Department of Communications and Networking

Techno-economic feasibility analysis of multipath protocols in the Internet

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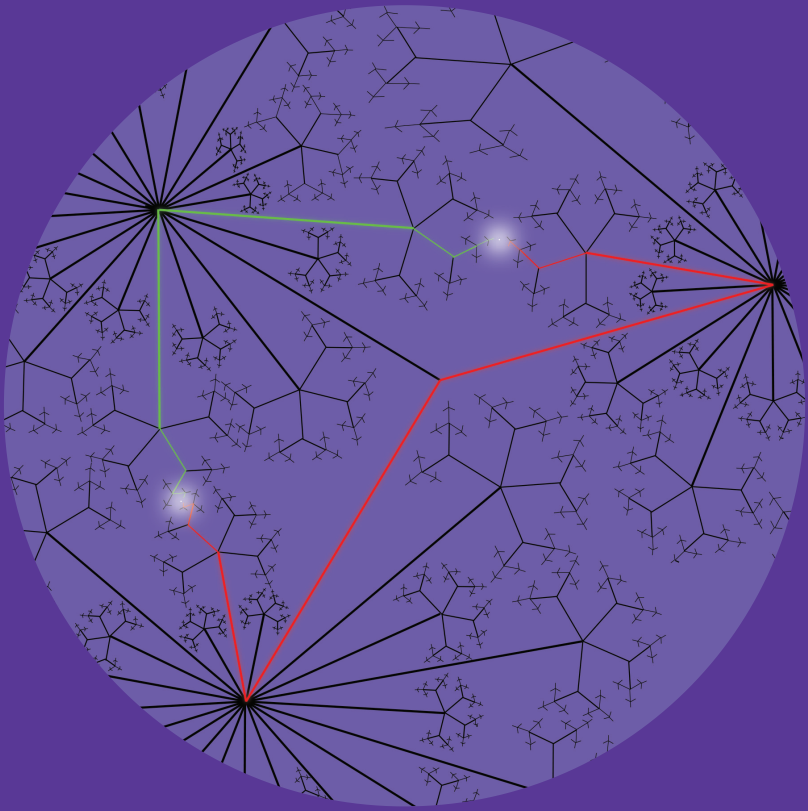
Henna Suomi



Aalto University

DOCTORAL DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 77/2014

Techno-economic feasibility analysis of multipath protocols in the Internet

Henna Suomi

A doctoral dissertation completed for the degree of Doctor of Science in Technology to be defended, with the permission of the Aalto University School of Electrical Engineering, at a public examination held at the lecture hall S1 of the school on the 17th of June 2014 at 12 noon.

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Aalto University publication series
DOCTORAL DISSERTATIONS 77/2014

ISBN 978-952-60-5704-0
ISBN 978-952-60-5705-7 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-5705-7

Unigrafia Oy
Helsinki 2014

Finland

NORDIC ECOLABEL
441 697
Printed matter

Abstract

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Author
Henna Suomi (née Warma)

Name of the doctoral dissertation
Techno-economic feasibility analysis of multipath protocols in the Internet

Publisher School of Electrical Engineering

Unit Department of Communications and Networking

Series Aalto University publication series DOCTORAL DISSERTATIONS 77/2014

Field of research Network Economics

Manuscript submitted 31 January 2014 **Date of the defence** 17 June 2014

Permission to publish granted (date) 14 April 2014 **Language** English

☐ **Monograph** ☒ **Article dissertation (summary + original articles)**

Abstract

During the past few decades, multipath protocols have been developed to improve load balancing in the Internet. These protocols can send the traffic of individual end users through several paths simultaneously and switch the traffic from one path to another. Despite many technical proposals, multipath protocols are not widely deployed and their economic feasibility remains unstudied.

This research fills the gap by analyzing the economic feasibility of multipath protocols from the perspective of different stakeholders. The research essentially considers the use case of accessing Internet services with mobile devices. The objective of the research is to identify and elaborate the factors affecting economic feasibility of multipath protocols, and also their effects on the Internet connectivity market. Furthermore, this research aims to develop the methods for studying not only the feasibility of multipath but also other Internet protocols.

Several methods are employed to attain these objectives. Economic theories of network effects and switching costs are taken as the basis for studying the feasibility. System dynamics and variants of techno-economic modeling are used to model the diffusion process and to elaborate the costs and benefits of multipath protocols. Data collection is based on literature, expert interviews and network performance measurements.

The results indicate that the protocols enabling host-controlled switch of access operators seem initially more compelling than the protocols that allow accessing several operators simultaneously. Especially, three factors are seen to affect the feasibility of multipath protocols positively: 1) growing number of multihoming-capable (e.g., multi-SIM) devices, 2) higher performance requirements of emerging applications, and 3) increasing capacity of batteries. In case of wide-scale deployment, the market impacts of client multihoming and multipath protocols are expected to be significant since they will reallocate the cost and revenue flows of operators and increase competition in the mobile access.

The modeling methods of this research create a novel and practical approach to the research of protocol feasibility. As opposed to traditional economics modeling which neglects the details of a technical structure (black box), techno-economic modeling considers the technical architecture as a white box allowing for the identification of the deployment challenges and opportunities of a protocol. In addition, the research observes that comparing the costs of a protocol against the non-monetary benefits, instead of a purely monetary comparison, is often more applicable approach to the techno-economic analysis of protocols.

Keywords multipath protocols, Internet, feasibility, techno-economic analysis

ISBN (printed) 978-952-60-5704-0 **ISBN (pdf)** 978-952-60-5705-7

ISSN-L 1799-4934 **ISSN (printed)** 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2014

Pages 220 **urn** http://urn.fi/URN:ISBN:978-952-60-5705-7

A? **Aalto-yliopisto**

Aalto-yliopisto, PL 11000, 00076 Aalto www.aalto.fi

Tiivistelmä

Tekijä
Henna Suomi (née Warma)

Väitöskirjan nimi
Internetin monitieprotokollien teknis-taloudellinen analyysi

Julkaisija Sähkötekniikan korkeakoulu

Yksikkö Tietoliikenne- ja tietoverkkotekniikan laitos

Sarja Aalto University publication series DOCTORAL DISSERTATIONS 77/2014

Tutkimusala Tietoverkkotalous

Käsikirjoituksen pvm 31.01.2014 **Väitöspäivä** 17.06.2014

Julkaisuluvan myöntämispäivä 14.04.2014 **Kieli** Englanti

☐ **Monografia** ☒ **Yhdistelmäväitöskirja (yhteenveto-osa + erillisartikkelit)**

Tiivistelmä

Viimeisten vuosikymmenten aikana monitieprotokollia on kehitetty parantamaan kuormantasausta Internetissä. Nämä protokollat voivat lähettää käyttäjän liikennettä useamman polun yli samanaikaisesti ja siirtää liikennettä polulta toiselle. Kyseisistä protokollista on tehty useita teknisiä toteutuksia, mutta ne eivät vielä ole levinneet laajempaan käyttöön ja niiden taloudellinen toteutettavuus on toistaiseksi jäänyt tutkimatta.

Tämä väitöskirja tutkii monitieprotokollien käyttöönottoa ja taloudellista toteutettavuutta eri toimijoiden näkökulmasta. Tutkimus keskittyy erityisesti Internet-palveluiden käyttöön mobiililaitteilla. Väitöskirjan tavoitteena on tunnistaa ja arvioida monitieprotokollien käyttöönottoon vaikuttavia tekijöitä sekä analysoida monitieprotokollien markkinavaikutuksia. Lisäksi väitöskirja pyrkii kehittämään uusia menetelmiä monitie- mutta myös muiden Internet-protokollien toteutettavuuden tutkimiseen.

Työssä käytetään useita menetelmiä. Teoriat verkkovaikutuksista sekä vaihtokustannuksista luovat pohjan tutkimukselle. Olennaisimpina mallinnustyökaluina käytetään systeemidynamiikkaa sekä teknis-taloudellisen mallinnuksen eri muotoja. Tietolähteinä toimivat kirjallisuus, haastattelut sekä päätelaitepohjaiset verkkomittaukset.

Tutkimuksen tulokset osoittavat, että protokollat, jotka mahdollistavat mobiilioperaattorin päätelaitevetoisen vaihtamisen, vaikuttavat ensivaiheessa taloudellisesti kiinnostavammilta kuin usean mobiilioperaattorin samanaikainen käyttö. Erityisesti kolme tekijää vaikuttaa positiivisesti monitieprotokollien käyttöönottoon: 1) monitieliitynnän mahdollistavien laitteiden markkinoille tulo, 2) Internet-palveluiden suorituskykyvaatimusten kasvu sekä 3) mobiililaitteiden akkukapasiteetin kasvu. Mikäli päätelaitteiden moniverkkoliityntä ja monitieprotokollat leviävät laajempaan käyttöön, markkinavaikutukset ovat oletettavasti mittavat, sillä operaattorien meno- ja tulovirrat jakautuvat uudelleen ja mobiilioperaattorien välinen kilpailu lisääntyy.

Väitöskirjassa käytetyt mallinnusmenetelmät luovat uuden ja käytännöllisen lähestymistavan Internet-protokollien taloudelliseen tutkimukseen. Verrattuna perinteisiin taloustieteiden menetelmiin, jotka tarkastelevat protokollia mustana laatikkona, työssä käytetty teknis-taloudellinen mallinnus paljastaa protokollien teknisen arkkitehtuurin ja mahdollistaa käyttöönottohaasteiden ja -mahdollisuuksien tunnistamisen. Tutkimuksen aikana havaittiin, että protokollan käyttöönottokustannusten vertaaminen ei-rahallisiin hyötyihin on usein soveltuvampi lähestymistapa protokollien teknis-taloudellisessa tutkimuksessa kuin puhdas rahavirtoihin perustuva analyysi.

Avainsanat monitieprotokollat, Internet, toteutettavuus, teknis-taloudellinen analyysi

ISBN (painettu) 978-952-60-5704-0 **ISBN (pdf)** 978-952-60-5705-7

ISSN-L 1799-4934 **ISSN (painettu)** 1799-4934 **ISSN (pdf)** 1799-4942

Julkaisupaikka Helsinki **Painopaikka** Helsinki **Vuosi** 2014

Sivumäärä 220 **urn** http://urn.fi/URN:ISBN:978-952-60-5705-7

Preface

“Gratitude is not only the greatest of virtues, but the parent of all others.”
–Cicero

You would not be reading this book today without the tremendous people who have shared this four and a half year journey with me. First and foremost, I want to thank Professor Heikki Hämmäinen for supervising and instructing my doctoral thesis as well as for providing the necessary resources to conduct the research. The expertise and holistic viewpoints of Heikki have not only been crucial in finding the research paths to complete this thesis but also in acquiring overall insight into the ICT industry, which will be highly valuable in my future endeavors.

I have been lucky to work and co-author the research papers with so many great people. The most heartfelt thanks go to my office neighbor Tapio Levä with whom I have not only co-authored several papers but also shared most of the joys and frustrations of doctoral studies. I will be missing our discussions and debates as we now both finish our studies. I am also grateful to Arturo Basaure for lively discussions and to Docent Kalevi Kilkki for sharing his valuable ideas during the research process. I would also like to thank Lars Eggert, Howard Tripp, Alan Ford and Aleksandros Kostopoulos who played a key role in getting my research career started. Furthermore, I want to thank Sebastian Sonntag and Professor Jukka Manner for the great technical consultation related to multipathing and multihoming, and for the access to the Netradar database.

Thereafter, I wish to thank the current and former members of the Netbizz team with whom I have shared great times on lunch tables as well as in sweaty team events. Nan Zhang, Antti Riikonen, Tapio Soikkeli, Michail Katsigiannis, Benjamin Finley, Pekka Kekolahti, Juuso Karikoski, Thomas Casey, Timo Smura, Juuso Töyli, you have really made my journey much more enjoyable. I would also like to thank all the Master’s students and especially Görkem Çakmak for the great collaboration.

During the doctoral studies, I had the opportunity to work in several interesting projects which, in many ways, have supported this research. Therefore, I also thank all the colleagues and funders of Trilogy, Digile's Future Internet and Internet of Things projects, which provided an interesting and inspiring environment for research. I would also like to extend my thanks to the entire Comnet staff for the interesting coffee break discussions and for all support.

I feel grateful to my honored pre-examiners Professor Burkhard Stiller from University of Zürich and Professor Andrew Odlyzko from University of Minnesota for carrying out a detailed review of the thesis manuscript. The pre-examination comments really helped me to further improve the quality of the compendium. I also wish to thank Professor Petri Mähönen from RWTH Aachen University for accepting the invitation to act as my opponent.

I feel privileged for my seat at GETA graduate school and the opportunity to meet such talented young researchers in different fields of engineering. Special thanks go to Professor Ari Sihvola and Marja Leppäharju for running the school and all events smoothly. I also wish to thank Tekniikan Edistämissäätiö, the Research and training foundation of TeliaSonera Finland Oyj and the Nokia Foundation for the financial support of the research. Furthermore, I would like to thank Professor Yrjö Neuvo for sharing his expertise during and after the Bit Bang course. I also thank all the Bit Bang friends for the best year of my doctoral studies, the great peer-support and the exchange of innovative ideas about the future of the Internet.

Last but definitely not least, I wish to thank my family and friends who have supported me in countless ways during the studies and provided excellent counterbalance to the thesis work. Especially, I want to thank my dear friend Johanna for her creative support in terms of the cover image. Mum and dad, you have really lived this journey with me and helped in all means during my entire study career. Anne and Johannes, although being physically distant in Luxembourg, the discussions with you have been utmost important to me. Mirja, Eero and Laura, thank you for all your support and interest in my research. Markus, I do not have enough words to express my gratitude to you. This book would never have been published without your endless love and encouragement.

Espoo, May 16th 2014

Henna Suomi

Contents

List of publications

This dissertation consists of an overview and of the following publications, which are referred to in the text by their Roman numerals.

I. H. Warma, T. Levä, H. Tripp, A. Ford, and A. Kostopoulos, ‘Dynamics of communication protocol diffusion: the case of multipath TCP’, Netnomics, vol. 12, no. 2, pp. 133-159, November 2011.

II. H. Warma, T. Levä, L. Eggert, H. Hämmäinen, and J. Manner, ‘Mobile Internet in Stereo: An End-to-End Scenario’, in Proceedings of the 3th Workshop on Economic Traffic Management (ETM 2010), pp. 64-75, Amsterdam, the Netherlands, September 2010.

III. H. Suomi, K. Kilkki, and H. Hämmäinen, ‘Modeling the Value of End-to-End Multipath Protocols’, Journal of Universal Computer Science, vol. 18, no. 14, pp. 2071-2092, July 2012.

IV. S. Sonntag, and H. Suomi, ‘Economic feasibility of multipath protocols in mobile Internet of Things applications’, Concurrency and Computation: Practice and Experience, in press, DOI: 10.1002/cpe.3127.

V. H. Suomi, A. Basaure, and H. Hämmäinen, ‘Effects of capacity sharing on mobile access competition’, in Proceedings of the 21st International IEEE Conference on Network Protocols (ICNP 2013), Göttingen, Germany, October 2013.

VI. T. Levä, and H. Suomi, ’Techno-economic feasibility analysis of Internet protocols: Framework and tools’, Computer Standards & Interfaces, vol. 36, no. 1, pp. 76-88, August 2013.

Author's contribution

I. Warma and Levä created the idea for the article together. Warma, Levä and Tripp created the first version of the adoption and diffusion models, which were further developed by Warma and Levä. Warma conducted the analysis. Warma was responsible for writing the article, except Sections 2 and 3 which she reviewed and edited.

II. Warma, Levä, Eggert and Hämmäinen created the first version of techno-economic model. Warma and Levä developed the model further and conducted the analysis. Warma wrote the entire article, except few paragraphs.

III. Suomi and Hämmäinen created the idea for the article together. Suomi and Kilkki further developed the value model. Suomi conducted the analysis and wrote the entire article.

IV. Sonntag and Suomi created the idea for the article together. Suomi was responsible for the creation of the cost-effectiveness model and its application. Both authors participated in the data collection and the planning of the measurement data analysis. Suomi wrote Sections 2.1, 4, 5 and 6. Introduction and conclusions were written collaboratively. Suomi reviewed and edited the rest of the sections.

V. Suomi and Basaure developed the scenario models together. Suomi wrote the article, except Sections 2.1 and 4.1 which she reviewed and edited.

VI. Levä and Suomi developed the framework and the toolbox together. Suomi was responsible for writing Sections 2, 4 and 6. Suomi reviewed and edited the rest of the sections.

List of abbreviations

3G	Third Generation
3GPP	3rd Generation Partnership Project
API	Application Programming Interface
AS	Autonomous System
ASN	Autonomous System Number
BGP	Border Gateway Protocol
BBM	Break Before Make
CAPEX	Capital Expenditure
CDN	Content Delivery Network
CEA	Cost-Effectiveness Analysis
CER	Cost-Efficiency Ratio
CoAP	Constrained Application Protocol
CP	Content Provider
DCCP	Datagram Congestion Control Protocol
DCF	Discounted Cash Flow
DNS	Domain Name System
DOI	Diffusion of Innovations
DSM	Dynamic Spectrum Management
FTTH	Fiber-to-the-Home
GSM	Global System for Mobile communications
HIP	Host Identity Protocol
HTTP	HyperText Transfer Protocol
IETF	Internet Engineering Task Force
ICT	Information and Communications Technology
IP	Internet Protocol
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
IoT	Internet of Things
ISA	Internet Standard Adoption
ISP	Internet Service Provider
IT	Information Technology

LTE	Long Term Evolution
MBB	Make Before Break
MIP	Mobile IP
MNO	Mobile Network Operator
MPRTP	Multipath Real-time Transport Protocol
MPTCP	Multipath TCP
NAT	Network Address Translation
OPEX	Operational Expenditure
OS	Operating System
PA	Provider Independent
PI	Provider-Assigned
P2P	Peer-to-Peer
QoE	Quality of Experience
RFC	Request for Comments
RTP	Real-time Transport Protocol
SB	Service Back-end
SCTP	Stream Control Transmission Protocol
SD	Smart Device
SDR	Software Defined Radio
SIP	Session Initiation Protocol
SIM	Subscriber Identity Module
TCO	Total Cost of Ownership
TCP	Transport Control Protocol
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide interoperability for Microwave Access
WLAN	Wireless Local Area Network

List of symbols

B	Incremental benefit
$BW_{\min}$	Minimum required bandwidth for a service
B_1	Approximated upper bound of bandwidth on subflow 1
B_2	Approximated upper bound of bandwidth on subflow 2
C_{CAPEX}	Capital expenditure
$C_{Ci,ISPi}^{SD}$	Connectivity setup costs per smart device
$C_{Cm,ISPi}^{SD}$	Connectivity maintenance costs per smart device
C_{E}^{SD}	Energy costs of a smart device
C_{HWa}^{SD}	Hardware acquisition costs of a smart device
C_{HWm}^{SD}	Hardware maintenance costs of a smart device
$C_{OPEX/t}$	Operational expenditure
$C_{SWd}^{SD,SB}$	Software development costs
$C_{SWi}^{SD,SB}$	Software installation costs
c_1	Ratio of approximated bandwidths on subflow 1
c_2	Ratio of approximated bandwidths on subflow 2
d	Inter-AS diversity (III); Active days of a smart device (IV)
E_{multi}	Expected download time with multipath
E_{single}	Expected download time with single-path
f	File size (III); Failure frequency of smart devices (IV)
$h_{diverse}$	Number of diverse inter-AS links
h_{total}	Total number of inter-AS links
k	Number of operator subscriptions of a smart device
l	Number of operator subscriptions of service back-end
m	Number of measurements (III); Number of web servers (IV)
n	Number of smart devices

p_{Multi}	Percentage of connectivity time with multipath
p_{Single}	Percentage of connectivity time with single-path
p_1	Probability of upper bandwidth on subflow 1
p_2	Probability of upper bandwidth on subflow 2
SB	Service back-end
SD	Smart device
t	Time period for measuring OPEX (e.g., a month)
T	Investment period
TC	Total cost
x	Active hours of a smart device

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1. Introduction

1.1 Motivation

During the past few decades, the Internet has undergone a drastic evolution from a research network to one of the most important infrastructures of society. The traffic volumes transmitted over the Internet are growing, raising concerns about the sufficiency of network capacity. If the demand for Internet services continues to grow as expected, two approaches can be taken to secure sufficient capacity supply: 1) building new capacity within network domains, or 2) benefiting from more efficient use of the existing capacity. The stakeholders in the Internet, such as Internet service providers (ISPs) and content providers (CPs), are adopting both strategies within their network domains.

Multipath protocols provide a solution for a more efficient application of the network resources allocated to and administrated by different stakeholders in the Internet. The multipath protocols are capable of transmitting the traffic of individual end users through several paths and switching – potentially seamlessly – from one path to another, which is expected to lead to an improved end-user experience of online services. These features have been specified in numerous Internet protocols, e.g., Stream Control Transmission Protocol (SCTP) (Stewart, 2007; Amer et al., 2013) and Multipath TCP (MPTCP) (Ford et al., 2013). Such protocols are mainly being developed and standardized within the Internet Engineering Task Force (IETF) community, which is the party responsible for standardizing Internet protocols.

Despite the many efforts to specify multipath capabilities in several standards, these protocols have not been deployed on a wide scale in the Internet so far. Technical comparisons of multipath and their competitor protocols have been made (e.g., Schmidt et al., 2012; Le et al., 2006), but the deployment and economic feasibility of multipath protocols remain unstudied. As a multi-stakeholder system, the Internet is a challenging environment for technology deployment (Handley, 2006), and therefore, the economic requirements concerning multipath protocols should not be ignored.

1.2 Research questions and scope

Based on the present research gap, the overarching goal of this research is to study and analyze multipath protocols in the Internet from a techno-economic perspective. The main research problem is stated as follows:

"What is the economic feasibility of multipath protocols in the Internet?"

The main research question can be divided into three more specific questions:

Q1. Which factors affect the economic feasibility of the multipath protocols in the Internet?
Q2. What consequences does the deployment of the multipath protocols have on the Internet connectivity market?
Q3. How can the feasibility of the multipath protocols be modeled and evaluated?

The study focuses on multipath protocols intended for client-server communication in the Internet. Although multipath protocols are applicable to both wired and wireless Internet access, the research essentially explores scenarios in which *mobile devices* use multipath protocols to access online services (e.g., newspapers, video portals or vehicle tracking information) residing on content *servers*. This scope has been selected for two reasons: 1) the significance of the mobile data is increasing, and 2) multipath protocols could facilitate host mobility between operator networks as well as provide gains in the dynamically changing and impairment-prone network environment. Scenarios in which multipath protocols are adopted in intranet environments or in peer-to-peer (P2P) communications are left outside of the scope of this work.

The capability of clients to dynamically select between different paths, even on per-packet basis, allows for optimization in terms of several criteria, such as connectivity performance (e.g., throughput), communication cost and energy consumption. This research, however, only considers the optimization of connectivity performance.

The present research concerns protocols developed within the IETF and implemented in the network, transport or application layers. The standardized protocols are favored, because their technical specifications are openly available, and the standards constitute the key drivers for compatibility between stakeholders, while also supporting economies of scale. The technical architecture presented in Figure 1 visualizes the technical scope of the research.

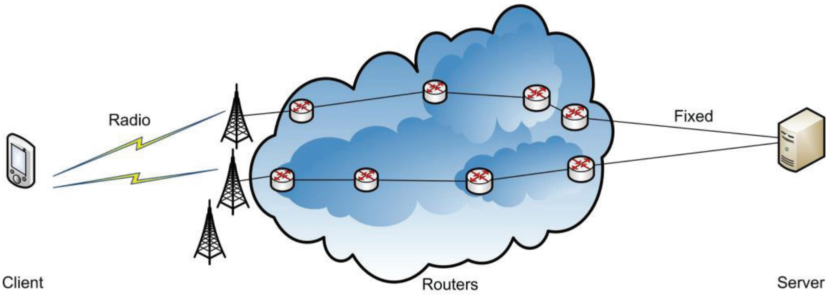

Figure 1. Technical architecture of the use case examined in this study[1]

1.3 Basic concepts

The Internet terminology in the literature is diverse and even contradictory. Therefore, the key terms of the research are defined and applied to position this research and to see how the terms are inter-linked. The three key concepts include multihoming, mobility and multipath.

Multihoming. An architectural document of the Internet (Braden, 1989) defines a multihomed host as an entity with multiple Internet protocol (IP) addresses[2]. These IP addresses can be connected to one or several physical interfaces (e.g., 3G or WLAN). From the business perspective, multihoming refers to the capability of an entity to communicate through several ISP networks, which requires a business contract to be established between the owner of the client and the ISPs. Besides a host, an entire site can be multihomed, in which case a group of computers, such as a data center, has access to the Internet through several ISPs. In this study, *multihoming refers to a mobile device or a site with access to multiple ISP networks on the basis of contracts between the user or organization administrating the device or site and several ISPs*.

Mobility. Traditionally, mobility refers to the physical movement of an entity, but the term has also been adopted to define the capability of a host or a group of devices to change its point of attachment to the network (e.g., Internet). The terminology related to mobility originates from the 3GPP and its predecessor organizations, which are responsible for standardizing mobile networks (e.g., GSM, UMTS). Networks can control local inter-operator mobility by means of national roaming (Mattioli & Dekker, 2013).

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[1] Adapted from Publication VI. Reprinted with permission from Elsevier B.V.

[2] Typically, the assumption is that the IP addresses are granted by different providers. Having several IP addresses from a single provider is called *multi-attachment*.

The 3GPP has specified its own mobility management procedures in the link layer (e.g., location updates, handovers), thus enabling mobility of a device between cellular networks. Recent specifications of mobile data offloading (Sankaran, 2012) facilitate handovers to wireless networks other than traditional cellular networks (e.g., WLAN).

The IETF has also made its contributions to support mobility, providing solutions primarily for the IP layer and above. Manner & Kojo (2004) extensively defined mobility-related terminology, encompassing both the IETF and 3GPP terminology. According to their definition, “host mobility support refers to the function of allowing a mobile node to change its point of attachment to the network, without interrupting IP packet delivery to/from that node” (p. 24). The mobility can be supported within one physical interface (such as WLAN) or between two separate interfaces (e.g., 3G-WLAN or 3G-3G[3]). The former is often referred to as horizontal and the latter as vertical handover. If a mobility technology is capable of sustaining online sessions, i.e., the handover is seamless, the handover is of type make-before-break (MBB). In a break-before-make (BBM) handover, the connectivity with the old access point is terminated before the attachment with the new access point, and the end user can experience interruptions in the connectivity.

Figure 2 clarifies the terminology related to the mobility. In this work, *mobility refers to the function whereby a host is controlling the switch of ISPs either through a horizontal or vertical handover.*

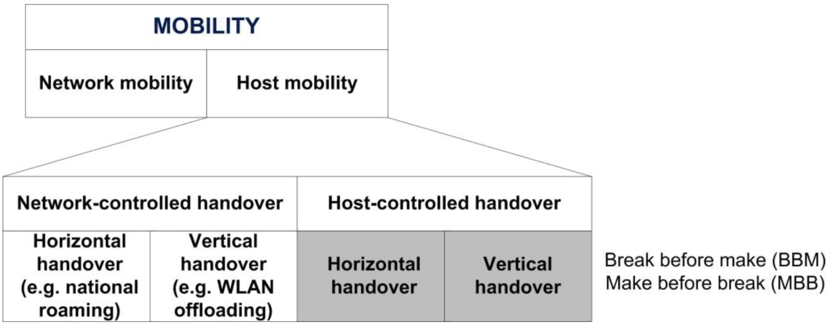

Figure 2. A classification of mobility related terminology. The areas at the core of the research are marked with gray.

Multipath. Multipath can refer to any type of communication that incorporates diverting paths between two specified end points. The scope of multipath solutions vary largely, ranging from parallel cable connectivity between two switches located side by side to the simultaneous use of several

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[3] A change between multiple cellular operators can be carried out either through a horizontal (multiple subscriptions associated with one physical interface) or vertical handover (each subscription associated with a separate physical interface).

IP interfaces in the communication between devices located in different corners of the globe. The multipath function in the Internet architecture may be implemented directly in end-hosts or in intermediate nodes, such as proxies or routers, without the end points being aware of it. Even an end user connecting to a web site (e.g., www.amazon.com) may be considered as multipath communication, since the sequential web page requests of the end user may be directed to different physical servers. In this dissertation, *multipath refers to the simultaneous use of several paths between a client and a specific server over the Internet.*

Other important concepts used in the thesis are defined as follows:

Multipath protocol: A protocol capable of using several end-to-end paths simultaneously, and typically also capable of switching from one path to another, thereby supporting mobility.

Mobility protocol: A protocol capable of switching from one path to another, but incapable of using them simultaneously.

Load balancing: The capability of a stakeholder to move traffic from heavily congested resources to underutilized ones.

Technical architecture: A set of interlinked technical components constituting an infrastructure for multipath communication.

Value network: A set of interlinked actors (e.g., end users, ISPs) which affect or are affected by the usage of a multipath protocol.

End user: A stakeholder (an individual person or organization) who owns and operates a host where a multipath protocol is installed.

Internet service provider (ISP): An actor providing Internet access to end users through fixed or wireless networks.

Mobile network operator (MNO): An ISP providing Internet connectivity through cellular (3GPP specified) networks.

Economic feasibility: A measure of the economic attractiveness of a technology, typically determined by comparing the costs and the benefits of a technology for a certain stakeholder.

Techno-economic analysis: An approach for evaluating the economic feasibility of a known technical structure.

1.4 Outline of the thesis

This thesis consists of six peer-reviewed publications and a compendium. Following the introduction in Chapter 1, Chapter 2 of the compendium provides an overview of the existing multihoming and load balancing mechanisms in the Internet, as well as the relevant prior research on innovation adoption. Thereafter, Chapter 3 introduces the research approach and process. Based on the results of the publications, the research questions of the compendium are addressed in Chapters 4 and 5. Chapter 4 discusses Q1 and Q2, whereas Chapter 5 deals with Q3. Finally, Chapter 6 summarizes the findings of the work, discusses the limitations of the research and provides an outlook for the future work. Figure 3 presents the structure of the thesis.

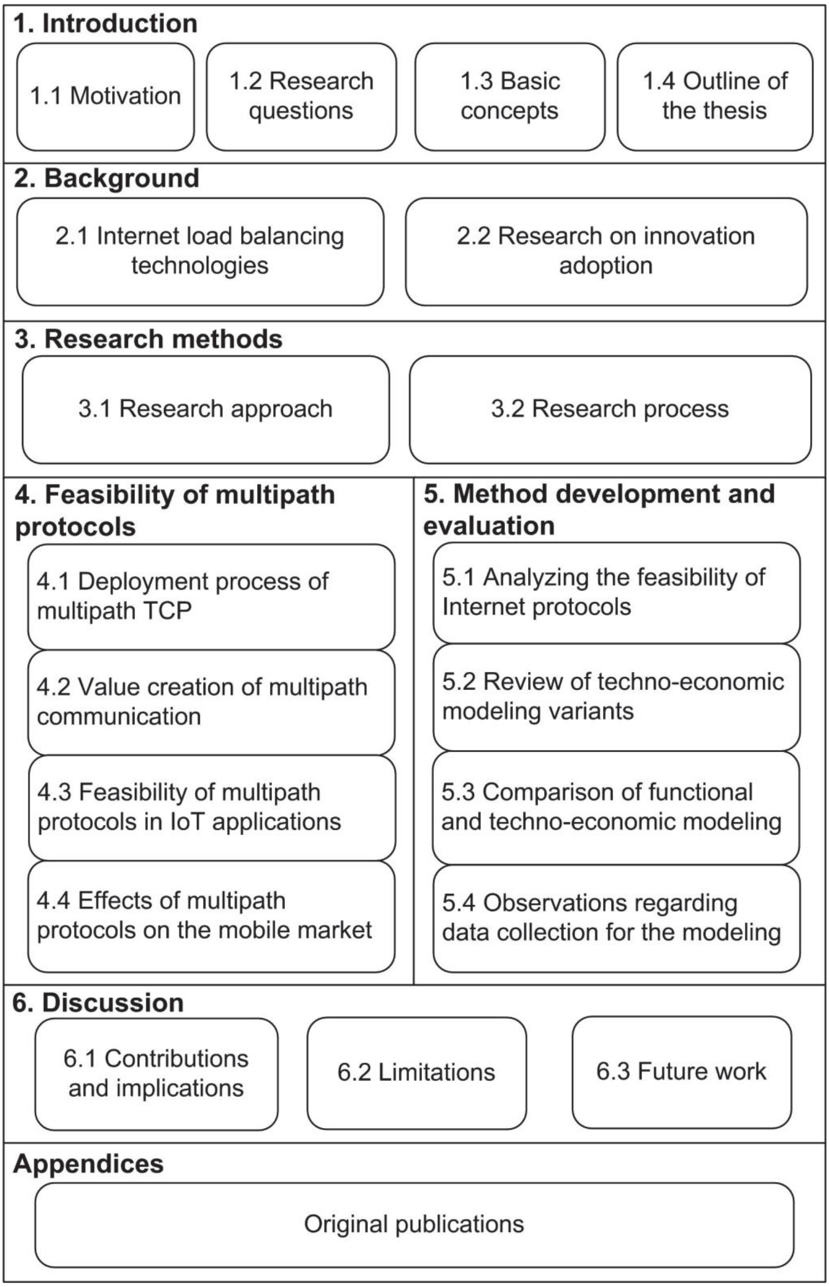

Figure 3. Structure of the thesis

2. Background

To study the feasibility of multipath protocols from techno-economic perspective, both the technical and economic background need to be understood. The first section introduces and categorizes the various load balancing technologies in the Internet. Both deployed and emerging solutions are discussed. The second section presents the relevant prior research on innovation adoption, which has been used as a basis for studying the economic feasibility of multipath protocols, and a literature overview of the feasibility studies on Internet protocols.

2.1 Internet load balancing technologies

Building and exploiting redundancy in the Internet communications is not a new phenomenon. Multihoming and load balancing have been practiced on a site level for a long time. According to Liu & Xiao (2007), the multihoming practice in the Internet can be traced back to the 1980s. However, the Internet community, namely the IETF, established a position on multihoming practices in 1998 when they published an informational request for comments (RFC) on addressing and routing strategies for enterprises attached to multiple ISPs (Bates & Rekhter, 1998). Nowadays, site multihoming is extremely common in the Internet since all large stakeholders, not only CPs but also ISPs, universities and enterprises, are multihomed. According to Perkins (1998), the origins of protocols enabling a client to transmit traffic through different ISPs date back to the early 1990s when the development of the first mobility protocols started within the IETF.

2.1.1 Site multihoming and load balancing

Essentially, two strategies can be taken to build redundancy in the content back-end. Firstly, the redundancy for connectivity can be built *locally*. In this case, a content provider acquires transit connectivity from several local ISPs to a single data center. Alternatively, content providers can replicate their content *globally* to multiple data centers and acquire connectivity in each geographical location. This is the basic choice[4] between centralized and decentralized network planning as discussed, e.g., by Gaynor (2003).

From the technical perspective, the most common way of arranging site multihoming is by applying the border gateway protocol (BGP). The content provider announces its IP address block[5] through several upstream ISPs. In case of an upstream link failure, BGP takes care of switching to the alternate connections. The session between the end user and a server is not necessarily interrupted, but cannot continue until BGP detects a route failure and starts using an alternate path to the same destination. This, however, can take several minutes or even up to an hour (Teixeira, 2007) owing to BGP route propagation.

To maximize the utilization of resources, content providers implement different BGP configurations to balance the traffic on the redundant local links. A common way to balance outbound traffic is to adjust the local preference of received routes. Mechanisms, such as prefix engineering, path prepending and provider-supported BGP communities, are used to balance the inbound traffic (e.g., Patterson & Lee, 2004). In addition, IP anycast or similar methods (Patridge et al., 1993) can be used to distribute the end user sessions globally. If one of the content locations becomes unreachable, other data centers can be used to respond to the content requests. BGP multihoming and its load balancing variants are typically used by the content providers with large data volumes (such as Google) or large content delivery networks (CDN) (such as Akamai). These solutions are technically complex and require high expertise in implementation and maintenance, but they also automate connection failover and load balancing.

Another technical alternative is to implement multihoming at the gateway router of the network applying network address translation (NAT). In NAT multihoming, network address translators (NATs) are assigned with separate public IP address blocks[6]. NAT multihoming is relatively simple and cheap to implement, but when a link failure occurs, any host requiring inbound connections (e.g., a server) will fail until the domain name system (DNS) is updated. Dynamic DNS (Vixie et al., 1997) can be used for directing inbound traffic to other links, but it cannot react quickly to rapid changes in conditions, such as link outages. In addition, DNS can be used to primitively balance the traffic of a site between available links. Instead of returning a single IP address, the DNS resolver can return a set of IP addresses, the order of which is based on round robin algorithm (Brisco,

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[4] Content providers even apply both strategies simultaneously.

[5] BGP multihoming requires the acquisition of own, provider independent (PI) addresses not belonging to the upstream providers.

[6] Content providers using NAT multihoming typically use provider-assigned (PA) addresses received from the upstream ISPs.

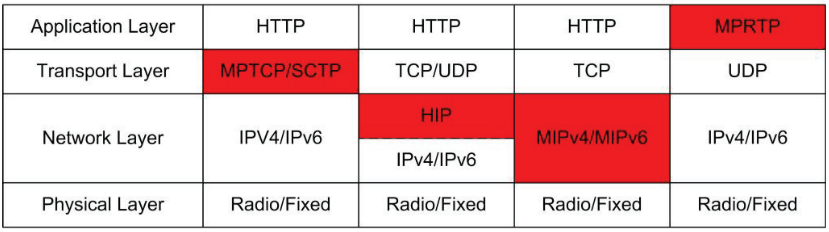
1995). Due to its rigid nature for failover and load balancing, NAT multihoming is a more feasible approach for small content providers without high requirements for availability and data volumes. Table 1 summarizes the features of multihoming mechanisms adopted by content providers.

Table 1. Comparison of site multihoming mechanisms

	BGP multihoming	*NAT multihoming*
Technical complexity	High	Low
Investment and operational costs	High	Medium
Availability level	High	Medium
Load balancing mechanism	BGP configurations, IP anycast	DNS round robin

2.1.2 Host-based multipath protocols and their competitors

Even though content providers use different kinds of failover and load balancing mechanisms in the server side, these solutions cannot build redundancy for individual end user sessions between a client and a server. Therefore, the IETF has proposed several host-based protocols in order to improve the performance of end-to-end connections. The protocols have been proposed in different layers of the Internet protocol suite as presented in Figure 4.



Application Layer	HTTP	HTTP	HTTP	MPRTP
Transport Layer	MPTCP/SCTP	TCP/UDP	TCP	UDP
Network Layer	IPV4/IPv6	HIP IPv4/IPv6	MIPv4/MIPv6	IPv4/IPv6
Physical Layer	Radio/Fixed	Radio/Fixed	Radio/Fixed	Radio/Fixed

Figure 4. Multipath and mobility protocols on different network layers[7]

A wide-scale deployment of multipath protocols in the Internet requires compatibility with both IP versions (IPv4 and IPv6). Therefore, the protocols that support mobility and/or multipath features for multihomed clients on top of either IPv4 or IPv6 are described below. For a more elaborate discussion on mobility and multipath protocols for IPv6, see Bagnulo & Launois (2006).

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[7] Adapted from Publication IV. Reprinted with permission from John Wiley & Sons, Ltd.

In the network layer, prominent proposals for public Internet usage are Mobile IP (MIPv4 and MIPv6) and Host Identity Protocol (HIP). MIP has a status of a well-defined standards track protocol in the IETF, and as stated earlier, its development has been ongoing for 20 years. MIPv4 (Perkins, 2010) requires the deployment of home and (optionally) foreign agents in the ISP network. When the mobile client is not at home network, all traffic is transmitted via these agents, which causes non-optimal routing. This drawback has been addressed in the newer version of the protocol (MIPv6) supports route optimization, but still requires deployment actions from operators (Johnson et al., 2004)[8]. Neither version of MIP supports path aggregation, thus making it a pure mobility protocol. In addition, MIP has limited access to information that could optimally support make-before-break mobility (Raiciu et al., 2011b).

HIP has been under development in the IETF since 1999. It utilizes the virtual-physical address mapping for implementing mobility (Moskowitz et al., 2008). In addition, extensions that would support multipath communication between HIP hosts have been proposed by Pierrel et al. (2006) and Gurtov & Polishchuk (2009)[9]. The former approach (HIP-SIMA) suggests a flow based binding to each path, whereas the latter would split a single Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) flow to parallel paths. Both approaches lack wider support from the IETF community and their development appears to have ceased. HIP requires modifications not only in client and server devices but also in DNS servers (Levä et al., 2013a) in order to be deployed in the Internet.

In the transport layer, Stream Control Transmission Protocol (SCTP) is the first established protocol that has an inherent support for multi-addressing of hosts and failover (Stewart, 2007). The initial specifications of SCTP were submitted to the IETF in 1998. Several SCTP extensions, including a standardization effort in the IETF (Amer et al., 2013), enable hosts to exploit multiple paths simultaneously[10]. Although implemented in multiple operating systems (OS), SCTP is still not widely used. SCTP suffers from deployability issues due to the fact that firewalls and NAT devices typically support only TCP and UDP (Hätönen et al., 2010). The proposals to encapsulate SCTP in UDP are not widely used either. Furthermore, applications need to explicitly request SCTP, which requires application changes.

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[8] Nikander et al. (2001) drafted a specification for Homeless Mobile IPv6, which does not require the deployment of home agent in operator network, but enables strict end-to-end implementation of mobility.

[9] The terms HIP-SIMA and mHIP are used to refer to the multipath extensions of HIP.

[10] The terms cmpSCTP and CMT-SCTP are used to refer to the multipath extensions of SCTP

Adding the multipath capability into TCP has been considered several times (Huitema, 1995; Matsumoto et al., 2003), and the most recent proposal is Multipath TCP (MPTCP) (Ford et al., 2013), which is backwards-compatible with the standard TCP. MPTCP exploits multiple paths between hosts and aims for better utilization of network resources by pooling the available resources (Wischik et al., 2008). MPTCP uses a coupled congestion control scheme, first proposed by Kelly & Voice (2005), to balance transmission rates across the paths it transmits over in order to guarantee fairness to standard TCP. By balancing the traffic throughout the network, the overall throughput and resiliency can be improved without the need to increase capacity. MPTCP enables MMB mobility between different access networks to improve resiliency of the connection, and simultaneous usage of multiple paths to improve throughput. In the IETF, MPTCP is on the experimental track and its standardization has been going on for five years. The design of MPTCP is based on a need for a solution that retains network and application compatibility.

Yet another proposal for the transport layer has been a part of the Datagram Congestion Control Protocol (DCCP) specifications which originally did not support the usage of several IP addresses in the end points. Later on, primitive mobility support was proposed to the protocol, but the specification did not support the simultaneous usage of the available paths (Kohler, 2004). However, the development of this protocol extension has ceased since the proposal did not get the support of the IETF community. The DCCP working group concluded its work in autumn 2012.

On the application layer, Multipath Real-time Transport Protocol (MPRTP) (Singh et al., 2013a) is proposed to deliver the benefits of multipath communication to multimedia transmission (e.g., video streaming). Similarly to MPTCP, MPRTP is supposed to be compatible with the incumbent RTP protocol used in the Internet. The development of MPRTP started in 2010 and is still in an early phase. The draft specification of the protocol has not yet received the acceptance of the wider IETF community.

The above-mentioned standardized solutions remain marginally deployed[11], but some application layer protocols (typically proprietary) may deliver similar benefits by retaining end-user sessions. For example, many web browsers (such as Mozilla Firefox) can automatically resume sessions (Komu, 2012). The end user may experience small interruptions, but the session will continue without the need for the end user to refresh or initiate

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[11] The only mobility protocol that has been adopted more widely is Session Initiation Protocol (SIP). However, SIP is a signaling standard for P2P communication although in many deployment scenarios, the mobility (e.g., over WLAN-3G) is managed by a SIP server.

downloads again. Figure 5 summarizes the proposals offering mobility and/or multipath in the Internet.

The modeling in the publications included in this dissertation is chiefly made for MPTCP as it seems the most advanced and deployable protocol among the range of standardized alternatives. In addition, a major portion of the traffic in the Internet carries TCP (Labovitz et al., 2010), which provides an opportunity for wide-scale deployment.

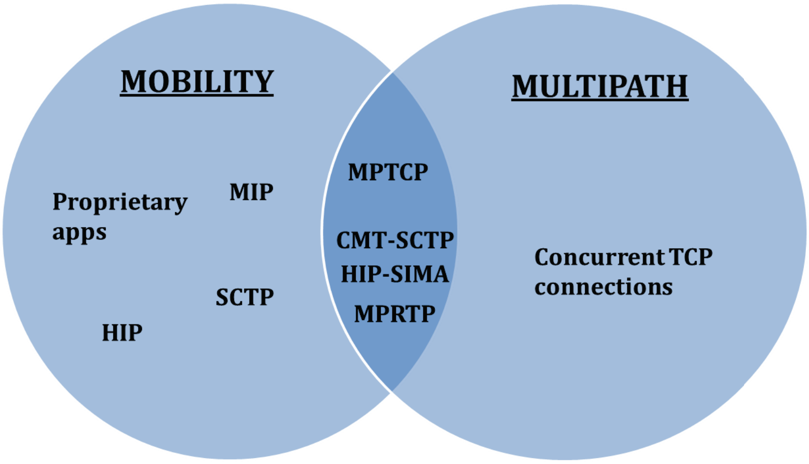

Figure 5. The solutions supporting mobility and/or multipath in the Internet[12]

2.2 Research on innovation adoption

As any novel technical solution, a new protocol can be regarded as an invention. When inventions become commercially deployed, they can be called innovations. The challenge of the protocol adoption and diffusion compared to other technical inventions (e.g., mobile phones) derives from the fact that the successful deployment typically requires adoption decisions from several stakeholders in the Internet. While research on innovation diffusion has a long history, it gained real momentum in the mid-1960s in different technical fields. Although new Internet protocols have been developed for decades, studies on the diffusion and feasibility of Internet protocols have started to emerge around the year 2005.

2.2.1 Relevant studies on innovation diffusion

Perhaps the best known scholar in this field is Everett M. Rogers who coined his observations into the theory of diffusion of innovations (DOI). In

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[12] Adapted from Publication VI. Reprinted with permission from Elsevier B.V.

his influential book (Rogers, 2003, first published in 1962), he describes the five main attributes of an innovation that affect potential adopters' decision-making*: relative advantage*, *compatibility, complexity*, *trialability* and *observability*. These factors frequently appear also in the more recent studies, sometimes expressed with different terms (e.g., Davis, 1989). According to Rogers, the rate of innovation diffusion is also affected by other aspects, such as the type of innovation-decision (individual vs. organizational), and the nature of the social system in which the innovation is diffusing (e.g., the degree of the interconnections between stakeholders).

Although Rogers discusses the topic mainly from the sociological perspective, diffusion of innovations has extensively been studied in the economic literature covering econometrics, marketing as well as business strategy. Economists, typically, see diffusion as a result of several individual adoption decisions that are based on the expectations of increased profits. This requires the comparison of costs and benefits of the innovation for a stakeholder, i.e., the relative advantage as compared to the incumbent technology and also to the competing solutions. Examples from the wireless telecommunication industry include Katsianis et al. (2001) and Smura et al. (2007) who analyzed the feasibility of WCDMA and WiMAX networks, respectively, in different market conditions (e.g., number of subscribers, average traffic demand). This approach yields a tangible idea of the cost and benefit components of deploying a new technology and their effect on its feasibility, but it lacks an important aspect of the dynamics between stakeholders. There are studies, such as Katz & Shapiro (1985), which discuss the technology adoption in terms of the value generated by the other adopters of the technology (i.e., network effects).

Since the first publication of Roger's DOI theory, the diffusion research has become more cross-disciplinary. However, as stated by Rogers (2003), the diffusion studies of individual innovations have been replaced by unnecessary standardization within different disciplines. Fichman & Kemerer (1993) complement this view by arguing that a single predictive theory of innovation adoption and diffusion is unlikely to emerge. Therefore, studying the diffusion of Internet protocols separately is important.

2.2.2 Studies on Internet protocols

Hovav et al. (2004) were the first to apply the general diffusion theories of Rogers on Internet standards. They constructed a model of Internet standard adoption (ISA) and applied it to IPv6. ISA defines a set of adoption modes based on the *usefulness of the standard's features* and *conduciveness of adoption environment* in the Internet. They also stated that, instead of seeing protocol adoption as a dichotomous outcome (between full adoption and non-adoption), also the existence through replacement and co-existence with the old technologies are potential and central modes of protocol diffusion. Later on, Thaler & Aboba (2008) introduced protocol success factors (similar to attributes of innovations developed by Rogers), which more specifically apply to Internet protocols. These success factors consist of ten attributes, including a positive net value, incremental deployability and good technical design.

Joseph et al. (2007) took a more economic perspective when studying the feasibility of IPv6. They analyzed the value of IPv6 as a function of network effects and in the presence of IPv4-IPv6 converters in the network. Iannone & Levä (2010) conducted a similar study on the Loc/ID split protocol (LISP) and elaborated the costs savings as a function of adopters in the network. Both studies concluded that the system adopting a new protocol has to withstand a period of decreasing overall utility until a critical mass has adopted the new protocol.

Ozment & Schechter (2006) adopted the same approach for studying the deployment of Internet security protocols (essentially DNSSEC), and they show that software development subsidies, partial adoption mandates and bundled technologies increase the likelihood and rate of adoption. Furthermore, Sen et al. (2010) created a model which is applicable for comparing the utility of emerging and incumbent networking technologies in the presence of converters. They concluded, for example, that converters between the incumbent and the emerging protocols may lead to a lower overall market penetration of a new protocol, if the efficiency of the converters and, thus, their price is high. Example cases studied by Sen et al. (2010) include IPv6 and IPv4 as well as high and low resolution video conferencing services.

Besides the publications included in this work, the deployment of multipath and mobility protocols has been studied in other research papers as well. The studies by Levä et al. (2010) and Kostopoulos et al. (2010) were the first efforts to explore MPTCP from the economic perspective. Levä et al. (2010) evaluated the different technical architecture and value network alternatives of MPTCP, and Kostopoulos et al. (2010) identified strategies that might foster the deployment of MPTCP. In addition, Mäkelä et al. (2011) and Levä et al. (2013a) studied the adoption of a specific MIP-based solution and HIP, respectively. Mäkelä et al. (2011) identified the incentives and disincentives of different market stakeholders (business-grade ISPs, hosting providers, IT integrators) in terms of implementing a mobility solution based on MIP for the purpose of providing resilient intranet connectivity for the office sites of a company. Levä et al. (2013a) took a more experimental approach when studying the factors behind the non-adoption of HIP. By interviewing several engineers and business-oriented persons, they found that the deployment of HIP has been negatively affected by, for example, competing solutions being developed within the IETF, as well as misconceptions about the protocol prevailing within the community.

However, none of these multipath protocol-related contributions have explicitly modeled and evaluated the feasibility of multipath protocols from the perspectives of all relevant stakeholders (different types of end users and ISPs), which is the focus of this thesis.

3. Research methods

This thesis takes a systems thinking approach for studying feasibility of multipath protocols, which requires combining methods from different disciplines. The chapter first presents the overall research approach and then proceeds to describe the research process. The description of the research process includes the introduction of the key economic theories, modeling tools and data collection procedures.

3.1 Research approach

The research is multi-disciplinary in nature; it combines several theories and research methods from the economic field and applies them to the engineering field of protocol development. The research of Internet protocols can be seen as a part of information technology (IT) research which, as opposed to natural phenomena, studies artificial world (March & Smith, 1995) created by humans. Simon (1996, first published in 1969) defines the science of design as "devising artifacts to attain goals". Therefore, *design science* attempts to create things that serve human purposes, whereas *natural science* pursues to understand the reality. March & Smith (1995) presented a research framework that categorizes research subjects in terms of research activities and research outputs. The research activities of natural science are claimed to have *theorizing* and *justifying* intent, whereas design science *builds* and *evaluates* artifacts.

Järvinen (2001, first published in 1999) further developed the framework of March & Smith (1995) and distinguished between six different research approaches. Järvinen differentiates *mathematical methods* from the methods of studying reality. Studies using mathematical methods prove certain theorems or assertions, and there is no direct reference to objects in reality. Approaches to study the reality are divided into research concerning questions related to what is reality and those related to the utility of innovations. This division is analogous to the dichotomy of natural and design science by March & Smith (1995). The research approaches which focus on the utility of innovation can further be divided into *innovation-building* and *innovation-evaluating* approaches. The research approaches focusing on what is reality include empirical (or data-driven) approaches and conceptual-analytical approaches. *Conceptual-analytical* approaches identify and analyze previous models, frameworks and theories used in earlier empirical studies and apply logical reasoning for explaining reality. Within empirical studies, both *theory-testing* and *theory-creating* approaches collect and analyze empirical data but they differ in terms of reasoning (deductive vs. inductive). Figure 6 shows the taxonomy of six research approaches (in bold) as presented by Järvinen (2001).

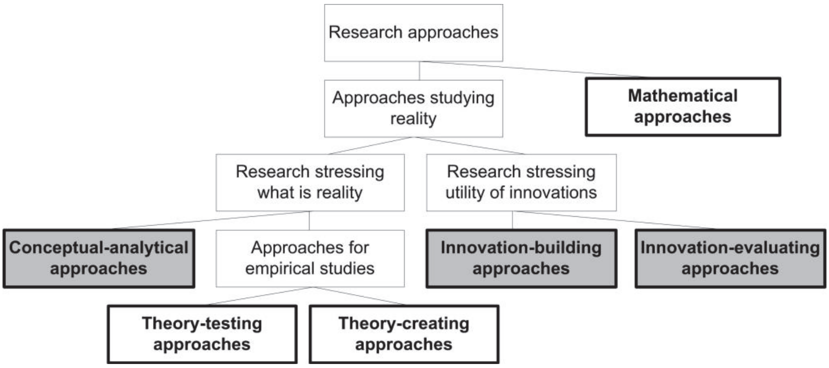

Figure 6. Taxonomy of research approaches[13]

The research reported in this thesis is essentially future-oriented as it investigates protocols that have gained increasing technical interest especially during the past years but are not yet widely deployed in the Internet. Therefore, design science provides a feasible approach for the research. This research can be considered mainly as innovation-evaluating as it is aims to analyze and estimate the economic feasibility of multipath protocols. Because the objective also aims at developing methods for studying new protocols, the research partly falls under the category of innovation-building approaches. The models used here for studying the feasibility rely on earlier empirical studies and theories, and hence, conceptual-analytical approaches are utilized in this thesis. The methods employed in this research are highlighted with gray in Figure 6.

3.2 Research process

The research process has consisted of several steps. During the research process, the basic idea has been to consider the feasibility of multipath protocols from the perspectives of different stakeholders in the Internet. This means that each article, except Publication VI which essentially makes a methodological contribution, has taken the viewpoint of a relevant

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[13] Adapted from Järvinen (2001)

stakeholder in terms of the deployment of multipath protocols. These results are reported in Section 4.

Overall, the research process is characterized by a multi-strategy approach combining several theories, modeling tools and data collection methods. Since the potential modeling tools and data collection methods for studying the feasibility of multipath protocols are not limited to the ones used in the articles, Section 5 provides an introduction and a comparison between the methods used in the articles and elsewhere in the literature.

3.2.1 Key economic theories

Network effects (also called network externalities) refer to the benefits or value of an innovation (product or service) as created by the other users of the same innovation (Katz & Shapiro, 1985). This means that in the presence of network effects, each additional adopter of an innovation has an increasing effect on the benefits to the other users. The network effects can benefit the innovation adoption in several ways. For communication technologies (e.g., protocols), the benefits essentially derive from the capability to communicate with other people using the same technology. In addition, the growing number of adopters increases the probability for creation of complementary technologies and services that create ever more value to the adopters. The former type of network effect is called direct and, the latter indirect network effects (Katz & Shapiro, 1985).

The network effects were popularized by Robert Metcalfe, a co-inventor of Ethernet, who argued that the value of a network is proportional to the square of the number of members in the network (n^2). However, this has been criticized, for example, by Briscoe et al. (2006), who considered Metcalfe's Law to be overestimated and presented their own proposal for the value created by the network effects. Briscoe et al. (2006) argued that the value of a network with n members is closer to $n \log n$.

Neither of the above-mentioned studies makes a distinction between the different types members, or users in the network. This is addressed in the research of two-sided markets distinguishing same-side and cross-side network effects (Eisenmann et al., 2006). In a two-sided market, a platform (e.g., a web search provider) connects two groups of users or sides (content searchers and advertisers). The two-sided market literature discusses mainly the pricing strategies of a platform in the presence of same-side and cross-side network effects but the analogy of the two-sided market structure is also generally useful in the adoption studies. Figure 7 visualizes the same-side and cross-side network effects between two dissimilar adopter groups in a two-sided network.

The theory of network effects is explicitly applied in Publication I, but the effects are also discussed in Publications III, and VI.

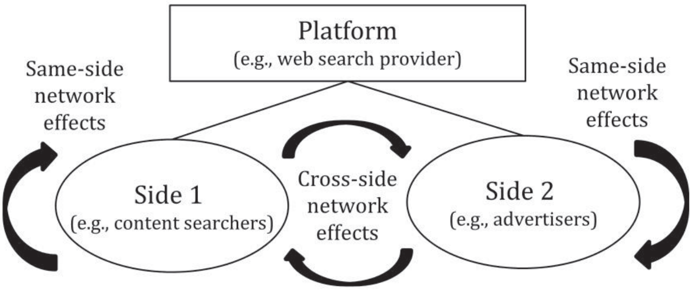

Figure 7. Same-side and cross-side network effects in a two-sided market

Switching costs are generally seen as a barrier to enter a market and defined as one-time costs that a buyer faces when switching from one provider's product to another's (Porter, 1980). If the switching costs are high, the customer may be *locked-in* to the incumbent provider. The customer will switch only if the long-term benefits of the new provider exceed the switching costs. Providers tend to intentionally increase the switching costs since they are generally seen to have positive impact on the profit of the incumbent provider, and because setting up new customer contracts is costly (Courcoubetis & Weber, 2003).

The seminal work on consumer switching costs has been conducted by Klemperer (1995), who concluded that in most cases switching costs make the markets less competitive. However, the researchers have pointed out some exceptions to this conclusion, for example, when competition is seen as a two-period problem. Providers desiring to charge higher prices from their locked-in customers in the future, may end up charging too low prices when trying to attract customers in the first place (Klemperer, 1987). This may intensify the competition during the first phase, thus decreasing the total profit of providers. Despite the exceptions to the general conclusion, Klemperer (1995) suggests that public policy should discourage activities that increase consumer switching costs and encourage activities that reduce them (such as standardization of products).

Klemperer first categorized switching costs into transaction, contractual and learning costs but later complemented the list with psychological and emotional costs (Klemperer, 1995). A study conducted by Burnham et al. (2003) categorized switching costs on the basis of the type of cost they incur: *financial*, *procedural* and *relational*. Financial costs consist of monetary expenses. Procedural costs require time and effort of the customer, whereas relational costs involve psychological or emotional discomfort due to the lost relationship. As it provides a clear and orthogonal classification of switching costs, the approach of Burnham et al. (2003) was adopted in Publication V.

3.2.2 Modeling tools

System dynamics is a method for analyzing the underlying interactions within complex systems (Sterman, 2000), such as the Internet. System dynamics is a visual tool to illustrate the causal relations and their types between system variables, which would be difficult to determine otherwise, e.g., through mathematical functions. Therefore, system dynamics is applicable to problems related to interdependencies between different stakeholders. A positive relation means that the effect of a certain variable (e.g., the birth rate) is positively related to the cause (e.g., the size of a population), whereas a negative relation has an opposite effect (e.g., the higher the death rate the smaller the size of a population).

System dynamics is suitable for both qualitative and quantitative studies. Qualitative modeling facilitates the illustration the interactions between certain variables in the system (e.g., factors affecting the adoption decision of a person). Quantitative modeling enables the analysis of the system behavior as a function of time, and therefore, requires the definition of the functions and initial values for the variables. The basic notation of system dynamics includes causal relationships (positive or negative) as explained above. For the purposes of quantitative analyses, stock variables are often used to measure the accumulation of a certain variable. For example, when an innovation starts to diffuse within a population the number of adopters accumulates with the adoption rate. Figure 8 explains the notation of system dynamic modeling by illustrating, how the birth and death rates affect the size of a population (right), and by showing an example of a stock variable (left).

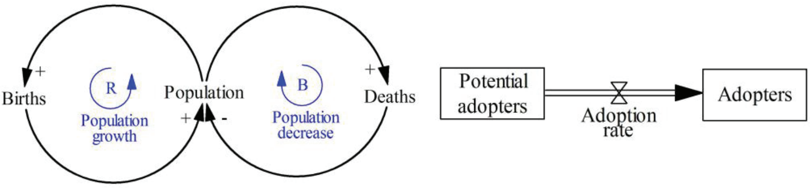

Figure 8. Notations of causal relationships and a stock variable in system dynamics

System dynamics considers the interactions of complex systems and is therefore feasible for studying the diffusion of Internet related innovations. For example, a study carried out by Kelic (2005) developed a system dynamic model of the adoption of fiber-to-the-home (FTTH) to aid policymakers in decision-making. Thun et al. (2000) applied system dynamics to investigate the diffusion of information goods with network effects, such as electronic mail, which has some analogy to the diffusion of end-to-end networking technologies. Publication I is the first contribution to apply system dynamics to Internet protocols.

Techno-economic modeling exploits future forecasting, technology design and investment theories for the purposes of evaluating the economic feasibility of complex technical systems. Numerous economic studies applying techno-economic modeling to the telecommunication industry have been published over the past few decades, as summarized by Smura (2012). In this domain, the modeling has focused on analyzing fixed and wireless broadband technologies (e.g., FTTH, UMTS, WiMAX) and related services. This work constitutes the first effort to apply techno-economic modeling to Internet protocols.

The process of techno-economic modeling starts by making certain assumptions about the market and technology under study. Firstly, the *use case* or the type of services offered to the end users is defined. Secondly, the assumptions regarding the *technical architecture* define which technical components and deployment actions are required to offer the services in scope. Finally, the definition of *value network* (also called industry architecture) includes identifying the roles to deliver the service to the end users and specifying the actors or stakeholders that are responsible for the identified roles. A role consists of technical components and actions regarding the implementation and operation of the service. For example, the provisioning of service software (role) can be adopted by a content provider (actor 1) or acquired from a third party (actor 2). A single stakeholder can adopt several roles regarding the service provisioning. Casey et al. (2010) describe methods for analyzing different value network configurations and mapping them into technical components. Typically, the actual techno-economic modeling of costs and benefits is made from the perspective of an individual stakeholder.

Once the technical architecture and value network are defined, the modeling of the costs and benefits begins. The technical architecture determines which costs are associated with the implementation of the service, whereas the value network specifies to whom the costs and the benefits of the service incur. The modeling of the costs and benefits requires a spreadsheet application (e.g., Microsoft Excel). In practice, the cost and benefit modeling includes the definition of investment costs (also called capital expenditure, CAPEX), operational costs (also called operational expenditure, OPEX), and the degree of benefits (typically revenue) based on the earlier assumptions of the service structure. Techno-economic modeling facilitates the analysis of incremental investments, which solely includes the evolutionary cost and benefit components.

The most traditional approach to compare the costs and benefits in techno-economic modeling is the discounted cash flow (DCF) analysis (Luehrman, 1997). The DCF analysis is commonly used by companies to estimate the value of their investments where the costs and revenues of an investment materialize at different times. In the DCF analysis, the expected future cash flows are discounted to present value by using an appropriate discount rate.

Another approach is to compare the costs of the technical structure against non-monetary benefits. This approach is called cost-effectiveness analysis (CEA). As a tool for supporting the decision-making, cost-effectiveness analysis first emerged in the military context during the mid-20th century (Quade, 1971). Since then, the cost-effectiveness analysis has been used for estimating the value of investments, especially in health economics (Tengs et al., 1995), but also, for example, in environmental economics (Schleiniger, 1999). CEA has been applied to decision-making issues concerning both technological and non-technological investments. Typically, the cost-effectiveness of different investments are compared using the cost-effectiveness ratio (CER), which is the ratio of costs to non-monetary outcomes, such as years of life saved through a health investment.

Because techno-economic modeling includes forecasting and inherently uncertain assumptions, the uncertainty should be controlled in a way or another. This means that the inputs of the model are varied and their effects on the output of the model are considered. This may reveal some useful insights regarding the feasibility of the service scenario. However, the uncertainty can be addressed in other ways as well. For example, Robinson (1993) discusses the usage of extreme scenarios in the context of CEA (i.e. overestimating the costs and underestimating the benefits).

Publications II-IV employ the means of techno-economic modeling in different ways and from different stakeholder perspectives. Figure 9 presents the process of techno-economic modeling in general.

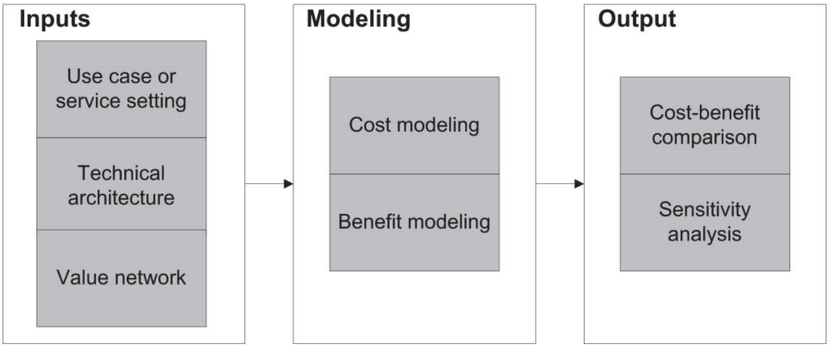

Figure 9. Techno-economic modeling process[14]

3.2.3 Data collection

In this thesis, several data collection methods have been adopted for the purpose of both model building and model quantification. Firstly, literature has been an important source of data. The literature sources include academic publications, consultancy reports and white papers, but also the websites of companies and public authorities. The academic literature, especially prior empirical studies in the field, have been used in the model building to identify the model components, whereas other literature sources have supported the quantification of the models. The values used in all models are real-world (or close to real-world) estimations. Publications I, III, V and VI rely on literature as the main data source.

Secondly, unstructured interviews have been used to increase the understanding of technical structures and protocol features. Interviews have not been conducted so as to provide statistical data from a sample of interviewees answering the same questions, but they have been more like individual discussions on specific topics within the field of the interviewee's expertise. In most cases, the interviewees were protocol developers, but the discussions also involved company experts who represented content providers and mobile operators and had knowledge on the ICT business and technology standardization. Some of the interviews were conducted in face-to-face meetings and some by email correspondence. Publications II and IV, in particular, employed interviews besides other data sources.

Thirdly, Publication IV took the advantage of handset-based measurements to explicitly quantify the expected benefits of multipath protocols. A mobile measurement database called Netradar (2013) was used to elaborate on the performance of the Finnish cellular networks. Netradar is a crowd-sourced service for measuring, gathering, and sharing cellular connectivity information. The measurements are performed by a

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[14] Adapted from Smura (2012)

smartphone application that transmits the results to a centralized database after each measurement session. There are client applications for most of the smart phone platforms. At the time of the study, the service had roughly 30,000 users.

The Netradar database consists of two measurement types. Signal strength measurements are carried out continuously on the background. At the time of the study, this dataset comprised over two million measurement observations spread all around Finland’s mainland area. Another measurement type is a real TCP bandwidth test with 10 seconds of both download and upload. This dataset contained 1,103,939 samples at the time of analysis. The measurements have been conducted with various phone models and operator subscriptions. The measurement parameters applied in the analysis for Publication IV were operator identification, download and upload bandwidth, location and timestamp.

In order to estimate the benefits of multipath protocols in the service scenarios presented in Publication IV, the TCP bandwidth measurements of Netradar database were utilized. Firstly, the measurements of a selected dataset (from a certain geographical area) were organized on the basis of location (areas of 200 m x 200 m). Thereafter, the average throughput of each operator in a specific location was calculated and used in the further analysis. Locations that had a minimum of three measurements from each operator were included in the analysis.

Table 2 summarizes the perspectives and research methods of the publications included in the research. The table also lists which research questions (Q1, Q2, Q3) are considered in each publication.

Table 2. Summary of the research process

Publication	**Substance area**	**Q1**	**Q2**	**Q3**	**Modeling method**	**Data source**	**Stakeholder perspective**
Publication I	Modeling and analysis of the diffusion process of MPTCP	x			System dynamics	Literature	Consumers and content providers
Publication II	Analysis of the incentives of a vertical content provider for deploying MPTCP	x			Techno-economic modeling, DCF	Literature, interviews	Content providers
Publication III	Analysis of the fundamental value of multipath communication and its components	x	x		Techno-economic modeling	Literature	Consumers
Publication IV	Analysis of the feasibility of multipath protocols for novel service contexts in cellular environment	x		x	Techno-economic modeling, CEA	Handset-based measurements, interviews, literature	IoT service user
Publication V	Analysis of switching costs due to the deployment of multipath protocols		x		Qualitative modeling of switching costs	Literature	Mobile network operators
Publication VI	Development of a framework for analyzing the feasibility of (multipath) protocols			x	-	Literature (including previous case studies)	General

4. Feasibility of multipath protocols

This chapter summarizes the results of the articles that elaborate on the economic feasibility of multipath protocols. Firstly, the deployment process of MPTCP, including the deployment actions, value network alternatives and diffusion of MPTCP within consumers and content providers, are analyzed (Publications I & II). Secondly, the chapter bridges the performance benefits of multipath protocols and end user value (Publication III). Thirdly, a techno-economic model for the purpose of analyzing the feasibility of multipath protocols is presented and applied to an analysis in selected service scenarios in order to understand the opportunities for the adoption of multipath protocols (Publication IV). Finally, the chapter elaborates the effects of the deployment of multipath protocols on the mobile access market (Publication V).

4.1 Deployment process of Multipath TCP

MPTCP is implemented as an extension to TCP in the transport layer of the OS kernel. In order to remain compatible with existing applications, an MPTCP implementation needs to operate effectively when accessed through the standard TCP application programming interface (API). Although this section discusses primarily MPTCP, the results are applicable to any type of an end-to-end multipath protocol implemented in the OS kernel.

4.1.1 Deployment actions and value network

The deployment of multipath protocols in the client-server communication environment consists of several steps. For MPTCP, the deployment steps are essentially the following:

- Implement MPTCP and other software changes to the operating systems of the client and server devices.
- Acquire multihoming capability on the clients and/or servers.
- Install MPTCP to devices.
- Take MPTCP into use.

The specification of MPTCP requires at least one multihomed end point (Ford et al., 2013). Many content providers are already multihomed, or are willing to acquire or reconfigure multiple access lines, if they decide to adopt MPTCP. Consumers, however, may never become aware of MPTCP, and thus, it will not be a driver for consumers to acquire multihoming support. On the other hand, many mobile handsets already have multiple physical interfaces (3G and WLAN), which provides an adoption route for multihoming.

The deployment actions require the involvement of many stakeholders. *OS vendors* implement MPTCP in operating systems on end systems and also decide whether or not MPTCP is enabled by default in the shipping configuration. *Device vendors* decide which OS version is pre-installed in the devices. The significance of device vendors depends on the importance of device acquisition as a diffusion channel for operating systems and the degree of device vendors' selectiveness for the OS version.

Consumers are end users of MPTCP consuming services provided by content providers. They own mobile devices, acquire multihoming capability, and possibly, install and take MPTCP into use. *Content providers* are end users of MPTCP providing services (e.g, web pages, videos or any type of useful information) to consumers. They own the servers in which they install MPTCP. They also acquire multihoming capability.

ISPs (or *MNOs)* provide connectivity for multihoming. The deployment of MPTCP does not require active participation from the part of ISPs because end users can acquire multihoming support by making separate agreements with multiple ISPs. However, ISPs may support or hinder the deployment of MPTCP by promoting or preventing multihoming.

Figure 10 illustrates the most basic value network of MPTCP deployment but other value network alternatives are foreseen. For example, Publication II evaluates a vertical actor not only taking MPTCP into use in its service but implementing the protocol software for both ends (e.g., Microsoft).

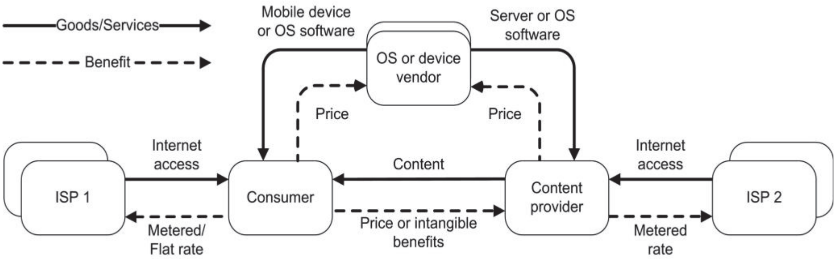

Figure 10. The value network of a selected deployment scenario of MPTCP[15]

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[15] Adapted from Publication VI. Reprinted with permission from Elsevier B.V.

4.1.2 Diffusion of MPTCP in the market

The overall usefulness of MPTCP for the potential end users is highly dependent on the network effects. Publication I presents a system dynamic model for analyzing the network effects between the consumers and content providers. The model (illustrated in Figure 11) shows the primary motivations why different stakeholders may begin to use MPTCP. Section 4.3 and Publications II, III and IV dive deeper into the decision-making and detailed cost and benefit analysis of end users.

The adoption process is essentially different for content providers and consumers[16]. Content providers are more likely to make an intentional and **direct adoption** choice to enable MPTCP, possibly by implementing the software themselves, enabling OS features that are not active by default, or pressuring their operating system vendors to provide the required software patch. Content providers can base their decision on three different motives as follows.

1. **Adoption via innovativeness**: Content providers expecting to benefit from MPTCP and, regardless of non-existent customer base, willing to adopt the protocol are innovators. The adoption motivation for innovators stem from the expected customer base, and the desire to benefit from MPTCP prior to competitors, and possibly, drive the adoption. In the model, innovators are assumed to amount to 2.5% of the total number of potential adopters as proposed by Rogers (2003). The rate at which potential innovators become adopters depends on their interest in MPTCP. The model assumes that each month 10% of all potential innovators become interested in, and thus adopters of MPTCP.
2. **Adoption via consumer access**: Content providers wishing to offer better service quality for their customers become interested when the installed base of MPTCP clients is large enough, i.e., there is a market that can be accessed. They may also be driven by the interest in attracting new customers with their improved service. The model proposes that the mapping between consumer adopters and content provider interest follows an s-shaped curve (Figure 3 in Publication I). As the diffusion of innovation typically follows an s-curve (Rogers, 2003), the potential adopter interest is

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[16] In Publication I, a consumer adopter implies an end user who has the software support for MPTCP (and may optionally have multihoming support), whereas a content provider adopter refers to an end user that has both software and multihoming support.

assumed to behave correspondingly[17]. In the model, all content providers may become interested in, and can therefore become adopters of MPTCP, although in reality this may not be the case.

3. **Adoption via competitive pressure**: Some content providers tend to follow the market leaders. Their motive for upgrading to a new technology derives from the fact that other providers have already employed it. Especially if the benefits from MPTCP are significant, the followers need to adopt the technology in order to stay competitive. This type of adoption is affected by the number of MPTCP capable content providers since the pressure to adopt increases in proportion to the number of adopters.

Consumers are not interested in the protocols as such, and hence, the diffusion to the end devices depends highly on the **indirect** or **unintentional adoption**. In indirect adoption, a consumer adopts a product or a service containing MPTCP as an integral part (e.g., a killer application). The consumer perceives the superior performance enabled by the protocol but may be unaware of the protocol's existence. Unintentional adoption refers to the adoption model in which the end user acquires a new OS version containing the protocol, but is fully unaware of the protocol itself or its benefits. Therefore, the model assumes two adoption channels for consumers.

1. **Adoption via content access:** A consumer may become interested in a certain service that employs MPTCP. Before starting to use the service the consumer first needs to install the protocol in order to experience the benefits. The content provider's site may instruct the consumer where to download and how to install the MPTCP OS patch before being able to start consuming the service. The model assumes a delay (a cross-line in the arrow in Figure 11) in service provision which represents the time it takes from content providers to advertise its service to consumers. The number of available services is directly proportional to the number of MPTCP capable content providers.
2. **Adoption via updates:** Operating system updates can be either full (e.g., Windows Vista, Windows 7) or partial (i.e., OS update patches). Full OS updates take place either by installing a new version of the software or by purchasing a device which contains a new OS. If the version of the updated OS supports MPTCP, the consumer automatically becomes an MPTCP adopter, and

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[17] The rate of CP interest (the gradient) increases slowly at the beginning, is assumed to be highest when the number of MPTCP capable consumers is 50%, and slows down thereafter.

> therefore the OS update rate needs to be scaled by a factor that represents the degree of the OS availability (i.e., the fraction of operating systems which support MPTCP). In the model, the software availability follows an s-shaped curve[18] (Figure 4 in Publication I).

As the number of MPTCP adopters increases and, consequently, MPTCP traffic starts to emerge in the Internet, both positive and negative externalities may unfold. On the positive side (the intention), the more MPTCP traffic appears, the more the congestion in the links is predicted to decrease. This means increased benefits to end users, such as improved throughput, which further fuels the content providers' interest in MPTCP. In the model, the benefits of MPTCP are assumed to follow a convex function. This means that when the level of MPTCP traffic is small, the benefits of the MPTCP also remain small since only a few MPTCP users are unlikely to relieve the congestion in the Internet significantly. However, once the traffic level starts growing and the traffic in the network becomes more balanced, the benefits of MPTCP increase more rapidly.

On the negative side, there is a possibility that MPTCP traffic might get blocked for two reasons. Firstly, incorrectly configured or poorly implemented middleboxes or routers may unintentionally block the MPTCP traffic due to unrecognizable header options. Secondly, MPTCP may have unexpected consequences to ISPs' internal traffic engineering and may even be seen to be harmful for their business. Being in the middle of MPTCP communication, ISPs are potentially able to intentionally block the MPTCP traffic, although it may be questionable from a regulatory point of view. The model assumes that the overall traffic blocking increases in the early phase of the diffusion as a result of intentional blocking. However, as MPTCP becomes adopted, ISPs will adapt along with negative publicity and regulatory interventions become more probable (see Figure 5 in Publication I). The traffic externalities only affect the channels "Adoption via consumer access" and "Adoption via competitive pressure", because the innovators are not facing any realized traffic externalities when they make the adoption decision. The proposed causal diagram of MPTCP diffusion is shown in Figure 11.

The quantification of the model employs an implicit approach, and all parameters are abstracted to normalized unitless quantities that vary between zero and one. Mostly, additive and multiplicative formulations were exploited in the model and the simulation time step was set to one

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[18] The availability of MPTCP software saturates to 90% and reaches the saturation level in five years. This is similar to IPv6 which had the OS support for the majority of installed systems within 5 years (IPv6 Forum, 2010).

month. The exact and detailed formulations and initial values are presented in Publication I (pp. 149-150). The intention of the model was not to forecast the deployment time of MPTCP, but rather to evaluate the impact of the model parameters on the diffusion of MPTCP by varying each parameter at a time.

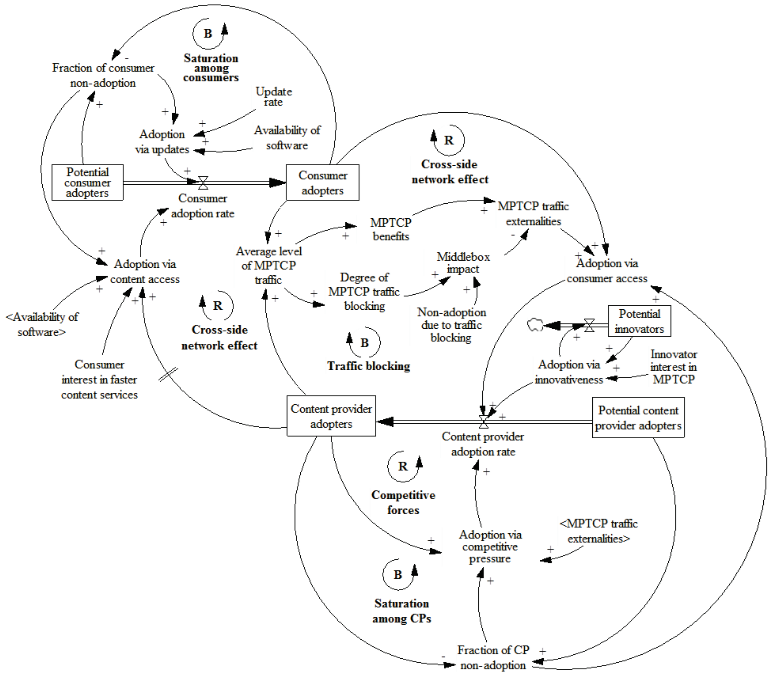

Figure 11. Diffusion of MPTCP to consumer devices and content provider networks[19]

The analysis shows that the lack of consumer access significantly delays the content provider adoption. While in the other cases the content provider adoption reaches over 80% level within roughly eight years, the absence of consumer access results in content provider adoption at only 10% within this timescale. On the other hand, an intriguing observation is that the number of consumer adopters is not significantly affected by the number of content providers, which implies that the impact of network effects on consumers is relatively weak. Figure 12 shows the evolution of the content providers and consumer adopter levels when CP adoption channels are excluded one at a time to see their effect on the diffusion of MPTCP among consumers and content providers. In Figure 12, the gray and black curves represent the consumer and CP adoption levels, respectively.

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[19] From Publication I. Reprinted with permission from Springer.

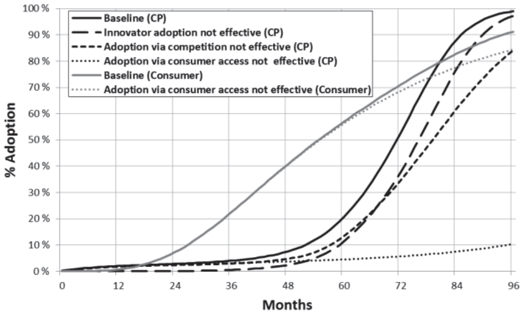

Figure 12. The adoption levels of consumers and CPs. The impact of individual CP adoption channels when excluded one at a time.[20]

The sensitivity analysis made on the parameter "Update rate" shows the system's high sensitivity to this parameter, as it takes roughly 20 months, in the best case, or 48 months, in the worst case, to reach a consumer adoption level of only 15%. In contrast, the system is reasonably tolerant to changes in the values of "Consumer interest in faster content services". For example, even an order of magnitude change in the intentional adoption parameter results in a minimal (less than six-month) shift to reach the relatively high 60% consumer (or content provider) adoption level. Figure 13 shows the consumer and content provider penetration levels when "Update rate" and "Consumer interest in faster content services" are varied.

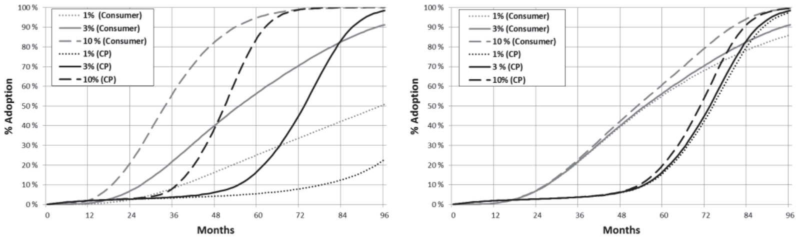

Figure 13. The adoption levels of consumers and CPs. The impact of varied values for "Update rate" (left) and "Consumer interest in faster content services" (right).[21]

The sensitivity of the MPTCP traffic externalities (which may affect the content providers' willingness to invest in MPTCP) was also tested. The analysis implies that the middlebox impact on the diffusion seems to be relatively small. The sensitivity analysis of MPTCP benefits shows that the exposure of benefits in the early phase of the diffusion process has a greater positive impact on the protocol diffusion than the benefits exposed after the adoption of a critical mass.

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[20] From Publication I. Reprinted with permission from Springer.
[21] From Publication I. Reprinted with permission from Springer.

4.2 Value creation of multipath communication

Protocol developers and engineers typically focus on studying and comparing the performance benefits (e.g., throughput) entailed by multipath protocols (e.g., Gurtov & Polishchuk, 2009), but they often fail to link these performance benefits into the economic value of the protocol for its users. Publications III and IV make a contribution by conceptualizing the performance benefits and the fundamental value of multipath communication. This section first identifies the technical measures that expose and affect the degree of benefits of multipath protocols. Thereafter, the links between the benefits and the economic value of multipath communication are described from the perspectives of different stakeholders in the Internet.

4.2.1 Value components of multipath protocols

The fundamental idea of multipath communication is to exploit the excess capacity on the pathways between a client and a server during an online session. Therefore, the fundamental value components of multipath protocols are path diversity and available capacity. These two components highly affect the degree of benefits entailed by multipath protocols as the multipath protocols essentially aim to utilize the excess capacity on the alternate paths. In addition, these two components will highly dictate the effects of the deployment of multipath protocols on ISPs.

Path diversity: If path diversity does not exist between the end users, multipath protocols will result in merely splitting data into smaller chunks to be transferred through the same path, which will not yield any benefits, just excess processing on a client and a server. Hosts in the Internet can discover intermediate paths by associating different IP addresses but they cannot control to what extent the subflows are traversing separate paths. The number of paths depends on the multihoming configuration of the hosts. Double multihoming (i.e., both ends have two addresses) leads up to four (2×2) potential paths. Therefore, the minimum requirement to establish multipath communication is 1×2 address configuration. However, a single entity has hardly any control over the inter-domain topology, and the paths that the packets actually traverse depend on the evolution of the stakeholder contracts as well as the routing policies of ISPs. Therefore, the concept of end-to-end path diversity is divided into the *degree of multihoming* and *Internet path diversity*.

The degree of multihoming is a component that can be affected by the user. Wireless devices supporting several access technologies are becoming more and more prevalent, which increases the potential of using several access operators. Most commonly, smart phones and tablets support two wireless interfaces, such as 3G and WLAN, but also devices with multiple subscriber identity modules (SIM), enabling two cellular connections, have been introduced in emerging markets (Sridhar, 2012; Tech 2, 2012). The number of physical interfaces on a mobile host does not straightly imply the degree of multihoming, but the user also needs to be contracted with a provider in order to use these interfaces. For example, an end user having a mobile phone accompanied with both 3G and WLAN interface cannot necessarily access the local WLAN providers' services when moving around, since they often require authentication. This issue is often neglected in technical studies which assume that the number of physical interfaces equals the degree of multihoming.

Whether the packets will continue traversing separate paths from a multihomed host depends on the path diversity in the Internet core. Since the Internet is a complex constellation of networks, estimating the degree of path diversity is more challenging than that of multihoming. Firstly, diversity depends on the physical connectivity between network devices (e.g., routers). Secondly, the Internet path diversity is affected by the routing policies between these interconnected devices, as defined by the routing protocols, essentially BGP[22]. The path diversity varies according to the level of abstraction (e.g., AS or router level). Basically, the only way of estimating the path diversity between two hosts in the Internet is by measuring.

The efforts to measure the path diversity in the Internet are based on a traceroute (or similar) diagnostic tool, which collects the IP addresses that the packets traverse on an end-to-end path (Huffaker et al., 2002). One of the first efforts to estimate the path diversity in the Internet was made by Teixeira et al. (2003). They took a dualistic approach where they studied the path diversity inside a single autonomous system (AS), such as an ISP network and across multiple ASes. They concluded that there is a high potential for path diversity inside the ISP networks, but the benefits depend on the capability of the ISPs to engineer the traffic. Akella et al. (2003) and Han et al. (2006) further contributed to the knowledge on the Internet path diversity. Han et al. (2006) studied two extensive datasets originating from the United States and concluded that a significant portion of the paths originating from different access ISP actually overlap, especially near the end hosts but also in the Internet core.

A key issue from the economic perspective is that the path diversity should be expressed in a general format (normalized between zero and one)

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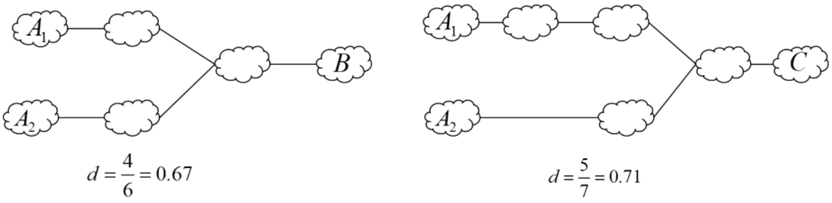
[22] Deployment of new protocols, such as multipath inter-domain routing (Xu, 2006) or source routing (Argyraki & Cheriton, 2004), would offer more capability for stakeholders to affect path diversity.

for use in further economic evaluations. Publication III proposes the following formula for estimating the relative inter-AS diversity in the Internet[23]:

$$d = \frac{1}{m}\sum_{i=1}^{m}\frac{h_{diverse}}{h_{total}} \qquad (1)$$

The variable h_{total} refers to the number of inter-AS links that packets traverse during a measurement round. For example, if the packets sent to a destination through ISP1 traverse for example three inter-AS hops and the packets sent through ISP2 traverse four hops before reaching the same destination, h_{total} equals seven. Similarly, the disjoint links on each path can be calculated. By dividing the number of disjoint hops by the number of total hops, we obtain the diversity for a specific combination of an origin and a destination. By conducting several measurements (m) with various origins and destinations globally, it is possible to estimate the average Internet path diversity. The same formula facilitates the quantification of path diversity also in specific contexts. Instead of defining the average Internet path diversity on a global level, diversity can be defined with regard to a single destination or a specific origin-destination pair. In this case, one of the parameters is kept constant while the other is varied. In addition, the path diversity of a specific geographical location can be measured by using local origin and destination ASs. Figure 14 shows two examples of quantifying the path diversity in the Internet.



$d = \frac{4}{6} = 0.67$

$d = \frac{5}{7} = 0.71$

Figure 14. Examples of inter-AS path diversity[24]

The reason why the measuring should focus on inter-AS diversity (instead of intra-AS) is that inter-AS diversity will essentially dictate how multipath protocols will affect the cost and revenue flows in the Internet core. The ISPs charge each other in a metered manner, and as the emergence of multipath protocols reallocates the traffic flows between ISPs, the costs and

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[23] Akella et al. (2003) propose two path-diversity metrics, one of which is similar to the proposal in Publication III, but the maximum diversity between end points equals zero, which poorly supports further modeling. In addition, the metric presented in Akella et al. (2003) results in more optimized results than the one in Publication III.

[24] From Publication III. Reprinted with permission from J.UCS.

revenues that traffic flows entail will reallocate accordingly. The intra-AS diversity leads only to an increase of performance, but does not affect the cash flows between the ISPs. In the context of Publication III, there was a clear intention to conduct own measurements for analyzing the Internet path diversity as a part of the value modeling of multipath protocols, but due to lacking resources, this intention was not realized. Therefore, the path diversity metrics used in the modeling in Publication III are only example values and should not be considered as realistic approximations of path diversity in the Internet.

Available capacity: The Internet path diversity does not alone guarantee the benefits of end-to-end multipath communication for the end users. The benefits of multipath communication highly depend on the available capacity on the potential paths and protocols' capability to exploit that capacity. Firstly, the available capacity is related to the number of available access ISPs. In a mobile context, this may depend on two factors: 1) the coverage of the MNOs the users have contracted with, or 2) the number of interfaces the application desires to use (interface *policy*)[25]. Secondly, the available capacity is dependent on the congestion state of available paths. The capability of a protocol to exploit the excess capacity on the available paths reverts to the design of protocols and the *policy* algorithm that dictate how to allocate the traffic of an end user (or parts of it) into alternate paths.

Multipath protocols allow the simultaneous path access and need to implement fairness mechanism in order to comply with the load balancing principle in the Internet[26]. This is inherently the idea of the coupled congestion control of MPTCP, which controls the sending rate on each path in proportion to the aggregate rate of the sender. The congestion control scheme on each path (e.g., TCP Reno) inherently allocates the majority of a packet flow to a path that is less congested by monitoring the dropped packets on each path. This means that, on each available path, MPTCP only uses the capacity that is left from the other users. Similarly to MPTCP, SCTP would employ its own congestion control schemes to allocate traffic to available paths. Currently, the IETF is specifying a fair load sharing mechanism also to SCTP which will not take more bandwidth on a shared bottleneck as a single-path user (Amer et al., 2013). In contrast, MPRTP works on top of UDP which does not support congestion control scheme, so the developers of UDP based applications should design appropriate

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[25] The application can dictate which ISP interfaces are used at a given time. Although several ISPs would be available, the application may deactivate certain interfaces.

[26] Otherwise the bandwidth increase of an end user will come at the cost of other Internet users.

congestion control. Congestion control schemes for the single-path media transmission are not standardized, whereof no incentive has been seen towards the standardization of the MPRTP congestion control either. The scheduling algorithms of MPRTP has been considered by Singh et al. (2013b) who prioritize the paths based on bandwidth-delay ratio and packet loss rate calculated from receiver reports.

Similar to Internet path diversity, available capacity can be estimated by measuring. User-centric measurements are the natural choice for estimating the available capacity for multipath communication. The available capacity in end-to-end paths, i.e., the maximum TCP throughput that does not affect the rate of existing flows, has been thoroughly investigated and several tools have been proposed for measuring it (e.g., Lu et al., 2005; Hu & Steenkiste, 2003; Jain & Dovrolis, 2002). Typically, these tools utilize the information on the end-to-end delay (either one way or two way) to evaluate the load or available bandwidth in end-to-end paths. Since the introduction of smart phones, many applications have emerged that measure the real subjective throughput of a host by downloading a test file from a server. The latter approach was adopted in Publication IV, and the main results are reported in Section 4.3.

4.2.2 Benefits and value of multipath communication

The path diversity and available capacity in networks are the key components exploited by multipath protocols to create benefits for end users. The benefits of multipath protocols for mobile end users are two-fold; the increased *availability* and *bandwidth* of Internet connections. Availability refers to the capability of having a network access in a certain location with minimum bandwidth. On the other hand, bandwidth refers to the capability of transferring files with high data rates (as required by, e.g., video streaming applications).[27]

The distinction of availability and bandwidth is important since the potential adopters in the Internet undoubtedly value these benefits differently. For example, business applications typically have higher performance requirements than consumer applications. In addition, applications rarely require both benefits at the same time. For certain alarm systems, a bandwidth of just a few kilobits per second is enough, but the connectivity should be available as ubiquitously as possible. On the other hand, various bandwidth-hogging services usually tolerate more restricted availability and do not need to be functional throughout a large

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[27] Improved availability, and even bandwidth can be achieved simply by means of multihoming without any multipath protocol installed on the device. However, to optimize the performance of Internet connections, some level of automation is required for selecting ISP(s).

geographical area. The evolution of mobile applications will define in which form multipath communication will potentially be needed in the future, achieving higher availability or higher bandwidth (if at all). Figure 15 categorizes example applications in terms of benefits. The figure only shows the business applications since, unlike consumers, the companies or organizations running these applications have the market power to drive the deployment of multipath protocols.

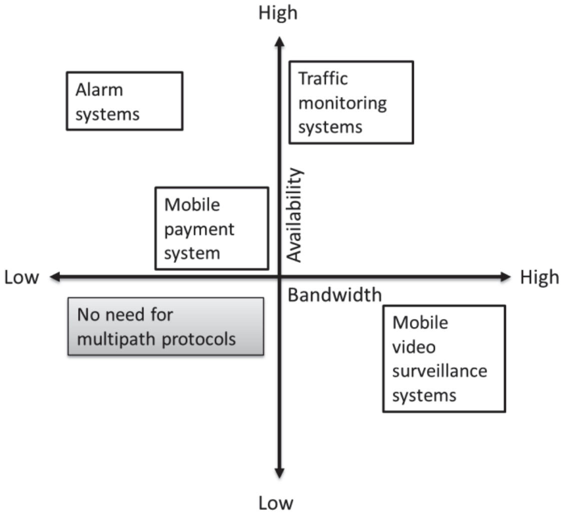

Figure 15. Categorizing example applications based on the benefits of multipath protocols.

Whichever the benefits for the end users are, the fundamental value of multipath protocols culminates with *saving in time*. This is because people undoubtedly value time; a more disputable question is the extent to which they value it. Pohjola & Kilkki (2007) propose that the value of time in communication services can be seen as an opportunity cost, i.e., the lost net benefit of alternative activities. While waiting for the connectivity to establish or a piece of content to download, users typically loose the opportunity to engage in more valuable activities. For example, consumers might preferably read news than wait files to download, whereas companies desire to see their employees doing actual work tasks instead of struggling with the network connectivity. The capability to focus on more valuable activities is generally seen to increase the economic productivity.

The publications included in the thesis show different ways of modeling the fundamental value of multipath communication. Publication II studies a scenario in which consumers having devices with multipath support increase their application downloads from a certain content provider because of the increased quality of experience (QoE) and the decreased download times. The increased number of downloads is assumed to turn into revenues of the content provider. Publication III presents a model where a consumer's time saving can be evaluated and turned into a monetary value. The monetary estimations of the value of time are based on the literature. Finally, Publication IV creates a model that compares the costs of deploying single-path and multipath services against the availability and bandwidth benefits they offer. The model is employed in two examples of mobile applications, which helps identify the deployment opportunities for emerging protocols. The next section summarizes the results of that study.

4.3 Feasibility of multipath protocols in IoT applications

The techno-economic modeling of Publication IV is based on the technical architecture presented in Figure 1. A smart device (SD), acting as a client or as a gateway for sensor clients, which do not have enough processing power or energy supply to run a multipath protocol[28], communicates with the service back-end. Smart devices take the advantage from several cellular subscriptions. In the service back-end (SB), the multipath connection can terminate either in a multipath/single-path proxy or in a web server[29]. The analysis assumes that the costs and benefits of a multipath service are expected to incur for a single stakeholder, *the end user of the service*, such as a logistics company. This means that the end user who enjoys the benefits of the multipath protocol also bears all the costs that incur from implementing and operating the infrastructure. In practice, however, the end user would be probably paying a fee, for example, on a monthly basis for a service provider who has implemented the service infrastructure.

4.3.1 Costs and benefits of a multipath service

The identification of the technical architecture and value network enables further modeling of a multipath service. The main idea of the model presented in Publication IV is to study the relative advantage of a multipath over single-path services. In practice, this means comparing the incremental costs and benefits of multipath protocols to their single-path alternatives. First, a generic model of a mobile IoT service is constructed. Thereafter, the components that introduce a higher cost with a multipath compared with a single-path protocol are extracted from the model.

The total costs of a service infrastructure consist of CAPEX and OPEX. CAPEX refers to the initial costs of building a service infrastructure. OPEX

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[28] Sensor devices were left out from the modeling since they will not be part of the multipath infrastructure. Levä et al. (2013b) provide a feasibility analysis of a low-power sensor infrastructure.

[29] Modeling does not significantly differ whether the multipath protocol is implemented in the actual web server or the proxy in the service back-end.

consists of cost components that incur while the desired service is being delivered, and the end users are using the service. CAPEX is a one-time expense, while OPEX recurs and needs to be presented for a certain time period (t), such as a month. The total cost of an IoT service infrastructure can be expressed as

$$TC = C_{CAPEX} + C_{OPEX/t} \cdot T \qquad (2)$$

where T corresponds to the investment period. The degree of CAPEX and OPEX depends on four components:

- number of smart devices in the installation (n),
- number of web servers (or proxies) in the installation (m),
- number of operator subscriptions used in SDs (k), and
- number of operator subscriptions used in SB (l).

These components vary from a service scenario to another and are visible in the cost model presented in Publication IV.

CAPEX comprises hardware, software and connectivity costs. Hardware costs include the purchase and installation of smart devices and service back-end devices. Software costs consist of the development or purchase and installation of required software components (actual protocol standard and the policy software for the interface management). Connectivity costs comprise all the costs required for initiating a connectivity subscription. In addition, there are costs that are not directly related to the service infrastructure, including costs for information search, preparing invitations to tender, and the selection of vendors. These costs are referred as transaction costs.

OPEX divides into maintenance, connectivity and energy costs. In a service infrastructure, both hardware and software require updates and maintenance. Connectivity costs consist of the monthly fees for operator subscriptions and depend on the pricing schemes of the operators in both ends. Energy costs depend on the energy consumption of the devices and the unit costs of electricity in the market. Besides the primary operational costs related to the service infrastructure, some general costs incur, such as facilities maintenance, the employee training and various administrative costs. For further elaboration of the cost components and the explicit functions refer to Publication IV (Sections 4.2.1 and 4.2.2).

Many of the cost components listed above are equal regardless of the underlying protocols in a single-path and multipath service. Table 3 summarizes all the cost components of a service infrastructure. The bolded components introduce a higher cost for the multipath service, and they were taken into account in the further analysis.

Table 3. Cost components of an IoT service

	Cost component	*Smart device (SD)*	*Service back-end (SB)*	*Other*
CAPEX	*Hardware*	**Purchase and installation of smart devices**	Purchase and installation of web servers or proxies	Transaction costs
	Software	**Development or purchase and installation of required SW components**	**Development or purchase and installation of required SW components**	
	Connectivity	**Subscription setup fee**	Subscription setup fee	
OPEX	*Maintenance*	Installation of SW updates, **correction of HW failures**	Installation of SW updates, correction of HW failures	Other supplies, training and administration
	Connectivity	**Connectivity fee**	Connectivity fee	
	Energy	**Electricity fee**	Electricity fee	

The deployment of a multipath service does not necessarily incur any further costs to the service back-end, as compared to the single-path service, but the hardware of smart devices needs to support several radio chips per cellular operator, which makes them more expensive than single-chip devices (ΔC_{HWa}^{SD}). In addition, the purchase or the development of the multipath protocol incurs CAPEX software costs. However, because some reference implementations of multipath protocols are available, the development costs ($\Delta C_{SWd}^{SD,SB}$), such as the salaries of the protocol developers, should remain reasonable. The software for managing several radio interfaces (i.e., the policy) needs to be developed. The multipath software also incurs installation costs ($\Delta C_{SWi}^{SD,SB}$). The connectivity costs consist of the subscription setup fees ($C_{Ci,ISPi}^{SD}$), which increase as a function of the number of cellular operators in use. The difference in transaction costs is assumed to be negligible. The difference of CAPEX between multipath and single-path services is calculated as:

$$\Delta C_{CAPEX} = C_{CAPEX}^{Multi} - C_{CAPEX}^{Single} = n \cdot \Delta C_{HWa}^{SD} + \Delta C_{SWd}^{SD,SB} + \Delta C_{SWi}^{SD,SB} + n \cdot \sum_{i=1}^{k-1} C_{Ci,ISPi}^{SD} \quad (3)$$

The assumption is that the underlying multipath protocol or the interface management software does not significantly affect the costs of software updates made on the devices. Even with the single-path service, the software updates are constant, and those of the multipath protocol are tightly coupled with the other software updates. However, the hardware failures will probably increase in smart devices because of more complicated implementation, which depend on the failure frequency (f)

and the cost of correcting the failure C^{SD}_{HWm}. The service back-end can be implemented with the same hardware as the single-path alternative; thus, failures presumably occur as often as with the baseline protocol. The connectivity costs again depend on the number of operators and the charge of a single operator $C^{SD}_{Cm,ISPi}$. In addition, the multipath software does not cause any increment in energy consumption in the service back-end, as does the use of several radios in the smart devices (ΔC^{SD}_{E}). The general maintenance costs (such as real estate costs) do not differ between the multipath and single-path installations. The difference of OPEX between the multipath and single-path services is calculated as:

$$\Delta C_{OPEX\ /\ t} = C^{Multi}_{OPEX} - C^{Single}_{OPEX} = (f_{Multi} - f_{Single}) \cdot n \cdot C^{SD}_{HWm} + n \cdot \sum_{i=1}^{k-1} C^{SD}_{Cm,ISPi} + n \cdot \Delta C^{SD}_{E} \quad (4)$$

The benefits of multipath communication are elaborated as a function of time. The end user is not necessarily interested in each additional kilobit per second achieved but rather in the degree of time that exceeds the minimum bandwidth requirement of the application ($BW_{\min}$), which can vary from (just) a few kbit/s to several Mbit/s. Each service has its own requirement for the active time of the smart devices; x hours per day and d days during t. Out of the active time, the smart devices have connectivity (i.e., the bandwidth exceeds $BW_{\min}$) for p_{Single} percentage of the time, if the service is implemented with a single-path protocol, whereas a multipath protocol enables connectivity for p_{Multi} percentage of the time. The incremental benefit of a multipath service can be presented as:

$$B = (p_{Multi} - p_{Single}) \cdot x \cdot d \cdot n \cdot T \quad (5)$$

where n and T equal the investment period and the number of devices.

At least two approaches can be employed for estimating p_{Single} and p_{Multi}. First, the smart devices can be expected to move randomly in a certain geographical area (e.g., a city). If a statistically viable number of measurements are attained from each sub-area, the parameters p_{Single} and p_{Multi} can be estimated based on locations. Another alternative is to conduct measurements relative to time and to simulate the exact route of a smart device. Whichever approach is applied, the benefits can be formulated as in the above equation (5). The former approach was adopted in Publication IV.

4.3.2 Feasibility in selected IoT service scenarios

The developed model was applied to two example IoT applications. The calculations analyzed the incremental costs-effectiveness ratios (CER) of a multipath service as compared to a single-path service. The CER value indicates how much the end user pays for an extra hour of connectivity achieved with multipath communication. Therefore, a small CER value indicates better economic feasibility than a high CER value. The scenarios differ in terms of the type of benefit (availability or bandwidth), the utilization rate and the number of smart devices. Minimum and maximum values for the cost parameters were set due to the uncertainty of the cost parameters. The estimations of minimum and maximum values are based on educated guesses of the highest and lowest cost level of each parameter. The cost estimations were made based on the data collected from the Finnish market, because the network performance data used for estimating the benefits originated from Finland. Cost values are presented in detail in Publication IV (Section 5). In the data analysis, the bandwidths of operators were aggregated in order to obtain the benefit estimates for the operator combinations. Locations which had a minimum of three measurements from each operator in a specific location (200 m × 200 m) were included in the analysis.

Driver's log

The first example application involved an automotive service scenario, in which a truck or a van is equipped with a smart device that uploads (possibly sensor originated) location or other data to the service back-end. The descriptive parameters in the baseline scenario were the following: n=50 (number of smart devices), x=12 h (active time per day), d=20 (active days per month). Given that the truck or van moves around the country, the application primarily requires availability of service. The bandwidth of 100 kbit/s was set as a limit for availability. The entire database of Netradar measurements conducted around Finland was used (2457 individual locations). Because the application used by the driver is expected to download more data than upload, the download bandwidth measurements were considered. Table 4 summarizes the results of data analysis for the prospected service area of the driver's log application.

Table 4. Percentage of availability time per MNO in the driver's log scenario

MNO1	MNO2	MNO3	Best MNO pair	All three MNOs
98.6%	97.9%	95.5%	100%	100%

In the calculations, the best performing operator was used as a baseline. The calculations show that, in the driver's log scenario, the cost effectiveness ratios (CERs) vary from roughly 35 €/h to 102 €/h, depending on the cost level and the number of operators (2 or 3) in use. Table 5 summarizes these results.

Table 5. Cost-effectiveness ratios of the driver's log scenario

	Two MNOs		Three MNOs	
	Min costs	**Max costs**	**Min costs**	**Max costs**
CER (€/h)	34.92	99.72	50.00	102.02

Mobile video surveillance

The second example application was about video surveillance of valuable objects, such as movable facilities or machines used at construction sites. The guards of a construction site could use the service for video streaming to obtain real-time information from the area under their responsibility. The video surveillance service is assumed to have a geographically more limited service area than the automotive application. The facilities and machines embedded with cameras are moved from one construction site to another within a city. To estimate the benefits for this scenario, the data from the four biggest cities in Finland were analyzed. Out of the four cities, two cities (Helsinki and Oulu) showing the most modest benefit increase for the multipath service were considered. Altogether 1092 and 133 locations were considered in Helsinki and Oulu, respectively. To deliver the video stream from a site to the service back-end, the upload bandwidth is more critical than the download bandwidth. Therefore, the upload measurements were extracted from the database. To deliver a video stream of decent quality, an upload capacity of 500 kbit/s was assumed. Table 6 summarizes the results of data analysis for the prospected service area of mobile video surveillance.

Table 6. Percentage of bandwidth time per MNO in the surveillance scenario

	MNO1	MNO2	MNO3	Best MNO pair	All three MNOs
Helsinki	87.7%	78.0%	80.4%	98.9%	99.8%
Oulu	51.2%	58.9%	84.5%	95.4%	100.00%

When calculating the cost-effectiveness ratios of mobile video surveillance scenario, the cost values were the same as in the driver's log scenario. The calculations show that the CERs of the mobile video surveillance application vary from roughly 1.00 €/h to 3.50 €/h. Table 7 summarizes the results.

Table 7. Cost-effectiveness ratios of the mobile video surveillance scenario

	Two MNOs		Three MNOs	
CER (€/h)	**Min costs**	**Max costs**	**Min costs**	**Max costs**
Helsinki	1.04	2.71	1.55	3.56
Oulu	1.07	2.78	1.21	2.78

The case-specific cost-efficiency calculations indicate that multipath protocols seem to be economically feasible in applications that require high bandwidth. The availability (Scenario 1) is increased by roughly 1.5 percentage units (Best MNO pair - MNO1), whereas the bandwidth increase (Scenario 2) is over 10 percentage units (Helsinki: Best MNO pair - MNO1; Oulu: Best MNO pair - MNO3). Although the case analysis assumed the multipath protocol to aggregate the bandwidths of all operators in use (multipath), the general analysis on the performance of Finnish mobile networks considered the differences between the aggregation and selection of the best operator. The selection of the best operator (e.g., with a mobility protocol) in a certain location can perform equally well at least up to 1 Mbit/s in download direction (see Table 8).

Table 8. Probability of download bandwidth of MNOs in Finland

Data rate (kbit/s)	All three MNOs (selection)	All three MNOs (aggregation)
4000	72.51%	92.56%
3000	85.65%	96.32%
2000	94.54%	98.54%
1000	98.87%	99.88%
500	99.84%	100%
100	100%	100%
10	100%	100%

These results imply that, with low data rates, the aggregation of the paths does not yield any further benefit, but might just increase the energy consumption on the smart devices. Although the increased energy consumption on the smart devices does not seem significant in terms of costs, the usage of two radios will quickly drain the battery, which prohibits the usage of smart devices in places with no energy supply.

The sensitivity analyses conducted for the application scenarios show that a certain turning point exists that defines whether the usage of two or three operators is more cost-efficient. This depends on the number of smart devices in the installation, as well as the benefits achieved by two and three operators. Although the benefit increase from two to three operators is high, the increased connectivity costs may exceed the benefits. This is visualized in Figure 16, which shows the evolution of CER values in the mobile video surveillance application when the number of smart devices is varied. Benefiting from two operators is initially less cost-efficient but becomes more cost-efficient when the number of smart devices in the installation increases. The crossing point is at 12 devices in Helsinki and at 100 in Oulu.

The results of the sensitivity analyses clearly show that service scenarios with a high utilization rate and a long investment period are more attractive for multipath protocols. This essentially derives from the fact that CAPEX dominates OPEX, which allows for exploiting scale advantages.

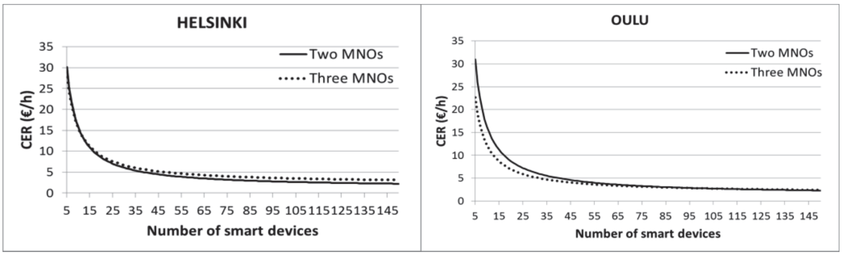

Figure 16. CER values of the mobile surveillance application when the number of smart devices is varied.[30]

4.4 Effects of multipath protocols on the mobile market

The analysis conducted in Section 4.3 showed that multihoming and multipath protocols can provide better end user experience with reasonable costs, in particular with higher bandwidth requirements. If multipath protocols become more widely adopted, they will reallocate the traffic flows to different operators, and thus have effects on the revenue flows in the Internet. This section elaborates on the foreseeable market changes in terms of wider deployment of multipath protocols.

4.4.1 Evolution of switching costs

Although multipath protocols cause a reallocation of traffic flows within the entire end-to-end paths, the deployment of these protocols will have a higher impact on the mobile network than core network operators. This is

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because multihoming and multipath protocols will significantly decrease the switching costs of end users. Publication V envisioned operator and end-user centric competition scenarios and compared them against the current subscription-based competition between MNOs. The evolution in the operator centric scenario is a potential outcome of the development and deployment of dynamic spectrum management (DSM) on the physical and link layers, whereas the end-user centric scenario stems from the wide-scale deployment of multipath and mobility protocols.

The realization of the end-user centric competition requires developments of the capabilities of end devices in the market, but the allocated spectrum bands remain in the full control of the MNOs, and no secondary usage of spectrum is being practiced. Three evolution phases are identified in the end-user centric competition: switching through subscription, through multi-SIM device and through multipath protocols. Figure 17 shows a graphical illustration of the evolution of switching costs in the end-user centric scenario.

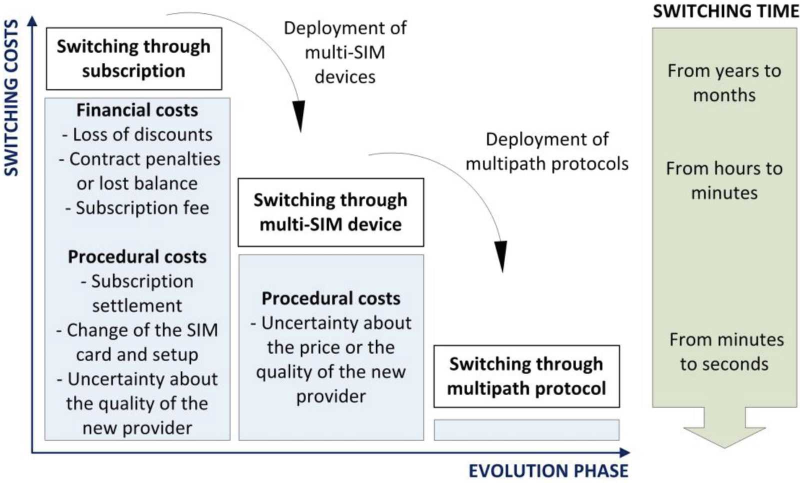

Figure 17. The evolution of switching costs in the end-user centric scenario[31]

Switching through subscription represents the current flat competition, which is based on relatively high switching costs for the end users, and where the switching frequency varies from several years to months. Inter-operator load balancing occurs when a user decides to switch the MNO. The biggest share of the financial switching costs consists of contract penalties if the end user desires to switch the operator during the contract period. In prepaid contracts, the exit fee may occur in the form of unused balance but this cost can be minimized easily. MNOs may charge a subscription setup fee, but they also often provide discounts on the setup and monthly fees of a

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[31] Publication V. Reprinted with permission from IEEE.

new subscription. In circuit switched services, MNOs are seen to provide low-priced or even free on-net calls, which increases the switching costs of end users having a major portion of their connections within the same MNO. With mobile data services, these network effect-based discounts are more difficult to implement, but any type of loyalty discount would have an increasing effect on the switching costs. The procedural costs consist of the time consumed for searching and settling a new subscription, as well as the change of the SIM card. This is made easy for the end user since the new provider often takes care of the switching process. Quality sensitive end users need to accept the effort of bearing the uncertainty about the overall quality of the new provider. For a price sensitive customer, the uncertainty is much lower since the prices of the new provider are easier to track.

The second evolution phase will emerge, if equipment vendors start providing multi-SIM devices on a larger scale. In some emerging markets, this is already happening to some extent, mostly for circuit-switched services since the access to mobile broadband is still limited. In the western markets, the MNOs have strong bonds with the device vendors and can partly affect the embedded features on the devices. With a multi-SIM device, the end user would have the capability to manually select which MNO to use in each specific location and session. This would decrease the switching time to hours and even up to minutes. The acquisition of a multi-SIM device and several MNO subscriptions embodies all the financial switching costs, and only procedural switching costs remain. The procedural switching costs culminate in the uncertainty about the quality or the price of the operator in a certain location and time depending on whether the end user is quality or price sensitive. For example, some operators use time dependent pricing to shift the demand outside peak hours. The end user may not be able to remember the prices at different locations and points of time. When it comes to the quality optimization, the uncertainty is much higher since the end user is hardly able to estimate the performance of each MNO at a certain point of time and location.

The third and the highest level of competition will emerge by switching through a multipath protocol. The realization of this evolution phase requires multipath capable devices to be available. The deployment of multipath protocols would decrease the switching time from minutes to seconds. The multipath protocol algorithms are designed to improve the end-to-end performance for the end users. For example, the MPTCP algorithm monitors the quality of each path by detecting dropped packets. Based on the monitored information, the protocol automatically switches the traffic – even on a per packet basis – to a path with better quality, i.e., the protocol will automatically optimize the end-to-end performance without any human intervention. In the most optimal case, the protocol would choose the best quality network(s) in each location. If the end user had the real-time price information available from the operator, a multipath protocol could, in theory, minimize the cost of a price sensitive customer. Assuming that a multipath protocol optimizes the right parameters for a price and quality sensitive customer, the switching costs will decrease to zero, i.e., the users are not affected by any switching costs.

4.4.2 Comparison to other capacity sharing technologies

As mentioned above, Publication V envisions an operator-centric scenario in which capacity sharing in the mobile access would be executed through more dynamic spectrum management on the physical and link layers (e.g., ITU, 2011). The mobile operators would lease their unused spectrum to a secondary user by utilizing technologies such as software-defined radio (SDR). Similar to the end-user centric scenario, the increased automation in capacity sharing would reduce the spectrum leasing times from years to minutes (per session). Smaller time scales of capacity sharing would likely mean higher competition when the traffic of a single end user can more dynamically shift from one MNO to another. Based on the assumption, the end-user centric scenario results in a more intense competition the operator-centric scenario.

The probability of each scenario depends on standardization efforts, market developments and legislative actions. The standardization of spectrum sharing for mobile operators is the first step towards DSM, but solutions based on sensing technologies require further regulatory and development work. For instance, the secondary usage of the spectrum requires a new regulatory regime, which is still under discussion in the legislative bodies. On the other hand, the first standards of multipath communication have already been finalized in the IETF, and even newer proposals that bypass the deficiencies of older specifications are being developed. As multipath protocols are part of the Internet architecture, no further regulatory interventions are expected in order to enable their usage between licensed spectrum bands. Table 9 summarizes the comparison of the final phases of each scenario in order to evaluate their potential and effect on the market dynamics.

Table 9. Comparison of operator centric and end user centric competition.

	Operator centric (DSM)	**End user centric (multipath)**
Intensity of competition	Medium	High
Required standardization effort	High	Medium
Amount of regulation required for deployment	High	Low

5. Method development and evaluation

The publications of the thesis employ several tools which have not previously been applied for studying the feasibility of Internet protocols. This chapter first introduces different tools for analyzing the feasibility of (multipath) protocols (Publication VI). Secondly, implications and lessons learned are presented regarding techno-economic and functional modeling tools by comparing the studies reported in Publications II, III and IV. Finally, this chapter discusses the relationship between modeling and data collection.

5.1 Analyzing the feasibility of Internet protocols

Publication VI creates a framework for studying the techno-economic feasibility of Internet protocols. The framework consists of six steps each of which poses questions to be answered. The main objective of the framework is to detect deployment challenges of a protocol already during the protocol development. By detecting deployment challenges early on, potential solutions can be envisioned and addressed during the deployment process of a protocol. The framework culminates in the feasibility analysis step that analyzes the economic feasibility of the protocol by evaluating the existence of incentives among various stakeholders to participate in the protocol deployment. In practice, this translates into comparing the costs and benefits of the protocol for each relevant stakeholder regarding the protocol deployment[32]. This approach has been adopted for MPTCP and corresponding protocols in Publications I–V and summarized on the basis of the earlier studies in Publication VI. For a more detailed introduction of the framework and its application, please refer to the dissertation of Levä (2014).

To be able to conduct a thorough feasibility analysis, appropriate tools are required. System dynamics and techno-economic modeling were the main

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[32] Relevant stakeholders not only include the participants in the value network of the protocol but also stakeholders who may have an impact on the protocol deployment (e.g., regulators).

tools used in the studies of this work and have been introduced in Chapter 3. Publication VI lists *qualitative cost-benefit analysis* and *functional modeling* as other potential tools for conducting feasibility analyses for emerging protocols.

Qualitative cost-benefit analysis (also known as pros and cons analysis) evaluates the feasibility of a particular protocol by listing the positive and negative factors of the protocol deployment for each relevant stakeholder. Due to its straightforward nature, qualitative cost-benefit analysis is typically used at the beginning of a feasibility analysis to get an idea of the potential deployment challenges and to identify the most interesting issues for more elaborate analysis. An example of a qualitative cost-benefit analysis can be found in the study conducted by Levä et al. (2010).

Functional modeling (also referred to as economic(s) or mathematical modeling) represents the traditional economistic approach in protocol research. The basic idea is to create models for understanding the functional behavior of a certain phenomenon, such as the stakeholder profit or social value of the protocol, which depends on the actions of other stakeholders in the system. The modeling starts by identifying the variables that create the gross utility of a networked system (such as IPv6 users) or the net utility (or payoff) of a stakeholder (typically an end user or ISP). Thereafter, a set of mathematical methods and derivations are applied to calculate the utility maximizing conditions for the entire system or for stakeholders, depending on the problem in question. Often, numeric simulations are an integral part of functional modeling for visualizing the behavior of the utility as a function of model parameters. Functional modeling typically utilizes theoretical values to conduct simulations and they are often normalized.

Functional modeling methods essentially include the utility and game theoretic methods. In the utility modeling, an equation models the utility of the protocol as a function of adopters in the network. This approach has been adopted in protocol studies conducted by Ozment & Schechter (2006), Joseph et al. (2007), Iannone & Levä (2010) and Sen et al. (2010).

Game theoretic modeling tackles the decision-making problems of certain stakeholders (e.g., two ISPs). Different game theoretic models analyze the strategies of decision-makers in different contexts. The decision-making context can vary, for example, based on the degree of co-operation or timing of the decision-making between stakeholders. Tang et al. (2008) modeled the profit outcomes of ISPs in a situation where end users can balance their load between two ISPs, and the ISPs need to decide the amount of bandwidth they offer. Kalogiros et al. (2009) applied game theory for modeling the incentives of prefix aggregation in BGP.

Although functional and techno-economic modeling may initially seem similar (i.e., they both model the costs and benefits of a networking technology or a protocol), they have some fundamental differences. Section 5.3 analyzes these differences in more detail. The potential tools for the feasibility analysis and example protocol studies are summarized in Table 10.

Table 10. Tools for protocol feasibility analysis and example protocol studies

Tool	*Example protocol studies*
Qualitative cost-benefit analysis	MPTCP (Levä et al., 2010)
Functional modeling	IPv6 (Joseph et al., 2006) LISP (Iannone & Levä, 2010) BGP (Kalogiros et al., 2009)
Techno-economic modeling	MPTCP (Publications II-IV) CoAP (Levä et al., 2013b)
System dynamics	MPTCP (Publication I)

Since several tools can be used for studying the feasibility of Internet protocols, the choice between the tools is not a trivial one. Available data, other resources and the type of the protocol under scrutiny are central issues that affect the choice. Naturally, protocol feasibility research can, and in fact should, utilize several modeling methods. A logical approach for studying the feasibility of a protocol is to start with the qualitative and less laborious tools, and gradually, to proceed to quantitative and more sophisticated modeling. Listing the cost components based on the deployment actions of the protocol and the expected benefits for each stakeholder involved in the deployment offers an easily approachable way to start. In addition, a qualitative conceptualization of the interactions between stakeholders can provide valuable insights at the beginning. System dynamics in its qualitative form can be useful here. Later on, functional, techno-economic and system dynamics modeling provide the route for quantitative analysis. To alleviate the choice between the different modeling tools, Table 11 compares the tools in terms of different criteria. The table considers the laboriousness of the tools (low, medium, high), their applicability for qualitative and quantitative analysis, and their applicability for modeling network effects.

Table 11. Evaluation of tools for analyzing the protocol feasibility

Tool	*Laboriousness*		*Qualitative*	*Quantitative*	*Applicable for modeling network effects*
Qualitative cost-benefit analysis	Low		Yes	No	No
Functional modeling	High		No	Yes	Yes
Techno-economic modeling	Medium	High	No	Yes	No
System dynamics	Medium	High	Yes	Yes	Yes

5.2 Review of techno-economic modeling variants

Similar to functional modeling, techno-economic modeling can also take different forms of analysis. In the narrowest sense, techno-economic modeling refers to the DCF analysis, which considers the cash flows regarding the deployment of a technology. This requires knowledge of the revenue flows in terms of protocol deployment. DCF approach was adopted in Publication II for the purpose of analyzing the profitability of MPTCP investment for a specific content provider controlling both the client and server devices, as compared to the regular TCP service. The assumption in the analysis was that the MPTCP will increase the number of downloads from the content provider's application store (such as Apple AppStore or NokiaStore). This assumption allowed for DCF modeling, but later on, it was realized to be a weak assumption of the MPTCP benefits for a content provider. Even if this assumption would hold for the free content, it is certainly not plausible for paid content. The end users have many other, more significant incentives (e.g., usefulness of the application, price) to download paid content than the download speed of the online store. Therefore, the results in Publication II should be considered with caution[33]. The key question in the DCF analysis is how to turn the features of a protocol (such as increased bandwidth or improved security) into revenue flows. This requires a deep understanding of the earning logic of each adopter company, which they rarely reveal even when asked in an interview.

As seen from the results presented in Section 4.3, Publication IV took a different line of approach. Due to limitations observed in Publication II,

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[33] The DFC model suggests that a relatively small increase in the number of content downloads as attributable to MPTCP could make the business case profitable for a content provider within five years. The percentage of the chargeable items among additional downloads is seen as the most uncertain parameter.

Publication IV widened the perspective of techno-economic modeling to comparing the costs of the protocol deployment against the non-monetary benefits achieved through the protocol deployment, i.e., the cost-effectiveness analysis (CEA) was applied. Yet another approach of techno-economic modeling can be found in Levä et al. (2013b). In this study, the benefits of a protocol and its competitor enabling a certain service are assumed to equal and the analysis only considers the costs of the lifecycle of the service, i.e., total cost of ownership (TCO). This approach has not been used to study the feasibility of multipath protocols, but falls within the wider definition of techno-economic modeling.

As seen from the literature, the traditional DCF analysis has been used in scenarios where the sources of revenue are known (e.g., voice calls or text messages in terms of radio network investments). However, in the case of protocols, the revenue logic is often vague and thus, approaches such as CEA and TCO are seen more appropriate for analyzing the feasibility protocols than the regular DCF. The application of CEA requires the identification of the factor in which the value of a protocol culminates.

5.3 Comparison of functional and techno-economic modeling

As the literature review shows, the earlier economic studies on Internet protocols have mainly focused on functional modeling. The functional modeling is characterized by the determination of high-level parameters representing the costs and the benefits of a particular protocol. In utility modeling, the benefits of a certain technology are typically divided into standalone and network benefits. The standalone parameter is supposed to represent all the benefits that are related to a new technology in the absence of other users in the network. For example, in the utility functions of Sen et al. (2010), the term θq_1 represents the standalone value of Technology 1 with q_1 representing the intrinsic quality of the technology, and θ a random variable accounting for heterogeneity in how users value technology. The term q_1 incorporates aspects of functionality, reliability, performance etc.

The simplification of the benefit parameters is mandatory to model the overall utility of technology diffusion but, as a drawback, it hides rather than exposes the benefits of a technology for relevant stakeholders. Although functional modeling starts from defining the utility functions of a single user, it culminates in considering the social welfare across the system as a whole (Berry & Johari, 2013), such as TCP users in the Internet or the users of a P2P file sharing system. Therefore, functional modeling helps understand the value creation as a function of protocol adopters, but hides the incentives (and disincentives) of relevant stakeholders, which lead to the actual adoption decision of a protocol.

The objective of Publication III was to create a functional model concerning the value of a multipath protocol, but after many trials and errors, it was found impossible. This was because the authors intended to explicitly expose the benefit components that create the value of multipath protocols for consumers in the Internet. Publication III develops the value model and shows example calculations for a population of MPTCP users, but the identification of the cost and benefit components in terms of a single end user is considered a more valuable result. Although the modeling method used in Publication III is referred to as functional modeling, it represents, retrospectively, a closer match to techno-economic modeling.

Techno-economic modeling requires the modeler to think of the costs and benefits of a protocol in a more detailed manner. In terms of the prior example, techno-economic modeling would force the modeler to divide the benefit component q_1 into the degree of performance or reliability that a certain user experiences. However, if the protocol is supposed to entail several benefits, they rarely can be analyzed simultaneously, but instead, they have to be separated (see Publication IV). Regarding the cost analysis, functional modeling tools typically neglect the investment costs and conceal the technical architecture of a protocol[34] (black box approach). Commonly, the monthly payment that a user needs to pay for the connectivity represents the only cost considered. In contrast, techno-economic modeling exposes technical architecture and considers both investment and operational costs of the service (white box approach). Therefore, techno-economic modeling requires more detailed knowledge of the technical design of a protocol.

Typically, functional modeling methods apply normalized, theoretical and unitless numbers, which are used to find the economic equilibrium, i.e., the optimal outcome for the society, and a massive sensitivity analysis is rarely applied. On the other hand, techno-economic modeling tools heavily rely on the real-world data as an input, which means that they require a decent strategy for managing the uncertainty. Publication IV demonstrates that sensitivity analysis can be conducted even if the model considers non-monetary benefits. Table 12 provides a comparison between functional and techno-economic modeling, representing a theoretical and a more practical approach, respectively.

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[34] For example, Sen et al. (2010) utilize the same model for analyzing IPv6-IPv4 transition and for comparing high and low video conferencing services although they undoubtedly have a different technical architecture.

Table 12. Comparison of functional and techno-economic modeling

	Modeling method	
	Functional modeling	*Techno-economic modeling*
Objective	Search of the economic equilibrium among stakeholders involved in the protocol deployment	Identification and evaluation of cost and benefit components of a protocol
Modeling perspective	Population, society	Individual stakeholder
Modeling dynamics	Time variant	Time invariant
Quantification	Theoretical values typically normalized between zero and one	Estimations based on real-world data
Sensitivity analysis	No	Yes
Required technical knowledge of the protocol	Low	High
Specific approaches	Utility modeling Game theory	Discounted cash flow (DCF) Cost-effectiveness analysis (CEA) Total cost of ownership (TCO)

5.4 Observations regarding data collection for modeling

Even though the means of qualitative visualization and modeling tools can significantly increase the understanding of the protocol feasibility, empirical data collection should not be neglected. Simulations and measurements of network performance and traffic can provide objective data for analyzing the relative advantage of a protocol, as compared to its competitors. To get a comprehensive view of the stakeholders' incentives and disincentives for deploying the emerging protocols, the consideration of the opinions of different stakeholders from early on is crucial to ensure that the analysis does not end up presenting the modeler's subjective view. For example, questionnaires, interviews and brainstorming can provide valuable data.

This research has clearly aimed to rely on measured or written real-world data in the quantification of the models[35]. This is because the market knowledge is considered crucial for narrowing down the gap between the

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[35] Even the normalized values used in the simulations in Publication I were based on earlier studies found in the literature.

theoretical protocol development and the practical understanding of the deployment environment of new protocols.

Publication VI lists the potential data sources for the different modeling tools. Prior studies concerning multipath protocols are largely based on protocol simulations (Gurtov & Polishchuk, 2009) and performance measurements, e.g, inside a data center (Raiciu et al., 2011a). This research has complemented the range of sources with small interviews and market reports. In addition, presenting questionnaires to or obtaining market data (e.g., sales data of operating systems or other software) from different stakeholders could provide valuable input to the feasibility studies of protocols. Data collection is not only useful in the phase of the quantification of the model, but already in the development of the models. Even the methods of functional modeling typically using theoretical quantification can draw benefit from interviewing different stakeholders in the market or utilizing market reports. Table 12 lists the potential data sources for different analysis tools.

Table 13. Data source for different feasibility analysis tools.

Tool	*Potential data sources*
Qualitative cost-benefit analysis	Interviews, questionnaires, market reports
Functional modeling	Interviews, market reports
Techno-economic modeling	Interviews, questionnaires, market reports or data, simulations, traffic and performance measurements
System dynamics	Interviews, market reports or data, traffic and performance measurements

Since the protocol feasibility studies are essentially cross-disciplinary, the gathering of knowledge of prior studies requires a greater effort than literature reviews in a narrow scope of disciplines. This requires continuous stretching of one’s limits both in technical and economic domains. However, a more elaborate analysis can be conducted if the developer of the analyzed protocol joins the feasibility study with the support of people with business-oriented background. This was the case in Publications I and IV.

Real-world data collection through own measurements and interviews may sometimes be challenging, so the role of the literature should not be neglected or underestimated. This was observed in Publication III as the original plan for conducting measurements was not realized. In fact, not having access to large data records may encourage the modeler to innovative thinking of what would be valuable to measure in the future rather than what already can be or has been measured.

Even though detailed measurement results are not available, the expected performance benefits can be estimated with reasonable accuracy by using literature, which importantly facilitates further modeling of the multipath protocol feasibility. In addition, this type of modeling approach allows the practical economic feasibility analysis of a multipath protocol even if no stable implementation of a protocol is at hand.

The following example illustrates the use of literature for estimating the expected bandwidth achieved with MPTCP (Publication III). The studies conducted by Franceschinis et al. (2005) and Halepovic et al. (2008) measured the performance of TCP over two wireless technologies, WiFi and WiMAX, respectively. The measurements show that, for most of the time, the throughput of a wireless link is quite evenly distributed between two throughput values. Figure 18 shows an example of a downlink throughput fluctuation on a radio link as a function of time and its bandwidth distribution.

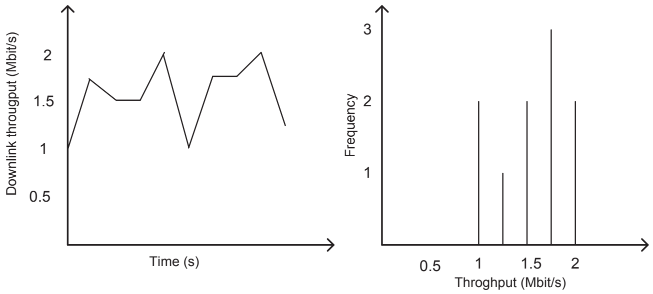

Figure 18. Downlink throughput over time and bandwidth distribution

When the downlink throughput of a wireless connection is mostly evenly distributed between two bandwidths, a simplified model of the bandwidth distribution can be used. For example, the expected value of bandwidth distribution in Figure 18 can be approximated by a simplified two-level probability distribution instead of the detailed expected value calculations. A two-level approximation of a user obtaining the throughput B=1.9 Mbit/s with probability p=0.5 and the throughput cB=1.2 with probability 1-p=0.5 has the same average (1.55 Mbit/s) and standard deviation (0.37 Mbit/s) as the original detailed distribution in Figure 18.

Following this approximation, simplified throughput distributions were used to model the throughputs on the subflows of a multipath protocol when a consumer downloads a piece of content from the Internet (e.g., a piece of music or a web page). Figure 19 illustrates the approximation approach.

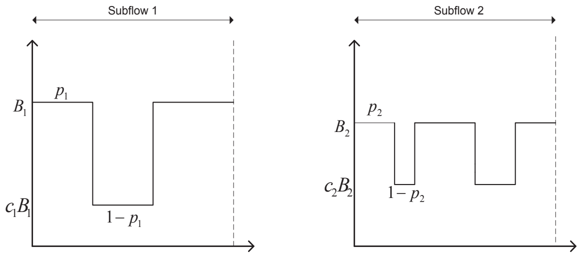

Figure 19. Throughput approximation of subflows[36]

The expected download time when a user downloads a file of size f from a server using two paths, can be estimated as:

$$E_{\text{multi}} = p_1 p_2 \frac{f}{B_1 + B_2} + p_1(1-p_2)\frac{f}{B_1 + c_2 B_2} + (1-p_1)p_2 \frac{f}{c_1 B_1 + B_2} + (1-p_1)(1-p_2)\frac{f}{c_1 B_1 + c_2 B_2} \quad (6)$$

which can be compared to the expected download time when a single-path protocol is used:

$$E_{\text{single}} = p_1 \frac{f}{B_1} + (1-p_1)\frac{f}{c_1 B_1} \quad (7)$$

This type of approximation raises the question whether more detailed approximations would result in significantly different results for the expected gain of multipath protocols ($E_{\text{single}} - E_{\text{multi}}$). This was tested with two and ten level approximations having the same average and standard deviation (originally 1.55 Mbit/s and 0.29 Mbit/s, respectively) when a user downloads a file (625 kB = 5 Mbit). The observation was that the effect on the expected download times is marginal if the bandwidth on each path is equally distributed (e.g., between 1 Mbit/s and 2 Mbit/s). If the throughput occasionally drops close to zero, it starts to have a significant effect (>10%) on the multipath gain, if the bandwidth drops below 0.3 Mbit/s. On the other hand, occasional spikes start to have significant effect (>10%), if the bandwidth spike exceeds 5 Mbit/s. This indicates that bandwidth drops towards zero should be considered more carefully than the bandwidth spikes of the corresponding degree when modeling the feasibility of multipath communication. In addition, a slight increase in the scale of the distribution does not affect the multipath gain either. For example, an equal distribution from 0.6 Mbit/s to 2.4 Mbit/s (p_i=0.1) has a marginal effect on the results. However, a distribution from 0.2 Mbit/s to 2.9 Mbit/s results in a difference of over 13% in multipath gain. Table 13 verifies the presented considerations.

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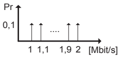
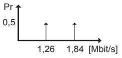
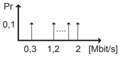
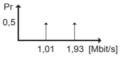
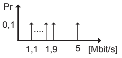
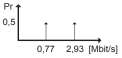
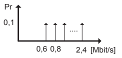
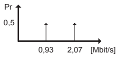
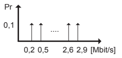
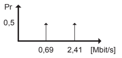
[36] Adapted from Publication III. Reprinted with permission from J.UCS.

Table 14. Comparison of throughput distributions

THROUGHPUT DISTRIBUTION	AVG [Mbit/s]	STDEV [Mbit/s]	E_single [s]	E_multi [s]	E_single-E_multi [s]	GAIN	GAIN RATIO
	1.55	0.29	3.344	1.642	1.702	50.9 %	100.2 %
	1.55	0.29	3.340	1.641	1.699	50.8 %	
	1.47	0.46	4.56	1.85	2.7	59.4 %	113.1 %
	1.47	0.46	3.77	1.8	1.98	52.5 %	
	1.85	1.08	3.19	1.51	1.68	52.7 %	90.2 %
	1.85	1.08	4.09	1.69	2.39	58.4 %	
	1.5	0.57	4.01	1.82	2.19	54.6 %	101.7 %
	1.5	0.57	3.91	1.81	2.096	53.7 %	
	1.55	0.86	6.06	2.08	3.98	65.7 %	113.6 %
	1.55	0.86	4.67	1.97	2.7	57.8 %	

6. Discussion

This work represents the first effort in studying the economic feasibility of multipath protocols in the Internet. The research has employed a techno-economic approach, and therefore offers added value to protocol developers. In addition, this study helps practitioners and regulatory authorities in the Internet connectivity market understand and foresee the market impacts of multipath protocols, thus supporting their decision making.

6.1 Contributions and implications

The high-level objective of the present research was to analyze the economic feasibility of multipath protocols in the Internet. Initially, multipath protocols seem economically feasible, especially in applications with high bandwidth and availability requirements (e.g, IoT context). However, the diffusion will highly depend on the support of software (e.g., operating system) vendors and mobile operators towards multipath protocols and multihoming. More detailed studies are needed to make more solid conclusions on this matter, and the results of this research provide the baseline and tools for conducting such analyses.

This research makes several practical and method-related contributions. Three main contributions, which respond to the research questions posed in Chapter 1, can be highlighted:

1. The identification and the evaluation of factors affecting the feasibility of multipath protocols.
2. The identification of the effects of multipath protocols in the Internet connectivity market.
3. The development and the evaluation of new modeling methods for studying the feasibility of (multipath) protocols.

Contribution 1: Consumers, who are one of the most potential end user groups of multipath protocols, acquire the protocol indirectly as a supplement part of an application or unintentionally as embedded in an operating system. Other end users of devices employed with a multipath protocol include, for example, employees of an organization who wish to benefit from the increased availability or bandwidth of Internet connections. Whoever the user of a multipath client is, the value of the multipath protocol culminates in time savings. The increased connectivity time enables the users to engage in activities which are more valuable instead of making them wait for the content to download or struggle with Internet connections. However, multihoming capability which is a key component exposing the benefits of multipath communication, requires an explicit adoption decision from the user of a multipath client.

Content and other service providers make a conscious decision to employ both multihoming capability and the software of the multipath protocol. Their primary motives to adopt a multipath protocol stem from innovativeness, pressure from competitors and potential to reach consumers who have the multipath capability on their devices. The last-mentioned motive has the strongest impact on the adoption rate of content providers, which places a huge pressure on operating system vendors implementing the multipath software on client devices.

End-to-end multipath protocols are highly prone to network effects, as either end lacking adoption hinders the diffusion of the protocol. The disparity between the adoption levels of consumers and content providers can be alleviated by vertical stakeholders exercising control over the both ends (e.g., Microsoft or Apple), or by the entry of a new actor in the market.

The results of this study indicate that protocols enabling the switch between access networks seem initially more compelling as compared to the protocols enabling simultaneous operator access. Essentially, two arguments support this:

1. With moderate bandwidths, selecting the best operator in a certain location will yield roughly the same performance as with simultaneous access of operators.
2. Running two radios simultaneously will increase the battery consumption of a mobile device.

Accordingly, only applications requiring high bandwidth seem to benefit from the multipath functionality (i.e., path aggregation). In terms of Finnish mobile networks, a high bandwidth corresponds to more than 1 Mbit/s in the download direction. The performance of the operators varies in terms of locations, and a single operator is capable of providing roughly 1 Mbit/s without aggregating the bandwidth of another operator. In addition, with low data rates (< 100 kbit/s), three operators seem to bring no more benefits than two. These thresholds presumably vary from one country to another and the results may be different for other mobile markets.

The energy consumption of multipath protocols has a major impact on protocol feasibility. The analysis shows that the increased energy consumption is not an issue in terms of costs since the other operational costs exceed the increased energy costs. Without energy optimization, the simultaneous employment of multiple radios will drain the battery, which prohibits the adoption in applications in which power supply for the client is unavailable. With the current battery capacities, this is a major restriction for mobile devices.

The capital expenditure required to implement a multipath infrastructure exceeds operational expenditure, which promotes scale advantages. Application scenarios that have a large number of mobile devices installed or in which the mobile devices have high utilization rates of a service, will benefit from a multipath service the most. The analysis of the cases examined in the present work shows that an increase of roughly 1.5 percentage units in connectivity time will correspond to a cost of tens, potentially hundreds, of euros, whereas an increase of 10 percentage units in the connectivity time can be achieved with only a few euros. The cost level varies from market to another, but this finding holds true for markets similar to Finland.

Although the results of this work show that multipath protocols can benefit some applications, the dominant technical design for a feasible multipath protocol is unclear. Of the standardized solutions, MPTCP seems the most potential alternative since it is a pure end-to-end protocol and requires no deployment actions from any other actors than those controlling the end devices. In addition, Apple has already implemented MPTCP in iOS7 (Bonaventure, 2013). MIP would require access operators to implement a MIP server component, which would take care of the mobility management mechanism of mobile devices, whereas HIP requires deployment actions in DNS servers. SCTP would require modifications in firewalls and other middleboxes. MPRTP is also a pure end-to-end protocol, but it is only applicable to multimedia communication and its development is in its early stages. Moreover, any proprietary protocol built on multihoming, either by switching from one operator to another or aggregating the paths, can emerge in the market. Presumably, several implementations will co-exist, especially in the early phases of the deployment process.

In addition to the internal strengths and weaknesses of each protocol, a number of external factors affect the feasibility of all multipath protocols. The analyses show that the three major opportunities for the deployment of multipath protocols in the Internet include[37]:

1. The number of multihoming-capable devices is growing;

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[37] The inverse of these statements has a negative effect on the feasibility of multipath protocols.

2. Emerging applications set higher performance requirements;
3. Battery capacities are increasing.

Contribution 2: If client multihoming and multipath protocols become more widely adopted, it will have a significant impact on the Internet connectivity market. Multipath protocols will change the logic of Internet communications since both technical and market mechanisms are currently optimized for single-path communication. For example, the data associated with a single end user would not be in the hands of a single access operator.

Multipath protocols will reallocate the traffic flows of a single end user, which will distribute the costs and revenues of intermediate ISPs accordingly. The degree of reallocation will depend on the end-to-end path diversity and the policy that a multipath protocol employs to exploit available capacity. Typically, the IETF standards only specify the *mechanism* (how the mobility or multipath capability is implemented) but the *policy* (how the packets are allocated to available paths) is dependent on each individual implementation. This separation facilitates the compatibility of different end systems, but allows local policies to decide how each application should benefit from the available access networks. For example, the application scenarios discussed in Section 4.3 show the different preferences of applications leading to the need for different path policies. However, lacking policy standards of protocols may also blur the use case of a protocol for potential adopters.

Many multipath protocols aim to balance the load in the Internet. For example, the objective of the congestion control algorithm of MPTCP is to allocate the traffic more to operator networks with available capacity. This, however, holds true only if the transferred data volumes in the Internet remain constant. The time saved by using multipath communication instead of single-path communication will probably lead to an increase in the overall demand of Internet services. Therefore, in the longer term, mobile users increase downloads, and it is impossible to say whether the multipath communication in the Internet will balance the load of intermediate ISPs. Whatever the new traffic allocation in the Internet will be in the longer term, the cost and revenue allocation between operators will change accordingly. This may result in unbalanced cost and revenue allocation.

The adoption of multipath protocols on multihomed devices will induce the largest paradigm change in the Internet connectivity market. The capability of a single end user to benefit from several access operators will increase the competition in the mobile access market. Multipath and mobility protocols will decrease the switching costs of the end user by automating the switching of the operator. Instead of manually switching the access operator, these protocols would automatically switch to the best available operator according to pre-coded algorithms in each device. Therefore, the deployment of multi-SIM devices and multipath protocols will decrease the switching times from years to minutes or even seconds, thus increasing competition in the mobile access market and decreasing the price of mobile Internet access.

The threat of increasing competition will presumably negatively affect the attitudes of mobile operators towards multihoming and multipath protocols. Being in the middle of the communication path, MNOs can potentially try to prevent the diffusion of multipath protocols, e.g., by blocking multipath traffic if it seems to be harmful for their business. However, the regulators might intervene if such blocking occurred. Another way of looking at the problem is that the increasing willingness to benefit from multipath communication could also increase the demand of mobile subscriptions. Instead of one, the end users would subscribe to several operators which would grow the market of mobile subscriptions. In addition, the pricing schemes (e.g., flat or metered rate) of MNOs would affect the net benefits of multipath communication for MNOs.

Contribution 3: This research also proposes novel methods for studying the feasibility of multipath protocols. Although only applied to multipath protocols, the suggested research approach and methods are applicable for studying other Internet protocols. Compared to the earlier economic-oriented studies on Internet protocols, the methods employed in this research are technology-centric, which means that the technical architecture and features are exposed and explicitly linked to the economic domain. Such approach should be easier to adopt by protocol developers and potentially decrease the often unnecessary gap between theoretical protocol development and business.

Firstly, this research has adopted a systematic approach for studying the feasibility of multipath protocols. Each stakeholder group, affecting or being affected by the deployment of multipath protocols, has been considered in the study process. This approach yields a comprehensive view on the stakeholder incentives and disincentives towards multipath protocols and multipath communication in the Internet and should expose the relevant deployment challenges related to protocol deployment.

Secondly, the research exploits novel modeling tools (system dynamics and techno-economic modeling) which have not earlier been applied in the research of Internet protocols and can complement the traditional way of modeling the feasibility of Internet protocols. These tools propose a more practical approach of modeling the feasibility of protocols than traditional functional modeling (utility and game theoretic modeling). This is because they aim for a detailed analysis of the cost and benefit components and the exploitation of real-world data. This study makes a contribution not only by applying these tools, but also by comparing them against each other to facilitate the choice between tools in future studies.

Techno-economic modeling, in particular, is seen as a potential tool for fostering techno-economic thinking of engineers and developers. The benefit of this approach is that the modeling process starts from the technical architecture and the deployment actions of a protocol, which is the strength area of protocol developers. However, the collaboration between technical and business-oriented persons is required to obtain the most successful outcome from the modeling. In addition, techno-economic modeling inherently forces the modeler to consider the deployment actions for a protocol, which reveals the deployment challenges and opportunities of a protocol.

This research has extended the notion of techno-economic modeling from the traditional discounted cash flow analysis to the comparison of costs of a technical structure against non-monetary benefits (or value of the protocol). This approach is known as cost-efficiency analysis. The strength of the new approach is that the exact revenue logic of a certain stakeholder does not need to be known, which reduces the uncertainty of techno-economic modeling.

6.2 Limitations

This research aimed for practical modeling of the deployment of multipath protocols; a perspective that was lacking in earlier protocol feasibility studies. Although gathering the real-world data for the quantification of the models was clearly stated as an objective, it turned out to be challenging, and the original plan for the collection of empirical data was not realized. For example, the empirical measurements of Internet path diversity were cancelled owing to the transfer of a co-researcher to other projects (Publication III). It was not possible to carry out measurements of that scale single-handedly. In addition, the measurement data analyzed in Publication IV represents a relatively small fraction of the Finnish land area and biases to populated areas. The lack of data has increased the uncertainty of the quantitative results, and the accuracy of the results can be improved when larger amount of data is available.

There was a clear intention to complete a higher number of interviews with company experts during the study process. At least, two main challenges in acquiring interviewees from companies are manifest. Firstly, an ideal interviewee for a study concerning protocol feasibility has cross-disciplinary knowledge. The experts that are deeply involved in the protocol development typically have limited understanding about the market dynamics. In contrast, those involved in business activities in companies may not have sufficient knowledge of the technical functionalities, especially during the early phases of the protocol development. A person having the understanding of both fields is the best to place judgments on the factors affecting the deployment and feasibility of a protocol. For example, senior managers who have earlier worked in technical domain are good interviewees, but finding these persons from companies is not always straightforward.

Secondly, many protocol developers and company representatives are based abroad. This is because the Internet is a global network and new Internet protocols are being developed by a large international community. The key adopters of Internet protocols, such as operating system vendors and major content providers, are multi-national companies, where the key experts are scattered around the globe. Smaller domestic content providers may not even be following the developments in the Internet protocol research.

Similar to any scientific model, the system dynamics and techno-economic models presented in this thesis are simplifications of the real world. Even though the analysis conducted in this thesis considers known technical structures, the economic modeling has required simplifications of technical details. For example, the cost-efficiency analysis assumed that multipath protocols would be able to exploit the average bandwidth offered by the different operators, which may not be the case in reality. The models call for future improvement as the knowledge on the details of different multipath protocols increases.

6.3 Future work

This study has provided an increment to understanding the economic feasibility of different multipath protocols in the Internet, but additional research is required to make more solid conclusions in terms of the economic feasibility of multipath protocols. The future studies could employ, for example, the following research perspectives.

This thesis has only analyzed multipath protocols in the Internet in terms of performance, but several other use cases are foreseen for multipath communication. Scenarios where end users aim for cost or energy optimization were not considered. Furthermore, the exploitation of multipath protocols in P2P or intra-domain communication fell out of the scope of this thesis. These use cases could provide a future direction for research. The research approach and economic models presented in this thesis can turn out useful in the research of other use cases.

The outcomes of the techno-economic models concern essentially the Finnish market as the cost and benefit estimates are from Finland. The results can be best generalized to other developed mobile markets, but a similar analysis might be conducted in other markets to see whether the conclusions regarding the feasibility of multipath protocols differ. Comparison of different mobile markets would allow for the identification of most potential markets for multipath protocols.

Client multihoming is the most important prerequisite to obtain the full benefits of multipath protocols, and therefore, more emphasis should be put on this area instead of just focusing on the feasibility of protocols. Two game theoretic studies considering client multihoming were found in the literature (Shakottai, 2007; Teng et al., 2008), but academic studies have not been employed with a practical approach. For example, the forthcoming standards of embedded SIM may enable multihoming of smart devices and pave the way for multipath protocols. However, it is not at all clear whether the end users are willing to bear the effort of contracting with several operators. Thus, the future studies could focus on the drivers and bottlenecks towards client multihoming in different markets and contexts. In addition, the effects of client multihoming on the revenue of MNOs could be studied under different pricing schemes (e.g., flat rate, metered rate).

Because the client multihoming and multipath protocols will change the logic of the current Internet communications from the technical and value network perspectives, more studies are needed to draw more in-depth conclusions on the effects of multipath protocols. The fact that the traffic flows of a mobile user are spread through several access operators raises multiple regulatory issues, let alone the technical and economic ones.

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Errata

I. No errata

II. No errata

III. No errata

IV. Equation 6 and Table III: $\Delta C_{HW}^{SD} \rightarrow \Delta C_{HWa}^{SD}$

V. No errata

VI. No errata

The increasing demand for Internet services raises concerns about the sufficiency of capacity in networks. Multipath protocols provide a solution to balance the traffic of Internet users, and thus, to improve the service quality of Internet connections. Despite several technical proposals, the deployment and economic impact of multipath protocols remain largely unstudied. This thesis examines the economic feasibility of multipath protocols in the context of mobile Internet services, and from different stakeholder perspectives. The research makes several contributions by evaluating the factors affecting the economic feasibility of multipath protocols and analyzing their potential market impacts. Furthermore, the thesis proposes a new approach and methods for studying the economic feasibility of multipath as well as other Internet protocols in the future.

Aalto-DD 77/2014

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ISBN 978-952-60-5704-0
ISBN 978-952-60-5705-7 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934
ISSN 1799-4942 (pdf)

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