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Zhonghong Ou

STRUCTURED PEER-TO-PEER NETWORKS: HIERARCHICAL ARCHITECTURE AND PERFORMANCE EVALUATION

FACULTY OF TECHNOLOGY,
DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING,
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UNIVERSITY OF OULU

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ZHONGHONG OU

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Academic dissertation to be presented with the assent of the Faculty of Technology of the University of Oulu for public defence in OP-sali (Auditorium L10), Linnanmaa, on 26 August 2010, at 12 noon

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Abstract

Peer-to-Peer (P2P) networking changes the way of people utilizing Internet, for example, sharing and consuming digital content, from the ground up. It continues to show its power and strength when it is combined with other emerging technologies, such as Web Services. This thesis contributes to the research and development of P2P networks from four aspects.

Firstly, a P2P and Web Services converged multiple-tier system architecture is proposed. The architecture proposed enables providing Web Services in the context of heterogeneous access networks in an efficient way by utilizing P2P paradigm. A lightweight middleware architecture is introduced to fit the diversified mobile terminals. A theoretical analysis is given to provide a comparative study with the conventional centralized architecture.

Secondly, a General Truncated Pyramid Peer-to-Peer (GTPP) architecture is presented to analyze the performance of hierarchical architecture compared with flat architecture. The motivation behind the GTPP architecture is to see whether an added tier can bring with it added value and functionality. A detailed mathematical analysis is provided which takes into consideration various performance metrics, including the lookup hopcount, lookup latency, maintenance traffic from a single peer point of view, and maintenance traffic from the whole system point of view. Furthermore, simulation results with respect to the lookup hopcount are also provided. Through mathematical analysis and simulation results, an optimal value regarding the number of tiers of the GTPP architecture is found, showing that 2~3 tiers are appropriate for most of situations. A specialized model is also proposed to improve the performance of hierarchical architecture.

Thirdly, the performance evaluation of a communication-oriented Kademlia-based P2P system is provided in detail. NetHawk EAST-based simulation models and a prototype are both utilized to evaluate the performance. Simulation results from NetHawk EAST-based simulation models demonstrate the optimal design choices regarding the resource lookup parallelism degree and resource replication degree, and show the unnecessary existence of the messages used to detect the liveness of peers in a DHT overlay. Measurements from the prototype show the feasibility of mobile nodes acting as fully fledged overlay nodes from three different perspectives, namely CPU processing load, network traffic load, and battery consumption. The optimal size of packets which consumes battery in the most efficient way is also found through battery consumption measurements.

Fourthly, the effects of different churn models on the performance of structured P2P networks are analyzed. Specifically, three typical churn models are analyzed to provide a comparative result. The simulation results show that the difference among the effects of different churn models on the performance of structured P2P networks is quantitative rather than qualitative. This provides some guidance for the selection of different churn models for the contemporary researchers.

Keywords: battery life, communication-oriented, GTPP, hierarchical architecture, performance evaluation, P2P, structured networks, system architecture, Web Services

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Oulu, May, 2010 Zhonghong Ou

Abbreviations

k	Hierarchy depth of vertical hierarchical architecture
3G	Third Generation
ACE	Adaptive Connection Establishment
ADSL	Asymmetric Digital Subscriber Line
AoR	Address of Record
ARPANET	Advanced Research Projects Agency Network
AS	Autonomous System
BGP	Border Gateway Protocol
C/S	Client/Server
CDN	Content Distributed Network
CPU	Central Processing Unit
DCMP	Distributed Cycle Minimization Protocol
DHT	Distributed Hash Table
DNS	Domain Name System
DoS	Denial of Service
DSHT	Distributed Sloppy Hash Table
ED	Exponential Distribution
FTP	File Transfer Protocol
G-MSB	GGSN-located Mobile Service Broker
GGSN	Gateway GPRS Support Node
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
GTPP	General Truncated Pyramid Peer-to-Peer
HA	Hierarchical Architecture
HoHA	Horizontal Hierarchical Architecture
HONet	Hybrid Overlay Networks
HyHA	Hybrid Hierarchical Architecture
ID	Identifier
IETF	Internet Engineering Task Force
IM	Instant Messaging
IMP	Interface Message Processor

IP	Internet Protocol
J2ME	Java 2 Platform, Micro Edition
JXTA	Juxtapose
MANET	Mobile Ad Hoc Network
MSB	Mobile Service Broker
MSISDN	Mobile Station Integrated Services Digital Network
MSP	Mobile Service Provider
MSR	Mobile Service Requestor
MWS	Mobile Web Service
NAT	Network Address Translation
OS	Operating System
OSPF	Open Shortest Path First
P2P	Peer-to-Peer
P2PNS	Peer-to-Peer Name Service
P2PP	Peer-to-Peer Protocol
P2PSIP	Peer-to-Peer Session Initiation Protocol
PCMS	P2P Community Management System
PD	Pareto Distribution
PDA	Personal Digital Assistant
PLMN	Public Land Mobile Network
PPMA	Plug-and-Play Middleware Architecture
PVC	Performance Versus Cost
R-MSB	RNC-located Mobile Service Broker
RELOAD	REsource LOcation And Discovery
RIP	Routing Information Protocol
RNC	Radio Network Controller
RNS	Radio Network Subsystems
RTT	Round-trip Time
RW	Random Walk
SAMP	Scalable Application-layer Mobility Protocol
SCCM	Service-oriented Community Coordinated Multimedia
SETI	Search for Extra-Terrestrial Intelligence
SGSN	Serving GPRS Support Node
SIP	Session Initiation Protocol
SOA	Service Oriented Architecture

SOAP	Simple Object Access Protocol
SSO	Sub-Sub-Overlay
T-MSB	Terminal-located Mobile Service Broker
TCP	Transmission Control Protocol
TPP	Truncated Pyramid P2P
TTL	Time-to-Live
UDP	User Datagram Protocol
UI	User Interface
UMTS	Universal Mobile Telecommunications System
URI	Uniform Resource Identifier
UTRAN	UMTS Terrestrial Radio Access Network
UUCP	Unix-to-Unix Copy Protocol
VeHA	Vertical Hierarchical Architecture
VoIP	Voice over Internet Protocol
VTM	Vertical Tunneling Model
WD	Weibull Distribution
WLAN	Wireless Local Area Network
WS	Web Service
WSN	Wireless Sensor Network
XML	Extensible Markup Language
XMPP	Extensible Messaging and Presence Protocol
YAPPERS	Yet Another Peer-to-PEeR System

List of original articles

This thesis is based on the following original articles, which are referred to in the text by their Roman numerals (I–X):

I Ou Z, Song M, Chen H & Song J (2008) Layered peer-to-peer architecture for mobile web services via converged cellular and Ad Hoc networks. Proceedings of the 3rd International Conference on Grid and Pervasive Computing Workshops (GPC Workshops ’08): 195–200.

II Zhou J, Ou Z, Rautiainen M & Ylianttila M (2008) P2P SCCM: Service-oriented community coordinated multimedia over P2P. Proceedings of the IEEE Congress on Services Part II 2008 (SERVICES-2): 34–40.

III Ou Z, Zhou J, Harjula E & Ylianttila M (2009) Truncated pyramid peer-to-peer architecture with vertical tunneling model. Proceedings of the 6th IEEE Consumer Communications and Networking Conference (CCNC 2009): 1–5.

IV Koskela T, Kassinen O, Ou Z & Ylianttila M (2010) Improving community management performance with two-level hierarchical DHT overlays. Journal of Internet Technology, Special Issue on Internet Resource Sharing and Discovery, 11 (2): 167–179.

V Ou Z, Harjula E & Ylianttila M (2008) GTPP: General truncated pyramid architecture over P2PSIP networks. Proceedings of the International Conference on Mobile Technology, Applications, and Systems (Mobility ’08): 1–4.

VI Ou Z, Harjula E, Koskela T & Ylianttila M (2010) GTPP: general truncated pyramid peer-to-peer architecture over structured DHT networks. Springer Mobile Networks and Applications, DOI: 10.1007/s11036-009-0193-2 (Online first, in press).

VII Kassinen O, Ou Z, Harjula E & Ylianttila M (2008) Effects of peer-to-peer overlay parameters on mobile battery duration and resource lookup efficiency. Proceedings of the 7th International Conference on Mobile and Ubiquitous Multimedia (MUM’08): 177–180.

VIII Ou Z, Harjula E, Kassinen O & Ylianttila M (2009) Feasibility evaluation of a communication-oriented P2P system in mobile environments. Proceedings of the International Conference on Mobile Technology, Applications and Systems (Mobility ’09): 1–8.

IX Ou Z, Harjula E, Kassinen O & Ylianttila M (2010) Performance evaluation of a Kademlia-based communication-oriented P2P system under churn. Elsevier Journal Computer Networks 54 (5): 689–705.

X Ou Z, Harjula E & Ylianttila M (2009) Effects of different churn models on the performance of structured peer-to-peer networks. Proceedings of the 20th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC ’09): 2856–2860.

Papers I and II, deal with the problems related to P2P and Web Services converged system architecture. Papers III, IV, V and VI address the research issues related to vertical hierarchical P2P architecture. Papers VII, VIII and IX studies the performance evaluation of communication-oriented structured P2P networks. Finally, Paper X analyzes the effects of different churn models on the performance of structured P2P networks.

Furthermore, the author of this thesis has participated extensively in the publications of magazine articles, book chapters, technical reports and conference papers in various research areas, ranging from digital television, Web Services, to mobile search. These studies supplement the research work presented in this thesis from their own perspectives.

Contents

1 Introduction

"*Consider the past and you shall know the future.*"
-Confucius

1.1 Background

Peer-to-Peer (P2P) networking is among the hottest topics in the research arena of computer communication in the last decade. However, P2P networking is not a new concept. Its origin can be traced back to the late 1960s. According to Andy (2001), the history of P2P networking can be roughly divided into four stages:(1969–1995),(1995–1999),(2000), and (2001–?). In this thesis, a revised chronology history of P2P networking is used to make the concept clearer, which is made up of three stages:

– (1969–1995) Prehistory: P2P thought burgeoning;
– (1995–1999) Internet explosion: P2P concept retrogressive;
– (1999–?) P2P term widely used: P2P-based applications blossom.

During the prehistory stage of P2P networking (1969–1995), the thought of P2P burgeoned through several systems, although the so-called "P2P" term was not adopted at that time.

When Advanced Research Projects Agency Network (ARPANET) (McQuillan & Walden 1977, McQuillan *et al.* 1978), the precursor of the current Internet, was originally initiated in the late 1960s, it was a de facto P2P system. The original ARPANET was designed to share the computing resources around the United States widely and efficiently. It was composed of small computers known as Interface Message Processors (IMPs), which are now called routers, connected as equal players instead of under Client/Server (C/S) relationship. The initial ARPANET consisted of four IMP sites, including University of California, Los Angeles (UCLA), Stanford Research Institute (SRI), University of California, Santa Barbara (UCSB), and the University of Utah in Salt Lake City. (Aboba 1993.)

Usenet was another example during the first stage which utilized the decentralized control and relatively simple administration. Usenet was first conceived in 1979 by two graduate students from Duke University and was publicly established in 1980 at the University of North Carolina and Duke University. (Andy 2001, Lueg & Fisher

2003.) Its original purpose was to exchange information in the Unix community with no central control. By utilizing the Unix-to-Unix Copy Protocol (UUCP), one Unix machine could automatically set up a connection with another machine, exchange files or other messages with it, and then disconnect. The current Usenet utilizes a Transmission Control Protocol (TCP)/ Internet Protocol (IP) based protocol, which is named as Network News Transport Protocol (NNTP), to discover newsgroups and exchange new messages in each group (Andy 2001). Usenet could be seen as the grandfather of the current P2P applications, for example Gnutella and Freenet, in the sense that it originally copied files between computers with no central authority control, and the addition of new newsgroups was based on a rigorous democratic voting process.

Even in the naturally hierarchical Domain Name System (DNS), we could see the shadow of P2P networking as well. In the early days of Internet, the mapping relationship between a user-friendly domain name, e.g. oulu.fi, to an IP address was recorded in a single flat file, *host.txt*, which was copied around the Internet periodically. DNS was put forward in 1983 (Andy 2001) to deal with the ever-increasing hosts on the Internet. In the hierarchical architecture of DNS, one name server could forward the request to its upper-level name server if it could not map the domain name to an IP address from its own namespace. From this point of view, the name servers, except the root name servers, operate as both clients and servers, which is the fundamental thought of P2P networking.

During the second stage of Internet explosion (1995-1999), the concept of P2P networking was retrogressive and gradually gave way to C/S network model. It mainly resulted from the following reasons (Andy 2001):

Firstly, the Internet explosion from the middle of the 1990s turned the Internet into a mass medium. Millions of ordinary folks swarmed into the Internet to retrieve information. They were not interested in or were not skilled enough to be able to publish or upload information to the Internet at that time. From this point of view, the asymmetric C/S network model satisfied the requirements of the ordinary folks to a large extent and accelerated the expansion of the C/S model accordingly.

Secondly, the breakdown of the cooperation among the Internet participants made the Internet much less open than it was originally designed. The original Internet was established simply to cooperate and exchange information among researchers. It was symmetric in the sense that if one computer could access the Internet, every other computer on the Internet could access this computer as well. As time went by, the Internet became more and more commercialized, accompanied with which was the ever-increasing unsolicited commercial information or spam advertisements. The "green card spam" occurred on April 12, 1994 on Usenet symbolized the end of the innocent Internet(Andy 2001). In order to filter the spam information, deal with the IP address scarcity problem and prevent the corporate networks from all kinds of malicious attacks, firewalls, dynamic IP addresses, and Network Address Translation (NAT) came into use accordingly in the mid-1990s. As a consequence, most of the Internet participants acted as clients.

Thirdly, technical push augmented the asymmetrical property of the Internet. Network bandwidth was among the most precious and scarce resources in the age of Internet explosion. In order to make full use of the limited network bandwidth, network manufacturers chose to provide asymmetric network connections, for example, Asymmetric Digital Subscriber Line (ADSL) and cable modem, with the speed of downlink multiple times of that of uplink. This feature benefited C/S model and augmented its popularity consequently.

The third stage of P2P networking (1999–?) is the stage during which the concept of P2P was formally used and widely accepted. Thanks to the high popularity, wide attention given to Napster, the Internet environment started to shift back to P2P climate in 1999. Napster was developed in May, 1999 by Shawn Fanning, a freshman at Northeastern University, to share music files freely among the music enthusiasts all over the world. Napster was labelled as the first-generation of P2P system. It adopted a centralized index server, the so-called hybrid architecture, to record the indices of the shared music files. At its peak time in the early 2000, Napster got together about 60 million registered users around the world. It was around the same time, the term *P2P* was associated with applications such as Napster. (Nagaraja *et al.* 2006.) Since then, the research around P2P-related topics and the associated commercial products emerged like bamboo shoots after a spring rain. Napster stopped operation in July 2001 owing to some prosecution against its violating copyright laws. However, it had ignited the P2P craze before its shutdown.

Gnutella version 0.4 (Ripeanu 2001), a flooding-based fully decentralized P2P system came into use in early 2000 to address the shortfall of Napster's hybrid architecture and to avoid unnecessary lawsuit. It was labelled as the second-generation of P2P system. The query and maintenance messages were propagated through a flooding technique in Gnutella, no central authority was used. However, accompanied with Gnutella's flexibility was its poor search efficiency and limited scalability.

In order to handle the shortcomings of the second-generation of P2P system, the third-generation of P2P system came into being in 2001. Typical examples included Gnutella version 0.6 (Xie *et al.* 2008), Kazaa (Leibowitz *et al.* 2003) and Juxtapose (JXTA) (Maibaum & Mundt 2002). Hierarchical architecture was utilized to improve the search efficiency and advance the network scalability in these systems. P2P participants were divided into *ultrapeers* and *edge peers*, according to different criteria such as node capability and online time. *Ultrapeers* are generally more powerful and stable than *edge peers* and are responsible for routing search and maintenance messages, while *edge peers* are mainly located at the 'edge' of the network and are not responsible for routing. This hierarchical architecture has gained broad attention and is still in use in the current P2P networks, it is also one of the main research topics of this thesis.

At around the same time as the birth of the third-generation of hierarchy-based P2P system, Distributed Hash Table (DHT) was developed in 2001, in another direction to solve the weak search efficiency problem of the second-generation of P2P system. Typical examples included Chord (Stoica *et al.* 2003), Content-Addressable Network (CAN) (Ratnasamy *et al.* 2001), Pastry (Rowstron & Druschel 2001), and Tapestry (Zhao *et al.* 2004), which were introduced around the same time in 2001. Later on, Kademlia was designed by Maymounkov & Mazires in 2002 (Maymounkov & Mazires 2002). Since then, the research on DHT had been active in the academia and is still a hot research topic in the current research community. DHT-based P2P algorithms usually adopt special mechanisms, for example consistent hashing, to map the key space with the value space. The address space of the participating nodes is organized in such a way that makes it look like certain structure, e.g. a ring or a torus. Thus, it is also called *structured* P2P networks. DHT-based P2P network has its advantages in precise search over the second-generation of P2P network. The lookup hop-count is usually within $O(log(N))$, N is the number of nodes of the P2P network. Although widely studied, there are still some research problems remaining to be solved. A thorough and detailed performance evaluation, including overhead, and energy efficiency, etc., of the structured P2P networks in mobile environments is one of them, and this is another main research topic of this thesis.

There are also some other research topics in the arena of P2P systems, for example distributed computation (Androutsellis-Theotokis & Spinellis 2004) and load balancing (Shen & Xu 2007). Since they are not related to this thesis, they are not listed here.

1.2 Motivation and research problems

There are many perspectives of structured P2P networks which deserve research attention. This thesis primarily concentrates on two categories. The first category is regarding the hierarchical architecture of structured P2P networks. As can be seen from the previous section, hierarchical architecture almost always accompanies with large-scale distributed systems. For example, flat ARPANET evolved into the current hierarchical Internet, original flat Usenet developed into multi-tier architecture, fully decentralized Gnutella v0.4 advanced into a differentiated role-based system, not even to mention the naturally hierarchical DNS. Hierarchical architecture shows its advantage in search efficiency and scalability compared to flat architecture, and consequently, has attracted a great deal of research efforts. However, the following problems still remain to be solved:

- How to provide Web Services (WS) via the converged cellular and Ad Hoc networks efficiently? What is the role and benefit of the hierarchical P2P architecture in this service provision?
- As far as multi-tier hierarchical P2P architecture is concerned, can the added tier of hierarchy provide added value in terms of performance and functionality? How many tiers are optimal for hierarchical P2P architectures, and what are the benefits of hierarchical P2P architecture compared to flat architecture?

The second category is related to the performance and feasibility evaluation of DHT-based structured P2P network in the context of mobile environments. As mentioned in the previous section, DHT-based structured P2P network shows its benefits in precise search[1] and efficiently decrease the search traffic compared to flooding-based lookup algorithms. Therefore, it is suitable for mobile environments that are characterized by the limited bandwidth. As ever-increasing number of mobile terminals are capable of joining the Internet, it is meaningful to evaluate the feasibility of mobile nodes acting as structured P2P nodes from the perspectives of Central Processing Unit (CPU) load, network traffic load and battery consumption. By utilizing Kademlia (Maymounkov & Mazires 2002) with some modifications as the example DHT algorithm, this thesis studies the performance evaluation of structured P2P network in order to solve the following problems:

[1] Another term used widely is *deterministic search*, which means given the key of an object, the value of the object can be found within bounded cost.

– In the mobile environments which are characterized by intermittent connections and limited bandwidths, what are the optimal design options and parameter configurations of the Kademlia-based structured P2P network? Is Kademlia-based structured P2P network feasible in mobile environments from the perspectives of CPU load, network traffic load and battery consumption?
– As for the effects of churn on the performance of structured P2P networks, are there significant differences among the typical churn models, including Exponential Distribution (ED), Pareto Distribution (PD) and Weibull Distribution (WD)?

1.3 Scope and methodology

In order to solve the problems presented in Section 1.2, three categories of methodology are utilized in this thesis.

Firstly, mathematical analysis is utilized to solve the first category of problems, i.e. hierarchical architecture. The reason for this is that mathematical analysis can provide theoretical direction for practical design options. From this perspective, a layered P2P architecture was designed for providing WS via converged mobile cellular and Ad Hoc networks. In order to decrease the lookup hop-count in hierarchical P2P architecture, a Vertical Tunneling Model (VTM) was put forward. Furthermore, a General Truncated Pyramid Peer-to-Peer (GTPP) architecture was built up to study the optimal number of tiers and optimal number of peers in each tier by analyzing the parameters of hierarchical P2P architecture, including lookup hop-count, lookup routing latency, and maintenance traffic.

Secondly, simulation models are used to analyze the performance of structured P2P networks. For this purpose, Kademlia (Maymounkov & Mazires 2002) with some modifications was chosen as the underlying DHT algorithm, and Peer-to-Peer Protocol (P2PP) (Baset *et al.* 2007) as the signaling protocol. NetHawk EAST software[2] is utilized to simulate the abovementioned structured P2P network. NetHawk EAST is a test automation and traffic generation tool to simulate the telecommunication networks. It has the functionality of supporting binary encoding and decoding that is suitable for simulating the binary formatted P2PP. The binary formatted messages of the protocol can be precisely emulated to make the simulated traffic load as close to real life traffic as possible. A complete set of scenarios regarding different overlay parameters, for exam-

[2]NetHawk EAST URI: https://www.nethawk.fi/products/nethawk_simulators/

ple, parallel lookup mechanism, resource replication mechanism, effects of churn, are tested in this thesis to provide a deep insight into the performance of Kademlia-based structured P2P network.

Thirdly, a real-life prototype system is utilized to analyze the feasibility of mobile nodes acting as full-fledged peers. It must be noted that the prototype system is not developed by the author of this thesis, it is just utilized to perform the aforementioned feasibility evaluation measurements. The functionality of the prototype system is the same as the NetHawk EAST-based simulation models. The prototype can work both on Symbian Operating System (OS) Series 60 on the Nokia N95 smartphone, and Ubuntu Linux on Sun Microsystems server hardware. When running simulations, a large number of processes are running separately in the Linux server to simulate the majority of the peers of an overlay, while two mobile devices (Nokia N95) participating in the overlay are used as mobile peers. The CPU processing load, network traffic load and battery consumption of Nokia N95 mobile phones are measured to evaluate the feasibility of mobile nodes participating P2P networks.

1.4 Contributions of the thesis

Regarding the aforementioned research problems, this thesis contributes from four different aspects. A brief overview of the contributions is provided below, while the detailed contributions with respect to each paper are presented in Chapter 3 where a summary of the research contributions of this thesis is listed.

The first contribution of this thesis is associated with the Web Services and P2P converged framework. In Paper I, a layered P2P architecture is designed for providing Web services via converged mobile cellular and Ad Hoc networks. The services are classified into three different categories according to their popularity: 'hot', 'warm', and 'cold'. In order to speed up the service lookup, the VTM concept, which forwards service lookup request from lower layers directly to upper layers, is put forward in Paper II.

The second contribution is regarding the generalized hierarchical P2P architecture. Paper III put the VTM a step further in the context of pure P2P environment by providing a detailed mathematical analysis with regard to the lookup hop-count, a most critical performance metric in P2P networks. Paper IV proposes a two-tier P2P community management system. In Paper V and Paper VI, a generalized hierarchical P2P architecture, i.e. GTPP, is built up to analyze the performance of hierarchical P2P architecture when it is compared to flat P2P architecture. To the best of the author's knowledge, these two papers are the first attempts to provide mathematical analysis for the performance of multiple-tier hierarchical P2P architectures. Through thorough mathematical analysis, it is shown that 2-3 tiers are optimal for hierarchical P2P architectures when considering all the parameters, including lookup hop-count, lookup latency, and maintenance traffic, etc.

The third contribution is related to the performance evaluation of structured P2P networks. In paper VII, Paper VIII, and Paper IX, a Kademlia-based communication-oriented P2P system is built up through simulation models and a prototype. Kademlia with some modifications is used as the underlying DHT algorithm, and P2PP as the signalling protocol. The results from the simulation models created using NetHawk EAST illustrate the optimal values for the lookup parallelism degree and resource replication degree. Through measurements from the prototype implementation, observations are made with respect to the CPU load, network traffic load and power consumption in Universal Mobile Telecommunications System (UMTS) and Wireless Local Area Network (WLAN) access modes, respectively. The feasibility of mobile nodes acting as full-fledged peers is also illustrated by the prototype measurements. To the best of the author's knowledge, the findings made in Paper VIII and Paper IX are the first research work to find the critical points of power consumption of mobile phones concerning diversified transmission time intervals and packet sizes.

The fourth contribution is associated with different churn models. In Paper X, the effects of different churn models on the performance of structured P2P networks are provided. Specifically, ED, PD, and WD are evaluated to provide a comparative analysis. Kademlia-based P2PP is utilized as the underlying signalling protocol. The simulation results show that different churn models do not have a significant difference regarding their effects on the performance of the simulated structured P2P network. Quantitatively, ED and PD outperform WD in terms of lookup success rate, mean network traffic load, and mean number of messages. It means that, if the simulation results concern the quantitative difference, it is best to choose WD so that the simulation results are not over-optimistic; otherwise, the selection of the three typical churn models can be random. The finding in this paper helps to quiet down the controversy concerning which churn model should be chosen in the simulation of churn effects.

1.5 Organization of the thesis

The organization of the thesis is as follows: In this chapter, the background of the research topics, motivation and research problems, scope and methodology, as well as a brief overview of the contributions of this thesis are shortly discussed.

Chapter 2 presents a literature overview of the related research topics of this thesis, including Web Services and P2P converged framework, hierarchical P2P architecture, performance evaluation of structured P2P networks from three distinct aspects, and churn models study of structured P2P networks.

Chapter 3 summarizes the main contributions of the original papers which is also made up of four parts: Web Services and P2P converged framework, vertical hierarchical architecture, performance evaluation, and churn models.

Chapter 4 draws a conclusion of the thesis and presents the future work.

2 Literature overview

This chapter provides an overview of the research topics related to Web Services and P2P converged framework, hierarchical architecture, performance evaluation and churn models of structured P2P networks. In order to make the description of the subsequent sections clearer, some related concepts are firstly introduced in Section 2.1. Then in Section 2.2, a literature overview regarding the Web Services and P2P converged framework is presented. Section 2.3 describes the hierarchical architecture. Section 2.4 states the related work of performance evaluation, and finally, Section 2.5 presents the current research status of churn models of P2P networks.

2.1 Background

2.1.1 Roadmap of P2P computing

Looking back on the history of P2P computing, some similarities can be found with the history of the evolution of human being. Originally, every single human was equal in primitive societies from the perspective of functionality and responsibility, similar to the equal roles which peers of early version of Gnutella, namely Gnutella v0.4 (Ripeanu 2001), took. As the human society evolves, social division of labour results in hierarchy of human being. Accordingly, people with different capabilities take different roles and bear different responsibilities, just like the hierarchical architecture of P2P networks, for example, Gnutella v0.6 (Xie *et al.* 2008), and Kazaa (Leibowitz *et al.* 2003). A short history of P2P computing is presented in Section 1.1, and a visual summarization of the roadmap of P2P computing is illustrated in Fig. 1.

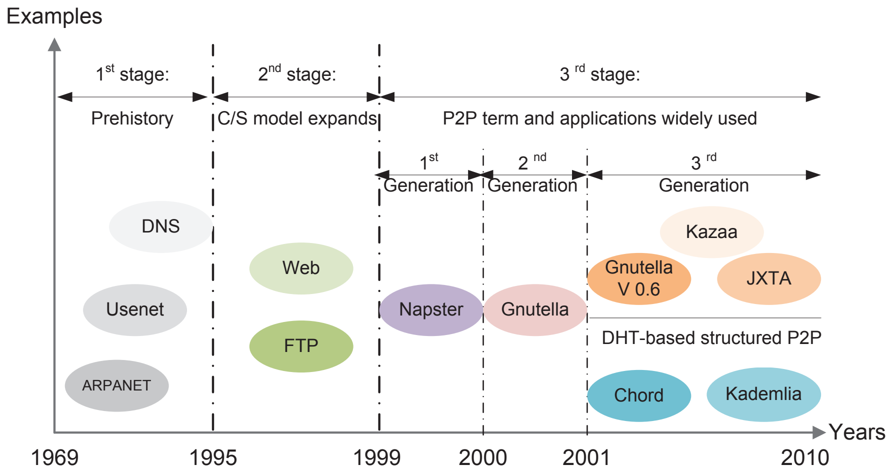

Fig. 1. Roadmap of P2P history.

2.1.2 Related concepts of P2P computing

In order to make the description of the subsequent sections clearer, the following concepts are firstly introduced in this thesis:

– *Peer-to-Peer* system: *Peer-to-Peer* systems are distributed systems consisting of interconnected nodes able to self-organize into network topologies with the purpose of sharing resources such as content, CPU cycles, storage and bandwidth, capable of adapting to failures and accommodating transient populations of nodes while maintaining acceptable connectivity and performance, without requiring the intermediation or support of a global centralized server or authority. (Androutsellis-Theotokis & Spinellis 2004.)
– *Overlay*: *Overlay* network is abstracted from and constructed above the underlying physical computer network, usually IP network. Accordingly, it shields itself from the underlying complicated physical computer network connection details. One hop in *overlay* network can be mapped onto multiple hops in physical networks.
– *Peer*: *Peer* is the participant of P2P overlay networks which acts both as client and server at the same time. Thus, it is sometimes referred to as *servent*. *Peer* is less powerful in capability and responsibility compared with *super-peer*. The terms *peer* and *node* are used interchangeably in this thesis.

– *Super-peer*: *Super-peer* is the counterpart of *peer*. It is usually more powerful and stable compared with *peer*, accordingly, more responsibilities are supposed to be taken or more services are supposed to be provided by *super-peer* than *peer*. For example, *super-peers* are responsible for routing, storing and forwarding information on behalf of *peers*, while *peers* are only responsible for initiating service requests and receiving the associated responses.

The differentiation of *structured* and *unstructured* is based on the topology of P2P overlay networks, for example, whether the construction of overlay network is based on some special rules or the overlay network is constructed randomly.

– *Structured* P2P network: The P2P overlay network topology is tightly controlled and content is not placed at random peers but rather at specified locations that makes subsequent queries more efficient (Lua *et al.* 2005). *Structured* P2P network usually utilizes DHT as a substrate. Chord (Stoica *et al.* 2003) and Kademlia (Maymounkov & Mazires 2002) are examples of this category.

– *Unstructured* P2P network: The P2P overlay network organizes peers in a random graph in a flat or hierarchical way, and uses flooding, random walks or expanding-ring Time-to-Live (TTL) search on the graph to query content stored by overlay peers (Lua *et al.* 2005). Gnutella v0.4 (Ripeanu 2001) is a typical example of this category.

The distinction between *hierarchical* and *flat* P2P network is based on how many levels the network topology is utilizing.

– *Hierarchical* P2P network: As its name shows, *hierarchical* P2P network utilizes multiple, usually equal to or larger than two, levels of hierarchy. Participants of *hierarchical* P2P network are divided into different roles, for example, *super-peer* and *peer*, as aforementioned, based on their capabilities and reliability. Generally, the network topology of each level can be different, for example, the upper level can be structured P2P network, while the lower level can be unstructured P2P network. To make it clear, as far as the *hierarchical* P2P network is concerned, only the structured (DHT-based) hierarchical P2P network is referred to in this thesis, if not otherwise mentioned.

– *Flat* P2P network: Just as its name implies, participants of *flat* P2P network are located at one level. Their roles are equal in terms of the undertaking responsibilities. No hierarchy is utilized to distribute the peers. Earlier version of Gnutella, namely Gnutella v0.4 (Ripeanu 2001) and basic form of Chord (Stoica *et al.* 2003) are examples of this category.

– *Hybrid* P2P network: *Hybrid* P2P network refers to combinations of different principles in the system organization. The term *hybrid* is more general than the term *hierarchical*. (Zoels *et al.* 2008.) *Structured* and *Unstructured* principles can both be used in hybrid organizations. Loo *et al.* (2005) is an example of this category.
– *Churn*: the phenomenon of the continuous arrival and departure of participating peers of a P2P overlay.
– *Graceful leaving*: a departing peer notifies its upcoming departure to its neighbours and transfers the resource items it stored to some other peer(s).
– *Ungraceful leaving*: a departing peer neither notifies its departure nor transfers resource items to its neighbours. This occurs upon certain failure events of peers, e.g. an abrupt network disconnection or running out of power.
– *Parallelism degree*: the number of same requests that an initiating peer sends in parallel to its routing neighbours. Parallel requests only take place in the resource lookup process.
– *Replication degree*: the number of instances of each specific resource item stored in the P2P overlay. Replication takes place in the resource publishing process.

2.1.3 P2P computing versus grid computing

There are also two easily-confusing concepts in the community of distributed systems, namely *P2P computing* and *grid computing*. A comparison is provided in this Section.

P2P computing and *grid computing* are two diverse yet correlated concepts. They both are concerned with the organization of resource sharing in large-scale distributed computational environments. Though there is no complete consensus regarding the definition of *grid computing*, one widely-accepted definition was given by Foster *et al.* (2001): *grid computing* aims to enable resource sharing and coordinated problem solving in dynamic, multi-institutional virtual organizations. Foster & Iamnitchi (2003) described the differences of *P2P computing* and *grid computing* as follows:

From the target communities and incentives perspective, *grid computing* were motivated initially by the professional communities while *P2P computing* was popularized by grass-roots, mass-culture file-sharing and highly parallel computing applications.

From the resources point of view, grid systems integrate resources that are more powerful, more diverse, and better connected than the typical P2P resource.

From the perspective of scale and failure, grid communities often involve modest numbers of participants, either institutions(tens), pooled computers(thousands), or simultaneous users(hundreds), while P2P communities can allow millions of simultaneous users.

As a summarization, Foster & Iamnitchi (2003) concluded that "*grid computing* addresses infrastructure but not yet failure, whereas *P2P* addresses failure but not yet infrastructure ".

2.2 Web Services and P2P converged framework

Web Services have gained a great deal of attention from industry and academia because of its platform-independent, programming language-neutral, etc., characteristics. P2P networks have been blossoming in the last decade as a result of its high-efficiency, scalability, no single-point-of failure, etc., features. Providing Web Services in a distributed P2P way naturally inherits the advantages from both sides, while avoiding the drawbacks from each. Accordingly, the combination of Web Services and P2P has attracted the eyeballs of scientific community and mass-culture in recent years. Along with the rapid development of mobile terminal capabilities and ever-increasing population of mobile end users, providing Web Services to mobile devices in a P2P way has been a hot research topic nowadays.

Gehlen & Pham (2005) distinguished and discussed different Service Oriented Architecture (SOA) realizations to enable P2P computing in heterogeneous environments being composed of mobile nodes with various computing and communication capabilities. In environments where infrastructure existed, they proposed to utilize the fixed infrastructure as a unique service-broker, while the other nodes acted both as service requestors and service providers. In pure Ad Hoc network, at least one node should take the broker role. If more than one service broker existed in the system, synchronization must be performed to maintain a consistency of the service repository. A server implementation of P2P Web Services based on Java 2 Platform, Micro Edition (J2ME) was also introduced.

Kim & Lee (2007) proposed a light-weight framework for hosting Web Services on mobile devices. P2P is used as the paradigm for providing the desired distributed services. The proposed framework consisted of some built-in functionalities, including the processing of Simple Object Access Protocol (SOAP) messages, migration and execution of services, management of service directory and context information etc. The performance of the framework was measured through real-world mobile devices connected by Bluetooth.

Koskela *et al.* (2007) introduced a context-aware mobile Web 2.0 service architecture that connected user context and community information with the Web Services. For the purpose of providing a secure and reliable platform for creating new services, four communication models were put forward to deliver services and context information. As for the provision of services and context information, each has two manners, namely centralized and P2P, thus, four communication models exist for the delivery. Furthermore, virtual communities and market structures of the proposed models were discussed from a multidisciplinary point of view.

Srirama *et al.* (2008) presented a mobile Web Service discovery mechanism in P2P networks utilizing JXTA modules. Several topologies were used to measure the scalability of the proposal. The scalability evaluation results proved that the discovery approach could scale to the needs of large cellular networks.

Chen *et al.* (2008) focused on the coordination of service provision in P2P environments. They put forward a solution which was made up of a labor-market model, a recruiting protocol, and a policy-driven decision architecture. Peers made their service provision decisions based on their local policies, which were controlled and operated by the users. They utilized measurements under five application scenarios to verify the proposed solution and demonstrate the effectiveness of the coordination mechanism.

The work presented in this thesis differs from the related work in the sense that it focuses on the architecture level, and makes full use of the existing infrastructure of cellular networks, while most of the related work concentrated on the middleware level, and did not take full advantage of the network infrastructure.

2.3 Hierarchical P2P architecture

As stated in the previous chapter, hierarchical architecture almost always accompanies the large-scale, complex distributed systems. Original four-nodes based flat ARPANET evolved into the current hierarchical Internet to host hundreds of millions of participants. DNS was even designed as a hierarchy from the date of its birth, and it still shows its benefit in terms of scalability. On the current Internet, routers are grouped into various Autonomous Systems (AS). Different routing protocols are used for the intra-AS routing and inter-AS routing; while the former utilizes Routing Information Protocol (RIP) or Open Shortest Path First (OSPF) protocol, etc., the latter uses Border Gateway Protocol (BGP), etc. When describing the design of a global name system, Lampson (1986) stated the hierarchy as a fundamental method for accommodating growth and isolating faults. Simon (1996) even argued that hierarchy emerged inevitably in any complex system.

In this Section, we first present the taxonomy of hierarchical P2P systems. The typical examples and their correlated characteristics of each category are discussed in detail in the subsequent subsections. For simplification, *P2P systems* and *P2P networks* are used interchangeably in this thesis.

2.3.1 Taxonomy of hierarchical P2P architecture

Based on the overlay topology, and the construction and organization of network connections, P2P networks can be classified as *structured* P2P network and *unstructured* P2P network. Analogously, hierarchical P2P networks can also be roughly classified as *structured* hierarchical P2P networks and *unstructured* hierarchical P2P networks in the same way. However, as hierarchical P2P systems utilize more than one level (or tier) hierarchy to distribute the overlay nodes, multiple options can be taken by each level, either *structured* or *unstructured*. Depending on the adopted overlay topology by each level, hierarchical P2P systems can be further classified into three categories: *unstructured*, *structured*, and *hybrid*, as shown in Fig. 2.

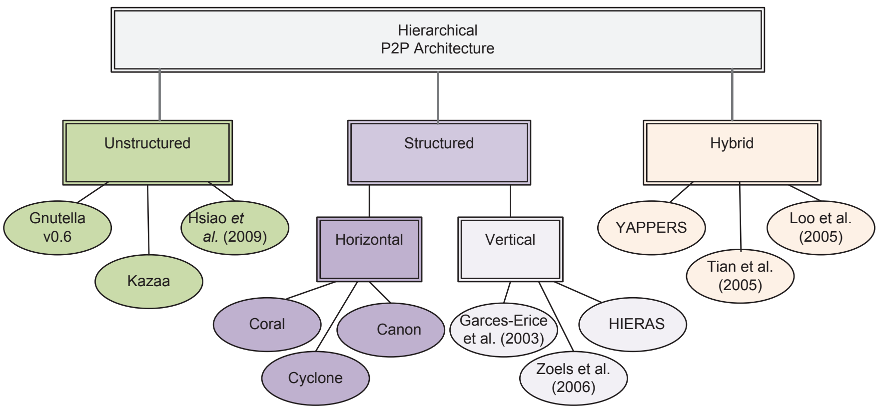

Fig. 2. Taxonomy of hierarchical P2P architecture.

Unstructured hierarchical P2P systems utilizes unstructured topology at each level only. Its characteristics and typical examples are described in Section 2.3.2.

Structured hierarchical P2P systems, just as its name implies, utilize only structured topology at each level. Its corresponding sub-categories, characteristics and typical examples are stated in Section 2.3.3.

Hybrid hierarchical P2P systems combine unstructured and structured overlay topology in its hierarchy. Based on the practical requirements, hybrid hierarchical P2P systems can utilize structured overlay topology at its upper level while utilizing unstructured overlay topology at its lower level, or vice versa. Its characteristics and typical examples are presented in Section 2.3.4.

2.3.2 Unstructured hierarchical P2P architecture

As mentioned in Section 1.1, the hierarchy-based third generation of P2P systems came into use in the year of 2001 to solve the shortcomings of the flooding-based second generation of P2P networks, e.g. earlier version (v0.4) of Gnutella (Ripeanu 2001). A large population of Gnutella v0.4 (Ripeanu 2001) application resulted in large scale P2P networks around the world, which in turn caused the ever-increasing search traffic across different administrative domains. Meanwhile, the search recall ratio, i.e. the ratio of the number of search results and the total number of available copies of the searched object, was significantly decreased as the network scale became larger (Zoels *et al.* 2008). To tackle this problem, Gnutella v0.6 (Xie *et al.* 2008), and Kazaa (Leibowitz *et al.* 2003) introduced hierarchy in its architecture respectively.

Gnutella v0.6 (Xie *et al.* 2008) employes a two-layer hierarchy, as shown in Fig. 3. *Servents* are categorized into *leaf* and *ultrapeer*. A *leaf* node only maintains connection with its own *ultrapeer*, while an *ultrapeer* maintains connections to its own *leaf* nodes, as well as to the other *ultrapeers* from the overlay, and acts as proxy for its connected *leaf* nodes. One *ultrapeer* can connect with multiple *leaf* nodes, depending on its capacity and capability. In the procedure of resource lookup, *leaf* nodes are only responsible for initiating lookup requests, receiving correlated lookup response, and responding the requests which they can exactly answer, for example, the requested resource is stored in the *leaf* node, otherwise they do not relay or forward queries to other *ultrapeers*. As far as *ultrapeers* are concerned, they are responsible for forwarding lookup requests to other *ultrapeers* or its own connected *leaf* nodes, if it knows exactly the *leaf* node is able to answer the request. Furthermore, *ultrapeers* also have the normal functionality of *leaf* nodes, namely initiating requests and receiving correlated responses. At the level of *ultrapeer*, similar flooding-based mechanism as Gnutella v0.4 is utilized to forward the lookup requests.

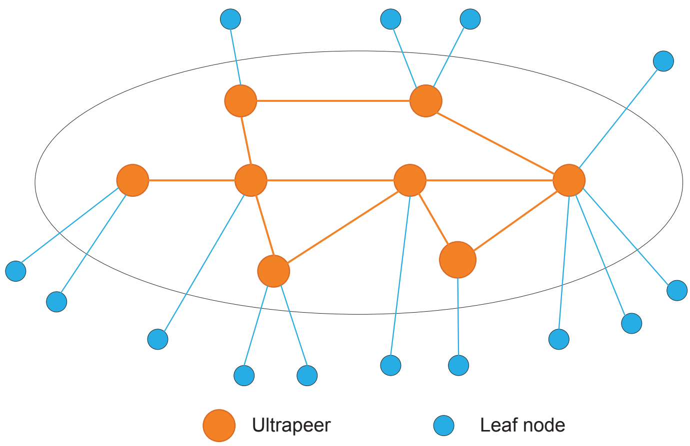

Fig. 3. Topology of the Gnutella v0.6 network.

Kazaa (Leibowitz *et al.* 2003) utilizes the similar overlay topology as Gnutella v0.6 (Xie *et al.* 2008). One remarkable distinction between these two mechanisms is that Gnutella v0.6, or Gnutella in general, is based on open source project, while Kazaa uses the proprietary FastTrack (Liang *et al.* 2006) protocol. Consequently, most of the technical details of Kazaa are not publicly available. According to Leibowitz *et al.* (2003), Kazaa nodes dynamically elect *supernodes* that are more powerful and available to form an unstructured overlay network and use query flooding to locate content, regular nodes connect to one or more *supernodes* to query the network content and in fact act as querying clients to *supernodes*. When a new peer joins a Kazaa overlay, it bins itself with the existing *supernodes* in the overlay, and establishes an overlay connection with the *supernodes* that has the shortest Round-trip Time (RTT). (Garcés-Erice *et al.* 2003.) Afterwards, the newly joined peer sends two categories of information to its connected *superpeer*, namely the list of files that the peer shares and the peer-related information, for example, a peer nickname, a (download) port number, and an IP address. (Shin *et al.* 2006.)

There are also a great number of research efforts which focus on addressing the problems of unstructured P2P network from different perspectives. For example, Hsiao *et al.* (2009) focus on addressing the topology mismatch problem of unstructured P2P networks by proposing a novel topology matching algorithm, in which each participating node creates and manages a constant number of overlay connections to other peers in a distributed manner. Tang *et al.* (2008) present an analytical model that studies the search performance and the freshness of P2P content sharing under TTL-based consistency. Zhu *et al.* (2008) introduce a dynamic fully decentralized protocol, namely Distributed Cycle Minimization Protocol (DCMP), to reduce the duplicate messages by eliminating unnecessary cycles. Furthermore, Lin *et al.* (2009) propose a dynamic search algorithm, which is a generalization of flooding and Random Walk (RW), Cai & Wang (2006) exploit geographical and temporal locality, Xiao *et al.* (2005) present Adaptive Connection Establishment (ACE), which builds an overlay multicast tree among each source node and the peers within a certain diameter from the source peer, Tewari & Kleinrock (2007) utilize clustered demands (i.e. file popularities vary across the set of nodes in the network), respectively, to boost search efficiency.

2.3.3 Structured hierarchical P2P architecture

As aforementioned, hierarchy-based unstructured P2P system and DHT-based structured P2P system appeared as two different directions, from the year of 2001, to solve the problems that were faced by the second-generation of P2P system. While the former shows its benefits in scalability and fuzzy search, etc., the latter has its advantages in precise search and search efficiency, etc. Consequently, researchers started to combine these two approaches from the year of 2003 to make full use of their respective merits, and resulted in structured hierarchical P2P systems.

In the context of structured hierarchical P2P systems, Artigas *et al.* (2005) classified the existing systems in two categories according to the inter-connection architecture: *Vertical* Hierarchical Architecture (VeHA) and *Horizontal* (leaf-based) Hierarchical Architecture (HoHA) in the year of 2005. *Vertical* approach follows a tree-based hierarchy in which "every layer or leaf in the hierarchical tree is a self-contained DHT overlay network", while in the *horizontal* approach, "all the leaf overlay networks are connected using a single DHT that contains the conceptual hierarchy and optimizes the routing in the whole network". (Artigas *et al.* 2005.)

In 2007, Artigas *et al.* (2007) relabelled these two categories as *superpeer* design and *homogeneous* design. In *superpeer* design, a relatively small number of peers, which are chosen by some specified performance metrics (e.g. availability and reliability), act as proxies for interconnecting different domains or clusters. In *homogeneous* design, all the nodes act as equal roles, which thus inspires the name *homogeneous*. The author of this thesis claims that these two taxonomies, in essence, are the same. The distinction exists simply in the appellation. The first taxonomy, namely VeHA and HoHA, is followed in this thesis because it is more intuitional and straightforward.

To the best knowledge of the author, the primary distinction between VeHA and HoHA is whether the dedicated *gateway peer* (*superpeer*) [3] is adopted or not. In VeHA, the interconnections among different domains (clusters or sub-overlays) [4] are achieved by utilizing the dedicated *gateway peer*. While in HoHA, higher level clusters are formed in such a way that each single peer in one cluster is able to setup connections to some other peers from other clusters, consequently, no dedicated *gateway peer* is needed.

The typical examples, advantages and disadvantages of each category are discussed in detail in the subsequent subsections.

Vertical hierarchical architecture

As aforementioned, VeHA utilizes dedicated *gateway peers* to achieve the interconnections among different clusters, and each cluster in the hierarchical tree is a self-contained DHT overlay network (Artigas *et al.* 2005). Typical and representative examples of this category include Garcés-Erice *et al.* (2003), HIERAS (Xu *et al.* 2003), Yang & Garcia-Molina (2003), and Zoels *et al.* (2006), just to name a few.

Zhao *et al.* (2002) proposed a systemic design, which was named Brocade, for a two-level overlay organization. In Brocade, all the participating nodes of Tapestry (Zhao *et al.* 2004) overlay form a Tapestry topology as usual. Furthermore, a secondary overlay is built on top of these nodes that utilizes the proximity information of the underlying network. The secondary overlay builds a location layer among the *superpeers* which are usually well-connected, located near the boundaries of administrative domains. Local nodes are connected with the nearby *superpeer* and the *superpeers* advertise periodically which peers are reachable through them at the secondary over-

[3] *Gateway peer* and *superpeer* are used interchangeably in this thesis.
[4] *Domain, cluster,* and *sub-overlay* are used interchangeably in this thesis.

lay. By doing this, Brocade can avoid unnecessary inter-domain message forwarding, which in its turn, decreases the point-to-point message latency as a whole. From the point of view of this thesis, Brocade is a modified version of their flat Tapestry and it only utilizes the conceptual hierarchy since all the nodes join the lower level Tapestry overlay. Therefore, it loses most of the advantages of vertical hierarchical architecture, which will be discussed in the subsequent sections.

Garcés-Erice *et al.* (2003) provided a general framework for hierarchical P2P lookup, as shown in Fig. 4, in which: (1) peers are organized into disjoint clusters (groups), and (2) lookup messages are first routed to the destination cluster using a inter-cluster overlay, and then routed to the destination peer through a intra-cluster overlay. Each cluster has one or more *superpeers* which are selected from certain criteria, e.g. reliability and connectivity. Each normal peer chooses to join one cluster based on the specific requirements of the application, e.g. topological proximity. *Superpeers* form the upper-level overlay. Each cluster can use autonomous intra-cluster overlay lookup service. Garcés-Erice *et al.* (2003) concluded several advantages of VeHA compared to flat overlay networks, including exploiting heterogeneous peers, transparency, faster lookup time, and less messages in the wide-area.

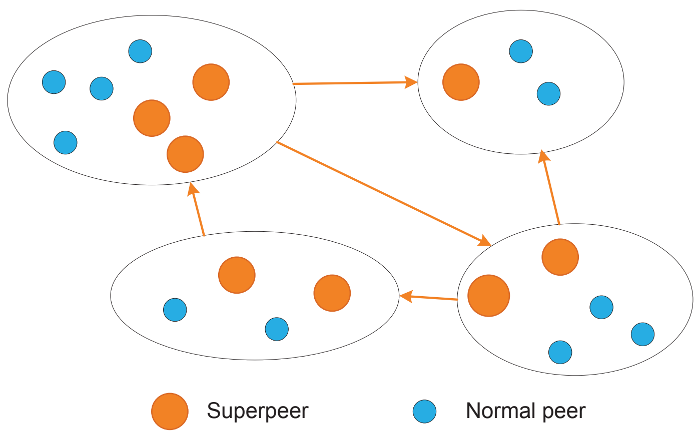

Fig. 4. General framework for hierarchical P2P lookup.

By designating the most reliable peers in the groups as *superpeers* and taking Chord (Stoica *et al.* 2003) as the upper-level instantiation of lookup service, Garcés-Erice *et* *al.* (2003) showed that the hierarchical design could significantly reduce the expected lookup hopcount in Chord.

HIERAS (Xu *et al.* 2003) presented an extreme scenario in which all the nodes participated in one cluster[5] from each hierarchy level. Several lower level P2P clusters are created, according to the topological proximity metric, besides the upmost level of P2P cluster which contains all the participating peers. A peer belongs to several P2P clusters simultaneously from different levels. The lower a P2P cluster is located, the shorter the routing latency inside this P2P cluster is. A routing procedure is executed at the lowest level of P2P cluster firstly, and then moves up to a higher level and eventually reaches the upmost level of P2P cluster. In this way, a large fraction of the routing hops which are previously executed in a global P2P cluster are now replaced by hops with shorter latency, thus, a lower overall routing latency can be achieved. Through simulations, Xu *et al.* (2003) showed that 2-level or 3-level were sufficient to achieve good routing performance without bringing much overheads. One explicit drawback of this mechanism is that each peer has to maintain much more routing tables (*k-1* routing tables if *k* stands for the hierarchy depth) than flat architecture. One point that should be noted here is that each peer participates one cluster from each level, therefore, no gateway peers are needed in HIERAS. [6]

Yang & Garcia-Molina (2003) studied two-level superpeer networks in detail to gain an understanding of their fundamental characteristics and performance tradeoffs. The network topology between *superpeer* and its connected *leafnodes* is star-like. Through performance evaluation, several practical rules of thumb was provided, including:

– Increasing cluster size decreases aggregate load, but increases individual load;
– Superpeer redundancy is good in terms of reducing individual load;
– Maximizing the outdegree of superpeers should be performed uniformly among all the superpeers;
– TTL should be minimized besides reaching all the nodes of the system.

Zoels *et al.* (2006) provided a cost[7] model of a specific two-level hierarchical DHT organization where the top-level *superpeers* run a conventional Chord (Stoica *et al.*

[5]Xu *et al.* 2003 used the word *ring* in their paper, for the sake of consistency, the term *cluster* is used in this thesis.
[6]From this point of view, HIERAS should be categorized as HoHA rather than VeHA. However, as the number of routing connections each peer in HIERAS maintains is much more than that of HoHA, HIERAS is categorized into VeHA instead of HoHA in this thesis.
[7]Cost includes both lookup traffic cost and maintenance traffic cost.

2003) protocol and acted as proxies for their connected *leafnodes*. The lower topology between one *superpeer* and its *leafnodes* is star-like. Through cost-based analysis, they concluded that hierarchical DHT design was better than flat design and there existed a natural trade-off between optimizing the total network cost and optimizing the cost of the highest loaded peer in the system. In 2008, the same authors extended their analytical model to include multiple alternatives at the lower level, namely star-like (*leafnodes* are connected only to the cluster's *superpeer*), fully-meshed (every *leafnode* is connected to the other *leafnodes* in the cluster), and DHT (the *leafnodes* of the cluster are connected through a specified DHT algorithm). (Zoels *et al.* 2008.) Their analytical evaluation showed that a simple star-like design was superior to a DHT or a fully-meshed lower level peer organization.

Lian *et al.* (2007) provided an analytical framework to compare the performance of clustering algorithms for hierarchical networks based on their generated cluster structures. Specifically, two performance metrics of hierarchical networks were discussed, namely the total routing-table size and the intra-cluster update cost. They gave a detailed treatment on how the total routing-table size was affected by changes in three network parameters: the total number of nodes, the number of levels, and the number of highest level cluster. As for the network size of hundreds of thousands of nodes, they found that two-level hierarchy was sufficient and three-level could be treated as a secondary alternative. They also proposed several desired properties for two-level cluster structures. However, since this framework is focused on table-driven routing[8] cluster algorithms, there is no explicit proof which shows the analytical results and design guidelines also work for hierarchical overlay networks of P2P systems, though the authors claimed that they should work without providing any performance analysis or evaluation. This is exactly one of the research focuses of this thesis.

Furthermore, there are also some other research efforts focusing on addressing different issues of VeHA. Li *et al.* (2008) designed a consistency maintenance scheme for heterogeneous P2P systems with shorter convergence time and lightweight bandwidth consumption, by taking into consideration the network locality information and the heterogeneity of node capacity. Pack *et al.* (2006) proposed a Scalable Application-layer Mobility Protocol (SAMP) that was based on P2P overlay networking and Session Initiation Protocol (SIP) to support scalable mobility. Hierarchical registration and two-tier caching schemes, were employed to localize signalling traffic for mobility and to re-

[8]Routing here means network-layer routing, rather than application-layer routing which is the case for P2P networks.

duce the session setup latency, respectively. Xiong *et al.* (2006) proposed a solution to reduce Chord (Stoica *et al.* 2003) routing latency by utilizing the hierarchical feature of IPv6 address. The hierarchical structure of IPv6 address can aggregate route entries in Internet. Thus, it can be used to cluster together physically nearby nodes in an overlay by taking advantage of the shared IPv6 prefix of specific length. Martinez-Yelmo *et al.* (2009) put forth a two level hierarchical P2P overlay architecture for the interconnection of different Peer-to-Peer Session Initiation Protocol (P2PSIP) clusters. A study of the routing performance and routing state of a particular two-level DHT hierarchy that used Kademlia (Maymounkov & Mazières 2002) was also presented in the paper.

As a conclusion, the primary advantages of VeHA are listed as follows:

- Distributing network traffic load in a more reasonable way by exploiting the heterogeneity of participants;
- Supporting various network environments in which a large number of peers are located behind firewall or NAT;
- Providing administrative autonomy for lower-level of sub-overlays or clusters;
- Decreasing the lookup latency, and in turn, alleviating overall lookup traffic effectively.

This thesis mainly focuses on the architectures which are appropriate for heterogeneous environments, for example, mobile environments. Consequently, only VeHA is studied in this thesis among all the hierarchical P2P architectures as it makes a clear distinction for the traffic load different peers are supposed to take in the system, and can deal with firewall and NAT problem efficiently. A General Truncated Pyramid Peer-to-Peer (GTPP) architecture, the generalized version of VeHA, is analyzed in detail. The idea of GTPP is to study whether added tiers of hierarchy can provide added value in terms of performance and functionality, and try to find out the optimal number of tiers, and optimal number of peers in each tier of the architecture. To the best knowledge of the author of this thesis, this work is the first attempt to provide mathematical analysis for these aspects in a multiple-tier VeHA.

Horizontal hierarchical architecture

In HoHA, as aforementioned, all the participating peers take equal roles and responsibilities, thus, no dedicated *gateway peer* is needed. All the lower-level clusters are connected utilizing a single DHT which follows the conceptual hierarchy, and as a result of which the routing connections are optimized in the whole network. Representative examples of HoHA includes Coral (Freedman & Mazières 2003), Canon (Ganesan *et al.* 2004), Cyclone (Artigas *et al.* 2005), and mDHT (Lee *et al.* 2009).

Coral(Freedman & Mazières 2003) is a P2P Content Distributed Network (CDN) which is based on a new abstraction named Distributed Sloppy Hash Table (DSHT). DSHT is similar to a normal DHT interface except the fact that one key may be mapped into multiple values: *put(key, value)* stores a value under a *key*, and *get(key)* needs only to return some subset of the values stored. (Freedman & Mazières 2003.) In order to give priority to closer resources, Coral organizes participating peers into a three level hierarchy of clusters (DSHT) which has increasing network *diameter*, wherein the *diameter* of a cluster means the maximum desired RTT between any two nodes it contains. The resource lookup is initiated from the lowest level which has the shortest *diameter*, and continues at the upper levels if no appropriate answers are returned. Since the Coral peers utilize the same Identifiers (IDs) in all of its three-level clusters, the lookup can be continued exactly from the point at which it left off in the ID space of the previous cluster. Therefore, Coral has the same lookup hopcount as the underlying DHT algorithm, while holding less lookup latency. Coral (Freedman & Mazières 2003) bears a great deal in common with HIERAS (Xu *et al.* 2003) except the fact that the former does not need to maintain multiple routing tables while the latter has to.

Ganesan *et al.* (2004) proposed Canon to utilize both the advantages of flat design, e.g. homogeneity of load and functionality, and hierarchical design, e.g. fault isolation, effective caching and bandwidth utilization. The basic idea of Canon is that participating peers in any sub-layer cluster form a DHT routing structure as usual, the interconnected DHT is synthesized by *merging* its children DHTs by the addition of some links. (Ganesan *et al.* 2004.) The additional links are carefully selected from each node in one cluster to some set of nodes in the other clusters, in such a way that the total number of links each node maintains is the same as flat DHT design. Ganesan *et al.* (2004) showed four different kinds of DHTs, namely Chord (Stoica *et al.* 2003), Symphony (Manku *et al.* 2003), CAN (Ratnasamy *et al.* 2001) and Kademlia (Maymounkov & Mazières 2002), to construct their respective hierarchical canonical versions by utilizing Canon.

Artigas *et al.* (2005) presented Cyclone, a horizontal hierarchical DHT system that provides optimal logarithmic routing hops in 2005. It utilizes a single circular ID space for all the nodes in different clusters of the conceptual hierarchy tree. The circular ID space consists of two parts: the *prefix* of the ID identifies a single node in a cluster, and the *suffix* stands for the cluster in the hierarchy tree. Every node in Cyclone takes an equal role, therefore, it maximizes the load balancing of the whole system. One explicit drawback of Cyclone is that its construction of hierarchical DHT system is based on the flat version of Chord (Stoica *et al.* 2003), it is hard to apply it to the other flat DHT algorithms, for example Kademlia (Maymounkov & Mazières 2002), and CAN (Ratnasamy *et al.* 2001). Some of the advantages of HoHA listed in Cyclone include load balancing, fault tolerance, topology awareness, and efficient replication and content caching.

Lee *et al.* (2009) introduced mDHT, as shown in Fig. 5, to architecturally enhance flat DHT mechanism by utilizing multicast service discovery for lower-layer clusters[9]. In mDHT, a cluster of host computers participate in a DHT overlay as a single node. A query is routed from cluster to cluster as a flat DHT algorithm does until it reaches the destined cluster, where the multicast service mechanism is used to resolve the destination node. A cluster ID is assigned to a cluster as a whole, and each participating peer carries a routing table which consists of cluster IDs, subnet IP addresses of the clusters, multiple IP addresses and port numbers of the peer set in the clusters.

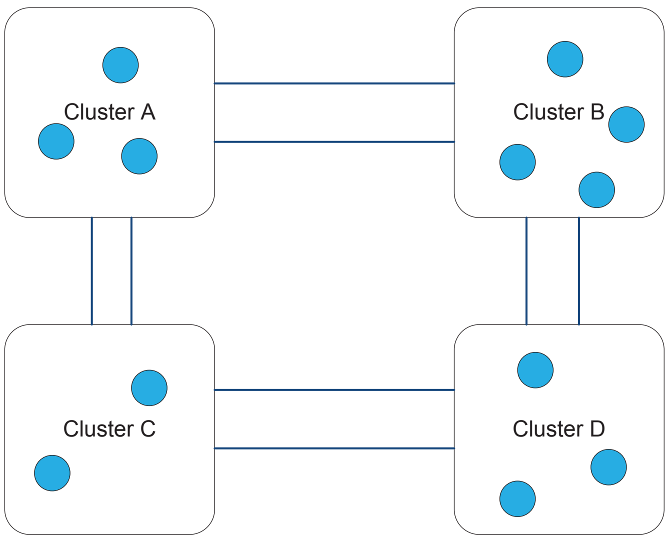

Fig. 5. mDHT architecture.

[9]Lee *et al.* (2009) used the term *subnet* in their paper as *clusters* are based on *subnets*.

As a summarization, the advantages of HoHA include homogeneity and load balancing of each node, administrative control and autonomy, topology awareness of physical proximity, and efficient replication and content caching.

2.3.4 Hybrid hierarchical P2P architecture

As stated in Section 2.3.1, hybrid hierarchical P2P systems combine unstructured and structured overlay topologies in their hierarchies so as to utilize the benefits from both ends farthest. Typical examples of Hybrid Hierarchical Architecture (HyHA) include YAPPERS (Ganesan *et al.* 2003), Loo *et al.* (2005), Tian *et al.* (2005), Zhang & Hu (2007), and Yang & Yang (2009).

Ganesan *et al.* (2003) introduced a hybrid scheme, named YAPPERS (Yet Another Peer-to-PEeR System), to build P2P lookup service over arbitrary topologies. YAPPERS divides the whole large arbitrary overlay into many small and overlapping neighbourhoods, which they name *immediate neighbourhoods*. The data within each neighbourhood are partitioned into a small number of colours (or buckets) among the neighbors similar to DHT. The data lookup is first carried out in one peer's *immediate neighbourhoods*. If no desirable result returns, then the lookup request is forwarded to its neighbours' neighbours, which they name *extended neighbourhoods*. The lookup procedure continues in this way until desirable results are acquired or all the peers of the system are covered. The request forwarding mechanism is designed in such a way that only the peers in the same colour are involved in the procedure to reduce the number of contacted nodes.

Loo *et al.* (2005) proposed a hybrid P2P search infrastructure which combined flooding-based technique and DHT-based structured search technique. Their proposal was based on the extensive measurements conducted on Gnutella (Xie *et al.* 2008) network which showed that Gnutella was effective for locating highly replicated items, and was less suited for locating rare items. Thus, they proposed to utilize selective publishing techniques to only identify and publish rare items into the DHT. All the *ultrapeers* in Gnutella network are organized into the DHT overlay, and each *ultrapeer* is responsible for identifying and publishing rare items on behalf of their *leaf nodes*. Resource lookup is first performed through conventional flooding techniques, if an inadequate number of results are returned within a predefined time period, the query is reissued as a DHT query.

Tian *et al.* (2005) put forth an application infrastructure, i.e. Hybrid Overlay Networks (HONet), as shown in Fig. 6, to integrate the scalability of structured overlay networks with the connection flexibility of unstructured overlay networks in a two-level hierarchical architecture. The lower level consists of clusters which are constructed utilizing network locality, and each cluster contains a dedicated *gateway peer*[10].The upper level *superpeer* network is formed by *gateway peers*. Both the upper level *superpeer* network and the lower level clusters are constructed as structured overlays with independent ID space. Furthermore, additional random connections are built up between clusters based on a random walk algorithm. During the routing procedure, fast routing utilizing the random connections between clusters is carried out firstly, if no result, then the regular hierarchical routing is utilized. In this way, HONet can reduce the end-to-end routing latency and bandwidth consumption between clusters.

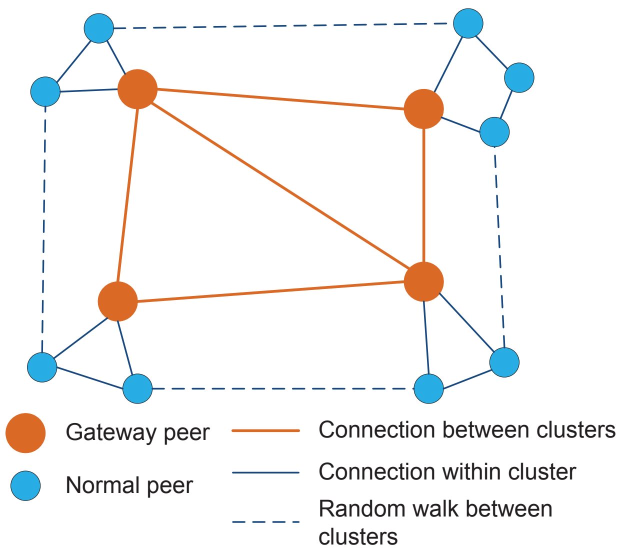

Fig. 6. HONet architecture.

Zhang & Hu (2007) presented a protocol for P2P search with the assistance from a partial indexing service based on peer interests and data popularity. The P2P network consists of two logical overlays: (1) the index is implemented through a *structured*

[10]The term *root node* was used by Tian *et al.* (2005) in their paper.

overlay which forms the *index* overlay; (2) the search is performed in an *unstructured* overlay which forms the *search* overlay. The *index* overlay assists the *search* overlay in three ways: (1) peers communicate their interests through the *index* overlay, and based on the communicated interests, the *search* overlay is constructed; (2) the *index* overlay provides search hints for those data which are difficult to locate by exploring the peer interest locality; (3) the *index* overlay also assists locating unpopular data items by explicitly registering the unpopular properties in the *index* overlay.

Yang & Yang (2009) proposed a two-level hybrid P2P system to make use of the advantages of both structured and unstructured P2P networks. The upper level of the system is a structured core network which forms the backbone of the hybrid system, while the lower level is multiple unstructured P2P networks, each of which is attached to a *superpeer* of the upper level. The basic difference, according to Yang & Yang (2009), between Loo *et al.* (2005) and this proposal is that the former "utilized the structured overlay as a supplement for the unsuccessful flooding lookup", while the latter "utilized the structured overlay to connect all the lower level unstructured networks and transmit queries among them". From the point of view of the author of this thesis, there is no significant difference between these two proposals.

Furthermore, some other issues of HyHA are studied and addressed in the current research community. Hierarchical architecture is utilized to address the scalability and efficiency issues in unstructured overlays, for example, hierarchical gossip (Kermarrec *et al.* 2003), and mOverlay (Zhang *et al.* 2004). Chen *et al.* (2009) proposed a difficulty-aware hybrid search, namely QRank, to distinguish whether items related to a query are distributed in many peers or just in a few peers. This information is then used to select the appropriate search strategy, e.g. DHT or flooding, for queries. Huang-Fu *et al.* (2009) presented a hybrid P2P system for mobile devices, namely iP2P, which utilizes the short message service as the control protocol to identify the address of the called peer. In the iP2P system, the Mobile Station Integrated Services Digital Network (MSISDN) number, i.e. the telephone number, is used as the globally unique identification for each participating peer. Koo *et al.* (2006) investigated the neighbour-selection process in hybrid P2P networks. Joung & Lin (2010) proposed a fully decentralized algorithm to build a hybrid peer-to-peer system with no need of human intervention or any centralized gateway to select peers or guide them to build the structured overlay.

As a conclusion, HyHA inherits the advantages from both structured P2P networks and unstructured P2P networks, thus, it shows its strong points in scalability, connection flexibility, and efficiency, etc.

2.4 Performance evaluation

As stated in Section 1.1, as the counterpart of the hierarchy-based third-generation of P2P system, DHT-based structured P2P networks were put forth in another direction to address the issues, e.g. the weak search efficiency, faced by the second-generation of P2P system. In this section, the research issues related to flat structured P2P networks are studied. However, as there is a great number of research topics associated with structured P2P networks, an exhaustive list of all the related issues is not possible. Consequently, three typical research issues are selectively picked up in this thesis, and a detailed survey of these three topics, i.e. communication-oriented P2P systems, evaluations of churn in Kademlia-based P2P networks, and power consumption of mobile devices participating in P2P networks, is presented in the subsequent subsections.

2.4.1 Communication-oriented P2P systems

According to Androutsellis-Theotokis & Spinellis (2004), P2P systems can be classified into the following different categories based on their various application environments:

- Communication and collaboration: this category mainly focuses on the infrastructure for facilitating direct, normally real-time communication and collaboration between participating peers. Typical examples include instant messaging applications, for example Yahoo messenger[11] (Jennings *et al.* 2006), MSN messenger[12] (Huang *et al.* 2007), Google Talk[13] (Freire *et al.* 2008), Skype[14] (Bonfiglio *et al.* 2009, Chen *et al.* 2006) and Jabber[15] (Saint-Andre 2005, Saint-Andre 2007).
- Distributed computation: this category includes the systems whose primary aims are to make full use of the distributed computing resources, e.g. CPU cycles and memory capacity. Representative examples include SETI@home (Search for Extra-Terrestrial Intelligence) (Korpela *et al.* 2001) and Genome@home[16].
- Internet service support: this category includes the applications based on the underlying P2P infrastructure to support a variety of Internet services, for example,

[11]Yahoo messenger URI: http://messenger.yahoo.com/
[12]MSN messemger URI: http://windowslive.com/Desktop/Messenger
[13]Google Talk URI: http://www.google.com/talk/
[14]Skype URI: http://www.skype.com/
[15]Jabber URI: http://www.jabber.com/
[16]Genome@home URI: http://gah.stanford.edu/

application-level multicast system (Castro *et al.* 2002), and Internet indirection infrastructure (Stoica *et al.* 2004).

– Database systems: this category primarily concentrates on providing distributed database service by utilizing P2P principles and infrastructures. Typical examples include Arai *et al.* (2007), and Wolff & Schuster (2004).
– Content distribution: most of the current P2P systems fall into this category, which includes systems and infrastructures designed for sharing and distributing of digital content. Some representative examples include Freenet (Clarke *et al.* 2002), Oceanstore (Rhea *et al.* 2001), and Chord (Stoica *et al.* 2003).

This thesis mainly focuses on the first category of P2P systems, i.e. the communication-oriented P2P systems that provide signalling for facilitating direct communication between participating peers. More specifically, P2PSIP is studied and surveyed in this thesis as P2PP (Baset *et al.* 2007) is adopted as the underlying signalling protocol to evaluate the performance of structured P2P networks. P2PP was one of the former candidates for the signalling protocol in the P2PSIP working group[17], and was merged into REsource LOcation And Discovery (RELOAD) (Jennings *et al.* 2009), the signalling protocol selected by the P2PSIP working group.

As aforementioned, communication-oriented P2P systems aim at facilitating direct, usually real-time, communication and collaboration among P2P network participants. Examples of such systems include Jabber (Saint-Andre 2005, Saint-Andre 2007) and Skype (Bonfiglio *et al.* 2009). The former is an open alternative to closed Instant Messaging (IM) and presence services (Saint-Andre 2005, Saint-Andre 2007), while the latter follows a closed source and proprietary design (Bonfiglio *et al.* 2009).

P2PSIP is a serverless version of SIP, and is an open standard mainly designed for communication-oriented P2P systems (Harjula *et al.* 2009). The standardization process of P2PSIP is still in progress, and a great deal of research effort has been focused on it. In their article, Bryan & Lowekamp (2007) explained what P2PSIP was, its distinction with conventional SIP, the potential application scenarios, the current efforts toward standardization, and the future of P2PSIP. Wauthy & Schumacher (2007) demonstrated a distributed SIP (Rosenberg *et al.* 2002) Proxy/Registrar based on DHT. Through several implementations and the associated measurements, they showed that P2PSIP could be a real option for large, decentralized deployments.

[17] P2PSIP Working Group URI: http://www.ietf.org/dyn/wg/charter/p2psip-charter.html.

Matuszewski & Kokkonen (2008) presented an implementation of a mobile P2PSIP Voice over Internet Protocol (VoIP) application and measured the registration, address discovery and call set-up delays in 3G and WLAN access networks. Their measurements showed that registration and call set-up delays, as well as the overhead traffic, did not impose significant restrictions on the commercial implementation of a server-less mobile VoIP service. Kokkonen *et al.* (2008) alleged to be first ones to demonstrate a P2PSIP application on a mobile platform. Their implementation, based on P2PP (Baset *et al.* 2007), demonstrated the establishment of SIP multimedia sessions between mobile phones with few or no centralized servers of any kind. It allowed a mobile phone user to use standard phone User Interface (UI) to make voice calls by utilizing the underlying resources of a P2P overlay.

Shi *et al.* (2007) proposed a hierarchical architecture to address the connectivity and overhead problems of P2PSIP systems. The feasibility of their proposed scheme was demonstrated by an implementation under Linux OS. The simulation results showed that the hierarchical approach could solve the connectivity problem caused by heterogeneous overlays, as well as perform more efficiently than the flat scheme when the ratio of *superpeer* and *normal peer* was less than 10%. Similarly, Martinez-Yelmo *et al.* (2009) proposed a two-level hierarchical overlay architecture, as shown in Fig. 7, to interconnect different domains of P2PSIP systems to support global multimedia services. Specifically, they presented a study of the routing performance and routing state in the a two-level DHT hierarchy that utilized Kademlia (Maymounkov & Mazières 2002). Their simulation results show that the adoption of a hierarchical architecture gives about the same routing performance as a global flat overlay network. The number of routing states of peers is decreased when increasing the number of domains, and connectivity between all domains is still assured through the *superpeers*.

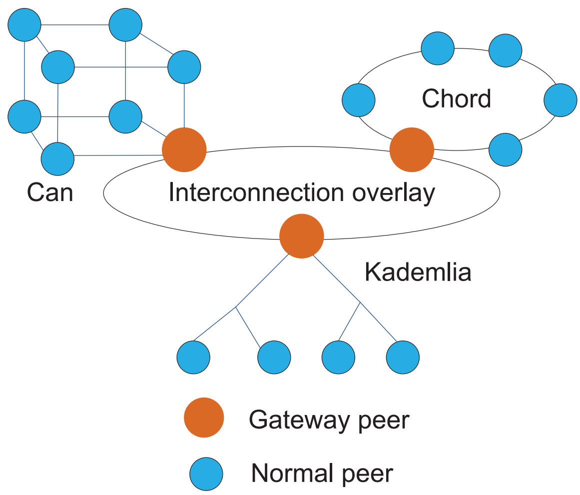

Fig. 7. Hierarchical overlay architecture.

Baumgart (2008) presented a two-stage name resolution mechanism for P2PSIP which was named Peer-to-Peer Name Service (P2PNS). P2PNS can be used to resolve SIP Address of Records (AoRs) to contact Uniform Resource Identifiers (URIs) without the need of DNS or centralized SIP servers. Several security mechanisms are provided to prevent identity theft and to ensure the uniqueness of SIP AoRs in a completely decentralized and untrusted network. The proposed two-stage resolution mechanism can handle the frequent IP address changes as well. Bryan *et al.* (2008) gave an analysis on how security and routing schemes could influence the integrity, scalability and performance of a P2PSIP communication system, based on the lessons and experiences they have encountered in moving DHT-based P2P communications systems from the lab to a real-world setting. In their turn, Chopra *et al.* (2009) discussed problems in P2P security and put forth some solutions at the state of the art, including attacks on the routing of queries, targeted Denial of Service (DoS) attacks and attacks on data integrity, and compared the suitability and drawbacks of the different schemes.

The most relevant study for the purpose of the research work of this thesis is Cohrs (2008), which presented a P2PP prototype implementation based on the Chord (Stoica *et al.* 2003) algorithm. The associated functionality, performance and real-world applicability was proved by local single-machine simulations and real-life measurements from PlanetLab[18](Chun *et al.* 2003). The size of both the PlanetLab overlay and local simulation overlay was 60 nodes for most of the measurements. The main differences of Cohrs (2008) and the work presented in this thesis are: (1) the work presented in this thesis was based on Kademlia (Maymounkov & Mazières 2002), while the work presented in Cohrs (2008) was based on Chord (Stoica *et al.* 2003); (2) the effects of churn on the performance of structured P2P networks were evaluated in detail in this thesis, whereas Cohrs (2008) excluded them, which made their results somehow impractical; and (3) a complete set of tests were evaluated in this thesis, which made the results more convincing than Cohrs (2008) that evaluated only a small number of test sets.

2.4.2 Churn in Kademlia-based P2P systems

The phenomenon of *churn* is an inherent property of P2P systems as the overlay participants can join or leave the overlay network freely and randomly. It describes the dynamics of peer participation, and has significant effects on the performance of P2P networks, e.g. obsolete routing items, inconsistency of storage, and signalling overhead. Therefore, it is critical for the design and evaluation of P2P networks. In this section, the state of the art of the research work on the churn of Kademlia-based P2P network is discussed, as Kademlia (Maymounkov & Mazières 2002) is chosen as the underlying DHT algorithm to implement the P2PP (Baset *et al.* 2007) signalling protocol.

There are basically two approaches to analyze the effect of churn on the associated DHT algorithms. One is to utilize the widely-deployed real systems, e.g. Kad [19], and Gnutella (Xie *et al.* 2008), to analyze the peer behaviour, e.g. the distribution of session lengths; the other is to utilize mathematical analysis, simulation and prototype implementations to provide theoretical support, etc.

For the former approach, several proposals have been put forth. Stutzbach & Rejaie (2006a) empirically studied the performance of the key lookup DHT operation over Kad. They analytically derived the benefits of different ways to increase the richness of routing tables in Kademlia-based DHTs. They also investigated the effects of parallel lookup and multiple replicas mechanisms on the lookup performance in Kad. Their results showed that a lookup parallelism degree of three was a good choice for the current Kad network, without significantly increasing the bandwidth for routing maintenance.

[18]PlanetLab is a test-bed for distributed systems research and consists of a cluster of computers connected globally.

[19]Kad network URI: http://en.wikipedia.org/wiki/Kad_network.

Afterwards, by utilizing three widely-deployed P2P systems, i.e. an unstructured file sharing system (Gnutella), a content-distribution system (BitTorrent), and a Distributed Hash Table (Kad), Stutzbach & Rejaie (2006b) presented a detailed study and revealed the following results regarding the properties of churn: (1) overall dynamics are similar across the three analyzed P2P systems, (2) session lengths are not exponential, (3) a large portion of active peers are highly stable while the remaining peers turn over quickly, and (4) peer session lengths across consecutive appearances are correlated.

Steiner *et al.* (2007a), Steiner *et al.* (2009) had been crawling a representative subset of Kad every five minutes for six months and obtained information about geographical distribution of peers, session times, daily usage, and peer lifetime. Their findings include: (1) Session times are heavy tailed following a Weibull distribution; (2) Kad IDs are not persistent, however, this phenomenon does not influence the most important metrics such as session times and inter-session times; (3) Peers in China differ significantly from peers in Europe with respect to key metrics such as session time, inter-session time, peer lifetime, and daily availability. Based on the same data set as in Steiner *et al.* (2007a) and Steiner *et al.* (2009), Carra *et al.* (2007) analyzed the probability of resource lookup success in Kad by utilizing the reliability theory (a theory that studies the reliability of the systems that are composed of separate units, which have their own reliability). Their work mainly focused on how to assure the availability of the published information in Kad in the presence of churn. Some advanced publishing scheme was also proposed to decrease the publishing cost, in terms of message exchanges. Furthermore, Steiner *et al.* (2007b) pointed out the possible uses and misuses of Kad, based on the potential security issues, for example, DoS attack and Sybil attack.

For the latter approach, several studies have also been conducted. Li *et al.* (2005a) and Li *et al.* (2005b) formulated a unified Performance Versus Cost (PVC) framework to compare the effects of different protocol features and parameter values for evaluating different DHTs. In PVC, communication costs are combined into a single cost measure (bytes), while performance benefits are referred to as a single latency measure. By simulating and analyzing several DHT algorithms, i.e. Chord (Stoica *et al.* 2003), Kademlia (Maymounkov & Mazières 2002), Kelips (Gupta *et al.* 2003), OneHop (Gupta *et al.* 2004), and Tapestry (Zhao *et al.* 2004), they showed that large routing tables with infrequent stabilizations combined with parallel lookup mechanism achieved better performance compared to other approaches.

Wu *et al.* (2006) conducted an analytical study on improving DHT lookup performance under churn. They compared the performance of two representative lookup strategies, namely recursive routing and iterative routing, and showed the effectiveness of parallel lookup mechanism and resource replication mechanism from the theoretical point of view. Through analytical study, they showed that the lookup parallelism degree of two or three was appropriate for systems where the message overhead was not critical.

Binzenhöfer & Schnabel (2007), in their turn, analyzed the performance and robustness of Kademlia and presented some modifications regarding the search efficiency and overlay stability in the presence of churn. The Exponential Distribution (ED) was utilized to model the online and offline time. The performance improvements of the modifications were confirmed by the measurements from a discrete event simulator developed by them.

Finally, some other studies addressed the issues of DHT performance in the presence of churn in a more general sense. For example, Binzenhöfer & Leibnitz (2007) discussed the mechanisms to estimate the current churn rate in the system by monitoring the changes in the neighbour lists of participating peers. Specifically, they showed how to obtain a robust estimate which was independent of the implementation details of the DHT. Rhea *et al.* (2004) demonstrated that DHT could handle high churn rates, and explored three factors affecting DHT performance under churn, namely reactive versus periodic failure recovery, message timeout calculation, and proximity neighbour selection. Godfrey *et al.* (2006) studied how to minimize churn by selectively choosing which subset of a set of available nodes to use. Their findings show that the simple strategy of picking a uniform-random replacement whenever a node fails performs very well. Sánchez-Artigas *et al.* (2009) examined the effect of high rates of churn on the rating mechanisms for P2P networks. Leonard *et al.* (2008) demonstrated that as long as the neighbour replacement delay was much smaller than the average user lifetime, dynamic P2P systems were resilient against nodes churn.

The findings in this thesis regarding the performance evaluation of a communication-oriented Kademlia-based P2P system are supported by a complete set of simulation results. Although the approaches are different, the results discovered are similar with respect to the parallelism degree and replication degree in Wu *et al.* (2006) and Stutzbach & Rejaie (2006a), and in this thesis. While Wu *et al.* (2006) and Stutzbach & Rejaie (2006a) utilized mathematical analysis and real-life measurements, respectively, simulation models are utilized in this thesis to acquire the desirable results. Even though the results presented in this thesis are from a different perspective and thus not directly comparable with the previous works in Wu *et al.* (2006) and Stutzbach & Rejaie (2006a), they nevertheless support each other.

2.4.3 Power consumption of mobile devices in P2P networks

Though an ever-increasing number of mobile terminals are capable of accessing the Internet through access networks such as UMTS and WLAN, their capabilities, in terms of battery life, are still limited compared to desktops. Consequently, it is of large concern of the current research community.

Gurun *et al.* (2006) claimed to be the first work to examine P2P protocols from the energy consumption perspective[20]. They performed a study of energy consumption by utilizing a P2P chat application named Chimera[21] on a Personal Digital Assistant (PDA) device. Their results showed that it was feasible to deploy lightweight P2P applications on low-power devices, e.g. PDA or mobile phones, from the energy consumption point of view. They also indicated that the energy efficiency can be improved by batching overlay messages and send them periodically.

Nurminen & Nöyränen (2008) carried out measurements of energy consumption of BitTorrent application on handheld devices through three different models of Nokia S60 mobile phones. Their results showed that P2P content sharing on handhelds was practical from the energy consumption point of view, and the energy consumption of P2P content sharing was at about the same level as voice calls. Another finding of them was that acting as a true peer and uploading content for other users did not cause much extra energy consumption during active downloading. However, in order to save power, the uploading should be terminated once the downloading was finished. Measurements from both 3G and WLAN access networks were conducted by Nurminen & Nöyränen (2008) to provide a comparative analysis.

Kelényi & Nurminen (2008a) carried out energy consumption measurements by connecting a mobile client to a widely-deployed DHT, referred to as MainLine BitTorrent DHT. Their results showed that using a mobile phone as a full-peer was feasible only for a few hours due to the high power consumption, while operating the nodes in client-only mode was a power-efficient alternative. Similar to Gurun *et al.* (2006),

[20] *Power consumption* and *energy consumption* are used interchangeably in this thesis.
[21] Chimera structured overlay network URI: http://current.cs.ucsb.edu/projects/chimera/.

Kelényi & Nurminen (2008a) just performed the measurements based on the WLAN network connection, i.e. IEEE 802.11g standard, no measurements in 3G connections were conducted.

Based on the observations obtained in (Kelényi & Nurminen 2008a), i.e. processing the incoming messages has the most significant effect on the power consumption of a mobile device participating in a DHT overlay network, Kelényi & Nurminen (2008b) put forth a mechanism to selectively drop the incoming messages based on the current battery status of the mobile device to save battery consumption. "*Dropping the incoming messages*" in this context simply means "*no response message is sent back to the initiator of the message*". Their measurement results showed that dropping 50% of the incoming requests could reduce the consumed energy by 55%; however, no significant benefit could be achieved if the dropping rate was over 70%.

Kassinen *et al.* (2009) measured the energy consumption in a P2PSIP overlay on Nokia N95 devices in both WLAN and UMTS access modes. Their measurements showed that WLAN access mode consumed slightly less battery than UMTS access mode. The battery consumption of sending and receiving User Datagram Protocol (UDP) packets was also measured. However, the sending and receiving of messages was measured separately, which made their results unrealistic. Meanwhile, the time intervals and packet sizes were too coarse-grained to grasp the varying trend of battery consumption.

Balasubramanian *et al.* (2009) presented a measurement study of the energy consumption characteristics of three mobile networking technologies, namely 3G, Global System for Mobile communications (GSM), and WiFi. They found that 3G and GSM incurred a high tail energy overhead because of lingering in high power states after completing a transfer. By utilizing these results, they defined a protocol, referred to as TailEnder, to reduce energy consumption of common mobile applications. Experiments from three different case study applications, including email, news feeds, and web search, were conducted to evaluate the efficiency and benefits of TailEnder.

Furthermore, Pentikousis (2009), Xiao *et al.* (2004), Shen *et al.* (2005), Wang & Xiao (2006), Zhu *et al.* (2006), and Wu *et al.* (2010) addressed the issues of energy consumption from a more general point of view. Pentikousis (2009) pinpointed the common pitfalls of the current energy consumption studies, and introduced a blueprint for a configurable and extensible energy consumption model which took into consideration two commonly missed characteristics, i.e. non-linear nature of battery depletion and battery recovery effects. Xiao *et al.* (2004) studied the timing when a processing unit and a user interface should wake up while the mobile handset was receiving and monitoring data packets. Shen *et al.* (2005) proposed algorithms for cache replacement and passive prefetching of data objects to save energy consumption for mobile devices. Wang & Xiao (2006) provided a survey of energy-efficient scheduling mechanisms in sensor networks. Zhu *et al.* (2006) developed energy consumption models that took into account energy consumption resulted from data packets, control packets and re-transmission for wireless Ad Hoc networks. Wu *et al.* (2010) designed energy-efficient protocols for low-data-rate Wireless Sensor Networks (WSNs).

Among the aforementioned related work, Gurun *et al.* (2006), Nurminen & Nöyränen (2008), Kelényi & Nurminen (2008a), Kelényi & Nurminen (2008b), and Kassinen *et al.* (2009) are explicitly associated with the research work performed in this thesis regarding the energy consumption of mobile devices. Among them, the first four papers performed the measurements within living P2P networks, while the last one, i.e. Kassinen *et al.* (2009), conducted energy consumption measurements by utilizing flat UDP packets. One limitation of the measurements made within a living network is that the conductor is not able to control how the network and other peers operate, consequently, no deep insight can be acquired. For example, it is hard to see in a living network how the transmitting packet sizes and intervals affect the battery consumption of mobile devices. This is exactly the motivation of the battery consumption measurements conducted in this thesis. From this point of view, the work performed by Kassinen *et al.* (2009) is the most relevant one. However, the above-mentioned drawbacks made the work of Kassinen *et al.* (2009) unrealistic. In this thesis, the energy consumption measurements of flat UDP packets with respect to different transmitting packet sizes and transmitting intervals are conducted in order to grasp a deeper insight of the battery consumption. Sending and receiving packets operations are performed in parallel. Meanwhile, the feasibility of mobile nodes participating in a communication-oriented Kademlia-based P2P system is evaluated by the measurements of CPU processing load and network traffic load.

2.5 Churn models analysis

Churn has a significant effect on the performance of P2P systems, e.g. frequent nodes joining and leaving result in stale routing information in routing tables and inconsistency of the stored resource items, the distribution of session length affects the overlay topology and key design parameters, just to name a few. Consequently, the effects of churn should be taken into account when designing or evaluating a P2P system. Furthermore, every simulation and analysis study of churn effect is built on the premise of a churn model. Several research activities have focused on this topic in order to accurately characterize and model the peer dynamics and characteristics, i.e. churn, in P2P systems.

Some research activities built the model of churn following Exponential distribution (ED), including Guo *et al.* (2005), Li *et al.* (2005a), Li *et al.* (2005b), Chord (Stoica *et al.* 2003), Tapestry (Zhao *et al.* 2004), and Binzenhöfer & Schnabel (2007). Others constructed the churn model as Pareto distribution (PD), e.g. Bustamante & Qiao (2004), Wu *et al.* (2006), Harchol-Balter & Downey (1997), and Paxson & Floyd (1995). Still some others argued that the Weibull distribution (WD) could best characterize the dynamics of peers participating in P2P systems through real life measurements, e.g. Nurmi *et al.* (2005), Stutzbach & Rejaie (2006b), and Steiner *et al.* (2007a). However, surprisingly, there are few studies focusing on the comparative study of effects of different models of churn on the performance of P2P systems. This is the motivation of the research work related to different churn models analysis in this thesis.

ED is widely used to model the time of a component to fail in reliability theory. It is also extensively used in modelling the session time of nodes taking part in P2P systems. Through extensive trace analysis and modelling of BitTorrent, Guo *et al.* (2005) concluded that both the lingering and downtime distributions were exponentially distributed. The unified cost versus performance framework which was put forth in Li *et al.* (2005a) and Li *et al.* (2005b) was also based on the churn model that follows ED. Meanwhile, ED was also used as the basis of availability assumptions in some other studies, including Chord (Stoica *et al.* 2003), Tapestry (Zhao *et al.* 2004), and Binzenhöfer & Schnabel (2007).

PD is another largely used model in P2P systems. Bustamante & Qiao (2004) monitored peers in Gnutella to motivate preferential neighbour selection based on nodes uptime. Their measurements showed that nodes session length fits well with PD. By utilizing two churn models, i.e. ED and PD, Wu *et al.* (2006) presented an analytical study of three strategies on improving DHT lookup performance under churn, i.e. lookup strategy (recursive routing and iterative routing), lookup parallelism, and lookup key replication. In other contexts, e.g. process lifetime estimation (Harchol-Balter & Downey 1997) and network performance (Paxson & Floyd 1995), *long-tailed* distributions, especially PD, are used as the fundamental models for analysis.

Though ED and PD are used extensively as the fundamental models to analyze the effect of churn on the performance of P2P systems, some studies doubt the accuracy of ED or PD to characterize the session lengths. Nurmi *et al.* (2005) analyzed the suitability of different statistical distribution for describing machine availability in three different data sets. Their results indicated that either a hyper-exponential or Weibull model effectively represent machine availability in enterprise and Internet computing environments. Stutzbach & Rejaie (2006b) presented a thorough analysis of churn in three real life P2P systems, i.e. Gnutella, Kad, and BitTorrent, and concluded that session-lengths were not heavy-tailed or Pareto, instead they were more accurately modelled by a Weibull distribution. Steiner *et al.* (2007a) explored the peer behaviour, e.g. the total number of peers online and their geographical distribution, by crawling a real system Kad continuously for six months. They found that the distribution of the session lengths was best characterized by a Weibull distribution, with shape parameter $k < 1$.

In this thesis, the aforementioned three typical distributions, i.e. ED, PD, and WD, are chosen to provide a comparative analysis of different churn models on the performance of structured P2P system. The purpose of this study is to see if there are significant differences among different churn models on the measurement results, and to quiet down the controversy regarding which churn model should be used to represent a realistic churn phenomenon.

3 Summary of research contributions

In this chapter, the contributions of the original publications are presented in detail. The contributions consist of four parts: P2P and Web Services converged platform, hierarchical P2P architecture, performance evaluation and churn models analysis. Papers I and II describe the converged architecture of P2P and Web Services. Papers III, IV, V, and VI deal with the VeHA-related issues. Papers VII, VIII, and IX address problems of performance evaluation of communication-oriented Kademlia-based P2P networks. Finally, Paper X presents the measurement results from different churn models.

3.1 P2P and Web Services converged architecture

This section describes the P2P and Web Services converged architecture, namely, providing Web Services in a P2P distributed way which is different from the conventional centralized mechanism. Paper I and Paper II contribute to this aspect.

Paper I, entitled "*Layered Peer-to-Peer Architecture for Mobile Web Services via Converged Cellular and Ad Hoc Networks*", presented a multi-tier P2P architecture to provide Mobile Web Services (MWS) in converged cellular and Ad Hoc networks. The author had the main responsibility for the technical content and paper writing work. Providing MWS in a converged cellular and Ad Hoc network environment needs to take into consideration the infrastructure of cellular network and non-infrastructure characteristic of Ad Hoc network. In Paper I, a three-tier Mobile Service Broker (MSB) architecture, which was organized according to some DHT algorithm (Chord as the instantiation) in a P2P way, was introduced, as shown in Fig. 8. MSBs were located in three different places in the hierarchy, namely Terminal-located MSB (T-MSB), RNC-located MSB (R-MSB), and GGSN-located MSB (G-MSB). In this way, the proposed MWS architecture could make full use of the infrastructure of cellular networks. For the terminal-tier cellular and Ad Hoc network, mobile terminals connected with each other through short-distance wireless transmission interfaces, e.g. Wi-Fi and Bluetooth. As no infrastructure existed in the terminal-level Mobile Ad Hoc Network (MANET), T-MSB had to be located in some relatively powerful mobile terminals. At least one node from each terminal-level MANET should act as the T-MSB. The other nodes could choose to act as Mobile Service Provider (MSP) or Mobile Service Requestor (MSR), or both, depending on their associated capabilities. A Plug-and-Play Middleware Architecture (PPMA) was also presented in Paper I to enable MWS. The modules in PPMA were classified into mandatory and optional. The modular design of PPMA allowed the mobile devices to load certain amount of modules according to their capabilities and corresponding roles, and to avoid overload.

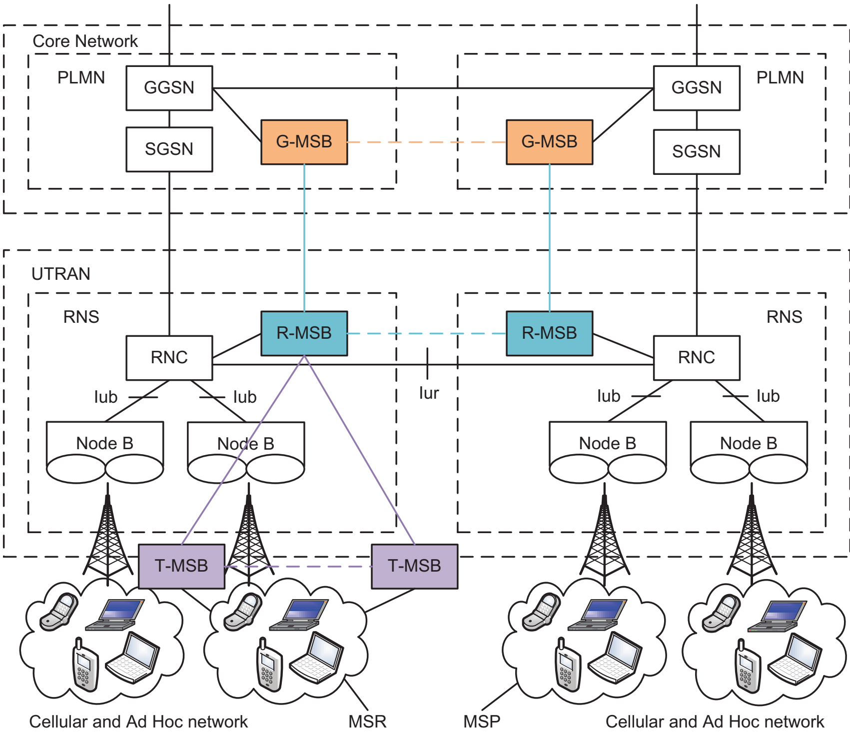

Fig. 8. Converged network architecture of MWS. (I.) ©2008 IEEE. Reprinted, with permission, from Proceedings of the 3rd International Conference on Grid and Pervasive Computing Workshops (GPC Workshops '08), Layered peer-to-peer architecture for mobile web services via converged cellular and Ad Hoc networks, Ou Z, Song M, Chen H & Song J.

Paper II, entitled "*P2P SCCM: Service-Oriented Community Coordinated Multimedia over P2P*", introduced a framework to provide Service-oriented Community Coordinated Multimedia (SCCM) service via P2P mechanism. The author of this thesis was a co-author in this paper, and was mainly responsible for the technical content of tunneled hierarchical P2P model and its associated performance analysis. SCCM is referred to as service-oriented, community-based (e.g. Youtube[22], Facebook[23]), coordination-participated (e.g. content annotation), and multimedia-intensive. To speed up the service lookup procedure, the whole set of services was categorized into three groups according to their popularity. The lookup operation targeting different category of service was forwarded to different layer of the hierarchical P2P model accordingly. Preliminary theoretical analysis showed that the tunneled hierarchical model could accelerate the service lookup in comparison with traditional P2P models.

It should be noted that, due to the shift of research focus from "*WS+P2P*" to "*pure P2P*" study, the work performed in Paper I and Paper II consisted only of architectural proposal and theoretical analysis, no simulation results or prototype measurements were performed to validate their performance, which was the main weak point of them.

3.2 Vertical hierarchical architecture

This section deals with the research issues related to vertical hierarchical P2P architecture. Four publications, namely Paper III, Paper IV, Paper V, and Paper VI, contribute to this from their own perspectives.

Paper III, entitled "*Truncated Pyramid Peer-to-Peer Architecture with Vertical Tunneling Model*", proposed a Truncated Pyramid P2P (TPP) architecture together with an enhanced model, namely Vertical Tunneling Model (VTM), to improve the lookup performance. The author of this thesis was the main author of the paper. The TPP architecture is a multiple-tier VeHA in which the network peers form multiple sub-overlays, the lowest sub-overlay has the most peers while the upmost one has the least peers, which makes it look like a pyramid being truncated (inspired the name TPP). In each tier of sub-overlay, all the peers are grouped into several disjointed sub-sub-overlays (SSO). The upper sub-overlay peers duplicate all the resource indices and mapping relationships between, for instance, IP addresses and node Identifiers (IDs), for their lower sub-overlay peers whose keys fall into their key intervals.[24] To speed up the lookup procedure, VTM is proposed in which vertical tunnels are built up between upper and lower levels of sub-overlays. For the service request initiated from the lower levels

[22]Youtube URI: http://www.youtube.com/
[23]Facebook URI: http://www.facebook.com/
[24]This limited assumption is removed in Paper V and Paper VI.

of sub-overlays, with some probability, the service request is forwarded directly to the upper levels of sub-overlays. This is due to the fact that the higher one sub-overlay is located, the more resource mappings it will store for the lower levels. The service request forwarded to the upper levels will have shorter lookup hopcount. By doing so, VTM can significantly decrease the average lookup hopcount for the whole TPP architecture. The mathematical analysis in Paper III shows that, in a three-tier architecture, compared with the flat architecture and another Hierarchical Architecture (HA) which was proposed by Le & Kuo (2007), TPP architecture has almost the same lookup efficiency in terms of lookup hopcount, while VTM can achieve significantly improved lookup efficiency which is around 1/3 of the lookup hopcount of the flat architecture and the HA proposed by Le & Kuo (2007).

Paper IV, entitled "*Improving Community Management Performance with Two-Level Hierarchical DHT Overlays*", presented a P2P Community Management System (PCMS) that worked on top of a DHT-based P2PSIP protocol implementation. The author of this thesis was a co-author of the article and mainly responsible for the technical content of latency analysis of the proposed PCMS. The key idea of PCMS is to establish a separate DHT overlay network for each community, resulting in multiple small overlays that are subsets of the main overlay. The main overlay is largely used for community and membership information discovery. The feasibility of PCMS is evaluated by a prototype implementation. Measurements from the prototype show that, compared with flat architecture, PCMS performs especially well when there are plenty of community-related activities of the nodes, namely resource publish and lookup operations.

Paper V, entitled "*GTPP: General Truncated Pyramid Architecture over P2PSIP Networks*", introduced a general truncated pyramid architecture over P2PSIP networks, namely GTPP. The idea was to study whether added tiers of hierarchy could provide added value in performance and functionality. The author of this thesis took the main responsibility for the technical content in that paper. Similar to the TPP architecture proposed in Paper III, GTPP also consists of multiple levels of sub-overlays and peers from different sub-overlays are grouped into multiple disjointed SSOs. However, the assumption made in Paper III that the upper sub-overlay peers duplicate the resource indices from lower sub-overlays is removed to make GTPP much more generalized. Furthermore, the number of peers at each level of sub-overlay is subject to Exponential Distribution (ED) in GTPP according to the maximum information entropy theorem. Utilizing the similarity between Geometric Distribution (GD) and ED, GD is utilized to distribute peers into multiple sub-overlays to convert the distribution function into discrete domain. Through mathematical evaluation of the lookup hopcount, the conclusion is made in Paper V which shows that 2∼4 levels of sub-overlays are appropriate for most of hierarchical P2PSIP systems.

Paper VI, entitled "*GTPP: General Truncated Pyramid Peer-to-Peer Architecture over Structured DHT Networks*", continued to study and analyze the GTPP architecture initially proposed in Paper V. The author of this thesis was the main contributing author of the technical content and simulation results. Paper V and Paper VI, to the best knowledge of the author of this thesis, were the first attempts to provide mathematical analysis for the performance of a multiple-tier VeHA.

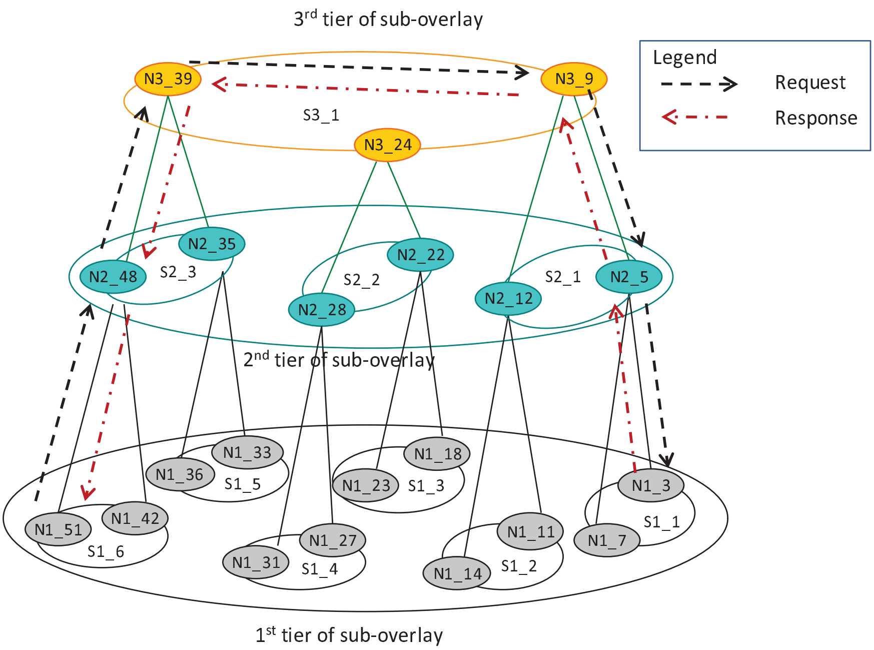

Fig. 9. General Truncated Pyramid P2P (GTPP) architecture. (VI.) ©2010 Springer. Reprinted, with permission, from Mobile Networks and Applications, GTPP: General Truncated Pyramid Peer-to-Peer Architecture over Structured DHT Networks, Ou Z, Harjula E, Koskela T & Ylianttila M.

A three-tier GTPP architecture is illustrated in Fig. 9. As shown in the figure, a lookup request is firstly forwarded to the upper level of sub-overlay through its connected gateway superpeers. This procedure is executed recursively until the request reaches the top-most sub-overlay. Then, the corresponding DHT algorithm is utilized to decide which SSO the request should target, and the resource lookup is executed in that SSO. This lookup procedure continues until a resource item is found or the request reaches the lowest level of SSO. The response follows the reverse path back to the initiator. Both mathematical analysis and simulations were utilized to evaluate the performance of GTPP. The performance metrics involved in mathematical analysis include expected lookup hop count, expected lookup routing latency, traffic distribution of a single peer from a different tier of sub-overlay, and the total traffic of GTPP. The performance metric performed in simulations is lookup hopcount. Through extensive mathematical analysis and simulations, the following conclusions were made in Paper VI:

– GTPP has slightly higher expected lookup hop count, although it can be decreased with optimizing the sub-overlay setup. However, GTPP significantly decreases the expected lookup routing latency;
– GTPP has clearer and more reasonable traffic distribution among all the peers from different tiers of sub-overlays, and can work with slightly lower overall maintenance traffic;
– 2∼3 tiers are most suitable in most cases for GTPP, considering all the parameters, including lookup hopcount, lookup latency, and maintenance traffic.

3.3 Performance evaluation of a communication-oriented Kademlia-based P2P system

This section addresses the research issues related to performance evaluation of a communication oriented Kademlia-based P2P system. Three publications, i.e. Paper VII, Paper VIII, and Paper IX, make their own contributions to this.

Paper VII is entitled "*Effects of Peer-to-Peer Overlay Parameters on Mobile Battery Duration and Resource Lookup Efficiency*". It evaluated the feasibility of mobile nodes acting as peers in a structured P2P overlay network. The author of this thesis was a co-author in Paper VII and took the main responsibility for the simulations of success rate regarding different levels of routing table exchanging intervals. P2PP (Baset *et al.* 2007) was utilized as the signalling protocol for the analysis. Through simulations and live-network measurements, some conclusions were made, including routing table exchanging intervals had the most significant effect on the resource lookup success rate compared to the other parameters, e.g. resource publishing rate and resource lookup rate, and there was some trade-off between the lookup success rate and the battery life of mobile devices.

Paper VIII is entitled "*Feasibility Evaluation of a Communication-Oriented P2P System in Mobile Environments*". This paper evaluated the feasibility of mobile nodes participating in a communication-oriented P2P system from three different aspects, namely CPU processing load, network traffic load, and battery consumption. The author of this thesis took the primary responsibility for the technical content and prototype measurements. Kademlia (Maymounkov & Mazières 2002) with some modifications was utilized as the underlying DHT algorithm, and P2PP (Baset *et al.* 2007) was used as the signalling protocol. A prototype was implemented to evaluate the feasibility of mobile nodes acting as fully fledged peers. One point that should be noted is that the author of this thesis was not responsible for the implementation of the prototype. The author's responsibility was to utilize the prototype to make the measurements, as aforementioned. Through prototype measurements, it was observed that the required bandwidth was low enough for P2PSIP peers to reside on devices in mobile access networks, such as UMTS and WLAN that have typical transfer rates of tens to hundreds of KB/s in the currently deployed networks. The measured CPU load was also acceptable for mobile nodes acting as P2PSIP peers. The power consumption measurements showed that UMTS access mode consumed more power than the WLAN access mode, and the protocol packets with sizes of 200 bytes or less were the most energy efficient in the UMTS access mode.

Paper IX is entitled "*Performance Evaluation of a Kademlia-Based Communication-Oriented P2P System under Churn*". This paper is an extension from the conference version of Paper VIII. The author of this thesis built up the simulation models based on NetHawk EAST (a telecommunication simulator software), made the prototype measurements and was responsible for the technical content. The motivation of Paper VIII and Paper IX is that, although there is a certain number of proposals to deal with the problem of churn, thorough analysis to guide the optimal design options and parameter configurations for structured P2P networks is still missing. In Paper IX, both simulation models and prototype measurements were utilized to evaluate the performance of a Kademlia-based communication-oriented P2P system in the presence of churn. The same as in Paper VIII, Kademlia-based P2PP was used in Paper IX to make the measurements. A complete set of simulations were performed in Paper IX, including parallel lookup mechanism versus serial lookup mechanism, graceful leaving approach versus ungraceful leaving approach, different parallelism degrees, and different resource replication degrees, etc. The results from the simulation models created using Nethawk EAST suggest that, in most situations, a lookup parallelism degree of three and resource replication degree of three are enough for guaranteeing a high resource lookup success ratio. It is also noticed that, with the parallel lookup mechanism, a good success ratio is achieved even without the KeepAlive traffic that is used for detecting the aliveness of overlay nodes. The findings acquired from the prototype measurements are the same as stated in Paper VIII.

3.4 Churn models analysis

This section handles the issue of effects of different churn models on the performance of structured P2P networks. Paper X contributes to this topic.

Paper X is entitled "*Effects of Different Churn Models on the Performance of Structured Peer-to-Peer Networks*". The author of this thesis built up the simulation models, performed the corresponding simulations and was responsible for the technical content. Paper X presents the effects of different churn models on the performance of structured P2P networks. Specifically, Exponential distribution (ED), Pareto distribution (PD), and Weibull distribution (WD), which are the most widely used churn models, are evaluated to provide a comparative analysis. Again, Kademlia-based Peer-to-Peer Protocol (P2PP) is utilized as the underlying signalling protocol. Through simulations, it is concluded that the simulated different churn models do not have a significant difference regarding their effects on the performance of structured P2P networks. Quantitatively, ED and PD outperform WD from the viewpoints of lookup success ratio, mean network traffic load, and mean number of messages. It means that, if the simulation results concern the quantitative difference, it is best to choose WD so that the simulation results are not over-optimistic; otherwise, the selection of the three typical churn models can be random. This provides some useful results for the current research community regarding the selection of different simulation models.

These original papers are reprinted at the end of the printed version of this thesis, with the permission from the original publishers. In the electronic version, they are not included, but are available via the original publishers.

4 Conclusions and future work

The idea of P2P has been put into practice for over four decades since the birth of the predecessor of Internet, namely ARPANET. The term of P2P has been widely accepted and used for more than ten years, symbolized by the emergence of Napster. In retrospect, the growing footprints of P2P are almost always accompanied by obstacles, typified by the force-out from the media industry, and regulations from governments throughout the world, etc. Though in face of predicament of sorts, as a disruptive technology, P2P successfully gets over them and is prospering with each passing day. The enhancement and evolution of P2P from the first generation to the second and third generation reveals the trend of technology. As two separate directions, hierarchical architecture and DHT algorithms address the scalability problem of P2P networks from different perspectives, and end up different merits. The combination of P2P technology with other emerging technologies, e.g. Web Services, pours new vigour into P2P systems.

This thesis presents an overall and detailed description of the history of P2P systems which consists of three phases, namely prehistory (1969–1995), retrogressive (1995–1999), and prosperous (1999–?) stages. The author claims that this thesis provides a complete and systemic description of the evolution history of P2P systems to date. It, therefore, provides useful information for the contemporary researchers to discern the developmental trends of P2P systems.

Regarding the technical details, this thesis firstly describes a P2P and Web Services converged architecture to provide Web Services for end users efficiently by utilizing P2P technology. Secondly, hierarchical architecture, vertical hierarchical P2P architecture, in particular, is introduced in detail. A generalized hierarchical architecture is put forward to analyze the performance of hierarchical architecture compared to flat architecture. The optimal number of tiers and the number of nodes at each tier are also studied in detail in the architecture proposed. Thirdly, the performance evaluation of a communication-oriented structured P2P system, and the feasibility analysis of mobile nodes acting as fully fledged peers of structured P2P overlays, are stated completely and thoroughly. Finally, effects of different churn models on the performance of structured P2P networks are presented to provide references on the selection of different churn models.

The P2P and Web Services converged framework provides a reference model in the context of cellular networks and mobile Ad Hoc network environments. The infrastructure of existing cellular networks and the flexibility of the Ad Hoc networks are utilized to maximize the output of the proposed framework. Admittedly, no simulation or real-life prototype has been implemented for the framework. Thus, the performance and feasibility of the framework proposed have not been proved in this thesis. However, this thesis does provide a beneficial attempt in the direction of converging Web Services and P2P networks efficiently.

From the architectural point of view, a multi-tier generalized architecture, namely GTPP, is proposed to analyze the performance of VeHA compared to flat architecture. Through thorough and detailed analysis, the optimal values regarding the number of tiers of the architecture and number of nodes at each tier of sub-overlay are derived. The advantages of VeHA compared to flat architecture are acquired through the analysis as well. These results provide useful guidance in selecting the architecture for real-life P2P systems, e.g. flat architecture or hierarchical architecture, number of tiers in the case of hierarchical architecture.

In the performance evaluation of a communication-oriented Kademlia-based P2P system, both simulation models and prototype measurements are utilized. The NetHawk EAST-based simulation models are mainly responsible for finding the optimal design parameters, while the measurements from the prototype are used for analyzing the feasibility of mobile nodes acting as fully fledged P2P overlay participants. The findings through both simulation models and prototype measurements provide referenced operating points for the practical P2P system design and protocol design.

The simulation results of churn models analysis show that the difference among different churn models is quantitative rather than qualitative. This provides some reference on the selection of different churn models, and helps quiet down the controversy regarding which churn model best characterizes the dynamics of P2P overlay participating nodes.

Future work includes deploying the prototype and simulation models in larger settings, e.g. PlanetLab test-bed, to confirm the conclusions made in this thesis. Meanwhile, the evolution of P2P technology is never deterministic or finite. The presented two directions in this thesis, namely hierarchical architecture and DHT algorithms, will continue to evolve in the future. Consequently, the findings of this thesis only stand for the beginning of the future technology evolution, never an end, and they need to be enhanced and advanced to reflect the future environments.

References

Aboba B (1993) The online user's encyclopedia. Addison-Wesley, ISBN 0-201-62214-9.

Androutsellis-Theotokis S & Spinellis D (2004) A survey of peer-to-peer content distribution technologies. ACM Computing Surveys 36(4): 335–371.

Andy O (2001) Peer-to-peer: harnessing the power of disruptive technologies. O'Reilly Media, ISBN:0-596-00110-X.

Arai B, Das G, Gunopulos D & Kalogeraki V (2007) Efficient approximate query processing in peer-to-peer networks. IEEE Transactions on Knowledge and Data Engineering 19(7): 919–933.

Artigas MS, López PG, Ahulló JP & Skarmeta AF (2005) Cyclone: a novel design schema for hierarchical DHTs. Proceedings of the Fifth IEEE International Conference on Peer-to-Peer Computing (P2P'05): 49–56.

Artigas MS, López PG, & Skarmeta AF (2007) A comparative study of hierarchical DHT systems. Proceedings of the 32nd IEEE Conference on Local Computer Networks (LCN 2007): 325–333.

Balasubramanian N, Balasubramanian A & Venkataramani A (2009) Energy consumption in mobile phones: a measurement study and implications for network applications. Proceedings of the 9th ACM SIGCOMM Conference on Internet Measurement Conference (IMC '09):280–293.

Baset S, Schulzrinne H & Matuszewski M (2007) Peer-to-Peer Protocol(P2PP). Internet Engineering Task Force (IETF) draft. URI: http://tools.ietf.org/html/draft-baset-p2psip-p2pp-01. (work-in-progress).

Baumgart I (2008) P2PNS: a secure distributed name service for P2PSIP. Proceedings of the Sixth Annual IEEE International Conference on Pervasive Computing and Communications (PerCom 2008): 480–485.

Binzenhöfer A & Leibnitz K (2007) Estimating churn in structured P2P networks. Springer Berlin/Heidelberg Lecture Notes in Computer Science, Managing Traffic Performance in Converged Networks 4516(2007): 630–641.

Binzenhöfer A & Schnabel H (2007) Improving the performance and robustness of Kademlia-based overlay networks. University of Würzburg, Institute of Computer Science, Research Report, Report No. 405, April 2007.

Bonfiglio D, Mellia M, Meo M & Rossi D (2009) Detailed analysis of skype traffic. IEEE Transactions on Multimedia 11(1): 117–127.

Bryan DA & Lowekamp BB (2007) Decentralizing SIP. ACM Queue 5(2): 34–41.

Bryan DA, Lowekamp BB & Zangrilli M (2008) The design of a versatile, secure P2PSIP communications architecture for the public internet. Proceedings of the IEEE International Symposium on Parallel and Distributed Processing 2008 (IPDPS 2008): 1–8.

Bustamante FE & Qiao Y (2004) Friendships that last: peer lifespan and its role in P2P protocols. Proceedings of the 8th International Workshop on Web Content Caching and Distribution: 233–246.

Cai H & Wang J (2006) Exploiting geographical and temporal locality to boost search efficiency in peer-to-peer systems. IEEE Transactions on Parallel and Distributed Systems 17(10): 1189–1203.

Carra D & Biersack EW (2007) Building a reliable P2P system out of unreliable P2P clients: the case of Kad. Proceedings of the 2007 ACM CoNEXT Conference (CoNEXT '07): 1–12.

Castro M, Druschel P, Kermarrec AM & Rowstron AIT (2002) Scribe: a large-scale and decentralized application-level multicast infrastructure. IEEE Journal on Selected Areas in Communications 20(8): 1489–1499.

Chen G, Low CP & Yang Z (2008) Coordinated services provision in peer-to-peer environments. IEEE Transactions on Parallel and Distributed Systems 19(4): 433–446.

Chen H, Jin H, Liu Y & Ni LM (2009) Difficulty-aware hybrid search in peer-to-peer networks. IEEE Transactions on Parallel and Distributed Systems 20(1): 71–82.

Chen KT, Huang CY, Huang P & Lei CL (2006) Quantifying Skype user satisfaction. SIGCOMM Computer Communication Review 36(4): 399–410.

Chopra D, Schulzrinne H, Marocco E & Ivov E (2009) Peer-to-peer overlays for real-time communication: security issues and solutions. IEEE Communications Surveys & Tutorials 11(1): 4–12.

Chun B, Culler D, Roscoe T, Bavier A, Peterson L, Wawrzoniak M & Bowman M (2003) PlanetLab: an overlay testbed for broad-coverage services. SIGCOMM Computer Communication Review 33(3): 3–12.

Clarke I, Miller SG, Hong TW, Sandberg O & Wiley B (2002) Protecting free expression online with Freenet. IEEE Internet Computing 6(1): 40–49.

Cohrs KM (2008) Implementation and evaluation of the Peer-to-Peer Protocol (P2PP) for P2PSIP. M.S. Thesis, Computer Networks Group, Institute of Computer Science, Georg-August-University of Göttingen, Göttingen, Germany, 2008.

Freedman MJ & Mazières D (2003) Sloppy hashing and self-organizing clusters. Proceedings of the Second International Workshop on Peer-to-Peer Systems (IPTPS'03): 45–55.

Freire EP, Ziviani A & Salles RM (2008) Detecting VoIP calls hidden in web traffic. IEEE Transactions on Network and Service Management 5(4): 204–214.

Foster I, Kesselman C & Tuecke S (2001) The anatomy of the grid: enabling scalable virtual organizations. International Journal of High Performance Coumputing Applicaitons 15(3): 200–222.

Foster I & Iamnitchi A (2003) On death, taxes, and the convergence of peer-to-peer and grid computing. Proceedings of the 2nd International Workshop on Peer-to-Peer Systems (IPTPS'03): 118–128.

Ganesan P, Gummadi K & Garcia-Molina H (2004) Canon in G major: designing DHTs with hierarchical structure. Proceedings of the 24th International Conference on Distributed Computing Systems (ICDCS'04): 263–272.

Ganesan P, Sun Q & Garcia-molina H (2003) YAPPERS: a peer-to-peer lookup service over arbitrary topology. Proceedings of the Twenty-Second Annual Joint Conference of the IEEE Computer and Communications (INFOCOM 2003) (2): 1250–1260.

Garcés-Erice L, Biersack EW, Felber PA, Ross KW & Urvoy-Keller G (2003) Hierarchical P2P systems. Proceedings of the ACM/IFIP International Conference on Parallel and Distributed Computing (Euro-Par): 643–657.

Gehlen G & Pham L (2005) Mobile Web services for peer-to-peer applications. Proceedings of the Second IEEE Consumer Communications and Networking Conference (CCNC 2005): 427–433.

Godfrey PB, Shenker S & Stoica I (2006) Minimizing churn in distributed systems. SIGCOMM Computer Communication Review 36(4): 147–158.

Guo L, Chen S, Xiao Z, Tan E, Ding X & Zhang X (2005) Measurements, analysis, and modeling of BitTorrent-like systems. Proceedings of the 5th ACM SIGCOMM Conference on Internet Measurement (IMC '05): 35–48.

Gurun S, Nagpurkar P & Zhao BY (2006) Energy consumption and conservation in mobile peer-to-peer systems. Proceedings of the 1st International Workshop on Decentralized Resource Sharing in Mobile Computing and Networking (MobiShare '06): 18–23.

Gupta I, Birman K, Linga P, Demers A & Renesse RV (2003) Kelips: building an efficient and stable P2P DHT through increased memory and background overhead. Springer Berlin/Heidelberg Lecture Notes in Computer Science, Peer-to-Peer Systems II 2735(2003): 160–169.

Gupta A, Liskov B & Rodrigues R (2004) Efficient routing for peer-to-peer overlays. Proceedings of the 1st Conference on Symposium on Networked Systems Design and Implementation (NSDI) (1): 9–22.

Harchol-Balter M & Downey AB (1997) Exploiting process lifetime distributions for dynamic load balancing. ACM Transactions on Computer Systems (TOCS) 15(3): 253–285.

Harjula E, Hautakorpi J, Beijar N & Ylianttila M (2009) Peer-to-Peer SIP for mobile computing: challenges and solutions. Seet B-C (ed.) Mobile Peer-to-Peer Computing for Next Generation Distributed Environments: Advancing Conceptual and Algorithmic Applications, Hershey, USA, IGI Publish: 326–347.

Hsiao HC, Liao H & Huang CC (2009) Resolving the topology mismatch problem in unstructured peer-to-peer networks. IEEE Transactions on Parallel and Distributed Systems 20(11): 1668–1681.

Huang C, Li J & Ross KW (2007) Can Internet Video-on-Demand be Profitable?. SIGCOMM Computer Communication Review 37(4): 133–144.

Huang-Fu CC, Lin YB & Rao H (2009) IP2P: a peer-to-peer system for mobile devices. IEEE Wireless Communications 16(2): 30–36.

Jennings C, Lowekamp B, Rescorla E, Baset S & Schulzrinne H (2009) REsource LOcation And Discovery (RELOAD) base protocol. Internet Engineering Task Force (IETF) draft. URI: http://tools.ietf.org/html/draft-ietf-p2psip-base-06. (work-in-progress).

Jennings RB, Nahum EM, Olshefski DP, Saha D, Shae ZY & Waters C (2006) A study of Internet instant messaging and chat protocols. IEEE Network 20(4): 16–21.

Joung YJ & Lin ZW (2010) On the self-organization of a hybrid peer-to-peer system. Journal of Network and Computer Applications 33(2): 183–202.

Kassinen O, Harjula E, Korhonen J & Ylianttila M (2009) Battery life of mobile peers with UMTS and WLAN in a Kademlia-based P2P overlay. Proceedings of the 20th Personal, Indoor and Mobile Radio Communications Symposium (PIMRC 2009): 662–665.

Kelényi I & Nurminen JK (2008a) Energy aspects of peer cooperation–measurements with a mobile DHT system. Proceedings of the Cognitive and Cooperative Wireless Networks Workshop in the IEEE International Conference on Communications: 164–168.

Kelényi I & Nurminen JK (2008b) Optimizing energy consumption of mobile nodes in heterogeneous Kademlia-based distributed hash tables. Proceedings of the Second International Conference on Next Generation Mobile Applications, Services and Technologies (NGMAST '08): 70–75.

Kermarrec AM, Massoulié L & Ganesh AJ (2003) Probabilistic reliable dissemination in large-scale systems. IEEE Transactions on Parallel and Distributed Systems 14(3): 248–258.

Kim YS & Lee KH (2007) A light-weight framework for hosting Web Services on mobile devices. Proceedings of the Fifth European Conference on Web Services (ECOWS ’07): 255–263.
Kokkonen E, Baset S & Matuszewski M (2008) Demonstration of peer-to-peer session initiation protocol (P2PSIP) in the mobile environment. Proceedings of the Fifth IEEE Consumer Communications and Networking Conference (CCNC 2008): 1221–1222.
Koo SGM, Kannan K & Lee CSG (2006) On neighbor-selection strategy in hybrid peer-to-peer networks. Future Generation Computer Systems 22(7): 732–741.
Korpela E, Werthimer D, Anderson D, Cobb J & Leboisky M (2001) SETI@home-massively distributed computing for SETI. Computing in Science & Engineering 3(1): 78–83.
Koskela T, Kostamo N, Kassinen O, Ohtonen J & Ylianttila M (2007) Towards context-aware mobile Web 2.0 service architecture. Proceedings of the International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies, 2007 (UBICOMM ’07): 41–48.
Lampson B (1986) Designing a global name service. Proceedings of the Fifth annual ACM Symposium on Principles of Distributed Computing (PODC ’86): 1–10.
Le L & Kuo GS (2007) Hierarchical and breathing peer-to-peer SIP system. IEEE International Conference on Communications, 2007 (ICC ’07): 1887–1892.
Lee JW, Schulzrinne H, Kellerer W & Despotovic Z (2009) Proceedings of the Sixth IEEE Consumer Communications and Networking Conference (CCNC 2009): 1–5.
Leibowitz N, Ripeanu M & Wierzbicki A (2003) Deconstructing the Kazaa network. Proceedings of the Third IEEE Workshop on Internet Applications (WIAPP 2003): 112-120.
Leonard D, Yao Z, Wang X & Loguinov D (2008) On static and dynamic partitioning behavior of large-scale P2P networks. IEEE/ACM Transactions on Networking 16(6): 1475–1488.
Li J, Stribling J, Gil TM, Morris R & Kaashoek F (2005a) Comparing the performance of distributed hash tables under churn. Springer Berlin/Heidelberg Lecture Notes in Computer Science, Peer-to-Peer Systems III 3279(2005): 87–99.
Li J, Stribling J, Morris R, Kaashoek MF & Gil TM (2005b) A performance vs. cost framework for evaluating DHT design tradeoffs under churn. Proceedings of the 24th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2005) (1):225–236.
Li Z, Xie G & Li Z (2008) Efficient and scalable consistency maintenance for heterogeneous peer-to-peer systems. IEEE Transactions on Parallel and Distributed Systems 19(12): 1695–1708.
Lian J, Naik K & Agnew GB (2007) A framework for evaluating the performance of cluster algorithms for hierarchical networks. IEEE/ACM Transactions on Networking 15(6): 1478–1489.
Liang J, Kumar R & Ross KW (2006) The FastTrack overlay: a measurement study. Computer Networks 50(6): 842–858.
Lin T, Lin P, Wang H & Chen C (2009) Dynamic search algorithm in unstructured peer-to-peer networks. IEEE Transactions on Parallel and Distributed Systems 20(5): 654–666.
Loo BT, Huebsch R, Stoica I & Hellerstein JM (2005) The case for a hybrid P2P search infrastructure. Springer Berlin/Heidelberg Lecture Notes in Computer Science 3279(2005): 141–150.
Lua EK, Crowcroft J, Pias M, Sharma R & Lim S (2005) A survey and comparison of peer-to-peer overlay network schemes. IEEE Communications Surveys & Tutorials 7(2): 72–93.
Lueg C & Fisher D (2003) From Usenet to CoWebs: interacting with social information spaces. Springer (2003), ISBN 1852335327, ISBN 9781852335328.

Maibaum N & Mundt T (2002) JXTA: a technology facilitating mobile peer-to-peer networks. International Mobility and Wireless Access Workshop (MobiWac 2002): 7–13.
Manku GS, Bawa M & Raghavan P (2003) Symphony: distributed hashing in a small world. Proceedings of the Fourth USENIX Symposium on Internet Technologies and Systems (USITS): 127–140.
Martinez-Yelmo I, Bikfalvi A, Cuevas R, Guerrero C & Jaime Garcia (2009) H-P2PSIP: Interconnection of P2PSIP domains for global multimedia services based on a hierarchical DHT overlay network. Computer Networks 53 (2009): 556–568.
Matuszewski M & Kokkonen E (2008) Mobile P2PSIP: peer-to-peer SIP communication in mobile communities. Proceedings of the Fifth IEEE Consumer Communications and Networking Conference (CCNC 2008): 1159–1165.
Maymounkov P & Mazières D (2002) Kademlia: a peer-to-peer information system based on the xor metric. First International Workshop on Peer-to-Peer Systems (IPTPS 2002): 53–65.
McQuillan JM & Walden DC (1977) The ARPANET design decisions. Computer Networks 1(5): 243–289.
McQuillan JM, Falk G & Richer I (1978) A review of the development and performance of the ARPANET routing algorithm. IEEE Transactions on Communications 26(12): 1802–1811.
Nagaraja K, Rollins S & Khambatti M (2006) Looking beyond the legacy of Napster and Gnutella. IEEE Distributed Systems Online 7(3), art. no. 0306-o3005.
Nurmi D, Brevik J & Wolski R (2005) Modeling machine availability in enterprise and wide-area distributed computing environments. Springer Berlin/Heidelberg Lecture Notes in Computer Science, Euro-Par 2005 Parallel Processing: 432–441.
Nurminen JK & Nöyränen J (2008) Energy-consumption in mobile peer-to-peer - quantitative results from file sharing. Proceedings of the 5th IEEE Consumer Communications and Networking Conference (CCNC 2008): 729–733.
Pack S, Park K, Kwon T & Choi Y (2006) SAMP: scalable application-layer mobility protocol. IEEE Communications Magazine 44(6): 86–92.
Paxson V & Floyd S (1995) Wide area traffic: the failure of Poisson modeling. IEEE/ACM Transactions on Networking 3(3): 226–244.
Pentikousis K (2009) Pitfalls in energy consumption evaluation studies. Proceedings of the 6th International Symposium on Wireless Communication Systems (ISWCS 2009): 368–372.
Ratnasamy S, Francis P, Handley M, Karp R & Shenker S (2001) A scalable content-addressable network. SIGCOMM Computer Communication Review 31(4): 161–172.
Rhea S, Geels D, Roscoe T & Kubiatowicz J (2004) Handling churn in a DHT. Proceedings of the USENIX 2004 Annual Technical Conference : 127–140.
Rhea S, Wells C, Eaton P, Geels D, Zhao B, Weatherspoon H & Kubiatowicz J (2001) Maintenance-free global data storage. IEEE Internet Computing 5(5): 40–49.
Ripeanu M (2001) Peer-to-peer architecture case study: Gnutella network. Proceedings of the First International Conference on Peer-to-Peer Computing (P2P'01): 99–100.
Rosenberg J, Schulzrinne H, Camarillo G, Johnston A, Peterson J, Sparks R, Handley M & Schooler E (2002) SIP:Session Initiation Protocol. IETF RFC 3261.
Rowstron A & Druschel P (2001) Pastry: scalable, distributed object location and routing for large-scale peer-to-peer systems. Proceedings of the IFIP/ACM International Conference on Distributed Systems Platforms (Middleware'01):329–350.
Saint-Andre P (2005) Streaming XML with Jabber/XMPP. IEEE Internet Computing 9(5): 82–89.

Saint-Andre P (2007) Jingle: Jabber does multimedia. IEEE Multimedia 14(1): 90–94.

Sánchez-Artigas M, García-López P & Herrera B (2009) Exploring the feasibility of reputation systems under churn. IEEE Communications Letters 13(7): 558–560.

Shen H, Kumar M, Das SK & Wang Z (2005) Energy-efficient data caching and prefetching for mobile devices based on utility. Mobile Networks and Applications 10(4): 475–486.

Shen H & Xu CZ (2007) Locality-aware and churn-resilient load-balancing algorithms in structured peer-to-peer networks. IEEE Transactions on Parallel and Distributed Systems 18(6): 849–862.

Shi J, Wang Y, Gu L, Li L, Lin W, Li Y, Ji Y & Zhang P (2007) A hierarchical peer-to-peer SIP system for heterogeneous overlays interworking. Proceedings of the IEEE Global Telecommunications Conference 2007 (GLOBECOM '07): 93–97.

Shin S, Jung J & Balakrishnan H (2006) Malware prevalence in the KazaA file-sharing network. Proceedings of the Sixth ACM SIGCOMM Conference on Internet Measurement (IMC'06): 333–336.

Simon H (1996) The Sciences of the artificial. MIT Press.

Srirama SN, Jarke M, Zhu H & Prinz W (2008) Scalable mobile Web Service discovery in peer to peer networks. Proceedings of the Third International Conference on Internet and Web Applications and Services, 2008 (ICIW '08): 668–674.

Steiner M, En-Najjary T & Biersack EW (2007a) A global view of Kad. Proceedings of the 7th ACM SIGCOMM Conference on Internet measurement (IMC '07): 117–122.

Steiner M, En-Najjary T & Biersack EW (2007b) Exploiting Kad: possible uses and misuses. SIGCOMM Computer Communication Review 37(5): 65–69.

Steiner M, En-Najjary T & Biersack EW (2009) Long term study of peer behavior in the Kad DHT. IEEE/ACM Transactions on Networking (TON) 17(5): 1371–1384.

Stoica I, Morris R, Liben-Nowell D, Karger DR, Kaashoek MF, Dabek F & Balakrishnan H (2003) Chord: a scalable peer-to-peer lookup protocol for Internet applications. IEEE/ACM Transactions on Networking 11(1): 17–32.

Stoica I, Adkins D, Zhuang S, Shenker S & Surana S (2004) Internet indirection infrastructure. IEEE/ACM Transactions on Networking 12(2): 205–218.

Stutzbach D & Rejaie R (2006a) Improving lookup performance over a widely-deployed DHT. Proceedings of the 25th IEEE International Conference on Computer Communications (INFOCOM 2006): 1–12.

Stutzbach D & Rejaie R (2006b) Understanding churn in peer-to-peer networks. Proceedings of the 6th ACM SIGCOMM Conference on Internet measurement (IMC '06): 189–201.

Tang X, Xu J & Lee WC (2008) Analysis of TTL-based consistency in unstructured peer-to-peer networks. IEEE Transactions on Parallel and Distributed Systems 19(12): 1683–1694.

Tewari S & Kleinrock L (2007) Optimal search performance in unstructured peer-to-peer networks with clustered demands. IEEE Journal on Selected Areas in Communications 25(1): 84–95.

Tian R, Xiong Y, Zhang Q, Li B, Zhao BY & Li X (2005) Hybrid overlay structure based on random walks. Springer Berlin/Heidelberg Lecture Notes in Computer Science 3640(2005): 152–162.

Wang L & Xiao Y (2006) A survey of energy-efficient scheduling mechanisms in sensor networks. Mobile Networks and Applications 11(5): 723–740.

Wauthy JF & Schumacher L (2007) Implementation and performance evaluation of a P2PSIP distributed proxy/registrar. Proceedings of the 2007 International Conference on Next Gener-

ation Mobile Applications, Services and Technologies (NGMAST '07): 119–124.
Wolff R & Schuster A (2004) Association rule mining in peer-to-peer systems. IEEE Transactions on Systems, Man, and Cybernetics, Part B 34(6): 2426–2438.
Wu D, Tian Y & Ng KW (2006) Analytical study on improving DHT lookup performance under churn. Proceedings of the Sixth IEEE International Conference on Peer-to-Peer Computing (P2P 2006): 249–258.
Wu Y, Li XY, Li YH & Lou W (2010) Energy-efficient wake-up scheduling for data collection and aggregation. IEEE Transactions on Parallel and Distributed Systems 21(2): 275–287.
Xiao L, Liu Y & Ni LM (2005) Improving unstructured peer-to-peer systems by adaptive connection establishment. IEEE Transactions on Computers 54(9): 1091–1103.
Xiao Y, Li H, Pan Y, Wu K & Li J (2004) On optimizing energy consumption for mobile handsets. IEEE Transactions on Vehicular Technology 53(6): 1927–1941.
Xie C, Chen G, Vandenberg A & Pan Y (2008) Analysis of hybrid P2P overlay network topology. Computer Communications 31(2): 190–200.
Xiong J, Zhang Y, Hong P, Li J & Guo L (2006) Reduce chord routing latency issue in the context of IPv6. IEEE Communications Letters 10(1): 62 –64.
Xu Z, Min R & Hu Y (2003) HIERAS: a DHT based hierarchical P2P routing algorithm. Proceedings of the 2003 International Conference on Parallel Processing (ICPP'03): 187–194.
Yang B & Garcia-Molina H (2003) Designing a super-peer network. Proceedings of 19th IEEE International Conference on Data Engineering (ICDE'03): 49–60.
Yang M & Yang Y (2009) An efficient hybrid peer-to-peer system for distributed data sharing. IEEE Transactions on Computers, 17 Nov. 2009. IEEE computer Society Digital Library. IEEE Computer Society. URI: http://doi.ieeecomputersociety.org/10.1109/TC.2009.175.
Zhang R & Hu YC (2007) Assisted peer-to-peer search with partial indexing. IEEE Transactions on Parallel and Distributed Systems 18(8): 1146–1158.
Zhang XY, Zhang Q, Zhang Z, Song G & Zhu W (2004) A construction of locality-aware overlay network: mOverlay and its performance. IEEE Journal on Selected Areas in Communications 22(1): 18–28.
Zhao BY, Duan Y, Huang L, Joseph AD & Kubiatowicz JD (2002) Brocade: Landmark Routing on Overlay Networks. Springer-Verlag Lecture Notes In Computer Science 2429: 34–44.
Zhao BY, Huang L, Stribling J, Rhea SC, Joseph AD, Kubiatowicz JD (2004) Tapestry: a resilient global-scale overlay for service deployment. IEEE Journal on Selected Areas in Communications 22(1):41–53.
Zhu J, Qiao C & Wang X (2006) On accurate energy consumption models for wireless ad hoc networks. IEEE Transactions on Wireless Communications 5(11): 3077–3086.
Zhu Z, Kalnis P & Bakiras S (2008) DCMP: A distributed cycle minimization protocol for peer-to-peer networks. IEEE Transactions on Parallel and Distributed Systems 19(3): 363–377.
Zoels S, Despotovic Z & Kellerer W (2006) Cost-based analysis of hierarchical DHT design. Proceedings of the Sixth IEEE International Conference on Peer-to-Peer Computing (P2P'06): 233–239.
Zoels S, Despotovic Z & Kellerer W (2008) On hierarchical DHT systems–An analytical approach for optimal designs. Computer Communications 31: 576–590.

Original articles

I Ou Z, Song M, Chen H & Song J (2008) Layered peer-to-peer architecture for mobile web services via converged cellular and Ad Hoc networks. Proceedings of the 3rd International Conference on Grid and Pervasive Computing Workshops (GPC Workshops '08): 195–200.

II Zhou J, Ou Z, Rautiainen M & Ylianttila M (2008) P2P SCCM: Service-oriented community coordinated multimedia over P2P. Proceedings of the IEEE Congress on Services Part II 2008 (SERVICES-2): 34–40.

III Ou Z, Zhou J, Harjula E & Ylianttila M (2009) Truncated pyramid peer-to-peer architecture with vertical tunneling model. Proceedings of the 6th IEEE Consumer Communications and Networking Conference (CCNC 2009): 1–5.

IV Koskela T, Kassinen O, Ou Z & Ylianttila M (2010) Improving community management performance with two-level hierarchical DHT overlays. Journal of Internet Technology, Special Issue on Internet Resource Sharing and Discovery, 11 (2): 167–179.

V Ou Z, Harjula E & Ylianttila M (2008) GTPP: General truncated pyramid architecture over P2PSIP networks. Proceedings of the International Conference on Mobile Technology, Applications, and Systems (Mobility '08): 1–4.

VI Ou Z, Harjula E, Koskela T & Ylianttila M (2010) GTPP: general truncated pyramid peer-to-peer architecture over structured DHT networks. Springer Mobile Networks and Applications, DOI: 10.1007/s11036-009-0193-2 (Online first, in press).

VII Kassinen O, Ou Z, Harjula E & Ylianttila M (2008) Effects of peer-to-peer overlay parameters on mobile battery duration and resource lookup efficiency. Proceedings of the 7th International Conference on Mobile and Ubiquitous Multimedia (MUM'08): 177–180.

VIII Ou Z, Harjula E, Kassinen O & Ylianttila M (2009) Feasibility evaluation of a communication-oriented P2P system in mobile environments. Proceedings of the International Conference on Mobile Technology, Applications and Systems (Mobility '09): 1–8.

IX Ou Z, Harjula E, Kassinen O & Ylianttila M (2010) Performance evaluation of a Kademlia-based communication-oriented P2P system under churn. Elsevier Journal Computer Networks 54 (5): 689–705.

X Ou Z, Harjula E & Ylianttila M (2009) Effects of different churn models on the performance of structured peer-to-peer networks. Proceedings of the 20th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '09): 2856–2860.

Original publications are not included in the electronic version of the dissertation.

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345. Väisänen, Tero (2009) Sedimentin kemikalointikäsittely. Tutkimus rehevän ja sisäkuormitteisen järven kunnostusmenetelmän mitoituksesta sekä sen tuloksellisuuden mittaamisesta

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