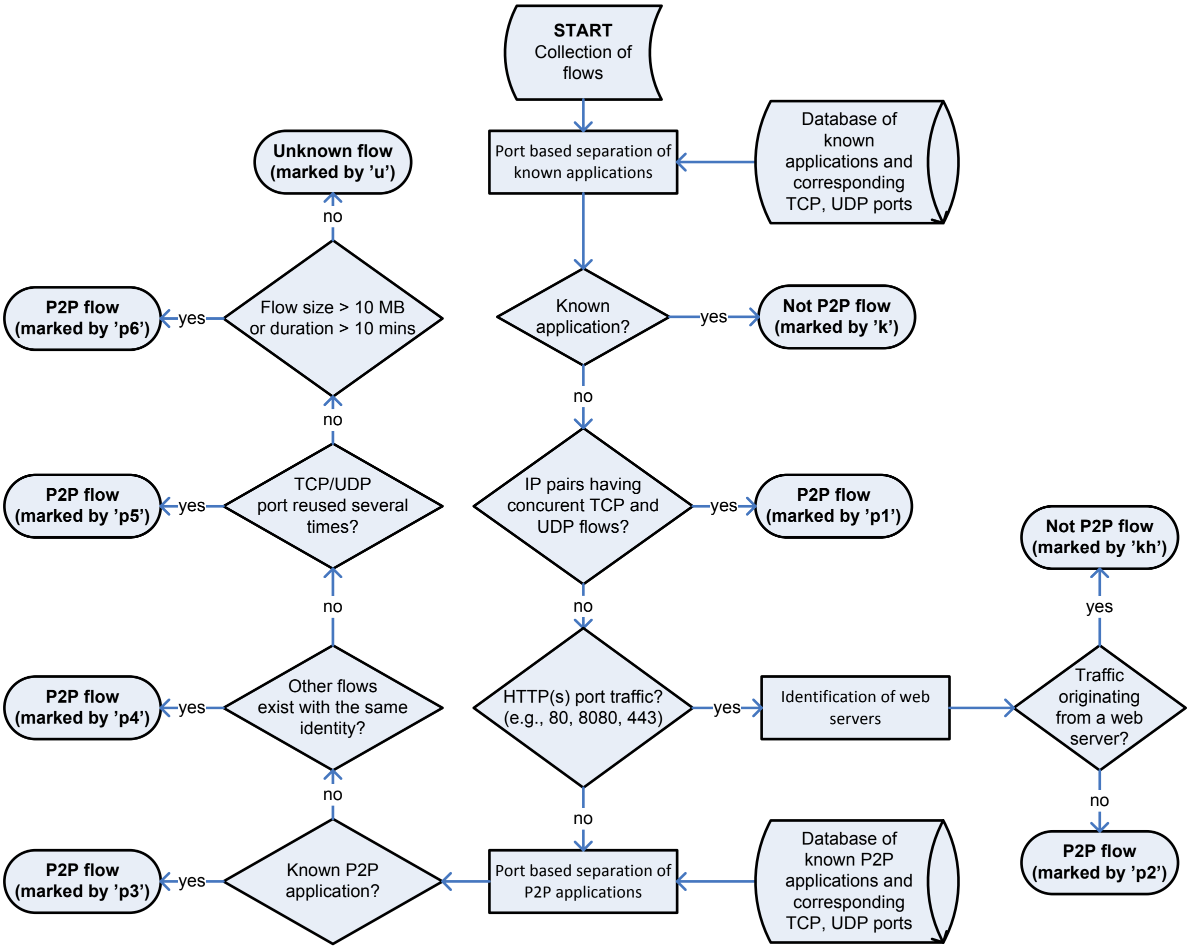

Fig. 2. Flow chart of the P2P traffic identification method

THESIS 3.2: *I have constructed methods for the identification of Skype traffic (a specific P2P application). The methods are based on typical characteristics not applied so far in flow dynamics based identification. Three methods (related to each other) were proposed to detect the following components of the traffic:*

- *client-super-node[5] connection that implicates user presence,*
- *default communication port of the client, which allows more reliable call detection,*
- *and Skype voice calls.*

The methods were validated and applied on real traffic traces.

Dissertation: Chapter 9
Related publications: [C7] [C8]

Skype is the most popular free VoIP application built on peer-to-peer technology. It is becoming a major rival of telephone network providers, especially mobile providers, since it allows flat rate conversation.

Skype employs numerous techniques to hinder its presence. It uses random communication ports and strong encryption to cipher all traffic inside the Skype overlay network. Therefore, traditional identification methods cannot be applied to detect Skype.

In this thesis, I introduce three methods – based on flow dynamics – for the identification of the component of Skype traffic. The methods do not use any payload information, only packet headers, the extracted flow level information, relation between flows, and their time behavior are investigated. The methods operate at flow level and are executed offline.

The first method detects the "signaling connection" between the client and the super-node (SN); the seconds determines the chosen communication ports of the clients; finally, the third (relying on the previous two) identifies voice calls. The overall process of the identification and the roles of the three methods are depicted in Fig. 3.

[5] Clients are the peers of the Skype network. Promoted clients become super-nodes.

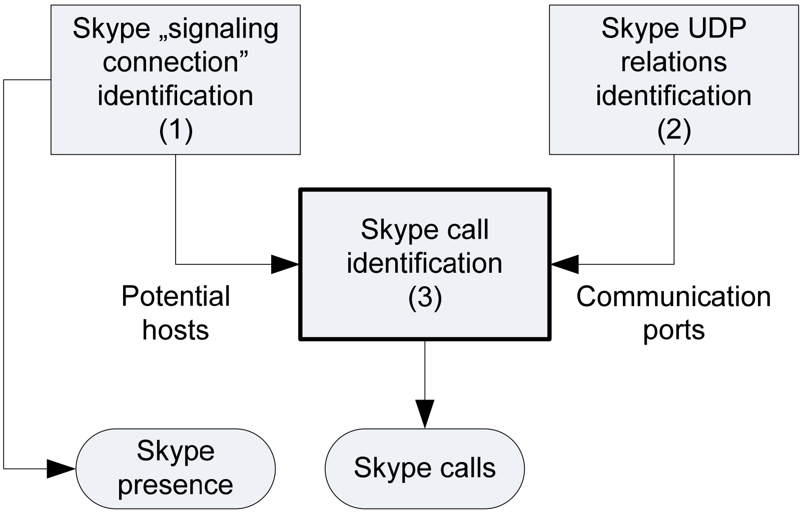

Fig. 3. The overall process of Skype traffic identification and the role of the three methods

I found that each Skype client maintains a permanent TCP connection while the user is logged on to the network. I proposed a method which can detect this signaling connection between the client and its SN. A TCP connection is considered a Skype signaling connection if it obeys all of the following rules:

1. The outbound and inbound data rates are not larger than 320 bps;
2. The intensity of packets (in outbound and inbound direction separately) is not larger than 0.4 packets/sec;
3. Every packet in outbound direction is smaller than 1000 bytes (including IP and TCP headers);
4. A periodicity of 1 minute is observable for outbound packets of size between 70 and 250 bytes (i.e., a certain percentage of such packets arrive in a specific, periodic time slot).

With the aid of the method, it is possible to estimate the number of active Skype users in the domain.

It is important to identify the (randomly selected but later fix) communication port of each Skype client. This is achieved by analyzing the communication between the Skype client and other clients. These so called “UDP relations” can be detected by a simple identification method shown in Fig. 4.

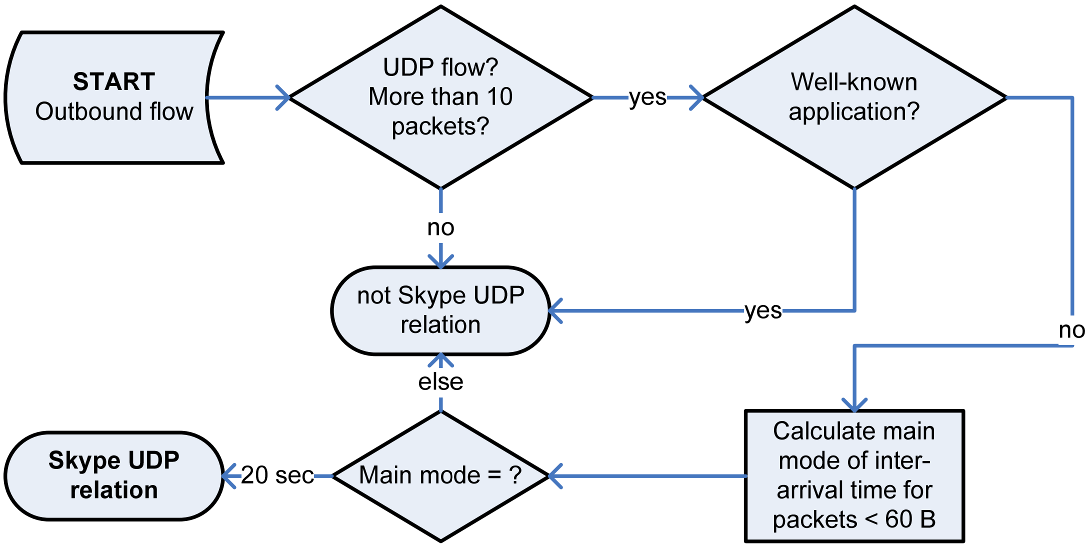

Fig. 4. Detection of Skype UDP relations between Skype hosts

Skype voice calls can be detected by a more complex identification method shown in Fig. 5. The method applies filtering conditions of flow and packet level properties (in addition to time behavior of connections), such as bandwidth, packet rate, average packet size, and the main mode of inter-arrival time. The method also strongly relies on the list of Skype hosts and default communication ports identified by the previous method.

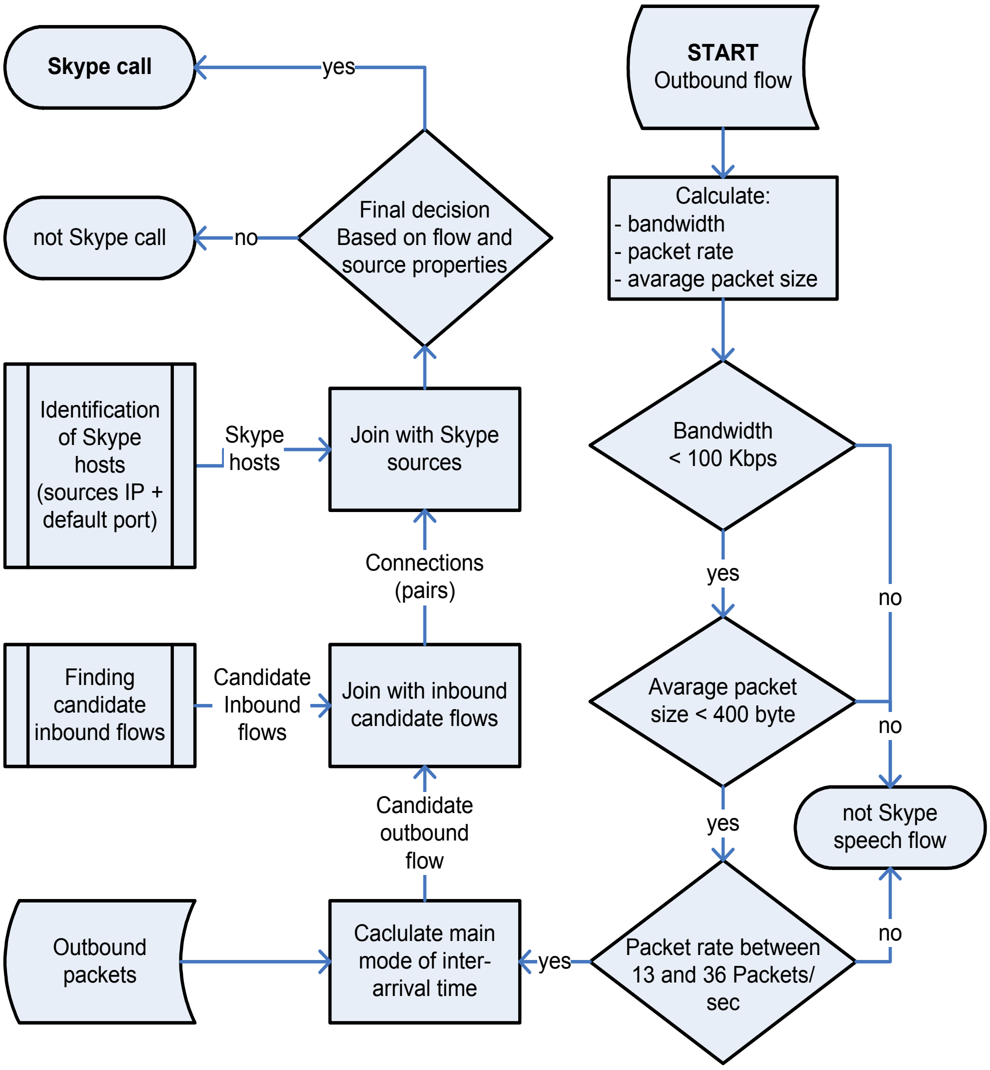

Fig. 5. Identification process of Skype calls

The methods were applied and verified in both fixed and mobile network environments.

The novel findings of a comparative traffic analysis built on the hereby proposed method are presented in Section 5.3.

5. Application of New Results

5.1. Optical Networks

All of my new results in the field of optical networks have practical real-world or industrial application.

Dimensioning and optimization of grooming capability and the number of wavelengths is an important issue in both static and dynamic optical networks. THESIS 1.1 solves the problem for dynamic multilayer optical networks. Although these networks are still in experimental phase, my results will be very valuable upon their deployment.

Since grooming ports are very expensive, determining the necessary number of this type of resource has a direct effect on costs (CAPEX). My results showed that, by applying optimization, the required number of grooming ports can be reduced significantly (20% or more).

Although the number of available wavelength in a fiber cannot be adjusted one-by-one (since it depends on the interface of the switching device), optimization of the required number of wavelengths still has a high importance. It allows changing a more expensive interface (supporting more WLs) to a cheaper one (supporting less WLs) on underutilized links. If such a scenario is assumed where multiple operators share a single physical network and they pay according to the used network resources, every operator has their own interest to reduce the network resource usage as much as possible.

The techniques – solving the joint optimization problem of routing and determining signal levels – proposed in THESIS 1.2 and THESIS 1.3 can be directly applied in real-world environment. They can be easily implemented in current optical networks, since recent modern switching devices already support adjusting of power levels separate for each wavelength. However, in practice this feature is not exploited. In fact, usually the shortest path method is applied for routing; and signal levels are tuned manually without deploying any optimization technique. I have shown, however, that by using these systematic optimization techniques significantly better performance can be achieved. The technique proposed in THESIS 1.2 is already protected by a patent [P1].

The optimization technique proposed in THESIS 2.1 can be applied for routing and network planning. It takes into account several circumstances (e.g., unicast and multicast, electronic and optical branching, topology constraints) that need to be considered in future networks.

THESIS 2.2 presents a comprehensive comparison of optical and electronic layer branching from several aspects. The results obtained from simulations (providing global optimum) can be used for network planning purposes.

Nowadays optical multicast (especially dynamic multicast) is a very popular research topic. In general, it can be said that it is the most economical to implement multicast in the lowest layers of the network hierarchy. Multicast service (though not directly available to end users) is an essential feature present in the core of the transport network because it is the key to the scalable implementation of the triple-play concept: digital media is usually multicasted from a content distributor to local caches/relays near the end users. The audience may vary in time: new customers appear, who subscribe for the content, and other customers with expired subscription leave the network. In this case a customer does not necessarily mean an individual home user, but rather a local provider. Another example can be a virtual LAN service, where LAN broadcast has to be delivered to all endpoints.

In THESIS 2.3 the regular reconfiguration of dynamic multicast trees is investigated from several aspects. The results of the widespread analysis can be used for network dimensioning and planning purposes. Expectedly these results will gain even higher importance as optical technology proceeds in the access network closer and closer to the end user (Fiber to the home/building/curb) and as high definition digital media becomes available for more and more users.

5.2. P2P Traffic Analysis

I applied the identification method proposed in THESIS 3.1 for several real, large scale traffic traces and made a comprehensive traffic analysis. I have shown the similarities and differences between P2P and non-P2P traffic in several aspects. I have also analyzed the behavior of P2P and non-P2P users and applications. *The details of the analysis are found in Section 8.5 of my Dissertation.*

I investigated and compared P2P and non-P2P traffic at packet level, flow level, and aggregate level. I confirmed several general characteristics that were given for traffic aggregates and, in addition, the following new findings were made:

- At packet level there are certain P2P applications that are responsible for certain packet sizes appearing with high frequency in the traffic (e.g., Gnutella for 528 byte, BitTorrent for 128 byte, eDonkey for 1200 byte packets, respectively).

- In an aggregation of P2P traffic (generated by several P2P applications) the distribution of flow sizes follows a heavy-tailed (Pareto) model. Similarly, in an aggregation of non-P2P traffic flow sizes also have a heavy-tailed distribution (Pareto, [35]). The shape parameter is about -0.3 for P2P and -0.25 for non-P2P flows.
- According to the ranking, the top 10% of P2P users is responsible for 90% of the P2P traffic volume, the difference is higher between "obsessive" and hobby P2P users than the difference in case of non-P2P users.
- The relation between the active P2P users and the total active users follows a strong linear relationship, which suggests that always a certain ratio (0.2-0.3) of users use P2P applications.
- At the top (about 10%) of the ranked list, the popular Zipf's law [34] seems to be accurate to describe both P2P and non-P2P traffic popularity. Standard Pareto distribution is a suitable model for the traffic of top ranked users.

5.3. Skype Traffic Analysis

I applied the identification method proposed in THESIS 3.2 for several real, large scale traffic traces and showed unique properties of Skype traffic at flow level and aggregate level. I have also analyzed the behavior of Skype users. I have compared the properties of Skype traffic and the behavior of Skype users in fixed and mobile networks. *The details of the traffic analysis are presented in Section 9.7 of the Dissertation.*

I investigated the daily fluctuation of the number of Skype calls and Skype users in several traffic traces, including ones captured in fixed ADSL domains and others from mobile networks. I also examined the daily fluctuation of speech hours[6]. *The results show that Skype has a unique daily profile which differs from general daily profiles typical in PSTN networks.* It suggests that most Skype users use Skype for hobby purposes as a free-time activity. The main busy hours are the night hours. The calls are also longer on average at this period.

I described the most important, characteristic properties of individual Skype calls, such as bandwidth, packet rate, average packet size, and call duration. *The results show that the duration of Skype calls have an exponential-like distribution.* These properties can serve network dimensioning purposes for the operator. I also provided measures of user

[6] The sum of the duration of all Skype calls performed by the users in a given hour

behavior, such as ranking of heavy user and MOU[7] (minutes of use), etc., which may support pricing decisions.

I also carried out Skype identification in 3G mobile networks which is extremely important for mobile operators because of pricing purposes. They are interested in Skype usage to find a tradeoff between per minute based traditional call tariffs and the flat rate data transmission (Skype) tariff. *I found that characteristic properties of Skype traffic are very similar in a fixed network and in a HS mobile network, which suggests that Skype is well applicable in both*.

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