Department of Communications and Networking

Techno-economic modelling of wireless network and industry architectures

Timo Smura

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Techno-economic modelling of wireless network and industry architectures

Timo Smura

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Abstract

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Abstract

Rapid innovation in the domains of wireless communications and Internet brings new opportunities and challenges for the industry stakeholders. As Internet services and applications migrate to mobile devices, increasing demands for wireless networks arise. At the same time, increasing uncertainty exists about the role of different wireless technologies and actors providing services in the future network environment. Decision-making and forecasting requires therefore a holistic view, taking into account technology, business, and policy-related aspects.

This dissertation applies and develops techno-economic modelling methods for the study of wireless networks and services in the context of evolving industry architectures. The research is organised both chronologically and logically into two parts: 1) techno-economic modelling of selected wireless network and industry architecture scenarios, and 2) development of the techno-economic modelling methods in selected areas.

The dissertation makes several contributions to the theory and practice of techno-economic modelling. First, the dissertation explores the use of the predominantly technology-focused modelling methods in studying alternative industry architectures. Three separate techno-economic modelling studies are presented, analysing the feasibility of fixed WiMAX network deployments, virtual operator models in mobile networks, and industry architectures for DVB-H -based mobile television. In each of these studies, a systematic modelling process is followed, consisting of the following steps: market and service definition, technology definition, industry architecture definition, revenue modelling, cost modelling, discounted cash flow analysis, and sensitivity analysis. Second, the dissertation advances the theory and practise of techno-economic modelling in selected areas. A novel approach for planning and forecasting technology product evolution and new product feature diffusion is developed, combining existing models of product category diffusion and product unit replacement behaviour with a previously unexplored phenomenon of product feature dissemination. In addition, a holistic framework for analysing the usage of mobile services is developed, linking available usage measurement points to the four main technical components of mobile services: devices, networks, applications, and content. The framework is utilised in a study of mobile data service usage in Finland. Finally, scenario planning methods are used to manage and bound uncertainties related to the future of local area access networks, and more generally suggested as a complement to techno-economic modelling in defining and selecting the technology and industry architectures for analysis.

Keywords Techno-economic modelling, mobile, wireless, industry architecture

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Tiivistelmä

Langattoman viestinnän ja Internetin alueella tapahtuva nopea kehitys ja innovaatiot luovat uusia mahdollisuuksia ja haasteita toimialalle. Internetin palveluiden ja sovellusten siirtyessä mobiililaitteisiin langattomille verkoille asetettavat vaatimukset kasvavat. Samanaikaisesti epävarmuus eri langattomien teknologioiden ja toisaalta palveluntarjoajien asemasta tulevaisuuden verkkoympäristöissä kasvaa. Päätöksenteko ja ennustaminen tässä ympäristössä vaatii kokonaisvaltaista lähestymistapaa, jossa huomioidaan sekä teknologiset, liiketoiminnalliset, että poliittiset näkökulmat.

Tämä väitöskirja hyödyntää ja kehittää teknis-taloudellisia mallintamismenetelmiä langattomien verkkojen ja palvelujen tutkimiseen kehittyvien toimiala-arkkitehtuurien kontekstissa. Tutkimus on jäsennetty sekä kronologisesti että loogisesti kahteen osaan: 1) valittujen langattomien verkko- ja toimiala-arkkitehtuuriskenaarioiden teknis-taloudellinen mallintaminen sekä 2) teknis-taloudellisten mallintamismenetelmien kehittäminen.

Väitöskirja edistää teknis-taloudellisen mallintamisen teoriaa ja käytäntöjä usealla tavalla. Ensinnäkin väitöskirjassa tarkastellaan aiemmin etupäässä teknologiapainotteisten mallintamismenetelmien käyttöä vaihtoehtoisten toimiala-arkkitehtuurien tutkimisessa. Työssä rakennettujen kolmen erillisen teknis-taloudellisen mallin avulla arvioidaan kiinteiden WiMAX-verkkojen, mobiiliverkkojen virtuaalioperaattorimallien, sekä DVB-H –pohjaisten mobiilitelevisioverkkojen taloudellista toteutettavuutta. Kussakin tapauksessa mallinnus seuraa systemaattista prosessia, jonka vaiheet ovat markkinan ja palvelujen, teknologian, sekä toimiala-arkkitehtuurin määrittely, tulojen ja kustannusten mallinnus, sekä kassavirta- ja herkkyysanalyysi. Toiseksi, väitöskirjassa kehitetään teknis-taloudellisia mallintamismenetelmiä valituilla osa-alueilla. Työssä kehitetään uudenlainen lähestymistapa teknologiatuotteiden evoluution ja uusien tuoteominaisuuksien diffuusion ennustamiseen yhdistämällä aiemmin tunnetut tuotekategoriatason diffuusiomallit ja tuoteyksikkötason korvaamismallit aiemmin tutkimattomaan tuoteominaisuuksien levittämisilmiöön. Työssä kehitetään myös mobiilipalvelujen käytön analysoimiseen tarkoitettu viitekehysmalli, jossa käytettävissä olevat mittapisteet yhdistetään mobiilipalvelujen neljään pääasialliseen teknologiakomponenttiin: laitteisiin, verkkoihin, sovelluksiin ja sisältöihin. Viitekehystä hyödynnetään Suomen mobiilidatapalvelujen käyttötutkimukseen. Lisäksi työssä hyödynnetään skenaariosuunnittelumenetelmää tulevaisuuden langattomiin lähiverkkoihin liittyvien epävarmuuksien analysointiin ja rajaamiseen. Menetelmää ehdotetaan yleisemmällä tasolla käytettäväksi teknis-taloudellisen mallintamisen tukena analysoitavien teknologia- ja toimiala-arkkitehtuurien määrittelyssä ja valinnassa.

Avainsanat Teknis-taloudellinen mallintaminen, mobiili, langaton, toimiala-arkkitehtuuri

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Preface

"A journey is best measured in friends rather than miles."

- *Tim Cahill, adventure travel writer*

This work would not have taken place in its current form without the support and contribution of many wonderful people. Here I take the opportunity to thank those who have walked beside me on this journey.

The path towards this dissertation began with a summer job at Nokia Networks in Düsseldorf in 2000. I would like to thank Dr. Esa Kemppinen for giving me the initial opportunity to study the area of wireless access networks and steering my subsequent studies towards this direction. I also want to thank Matti Swan and Kim Tikkanen of Elisa Research for the opportunity to continue working in this area and to finish my Master's thesis in 2004.

In 2004, I joined the newly founded research team of Prof. Heikki Hämmäinen at TKK Helsinki University of Technology. I owe my gratitude to Heikki for his patience and trust in me, allowing me the freedom to work according to my research interests throughout my time in his team. Heikki has done great work in building and managing the team and securing its position as a respected unit in the academia and among industry partners, thus creating the conditions for me to pursue this doctoral dissertation.

I would also like to thank the original core members of the Netbizz team, including Annukka Kiiski, Mathias Tallberg, Renjish Kumar, and Sauli Kamppari; you made it easy for me to enjoy my time at work from the very beginning. From the early days of my dissertation work, I want to also thank the core members of the Ecosys project, including Ilari Welling, Dr. Jarmo Harno, Dr. Kjell Stordahl, Dr. Borgar Olsen, Dr. Dimitris Katsianis, Theodoros Rokkas, Jean-Sebastian Bedo, Beatriz Craignou, and Thomas Monath; the words "techno-economic modelling" in the dissertation title are dedicated to you.

With Dr. Antero Kivi and Dr. Juuso Töyli I have shared the most rewarding times in my research and writing. Thank you both for the

numerous debates and iterations during the writing process of our papers, especially the "KiSmuT" article. I have been privileged to have you as colleagues, co-authors, and friends.

Throughout my research work, I have enjoyed co-operating with many people in producing the academic results and contributions; some of these results have been included in this dissertation whereas some have not. In addition to many of the people already mentioned above, I want to thank Eino Kivisaari and Tuukka Autio for their contributions to the mobile TV study. I also want to thank Antti Sorri, Thomas Casey, and Michail Katsigiannis for the collaboration in local area access network projects. Furthermore, I thank Mikko Heikkinen and Antti Riikonen for collaboration in various areas of my research.

All the other members, past and present, of our Netbizz team also deserve to be mentioned and thanked, at least for making this journey more enjoyable. I want to thank Dr. Kalevi Kilkki for his wise words on research and life. I also want to thank and congratulate Dr. Hannu Verkasalo for showing example in efficiently completing a doctoral dissertation. I challenge the current members of the team, including Olli-Pekka Pohjola, Juuso Karikoski, Tapio Levä, Henna Warma, Tapio Soikkeli, and Nan Chang, among some of the previously mentioned, to finish their respective theses faster than I did; the bar has surely not been raised beyond reach.

I would also like to thank my two pre-examiners Dr. Luís M. Correia from Technical University of Lisbon and Dr. William Lehr from Massachusetts Institute of Technology for their valuable comments and improvement suggestions in the very final stages of the dissertation work. I am also indebted to Nokia Foundation and the Research and Training Foundation of TeliaSonera Finland Oyj for financial support.

Finally, and most importantly, a journey like this would not be possible without the support, love, and patience of the closest ones. I want to thank my parents for the encouragement and pride shown throughout my life. I owe my deepest gratitude to my wife Kati: you constantly bring joy, warmth, and happiness to my life. To our two precious daughters Emmi and Salla, I hope to provide the inspiration to keep learning, exploring, and being amazed by the world and life; you certainly inspire me every single day.

Helsinki, January 1st, 2012

Timo Smura

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List of publications

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I T. Smura, A. Kiiski and H. Hämmäinen, 'Virtual operators in the mobile industry: A techno-economic analysis', Netnomics, vol. 8, no. 1-2, pp. 25-48, 2007.

II E. Kivisaari, T. Autio, T. Smura and H. Hämmäinen, 'Operator Roles in Mobile Broadcast', Nordic and Baltic Journal of Information and Communication Technologies, vol. 2, no. 1, pp. 48-60, 2008.

III T. Smura, H. Hämmäinen, T. Rokkas and D. Katsianis, 'Techno-economic analysis of fixed WiMAX network deployments', in Mobile WiMAX – Toward Broadband Wireless Metropolitan Area Networks, New York: Auerbach Publications, 2008.

IV T. Smura, A. Kivi and J. Töyli, 'A Framework for Analyzing the Usage of Mobile Services', INFO – The journal of policy, regulation and strategy for telecommunications, information and media, vol. 11, no. 4, pp. 53-67, 2009.

V T. Smura and A. Sorri, 'Future Scenarios for Local Area Access: Industry Structure and Access Fragmentation', in Proceedings of the Eighth International Conference on Mobile Business (ICMB 2009), Dalian, China, June 27-28, 2009.

VI T. Smura, A. Kivi and J. Töyli, 'Mobile Data Services in Finland: Usage of Networks, Devices, Applications, and Content', International Journal of Electronic Business, vol. 9, no. 1/2, pp. 138-157, 2011.

VII A. Kivi, T. Smura and J. Töyli, 'Technology product evolution and the diffusion of new product features', Technological Forecasting and Social Change, vol. 79, no. 1, pp. 107-126, 2012.

Author's contribution

I The idea for this article was formed jointly with Kiiski and Hämmäinen. The strategic mapping of virtual operators was done jointly with Kiiski. The author was responsible for creating the techno-economic model and producing the quantitative results. The author assembled the manuscript, and edited it iteratively together with Kiiski and Hämmäinen.

II The idea for this article was formed jointly with Kivisaari and Autio. The techno-economic model is based on the Master's Thesis work of Autio, in which the author was the instructor. The author assembled and edited the manuscript jointly with Kivisaari.

III The idea for this article was formed by the author. The article and the techno-economic model are based on the author's Master's Thesis and an earlier conference paper, in both of which the author was the sole contributor. In this article, Rokkas was responsible for the risk analysis. The author assembled and edited the manuscript.

IV The idea for this article was formed jointly with Kivi, and the framework was also developed jointly with Kivi. The author assembled the manuscript and was responsible for writing Chapters 1, 3, and 5. The manuscript was edited iteratively together with Kivi and Töyli.

V The idea for this article was formed jointly with Sorri. The author was responsible for the literature review, and organising and facilitating the scenario workshops. The scenarios were constructed jointly with Sorri. The author assembled and edited the manuscript.

VI The idea for this article was formed jointly with Kivi. The author participated in collecting the research data, and data analysis was conducted jointly with Kivi. The author assembled the manuscript and was responsible for writing Chapters 1, 2, 5, and 6. Kivi and the author edited the manuscript iteratively together, while Töyli provided comments.

VII The idea for this article was formed jointly with Kivi. The author participated in collecting the research data, and the data analysis was conducted jointly with Kivi and Töyli. The planning and forecasting approach was developed jointly with Kivi and implemented by the author. The author was responsible for writing Chapters 2 and 4. The manuscript was edited iteratively together with Kivi and Töyli.

List of abbreviations

2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
3GPP2	3rd Generation Partnership Project 2
AAA	Authentication, Authorisation, and Accounting
ABPU	Average Billing Per User
ADSL	Asymmetric Digital Subscriber Line
ARPU	Average Revenue Per User
ATM	Asynchronous Transfer Mode
ATSC	Advanced Television Systems Committee
ATSC-M/H	ATSC - Mobile / Handheld
A/V	Audio/Video
BAM	Broadcast Account Manager
B-ISDN	Broadband Integrated Services Digital Network
BS	Base Station
BSM	Broadcast Service Manager
CAPEX	Capital Expenditure
CDMA	Code Division Multiple Access
CDR	Charging Data Record (formerly Call Detail Record)
CPE	Customer-Premises Equipment
CRM	Customer Relationship Management
D-AMPS	Digital Advanced Mobile Phone System
DCF	Discounted Cash Flow
DNS	Domain Name System
DPI	Deep Packet Inspection
DSSS	Direct Sequence Spread Spectrum
DSL	Digital Subscriber Line
DTMB	Digital Terrestrial Multimedia Broadcast
DVB-H	Digital Video Broadcasting - Handheld
EDGE	Enhanced Data rates for Global Evolution
ETSI	European Telecommunications Standards Institute
EV-DO	Evolution-Data Optimized
FHSS	Frequency Hopping Spread Spectrum

FM	Frequency Modulation
FTA	Future-oriented Technology Analysis
GGSN	Gateway GPRS Support Node
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile communications
HDSL	High bit rate Digital Subscriber Line
HFC	Hybrid Fibre-Coaxial
HSCSD	High-Speed Circuit-Switched Data
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSPA+	Evolved High-Speed Packet Access
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
iDEN	Integrated Digital Enhanced Network
IEEE	Institute of Electrical and Electronics Engineers
IMEI	International Mobile station Equipment Identity
IMT-2000	International Mobile Telecommunications-2000
IMT-A	International Mobile Telecommunications-Advanced
IP	Internet Protocol
IPE	Internet Protocol Encapsulator
IRR	Internal Rate of Return
IS	Interim Standard (e.g. IS-54, IS-95, and IS-136)
ISDB	Integrated Services Digital Broadcasting
IT	Information Technology
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication sector
LA	Local Area
LAN	Local Area Network
LRAIC	Long-Run Average Incremental Cost
LRIC	Long-Run Incremental Cost
LTE	Long Term Evolution
MAN	Metropolitan Area Network
MAPE	Mean Absolute Percentage Error
MMS	Multimedia Messaging Service
MNO	Mobile Network Operator
MVNO	Mobile Virtual Network Operator
NPV	Net Present Value
OA&M	Operations, Administration, and Maintenance
OFDM	Orthogonal Frequency-Division Multiplexing
OPEX	Operational Expenditure

OS	Operating System
P2P	Peer-to-Peer
PAN	Personal Area Network
PC	Personal Computer
PDA	Personal Digital Assistant
PDC	Personal Digital Cellular
PHS	Personal Handy-phone System
PLC	Power Line Communication
PON	Passive Optical Network
RLL	Radio Local Loop
RMSE	Root Mean Square Error
RTT	Radio Transmission Technology (in 1xRTT)
S-DMB	Satellite Digital Multimedia Broadcasting
SGSN	Serving GPRS Support Node
SME	Small and Medium Enterprise
SMS	Short message service
SP	Service Provider
STM	Synchronous Transfer Mode
T-DMB	Terrestrial Digital Multimedia Broadcasting
TB	Terabyte
TCE	Transaction Cost Economics
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TE	Techno-economic
TV	Television
UMB	Ultra Mobile Broadband
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
WA	Wide Area
WACC	Weighted Average Cost of Capital
WAP	Wireless Application Protocol
VAT	Value Added Tax
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
VoIP	Voice over Internet Protocol

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1. Introduction

1.1 Background

Wireless networks of the future will utilise a number of different radio access technologies having different kind of coverage, capacity, and cost characteristics. Technologies developed in the Third Generation Partnership Project (3GPP) provide upgrade paths for the nationwide cellular networks towards higher data rates and richer multimedia services. Independently from the 3GPP evolution, wireless local area networks (WLANs) provide alternative means for broadband wireless connectivity, albeit in more limited geographical areas. WiMAX and DVB-H technologies have also been proposed as alternatives complementing and competing with the other radio accesses. Moreover, for the next generation of mobile communications systems, new spectrum bands have been identified, for which a new family of standards (IMT-A) will be developed.

Due to these parallel developments, increasing uncertainty exists about the role of different wireless access technologies in the future network environment. Particularly, fragmentation between separate local area, wide area, and broadcasting technologies remains an open question. In addition to the technical architecture, uncertainty exists regarding the industry architecture and the positions of different actors within, as network vendors, network operators, device vendors, and service providers have overlapping interests in controlling the key roles within the industry. Technology choices and investment decisions of these actors are affected by the comparative performance levels of the alternative technologies, existing infrastructures and resources of the actors, foreseeable evolution and diffusion of mobile Internet and data services, as well as political and regulatory decisions. Decision-making and forecasting requires therefore a holistic view, taking into account the technology, business, and policy-related aspects of wireless technology and industry evolution.

Since the early 1990s, techno-economic modelling methods have been utilised to analyse and compare the feasibility of emerging telecommunications networks and services. The early applications were focused at analysing and comparing strategies for upgrading the fixed access networks to support broadband services, typically from the point of view of government-owned, monopoly operators (e.g. Olsen et al. 1996, Ims et al. 1996). As the markets have liberalised and new fixed and mobile technologies have been introduced, the focus has shifted accordingly, although mainly preserving the point-of-view of large established operators deploying the networks and controlling the services (e.g. Olsen et al. 2006). With emphasis on the emerging technologies and alternative technological architectures, analysis of alternative industry architectures has received less attention.

Industry architecture as defined by Jacobides et al. (2006) describes the roles and actors within an industry and the relationships among them. In the domain of fixed and mobile telecommunications, the rapid changes in technology and regulations as well as increasing convergence with earlier separate industries of IT and media have motivated a number of academic studies analysing the differences and changes in the roles and interactions of the respective firms (e.g., Maitland et al. 2002, Barnes 2002, Li & Whalley 2002, Pagani & Fine 2008, Ballon 2009, Tee & Gawer 2009). In the field of techno-economic modelling, however, explicit definition and analysis of industry architectures has been largely neglected.

1.2 Research problem and objectives

Motivated by the research gap identified above, the main research problem of this dissertation is defined as follows:

"How can techno-economic modelling be used for analysing and comparing the feasibility of wireless network and industry architectures?"

Consequently, the objective of this research is

1) to model and evaluate the feasibility of selected wireless network and industry architecture scenarios, and
2) to further develop the techno-economic modelling and analysis methods in selected areas.

1.3 Definitions and scope of the research

Terminology and definitions used by researchers in the field of this research are often non-uniform and even contradictory. Key terms used in this dissertation are defined here to establish positions taken in the research.

Techno-economic (e.g. modelling): method for evaluating the economic feasibility of a complex technical system.

Technical architecture: an abstract description of the technical components and functionalities within a technical system and the interfaces between them.

Industry architecture: an abstract description of the roles and actors within an industry and the relationships among them.

Wireless (e.g. network, service): something, in which the transfer of information over distance does not require a wire or wires.

Mobile (e.g. service, device, application, or network): something the use of which is not contingent on being at a fixed physical location at a particular point in time (Balasubramanian et al. 2002).

Network: a system of interconnected nodes (e.g. computers)

Service: a process, in which one's resources or competences are used for the benefit of another entity (Vargo and Lusch 2004)

1.4 Outline of the dissertation

Following the two-fold objective of this dissertation, also the structure of is logically split into two separate parts. In the first part, quantitative techno-economic modelling of specific wireless technology and industry scenarios is carried out. The second part focuses on developing and extending the methods used for techno-economic modelling and analysis, aiming to improve the quality of inputs to the techno-economic models. Accordingly, the structure of the dissertation is presented in Figure 1.1.

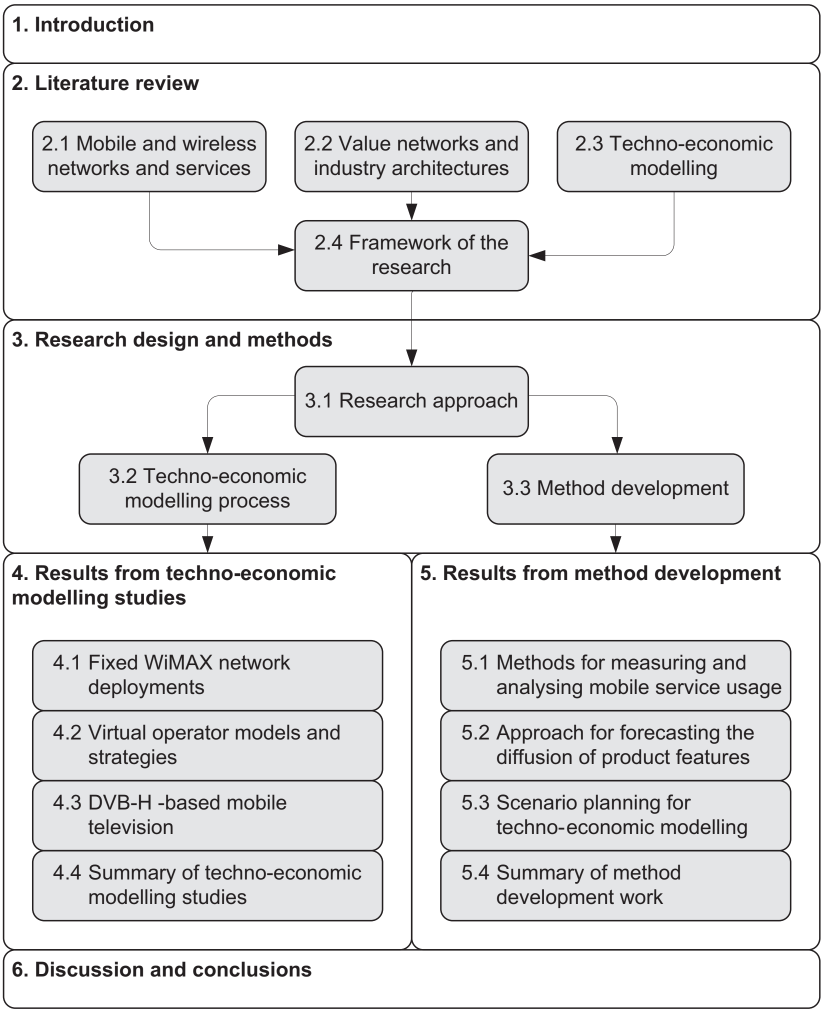

Figure 1.1 Structure of the dissertation

2. Literature review

This research develops and applies techno-economic modelling and analysis methods for the study of mobile and wireless networks and services in the context of evolving industry architectures. In the following subsections, the main concepts and related streams of literature are introduced.

2.1 Mobile and wireless networks and services

The telephone, when invented in the late 19th century, made immediate interpersonal communication and interaction independent of the physical distance between people (e.g. Roos 1993). A hundred years later, two major developments have further shaped the ways of communication. First, the emergence of mobile communications has brought telephony to people and places not reached by fixed telephone lines, allowing people to communicate regardless of time and place. Second, the Internet has dramatically changed the ways in which people and businesses find, use, and share information. Although the idea of convergence between these two developments is certainly not new[1], mobile data usage has remained relatively modest until the very recent years.

Whereas in early 1990s, mobile networks were used with single-purpose devices, i.e. mobile phones, with a single wide area radio network (e.g. GSM), the environment of today is richer and more complex. Advanced mobile handsets are used not only as a phone, but also as a camera, calendar, web browser, media player, and navigator, utilising a vast number of different radio interfaces[2]. In addition to mobile handsets, these radio interfaces are also integrated in a wide variety of other specific devices,

[1] For example, already in 1982, when the Racal Electronics Group won a cellular licence in UK, they named the new network 'Vodafone' to reflect the provision of both voice and data services over mobile phones.

[2] For example, radio interfaces in the Nokia N8 handset include GSM, GPRS, and EDGE for the 850/900/1800/1900 MHz bands, WCDMA (and HSDPA/HSUPA) in the 850/900/1700/1900/2100 MHz bands, IEEE 802.11 b/g/n WLAN in the 2.4 GHz band, as well as Bluetooth, GPS, and FM radio receiver and transmitter.

including laptops, tablets, game consoles, digital cameras, MP3 players, and digital photo frames, among others.

Technical standards are of special importance in communications networks and services, where network effects (or network externalities) are strong (e.g. Shapiro & Varian 1999). The increasing number of mobile and wireless network technologies leads to a complex environment of complementary and competing standards[3]. Figure 2.1 illustrates ITU's vision of the different network 'layers' complementing each other.

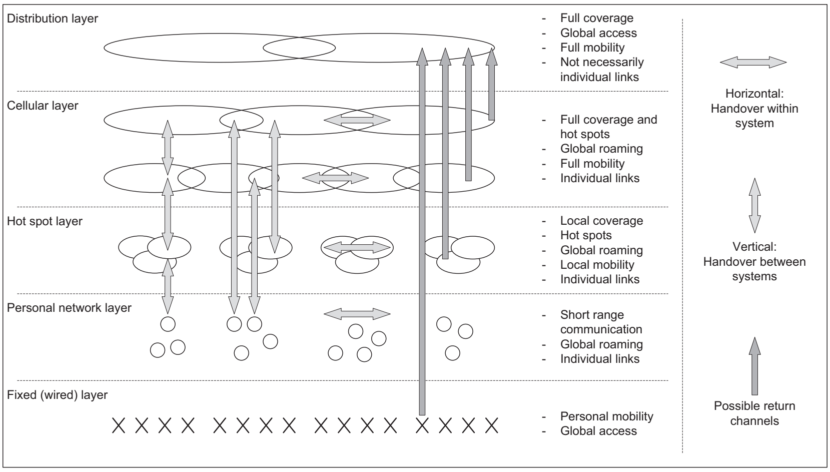

Figure 2.1 ITU's vision of complementary access systems for IMT-Advanced (Adopted from ITU-R M.1645)

In ITU's multi-layer structure (ITU-R Recommendation M.1645), the first layer comprises of wired connections to fixed locations, limiting mobility to a "nomadic" level where users can move from a fixed access point to another. The next layer of personal networks connects multiple devices in the possession and vicinity of users together using direct short-range communication links. Hot spot layer provides local wireless coverage and mobility in locations where the demand for wireless access is high. Cellular layer, on the other hand, provides full coverage and mobility over large geographical areas, comprising of several layers with different cell sizes. Finally, the distribution layer utilises broadcast systems to distribute the same information to many users simultaneously through unidirectional links, possibly using the other layers as return channels (single-ended arrows). Interworking between different access systems (vertical double-sided arrows) is also envisioned.

[3] See, e.g., Lehr & McKnight (2003) for analysis of the competition and complementarity between 3G and Wi-Fi networks.

Technical standards for the mobile and wireless communication systems are specified by a number of organisations, including 3GPP (Third Generation Partnership Project), 3GPP2, and IEEE (Institute of Electrical and Electronics Engineers).[4] In addition, a number of proprietary technologies and de facto standards have been developed by firms within the industry. Following the layered structure of Figure 2.1, an overview of the standards and technologies utilised in past, present, and future mobile and wireless communication systems is given in Figure 2.2.

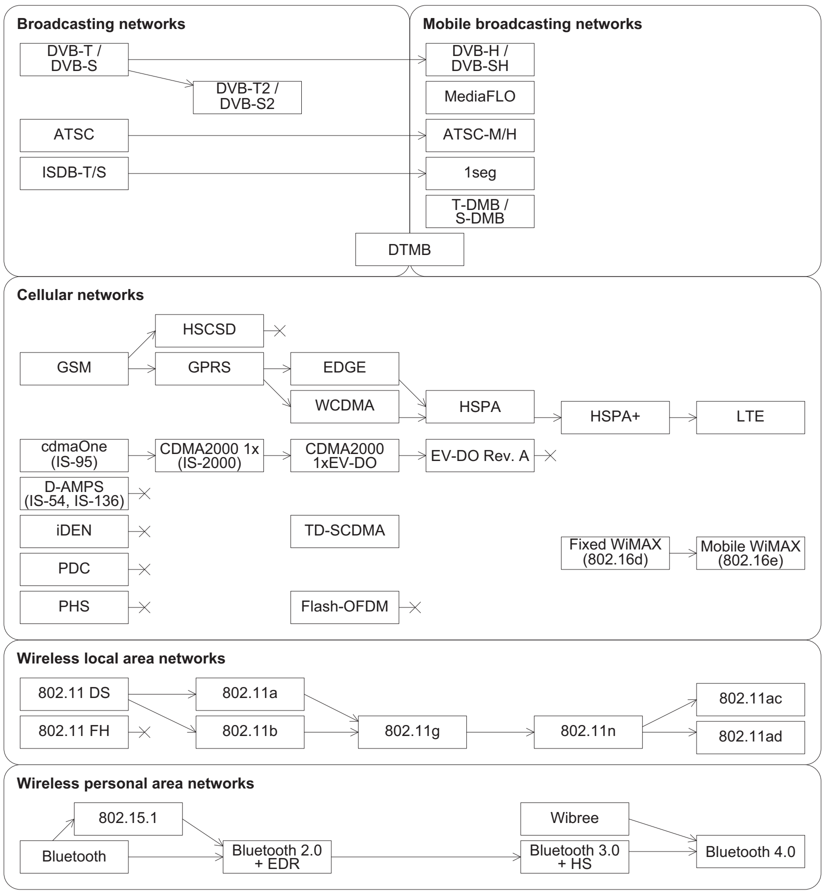

Figure 2.2 **Mobile and wireless communication systems and standards. Arrows represent the dominant upgrade paths of manufacturers and network operators.**[5]

[4] These organisations are responsible for standards and specifications regarding the radio interfaces and overall system architectures of the mobile and wireless communication systems. A vast number of standards specified by other organisations, such as the IETF (Internet Engineering Task Force), are also utilised in the systems.

[5] For the sake of readability, early analogue systems have been omitted and only digital systems have been included in the figure. Furthermore, a number of standards that have not succeeded to enter the market (e.g. CDMA2000 1xEV-DV,

Mobile networks have evolved somewhat differently in different regions. In Europe, second generation (2G) mobile networks are based on the GSM family of standards. General Packet Radio Service (GPRS) extends the GSM networks to packet-switched data services, replacing the circuit-switched HSCSD technology. Data rates are further enhanced by EDGE as well as by third generation (3G) systems utilising WCDMA and later HSPA and HSPA+ radio technologies. In North America, a number of 2G systems have existed, including cdmaOne (Interim Standard IS-95), D-AMPS (IS-54 and IS-136), and iDEN. 3GPP2 has further developed the CDMA2000 family of standards, including 1xRTT, 1xEV-DO, and 1xEV-DO Rev. A, each providing data rate enhancements over the previous one. Further evolutionary steps have also been specified (EV-DO Rev. B and UMB), but not adopted by mobile operators. Instead, established CDMA2000 operators have chosen either LTE or mobile WiMAX as their next generation mobile network technology. In Asia, a number of other standards have been specified and used for mobile services, including PDC (2G standard used in Japan), PHS (2G in Japan, China), and TD-SCDMA (3G in China).

The IEEE 802.16 working group develops standards for broadband wireless metropolitan area networks (WMANs). The 802.16 family of standards includes specifications for both fixed and mobile (802.16e) networks. Interoperability of products conforming to these standards is certified by the WiMAX Forum, giving the technology also its better known brand name. A new version of the standard (802.16m) is being develop, targeting the cellular layer of IMT-Advanced.

Wireless local area networks (WLANs) provide local connectivity and mobility within offices, homes, and other hot spot locations. The dominant standards have been developed by the IEEE 802.11 working group, starting with early direct sequence and frequency hopping spread spectrum (DSSS and FHSS) based systems, and extended with the current OFDM-based versions of the standard (a, g, and n). In the future, new physical layer specifications (ac and ad) will increase the data rates further.

Bluetooth is the dominant standard for wireless personal area networks and short-range wireless communications between devices. Several versions of Bluetooth specifications have been developed.

Finally, many standards for digital broadcasting networks have been developed in different regions. In Europe and some other countries, standards developed by the DVB consortium are used in terrestrial and satellite broadcasting networks. DVB-H adds new features to the standard to enable its use by handheld devices. ATSC systems are used e.g. in North

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EV-DO Rev. B, UMB, ETSI HiperLAN/2, HiperMAN, IEEE 802.15.3, 802.11 infrared) have been omitted.

America and ISDB systems in Japan, ATSC-M/H and 1seg being the mobile versions of the standards respectively. Korea and China have their own standards, T/S-DMB and DTMB, whereas Qualcomm's MediaFLO provides yet another alternative for mobile broadcasting systems.

In summary, the number of technical standards and specifications for wireless communications systems is high and growing. Operators and device vendors have to choose between a vast number of alternatives when optimising their portfolio of supported access technologies. These technologies are often partly complementing and partly competing with one another at the same time, adding to the complexity of decision-making. Further complexity results from the linkages between technical architectures and industry architectures, discussed in the next subsection.

2.2 Value networks and industry architectures

The organisation, boundaries, and scope of firms are central questions for business executives and corporate executives, as demonstrated by the continuous mergers, acquisitions, and other arrangements adjusting firm boundaries (Holmström & Roberts 1998). In consequence, the topics of vertical integration, outsourcing, and make-or-buy decisions have been widely discussed also in academic literature, both in economics as well as in business strategy and innovation literature.

In economics, the concept of *transaction costs* was used to explain the nature and limits of firms by Coase (1937), and later extended to *transaction cost economics* (TCE) by Williamson (1975, 1985). According to TCE, firm boundaries are explained by the costs associated with acquiring inputs for the operation of the business, including e.g. search and information costs, bargaining costs, and contracting costs. Activities should be integrated into the firm when the external transaction costs are larger than the internal costs of performing the activities.

Activities and their interactions within and between firms have been studied extensively in the field of strategic management. Porter (1985) introduced a *value chain* as a framework and tool for representing and examining the set of discrete but interconnected activities of a firm, through which a product or service is created and delivered to customers, and which act as potential sources of competitive advantage. More specifically, a value chain includes one firm's activities in a particular industry, whereas a *value system* comprises the set of value chains of multiple firms or an entire industry, including the value chains of suppliers, channels, and customers.

Stabell & Fjeldstad (1998) argued that whereas Porter's value chain appears well suited to describing and understanding a traditional manufacturing company, the typology and underlying value creation logic are less suitable to the analysis of activities in a number of service industries, such as insurance, banking, or telecommunications. In addition to the value chain, they suggested two additional generic *value configurations*: *value shop* for firms where value is created by resolving particular customer problems and *value network* for firms that create value by facilitating a network relationship between their customers. Also here, the scope is the value-creating logic of one firm, although the value configuration of the firm is also seen to affect also the structure of the whole value system.

In contrast to Stabell & Fjeldstad (1998), a number of authors understand a value network as a network of firms instead of an internal value-creating logic of a single firm. Christensen & Rosenbloom (1995) describe products as nested hierarchies of components and sub-components, implying a corresponding network of producers and markets. These nested commercial systems are called *value networks*, and companies are embedded in them similarly as their products are embedded as components within other products and eventually within end systems of use. Later, Chesbrough & Rosenbloom (2002) define the functions of a firm's business model to include, among other things, the structure of the value chain within the firm and the position of the firm within the value network. More specifically, a value network is explained to position a firm among its suppliers, customers, complementors, and competitors. The concept of *industry platform* as defined by Gawer (2009) further emphasizes the role of the complementors.

The boundaries of firms have also been widely discussed in innovation literature, where benefiting from innovation has been linked to the nature of relationships between the innovator and other, vertically related firms. Extending the work of Teece (1986), Jacobides et al. (2006) introduce the concept of *industry architecture* as a construct defining the terms of the division of labor within an industry or sector. Industry architecture is defined as "an abstract description of the economic agents within an economic system and the relationships among those agents in terms of a minimal set of rules governing their arrangement, interconnections, and interdependence". Essentially, industry architecture defines the ways in which roles are distributed among a set of interacting firms. Industry architecture is seen as a framework, partly emergent and partly designed e.g. by regulation and standards. For a firm, benefiting from innovation is possible by managing the architecture and becoming a "bottleneck" of the industry (Jacobides 2006).

For the purposes of this dissertation, the concept of industry architecture (Jacobides 2006) is most useful. Accordingly, industry architecture is defined as an abstract description of the roles and actors within an industry and the relationships among them. Whereas many of the other related terms, having their roots in business strategy literature, have a single firm in focus (see Table 2.1), the concept of industry architecture takes an industry-wide view of all relevant value-creating activities, roles, and actors.

Table 2.1 Value network and industry architecture related concepts

Scope / Structure	**Value-creating activities and logic of one firm**	**Positioning of a firm among its suppliers and customers**	**Positioning of a firm among its suppliers, customers, complementors, and competitors**	**Industry-wide view of all relevant value-creating activities, roles, and/or actors**
Linear structure	*Value chain* (Porter 1985: 33)	*Value system* (Porter 1985: 34)		
Non-linear structure	*Value network* (Stabell & Fjeldstad 1998) *Value shop* (Stabell & Fjeldstad 1998)	*Value network* (Christensen & Rosenbloom 1995, Christensen 1997)	*Value network* (Chesbrough & Rosenbloom 2002) *Value net* (Brandenburger & Nalebuff 1996) *Value constellation* (Normann & Ramírez 1993) *Industry platform* (Gawer 2009)	*Industry architecture* (Jacobides 2006) *Industry ecosystem* (Iansiti & Levien 2004)

2.3 Techno-economic modelling

Techno-economic modelling is a method used for evaluating the economic feasibility of complex technical systems. The nature of the modelling and analysis is future-oriented, utilising and combining a number of methods from the wide field of future-oriented technology analysis (FTA) (see e.g. Cagnin et al. 2008), including cost-benefit analysis, scenarios, trend analysis, expert opinion, and quantitative modelling (for an extensive list of other FTA methods families and methods, see TFAMWG, 2004, and Scapolo & Porter, 2008, p. 152). Although these methods and their combinations have been widely used by both academics and practitioners, academic work under the term *techno-economic* (e.g. modelling, analysis, evaluation, assessment) has mainly been published related to the energy (e.g. Zoulias & Lymberopoulos 2006), biotechnology (e.g. Hamelinck et al.

2005), and telecommunications (e.g. Olsen et al. 1996) industries, especially by European research groups.

In the context of telecommunications, the term *techno-economic* was introduced during the European research programme RACE (Research into Advanced Communications for Europe) in 1985-1995. Early techno-economic modelling work was done in e.g. the RACE 1014 ATMOSPHERIC project (Graff et al. 1990), and in the RACE 1044 project (e.g. Maggi & Polese 1993) where alternative scenarios and strategies for evolution towards broadband systems were analysed. Later, the RACE 2087 TITAN (Tool for Introduction scenarios and Techno-economic studies for the Access Network) project developed a methodology and a tool for techno-economic evaluation of new narrowband and broadband services and access networks (see e.g. Olsen et al. 1996, Ims 1998). Since the late 1990s, many European research projects have used and extended the methodologies and tools created in the early projects, as listed in Table 2.2.

Table 2.2 Projects developing and using techno-economic modelling methods

Project name	Research Programme	Timeframe
R1014 ATMOSPHERIC	RACE I (FP2)	1988-1991
R1044 (Integrated broadband communications development and implementation strategies)	RACE I (FP2)	1988-1991
R2087 TITAN (Tool for introduction scenario and techno-economic evaluation of access network)	RACE II (FP3)	1990-1994
P306 (Access network evolution and preparation for implementation)	EURESCOM	1993-1996
P416 (Optical networking)	EURESCOM	1994-1996
OPTIMUM (Optimised architectures for Multimedia networks and services)	ACTS (FP4)	1994-1998
TERA (Techno-economic results from ACTS)	ACTS (FP4)	1994-1998
P614 (Implementation strategies for advanced access networks)	EURESCOM	1996-1998
TONIC (Techno-economics of IP optimised networks and services)	IST (FP5)	1998-2002
P901(Extended investment analysis of telecommunication operator strategies)	EURESCOM	1999-2001
BROADWAN (Broadband services for everyone over fixed wireless access networks)	IST (FP6)	2003-2006
BREAD (Broadband in Europe for all: a multidisciplinary approach)	IST (FP6)	2004-2006
ECOSYS (Techno-economics of integrated communication systems and services)	EUREKA / CELTIC	2004-2007

Typically, techno-economic models combine high-level market and service related parameters and forecasts together with relevant cost and performance related parameters of the technologies required to deliver the services to the customers (e.g. Lähteenoja et al. 1998). Based on the calculated costs and revenues, a number of indicators are used to determine the profitability of the scenarios, including e.g. payback period, net present value (NPV), and internal rate of return (IRR). A techno-economic modelling framework followed e.g. in the TERA, TONIC, and ECOSYS projects is shown in Figure 2.3.

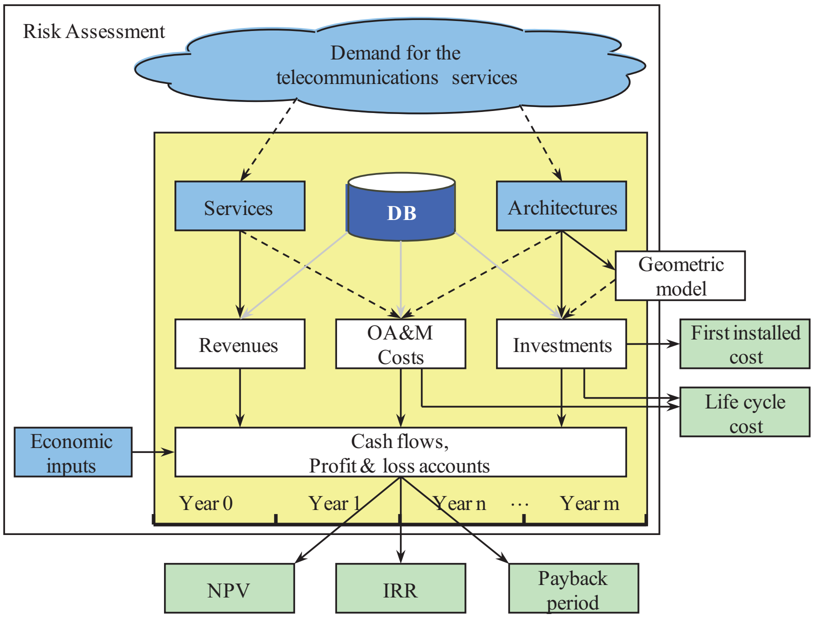


Figure 2.3 Framework for techno-economic modelling and analysis (Olsen 1999)

The framework of Figure 2.3 shows clearly the two main starting points of traditional techno-economic modelling: services and (technical) architectures. Based on forecasts and assumptions regarding these as well as a few generic economic inputs such as the discount factor, time period of study, and rest value of investments at the end of the time period, the models calculate revenues, operational costs, and investments, as well as cumulative cash flows and decision-making criteria such as net present value (NPV), internal rate of return (IRR), and payback period. (Olsen 1999)

During the past two decades, a number of techno-economic modelling studies have been published, mainly in domain-specific technology journals and conferences, as well as in policy-related publications. To identify the similarities and differences between the studies, the papers published in the leading journals and conferences were analysed.

Table 2.3 Articles using techno-economic modelling methods

Author, year, title	Methods / tools used	Scope: Market and service	Scope: Technology	Scope: Industry architecture and competition
Reed & Sirbu (1989) 'An Optimal Investment Strategy Model for Fiber to the Home'	Dynamic programming, DCF analysis, sensitivity analysis	Television and on-demand video for households	Fiber-to-the-home	Integrated operator, no competition assumed
Lu et al. (1990) 'System and Cost Analyses of Broad-Band Fiber Loop Architectures'	Cost modelling, sensitivity analysis	Telephony, data, video conferencing, on-demand and broadcast video for businesses and residentials	B-ISDN, four alternative fiber loop architectures	Focus on cost analysis, service provisioning or competition not discussed
Graff et al. (1990) 'Techno-economic evaluation of the transition to broadband networks'	Basic TE modelling, DCF analysis Analysys STEM modelling system	Fixed access service to businesses	Evolution from STM to ATM	Integrated operator, competition not discussed
Ims et al. (1996) 'Multiservice access network upgrading in Europe: a techno-economic analysis'	Basic TE modelling, DCF analysis TITAN tool	Consumers, Urban and suburban areas in Europe	Comparison between e.g. ADSL, HDSL, PON, HFC	Single integrated operator, competition between integrated operators
Olsen et al. (1996) 'Techno-economic evaluation of narrowband and broadband access network alternatives and evolution scenario assessment'	Basic TE modelling, DCF analysis TITAN tool	New narrowband and broadband services in the residential and small business market, video-on-demand	Narrowband: optical access and RLL, Broadband: Enhanced copper, HFC, PON	Two competing integrated operators (public network operator and new cable operator)
Ims et al. (1997) 'Risk analysis of residential broadband upgrade in a competitive and changing market'	Basic TE modelling, DCF analysis, risk analysis TITAN tool	Telephony, cable TV and broadband services for an urban residential area in Europe	DSL, HFC, ATM PON	Two competing integrated operators (public network operator and cable operator)
Katsianis et al. (2001) 'The financial perspective of the mobile networks in Europe'	Basic TE modelling, DCF analysis, sensitivity analysis, TONIC tool	Mobile services for consumers and businesses within a large and a small European country	GPRS, WCDMA	Integrated mobile operator (existing or new entrant) in a competitive market

Table 2.3 cont.

Author, year, title	Methods / tools used	Scope		
		Market and service	**Technology**	**Industry architecture and competition**
Monath et al. (2003) 'Economics of fixed broadband access network strategies'	Basic TE modelling, DCF analysis, TONIC tool	Fixed broadband services for residential and small business customers	Fiber-to-the-cabinet, Fiber-to-the-home/office, Ethernet, ATM	Separation between ISP and access network operator in a competitive market
Park & Chang (2004) 'Mobile network evolution toward IMT-2000 in Korea: a techno-economic analysis'	Basic TE modelling, DCF analysis scenario analysis,	Mobile voice and data services in Korea	IS-95, CDMA2000 1x, 1xEV-DO, 1xEV-DV, WCDMA	Integrated mobile operator in a competitive market
Tongia (2004) 'Can broadband over powerline carrier (PLC) compete? A techno-economic analysis'	Cost modelling, Monte Carlo simulation, Analytica™ tool	Broadband access for households	Powerline communi-cations (PLC)	Focus on cost analysis, competition between PLC, DSL and cable
Varoutas et al. (2006) 'On the Economics of 3G Mobile Virtual Network Operators (MVNOs)'	Basic TE modelling, DCF analysis, sensitivity analysis, TONIC tool	Mobile services for consumers and businesses	UMTS	Separation between two types of MVNOs and an MNO, competitive market
Riihimäki (2009) 'Analyzing the WiMAX investment costs and NPV distributions for real option valuation'	DCF analysis, real options analysis	Broadband access for households and summer cottages in rural areas	WiMAX	Integrated operator, no competition assumed (underserved area)
Tahon et al. (2011) 'Municipal support of wireless access network rollout: A game theoretic approach'	Basic TE modelling, DCF analysis, game theory	Wireless broadband access for a city-wide area	Wi-Fi, 3G +femtocells	Separation between MVNO and MNO, multiple operators in a competitive market
Kyriakidou et al. (2011) 'Business modeling and financial analysis for Metropolitan Area Networks: Evidence from Greece'	Basic TE modelling, DCF analysis, sensitivity analysis	Metropolitan Area Networks for Greece municipali-ties	Fiber-to-the-curb	Quantitative model assumes integrated operator and no competition (underserved area)

In the early 1990s, the focus in techno-economic modelling was on detailed cost modelling. For example, Graff et al. (1990) listed the main objectives of techno-economic modelling as 1) to compare different technical options in order to find the most cost-effective solutions, 2) to look at the feasibility of different evolution scenarios, 3) to find what parts of the network contribute most to the overall cost, and 4) to identify strategies which are robust to different patterns of demand. Furthermore, they stressed the importance of systematic modelling in forcing a structure upon complex techno-economic problems, requiring modellers to make their assumptions explicit and allowing meaningful comparisons to be made. Later, as liberalisation in telecommunications had advanced, competition between network and service providers started to be taken explicitly in account also in techno-economic modelling work. In their studies on broadband access network upgrade scenarios, Ims et al. (1996) and Olsen et al. (1996) assume competition between public network operators and cable operators to exist, affecting the achievable market shares. Integrated operators controlling both network and service operator roles have been typically assumed, the first exceptions made by Monath (2003) and Varoutas et al. (2006), separating between the two roles.

In summary, techno-economic modelling refers to a set of methods used for evaluating the economic feasibility of complex technical systems. The core of these methods is constituted by forecasts for future demand of services provided by a technical system, detailed modelling of the system itself as well as the costs required to set up and maintain it, and discounted cash flow analysis methods combining all the related revenues and costs and calculating NPVs and other financial outputs. By far, techno-economic modelling has focused mainly on analysing new technologies from the point of view of established actors, implicitly assuming also the traditional industry architectures to be preserved in the future. This is in contrast to the purpose of this dissertation, which aims at utilising the methods also in analysing and comparing the feasibility of alternative industry architectures.

2.4 Framework of the research

In summary, Figure 2.4 presents the framework of the research. The technical focus of the research is on mobile and wireless networks and services. These are modelled and analysed in the context of evolving industry architectures, using techno-economic modelling as the method.

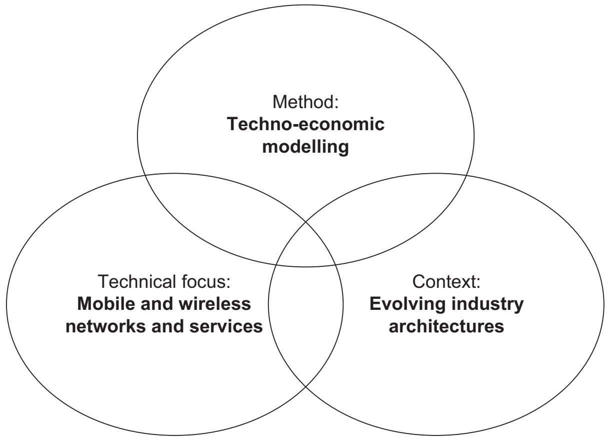


Figure 2.4 Framework of the research

3. Research design and methods

3.1 Research approach

This research is multi-disciplinary in scope, combining theories, models, and methods from the broad fields of engineering and economics. The research can be described as technology-oriented, the main focus being on economic evaluation of technical systems. Accordingly, the research studies artificial as opposed to natural phenomena, and therefore fits well within the scope of design science, grounded in Herbert Simon's work (1996, first published in 1969).

Design science seeks to extend the boundaries of human and organisational capabilities by creating new and innovative artefacts (Hevner et al. 2004). Knowledge and understanding of a problem domain and its solution are achieved in the building and application of the designed artefacts, including constructs, models, methods, and instantiations, which comprise the four types of outputs of the research (March & Smith 1995, Hevner et al. 2004). Research activities, on the other hand, include building and evaluating the artefacts, as well as theorising about them and justifying the theories. Building and evaluating artefacts have design science intent whereas theorising and justifying have natural science intent (March & Smith 1995).

Järvinen (2004) expands the research framework of March & Smith (1995) and suggests taxonomy of six research approaches, which is also useful in positioning the approaches used in this dissertation (Figure 3.1).

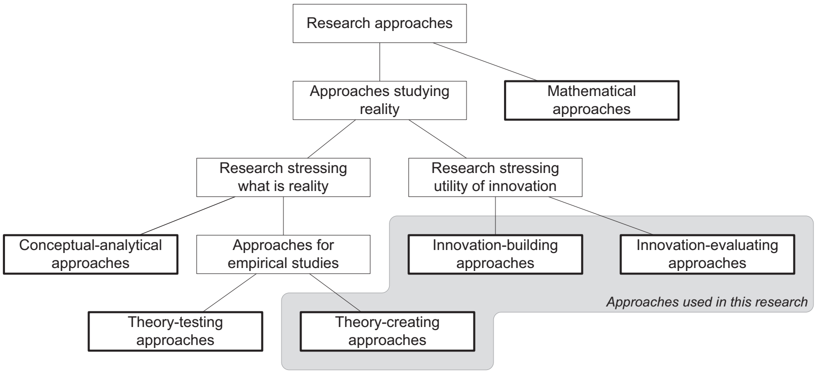


Figure 3.1 Taxonomy of research methods (Järvinen 2004). Modified by adding emphasis on the approaches used in this research.

The techno-economic modelling method aims to determine the economic feasibility of complex technical systems. According to the taxonomy of Järvinen (2004) techno-economic modelling can therefore be categorised as research stressing the utility of innovation, the primary focus being on innovation-evaluating research approach. Additionally, when one considers the actual techno-economic models as outputs of the research, innovation-building approaches are used. Finally, the set of theories, methods, and techniques used in the modelling work can be improved and extended, often requiring theory-creating research approaches to be used. This research uses these three approaches, as presented in Table 3.1.

Table 3.1 Research approaches, methods, and data used in the dissertation

	Objective	Research approach (Järvinen 2004)	Research activities and outputs (March & Smith 1995)	Research methods	Data
Article I: “Virtual operators in the mobile industry: A techno-economic analysis“	To describe the strategic alternatives of virtual operators, and to model and analyse the feasibility of four virtual operator scenarios	Innovation-evaluating (+ innovation-building)	Building and evaluating a model	Techno-economic modelling	Publicly available information on European MVNOs, Mobile network component cost data from ECOSYS project
Article II: “Operator roles in mobile broadcast”	To describe and analyse operator roles in mobile broadcast, and to model the feasibility of selected mobile broadcast value network configurations in the Finnish market				Pricing and cost assumptions based on expert interviews and publicly available reports
Article III: “Techno-economic analysis of fixed WiMAX network deployments”	To analyse the coverage, capacity, and cost characteristics, as well as the competitive potential of fixed WiMAX networks in different market conditions				Publicly available data and statistics about broadband penetration and pricing, component cost data collected from fixed WiMAX vendors.
Article IV: “Framework for analyzing the usage of mobile services”	To suggest and apply a holistic framework that helps in designing communicating, positioning, and comparing mobile service usage research	Innovation-building	Building and evaluating a construct	Literature review	No empirical data, practical experiences from multiple data sets, and data collection and analysis methods
Article V: “Future scenarios for local area access: industry structure and access fragmentation”	To identify and analyse the key uncertainties and to construct alternative future scenarios for local area access	Innovation-building	Evaluating a method Evaluating instantiations	Scenario planning method	Expert opinions collected in number of scenario planning workshops
Article VI: “Mobile data services in Finland: usage of networks, devices, applications, and content”	To analyse the usage of mobile data services in Finland, and to suggest mobile data market metrics that improve the quality of collected statistics	Innovation-evaluating	Evaluating an instantiation (mobile internet in Finland)	Descriptive statistics, analytical framework developed in Article IV	Annual handset populations, monthly handset unit sales, handset feature database, mobile network IP traffic, mobile handset application usage
Article VII: “Technology product evolution and the diffusion of new product features”	To model the evolution process of technology products and the resulting diffusion of new product features, and to develop a forecasting approach for this diffusion	Theory-creating + Innovation-building + Innovation-evaluating	Theorizing a model and method, Building a model and its instantiation Evaluating an instantiation (mobile handsets in Finland)	Estimation of multiple diffusion and replacement models, Time series forecasting	Annual handset populations, monthly handset unit sales, handset feature database

In the techno-economic modelling studies reported in Articles I – III, the research approach is best described as innovation-evaluating, the evaluated innovations comprising of the alternative technical and industry architectures of each study. The approach in these studies is also partly innovation-building, as the techno-economic models built in each study can be seen as innovations, requiring a systematic design process before implementation. The techno-economic modelling process and method is presented in more detail in Section 3.2.

In Article IV, an innovation-building research approach is used, the innovation being a framework for analysing the usage of mobile services, which itself is designed for innovation-evaluating purpose. Accordingly, the framework is utilised in Article VI, in which the broadly defined innovation of mobile internet is evaluated. The purpose of the framework is not to create or justify new theory, but instead help in evaluating the diffusion and usage of mobile service related innovations.

The research approach used in Article V is innovation-building, as the focus is on building the scenarios and the framework around them. On the other hand, the purpose of the scenarios is to aid in evaluating future technology options, linking the results indirectly to a higher level innovation-evaluating approach (i.e. that of evaluating options for future indoor access networks).

A theory-creating research approach is used in Article VII, which identifies the relevance of product features instead of only the aggregate product category level in diffusion research. In the article, the process of technology product evolution and the phenomenon of product feature dissemination are suggested as extensions to research on product category diffusion and replacement. The article uses also an innovation-building approach in developing and implementing a new planning and forecasting approach for the diffusion of mobile handset features. Finally, an innovation-evaluating approach is used when the evolution of mobile handsets and diffusion of handset features in Finland is studied.

3.2 Techno-economic modelling process

In this research, techno-economic modelling methods were used in three different studies:

1. Fixed WiMAX study
2. Virtual operator study
3. DVB-H -based mobile television study

In each of the studies, the modelling followed broadly a similar process, illustrated in Figure 3.2 and described in the following subsections.

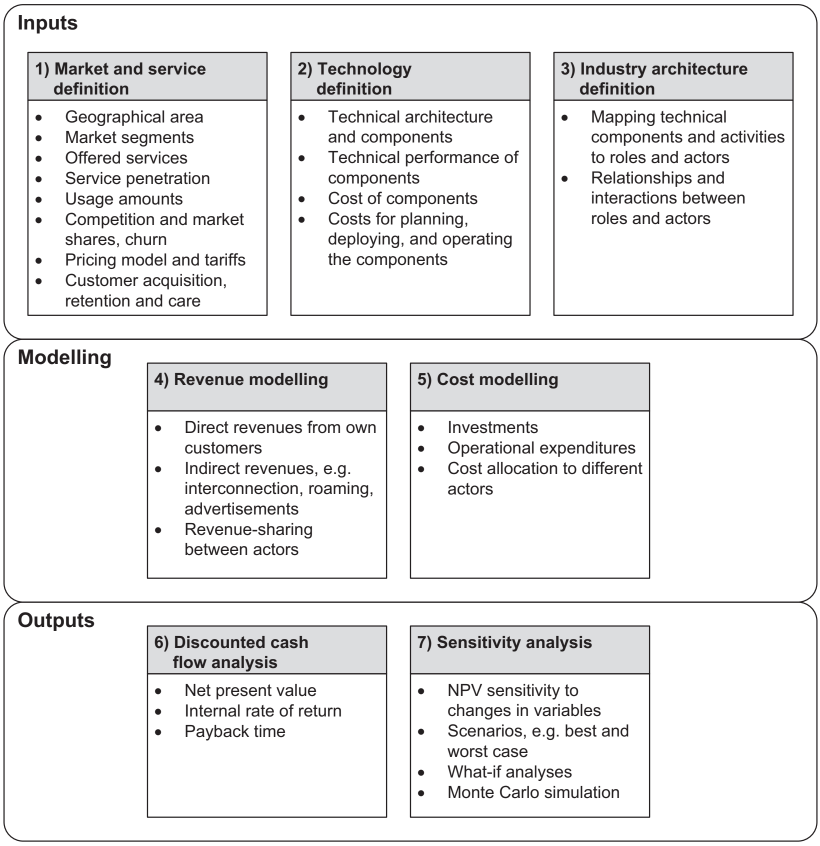


Figure 3.2 Techno-economic modelling process

3.2.1 Service and market definition

The modelling process starts by defining the services and markets in scope of the analysis. The set of services to be offered to the end customers is defined, together with assumptions and forecasts regarding their market penetration, pricing and tariffs, and usage amounts. The market is defined in terms of geographical area and targeted market segments, e.g. different types of businesses and consumers. Also the general market conditions have to be defined, regarding e.g. the level of competition and achievable market share.

3.2.2 Technical architecture definition

Technical architecture defines the technologies, systems, and technical components that are needed to provide the services to the end-users within the market. In case of an incremental investment, the evolutionary steps between the existing and final architectures are defined. Furthermore, the activities required for planning and installing the required equipment are defined, together with operations, administration, and maintenance (OA&M) procedures.

Typically, the technical architecture can be presented as a figure showing the technical components and interfaces between them.

3.2.3 Industry architecture definition

Industry architecture defines the roles required to deliver the services to the end-users, as well as the actors responsible for these roles. A role can be defined as a set of technical components and activities, the responsibility of which is typically not divided between separate actors. Each of the technical components and activities defined in the technical architecture are therefore mapped to roles either separately or together with other components and activities.

Whereas technical architecture is often straightforward to depict as a graphical figure, visualisation of alternative industry architectures can be challenging. Nonetheless, clear graphical representation makes it easier to understand the scope and granularity of the architecture, as well as the roles and interactions of different actors within.

3.2.4 Revenue modelling

After defining the services and markets as well as technological and industry architectures, the modelling process proceeds to the actual modelling of revenues and costs, i.e. cash flows. Implementation of the models typically takes place using spreadsheet applications such as Microsoft Excel, although a number of other, more dedicated tools can be used to carry out some or all parts of the modelling work. Regardless of the tools in use, explicit communication of the modelling logic and input assumptions is essential to establish confidence to the sensibility and correctness of the results, as well as for repeatability purposes.

The number of customers for the services and the tariffs charged are the main inputs for calculating the revenues. In many cases, however, there are also indirect revenues that have to be taken into account. For example, regarding voice call services in mobile networks, interconnection with other operators and roaming users generate additional revenues (as well as costs) for the operator. Other indirect revenue types include e.g. advertising revenues, which in some cases may even dominate over the direct revenues.

Revenue sharing arrangements between different actors within the industry are also modelled, typically as costs from one actor's point of view and as revenues from the other.

3.2.5 Cost modelling

Costs can be generally split between investments and operational costs, or capital expenditure (CAPEX) and operational expenditure (OPEX) in accounting terms[6].

Network dimensioning is carried out to calculate the investments in network equipment required to offer the planned services the end customers. Based on the technical architecture of the modelled system, the characteristics and performance of the nodes and links within, as well as the service usage forecasts, the numbers of network elements and related investments are calculated.

Operational costs include, for example, network-related OPEX (i.e. operations, administration, and maintenance OA&M), sales and marketing costs, billing and customer care costs, interconnection and roaming costs, and general and administration costs. Network-related costs are typically modelled using the calculated numbers of network elements as inputs. Sales and marketing costs depend heavily on strategy and market conditions, and are affected by e.g. churn, handset subsidies, and advertising campaigns. Cost of billing and customer care depends on number of subscribers, whereas interconnection and roaming costs depend on traffic distribution between networks. Finally, general & administration costs are often modelled simply as e.g. some percentage of revenues.

Two approaches exist for cost modelling, differing in their starting point for the modelling process. In a *top-down* approach, the modelling starts from an existing business and network infrastructure, using the observed CAPEX, OPEX, and service usage levels as inputs to calculate costs per e.g. service or customer. In a *bottom-up* approach, the forecast demand for services is used as a starting point and the required costs are modelled so that all customers can be served with sufficient quality (Verbrugge 2007). In techno-economic modelling, the bottom-up approach is preferable and typically used when calculating investments. Operational costs are often modelled using a combination of the two approaches, e.g. by using top-down-calculated reference values from a similar business or project as inputs in a bottom-up-structured model.

3.2.6 Discounted cash flow analysis

In 1970s, discounted cash flow (DCF) analysis emerged as a best practice for valuing corporate assets and investment opportunities (Luehrman

[6] It should be noted that in accounting, CAPEX is capitalised, i.e. added to an asset account and depreciated over many years, whereas OPEX is expensed, having an effect on the current year only. In cash flow analysis, however, both CAPEX and OPEX are attached to the actual time period during which they occur, and no depreciations are considered.

1997). In DCF analysis, the value of a business project equals its expected future cash flows discounted to present value using a proper discount factor. In mathematical terms, the net present value (NPV) of a project can be calculated as

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t}$$

where T is the length of the study period (e.g. in years), CF_t is a cash flow occurring in time period t, and r is the discount rate. NPV is generally considered as the most favourable measure of profitability, leading to better investment decisions than other criteria. According to the NPV rule, a company should invest in any project with a positive NPV. (Brealey & Myers 2000)

Within real firms, the weighted-average cost of capital (WACC) is typically used as the discount rate, although alternative approaches have also been proposed (see e.g. Luehrman 1997). If the analysis is, however, not specific to any particular firm, alternative ways of selecting the discount rate have to be used. In this dissertation, the discount rates have been set to present the industry average at the time of analysis, as perceived by the companies participating in the modelling work and projects.

Another decision has to be made regarding the rest values of the investments made during the time period of analysis at the end of the time period. A number of alternative choices exist, e.g. A, B, and C. In this dissertation, the rest values have been assumed to be zero.

In addition to NPV, other criteria widely used in project valuation include the internal rate of return (IRR) and (discounted) payback period. IRR is closely related to the NPV, as the discount rate that makes NPV=0 is also the IRR of a project. According to the IRR rule, a company should accept investment opportunities offering IRR in excess of their opportunity cost of capital. Payback period is the amount of time it takes before the cumulative incomes equal the initial investments. According to the payback rule, all projects that pay themselves back before a defined cut-off date are considered profitable, thereby ignoring all cash flows after the cut-off date. In its basic form, the payback rule does not take the time value of money into account, although it is possible to use discounted cash flows when calculating a discounted payback period. (Brealey & Myers 2000)

3.2.7 Sensitivity analysis

Base results from the discounted cash flow analysis are important but typically insufficient outputs from techno-economic models. Due to the unavoidable uncertainties in the multitude of input assumptions and forecasts, some insight to the sensitivity of the result to changes in the assumptions is necessary.

The purpose of sensitivity analysis is to study the impact of changes in the input assumptions on the profitability (e.g. the NPV) of the project. The results of the sensitivity analysis can be visualised e.g. in a so-called sensitivity graph, in which the sensitivity of each input variable is reflected by the slope of the respective line.

Whereas sensitivity analysis considers the changes in input variables only one at a time, in scenario analysis many or all of the variables are changed simultaneously. This enables different types of what-if and worst/best case scenarios to be analysed. In Monte Carlo simulation hundreds or thousands of possible scenarios, i.e. combinations of input variables, are generated according to pre-defined probability distributions. Each scenario produces an NPV, and all the NPVs together produce a probability distribution, which is the outcome of the simulation. Monte Carlo simulation requires probability distributions to be specified for all the studied variables, which may often be difficult. (Pike & Neale 2003, p. 288-292)

3.3 Method development

As described above, the research was initiated by conducting the three techno-economic studies included in this dissertation. During this process, the researcher familiarised himself with the available literature, tools, and practices for techno-economic modelling. The researcher also actively participated in the CELTIC/ECOSYS project, during which a new techno-economic modelling tool was built and applied to evaluate a number fixed and mobile network deployment scenarios, not reported in this dissertation. Working closely with a number of method experts and getting constant feedback to the techno-economic modelling work was important in moving from theory to practice and in improving the quality and transparency of the models and results.

Based on the experiences and results from the first part of the research process, a number of improvements to the techno-economic modelling methods were envisioned. Some of these improvements and developments were already utilised during the modelling work, including e.g. extending the scope of the models to analysis and comparison of industry architectures, as well as increasing transparency of the models by explicitly depicting their logical structure together with complete lists of input parameters and values. Most of the actual method development work was, however, done separately from the modelling work. Common to these method development tasks was their overall aim to improve the quality of inputs to the techno-economic models. The tasks included:

1. Constructing a framework for analysing the usage of mobile services
2. Improving the methods used for forecasting the diffusion of mobile handset features
3. Complementing techno-economic modelling methods with scenario planning methods

Results of the method development work are reported in Articles IV-VII and in Section 5.

4. Results from techno-economic modelling studies

In the first part of the research, three separate techno-economic modelling studies were conducted, analysing the feasibility of fixed WiMAX network deployments, virtual operator models in mobile networks, and industry architectures for DVB-H -based mobile television. In the following subsections the purpose, logic, and main results of each of the three studies are presented.

4.1 Fixed WiMAX network deployments

In the first study[7], the purpose was to analyse an 802.16-2004-based fixed WiMAX network deployment, providing fixed broadband services for residential customers and small to medium size enterprises (SMEs). The focus in modelling was on the technical architecture and cost of fixed WiMAX deployment, whereas the industry architecture was assumed to be identical to that of existing broadband networks, comprising of a network operator selling wholesale broadband access services to service operators (Figure 4.1).

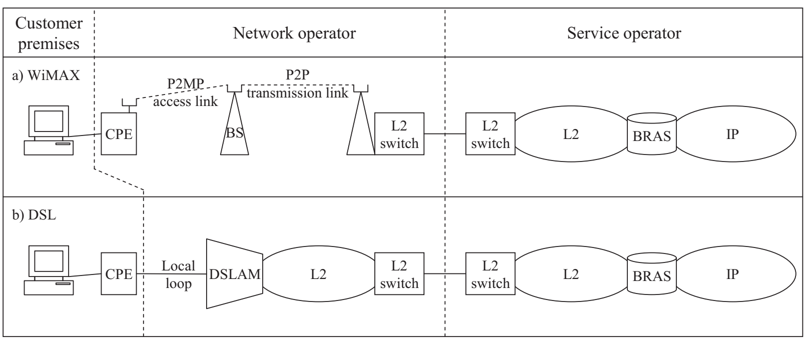


Figure 4.1 Fixed WiMAX study – technical and industry architecture

[7] First version of the study was conducted as the author's Master's thesis project (Smura 2004). The work was then further extended and published first as a conference paper (Smura 2005). Finally, based on another iteration round, the final results were published as a peer-reviewed article in 2008 (Article III of this dissertation).

At the moment of analysis, in late 2005, WiMAX had emerged as a potential challenger for both fixed and mobile broadband technologies, and was surrounded by a lot of hype and often exaggerating views of its performance in the industry press. This served as a motivation also for this study, as systematic, non-biased analysis of the techno-economic performance uncertain of WiMAX was largely missing. In the analysis, the focus was on fixed broadband access services, where WiMAX was assumed to provide a direct substitute to existing DSL and cable modem networks.

The logic of the techno-economic model in the fixed WiMAX study is shown in Figure 4.2. In the model, various market and service related assumptions were first made to calculate the revenues and network capacity demands. The capacity and coverage demands were then used to calculate the required network investments and related OPEX for two fixed WiMAX systems, operating on both 2.5 GHz and 3.5 GHz frequency bands respectively. The economic results were then obtained by assuming a 5-year study period from 2006 to 2010 and a discount rate of 10%.

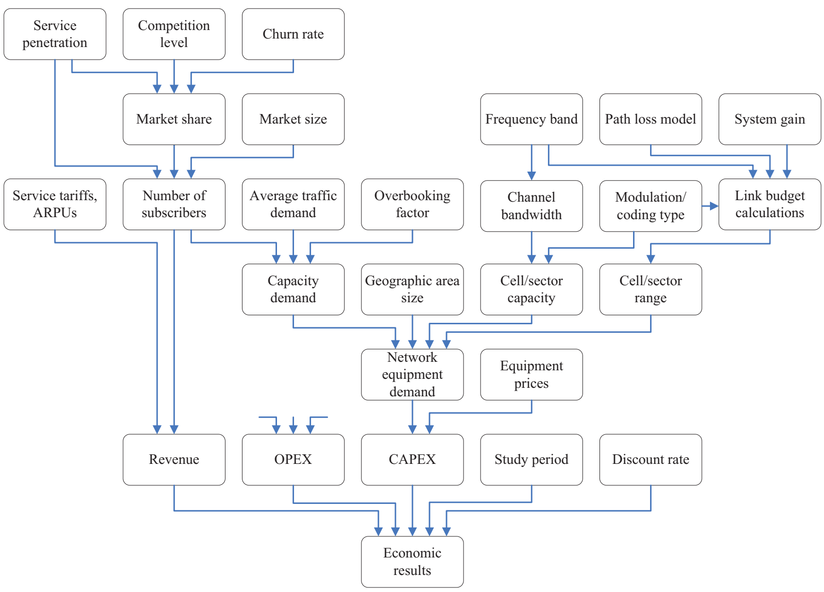
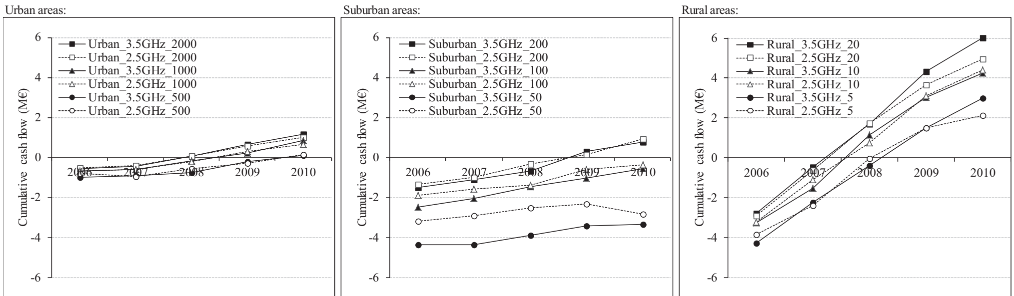


Figure 4.2 Fixed WiMAX study – logic of techno-economic model

For the analysis, a separation between urban, suburban, and rural areas was made, each having different household and business densities and experiencing different levels of competition. For simplicity and comparability, 50.000 households and 5.000 SME offices were assumed to exist in each area type. We forecasted the average maximum data rates (uplink + downlink) to grow 20% per annum from the initial levels of 1 Mbps for households and 2 Mbps for SMEs, and the retail ARPU to decrease 15% per annum from the 2005 levels of 30 and 200 Eur/month (excluding VAT). The higher price per Mbps for SMEs was justified by a lower overbooking factor.

The deployment was assumed to follow the technical architecture of Figure 4.2 and the analysed system to be based on the OFDM physical layer specification of the IEEE 802.16-2004 standard. Channel bandwidths of 5.5 MHz for the 2.5 GHz frequency band and 7 MHz for the 3.5 GHz bands were assumed, and TDD to be used for separating between uplink and downlink transmissions. The spectrum allocation of the analysed operator was assumed to be sufficient for 6-sector base stations to be deployed without co-channel interference having any significant effect on system capacity.

After deciding on the market, service, and technology related inputs and assumptions, economic results for different geographical area types and technology options were calculated. Figure 4.3 shows the results for 2.5 GHz and 3.5 GHz fixed WiMAX systems in urban, suburban, and rural areas with different household densities, respectively.



Case	NPV (M€)	IRR
Urban_3.5GHz_2000	1,017	56,4 %
Urban_2.5GHz_2000	0,956	55,3 %
Urban_3.5GHz_1000	0,695	37,7 %
Urban_2.5GHz_1000	0,634	35,5 %
Urban_3.5GHz_500	0,111	13,4 %
Urban_2.5GHz_500	0,174	15,8 %

Case	NPV (M€)	IRR
Suburban_3.5GHz_200	0,664	24,6 %
Suburban_2.5GHz_200	0,808	29,2 %
Suburban_3.5GHz_100	-0,588	0,5 %
Suburban_2.5GHz_100	-0,236	5,6 %
Suburban_3.5GHz_50	-3,298	-26,2 %
Suburban_2.5GHz_50	-2,186	-19,8 %

Case	NPV (M€)	IRR
Rural_3.5GHz_20	4,887	74,3 %
Rural_2.5GHz_20	4,307	66,9 %
Rural_3.5GHz_10	3,565	50,9 %
Rural_2.5GHz_10	3,658	52,9 %
Rural_3.5GHz_5	2,213	30,7 %
Rural_2.5GHz_5	1,988	30,2 %

Figure 4.3 Fixed WiMAX study – cash flow curves for urban, suburban, and rural areas (NPV and cash flow values in millions of euros)

In urban areas, the more densely populated area scenarios provided clearly positive NPVs, whereas with a density of 500 households / km² the profitability became less clear. In suburban areas, only the most densely populated area turned out positive, whereas with household density of 50 households / km² the profitability of WiMAX deployment was poor. All rural areas proved to be profitable, providing fast payback times and high NPV and IRR levels. Differences between 2.5 GHz and 3.5 GHz systems were generally small, although in suburban areas the 2.5 GHz systems were more profitable due to higher cell range.

The NPV sensitivity to broadband tariffs, base station price, and CPE price assumptions was rather similar in all the area types. Generally, decreasing the total cost of CPEs, including both equipment and installation costs, was identified as the main requirement for fixed WiMAX to succeed in competition against DSL and cable networks. Sensitivity analysis with regard to WiMAX base station sector capacity and range gave different type of results for the different area types, as shown in Figure 4.4.

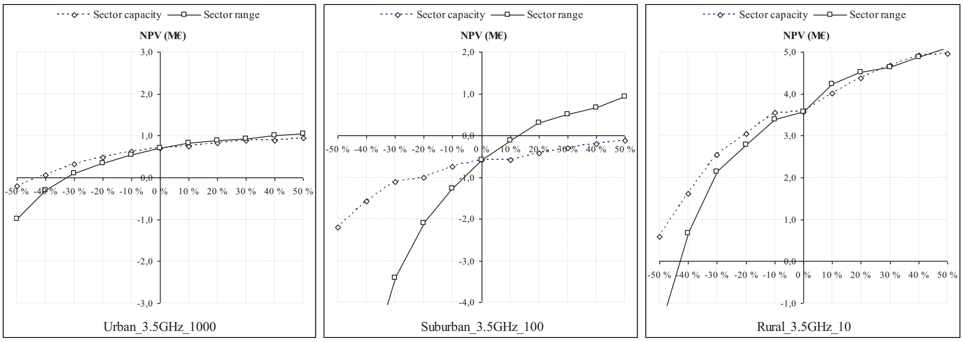


Figure 4.4 Fixed WiMAX study – NPV sensitivity to sector capacity and range assumptions

Whereas the overall shape of the sensitivity graphs is similar in all the areas, the slope of the curves and the relative importance of sector capacity and range differ between the area types. In the urban and suburban areas, NPV sensitivity to sector range is growing slowly when the range is increased, and falling more rapidly when the range is decreased below the base assumption[8], showing that as the number of BS cells becomes capacity-limited rather than coverage-limited[9], the importance of the cell range diminishes. In suburban areas, the project NPV is quite indifferent to increases in the sector capacity, suggesting that the network deployment is still coverage-limited with the base assumptions. In rural areas, the network deployment is more capacity-limited, as the NPV is more sensitive to changes in the sector capacity.

The fixed WiMAX study provides an example of traditional techno-economic modelling, in which the technical architecture and detailed cost modelling of emerging technology alternatives are in focus. Although the industry architecture had to be also clearly and explicitly defined, it was

[8] In sensitivity analysis, the *base assumption* term is used for the original parameter values that are then individually changed to find out their effect on the outputs. Base assumptions represent the objective, best knowledge of the modeller.
[9] A coverage limited network deployment is one in which the maximum range of the base station sectors defines the number of base stations. A capacity limited deployment, on the other hand, is one in which the maximum base station range is not needed, and in which the capacity demand of the service area defines the number of base stations.

assumed as a constant, and alternative industry architectures were not analysed. In the following two studies, this setting was reversed, by assuming the networks to be largely in place and then analysing and comparing the feasibility of alternative industry architectures on top of the technical architecture.

4.2 Virtual operator models

In the second study[10], the purpose was to analyse and compare virtual operator models in the mobile industry. Four virtual operator scenarios were modelled, differing from one another regarding the level of network infrastructure investments and service differentiation. Unlike in the first study on fixed WiMAX, the focus in this study was on the industry architecture, whereas regarding the technical architecture the study simply assumed a standard GSM/WCDMA network, partly outsourced to an existing mobile network operator, partly owned and operated by the analysed virtual operator. Figure 4.5 illustrates the assumed technical and industry architectures for the virtual operator models analysed in this study.

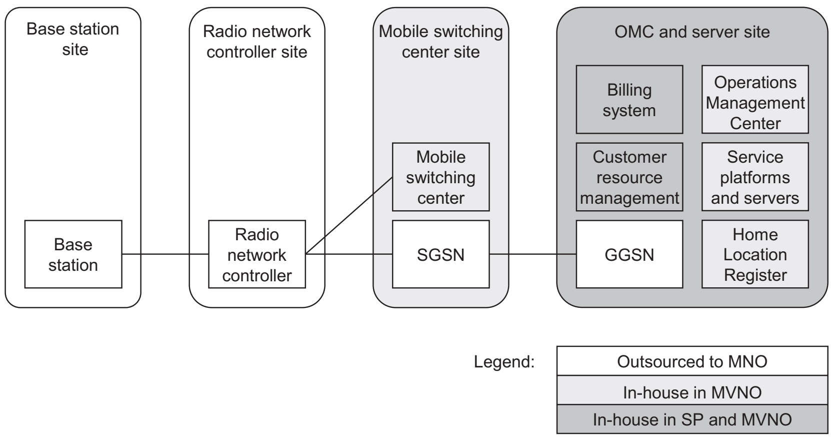


Figure 4.5 Virtual operator study – technical and industry architecture

Two essentially different types of virtual operators were identified based on their level of investments to mobile network infrastructure: Mobile Virtual Network Operators (MVNO) and Service Providers (SP), as

[10] The first version of the techno-economic model was constructed in the ECOSYS project in 2005 and published as a project deliverable edited by the author (Ecosys 2005). The model and analysis was then extended and the results were published first as a peer-reviewed conference paper (Smura et al. 2006) and later as a peer-reviewed journal article (Article I of this dissertation).

illustrated in Figure 4.5. Furthermore, in this study we separated between two different market strategies: a cost leader strategy in which the analysed operator focuses on low-cost voice calls and SMS messages, and a service differentiator strategy in which the operator aims its services at a smaller but more profitable market segment.

At the moment of analysis, in late 2005, virtual operators were still a relatively new phenomenon in the mobile market. After the entrance of Virgin Mobile in the U.K. in 1999, the number of virtual operators increased constantly during the early 2000s, and had reached over 200 in Europe by 2005. However, within this large group, successful virtual operators were rare, exceptions including e.g. Saunalahti in Finland, Chess/Sense in Norway, Telmore in Denmark, and Virgin Mobile in the U.K.[11] This served as further motivation for the analysis work, as detailed cost-benefit analysis of different virtual operator models had not been published earlier.

The logic of the techno-economic model in the virtual operator study is shown in Figure 4.6. Similarly to the fixed WiMAX study, market and service related assumptions were first made to calculate the revenues and network capacity demands. In this study, however, the radio access network was assumed to be in place and the network dimensioning was limited to calculating the required amounts of core network and support system components as depicted in Figure 4.5. Furthermore, special attention was given at detailed modelling of interconnection revenues and costs, as these were identified as a potential reason for operators to choose the MVNO model over the SP model. The economic results were obtained by assuming a 5-year study period from 2006 to 2010 and a discount rate of 10%.

[11] Saunalahti, Chess/Sense, and Telmore were able to reach a market share of about 10% in Finland, Norway, and Denmark, respectively. Notably, Saunalahti was then acquired by the Finnish MNO Elisa in 2005, Chess/Sense by the Swedish MNO TeliaSonera in 2004, and Telmore by the Danish MNO TDC in 2005. In the U.K., Virgin Mobile reached a market share of 8% by 2005 when it was acquired by the cable operator NTL:Telewest, later rebranded as Virgin Media.

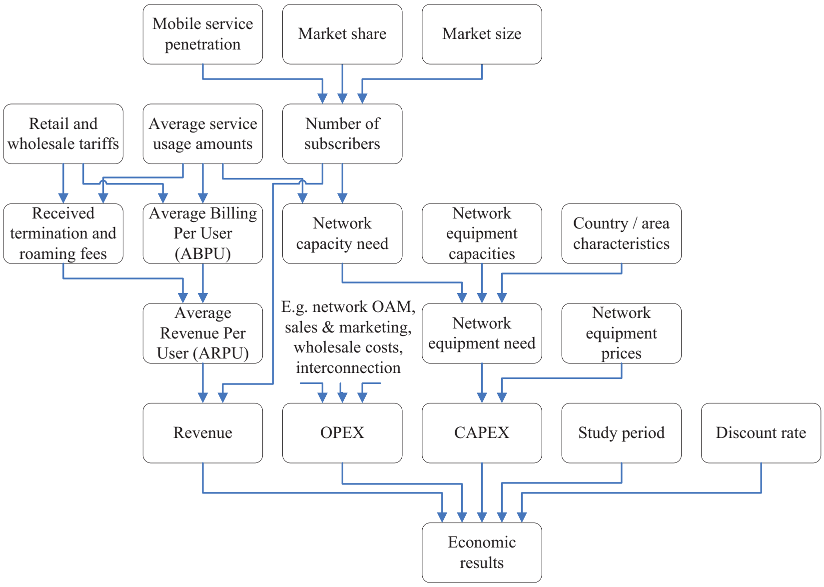


Figure 4.6 Virtual operator study – logic of techno-economic model

In our model, the operator was assumed to enter a market with a population of 6 million people, where significant competition exists and mobile subscription penetrations are at a mature level of 92 percent, growing 2% annually. Majority of the virtual operator's customers were therefore assumed to be acquired from other operators, and the market share of the analysed operator was assumed to reach levels of 10% and 5% at the end of the study period, for the cost leader and service differentiator strategies, respectively.

In the SP model, the revenue streams were assumed to consist only of retail service incomes, whereas in the MVNO model also interconnection (i.e. voice call termination) was assumed to generate revenue. Incomes from retail services were modelled as the product of service tariffs and usage amounts for four different service classes: calling, messaging, data, and content. In the cost leader strategy, Average Billing Per User (ABPU[12]) was assumed to stay in the levels of 24 €/month for the whole study period, whereas in the service differentiator strategy it was assumed to grow linearly from 26 to 30 €/month as a result of increasingly higher revenues from content and data services.

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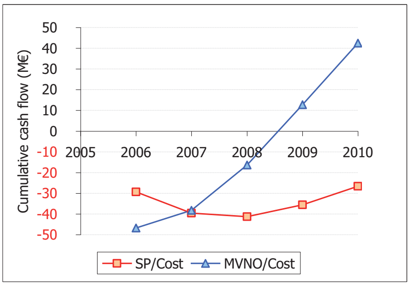
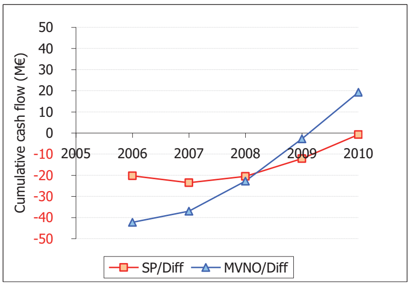
[12] ABPU refers here to the retail revenues collected directly from the customers. In contrast, Average Revenue Per User (ARPU) includes also wholesale revenues collected from other operators, including interconnection and roaming revenues. The traffic and interconnection fee assumptions made in this study resulted in ARPUs of 44 Eur/month and 46 Eur/month in 2006, for the MVNO / cost leader and MVNO / service differentiator strategies, respectively. In the SP model, ARPU is the same as ABPU.

Network investments were assumed to follow the technical architecture of Figure 4.5. In the SP model the investments included the Billing system and the Customer Resource Management (CRM) system, whereas in the MVNO model investments to Operations and Maintenance Center, Mobile Switching Center, Home Location Register, and Intelligent Network platform were also assumed, together with a number of value-added service specific network elements. The packet switched core network (including SGSN and GGSN) was assumed to be outsourced to the MNO also in the MVNO model. Using equipment prices data acquired from a mobile network vendor in the ECOSYS project, the total investments were calculated to be 28 Million euros in the MVNO model and 9 Million euros in the SP model.[13]





Scenario	NPV (M€)	IRR	Payback (yrs)	Scenario	NPV (M€)	IRR	Payback (yrs)
SP/Cost	-27,0	-	>5	SP/Diff	-6,1	-1,0 %	>5
MVNO/Cost	19,3	26,1 %	3,6	MVNO/Diff	4,0	13,8 %	4,1

Figure 4.7 **Virtual operator study – cash flow curves for the SP / MVNO models and cost leader / service differentiator strategies**

For a cost leader strategy, the MVNO model performs significantly better than the SP model, having clearly positive NPV and IRR of 19.3 M€ and 26.1%. The payback time is 3.6 years, whereas for the SP model the cumulative cash flow does not turn positive during the whole study period. For a service differentiator strategy, the difference between the MVNO and SP models is not as significant. Notably, in the MVNO model a cost leader strategy is more profitable, whereas in the SP model it shows clearly worse performance than a service differentiator strategy.

Figure 4.8 illustrates the revenues and cost breakdowns of all the four model / strategy combinations. In the MVNO model, the margin between revenues and costs becomes clearly larger already in the second year of operation, which more than compensates the higher investments and operational costs. The higher margins result directly from the termination

[13] Detailed equipment price lists can be found in ECOSYS Project Deliverable 13 (Ecosys 2005).

fees received by the MVNO, and more precisely from the fixed-to-mobile termination revenues which more than compensate for the mobile-to-fixed termination costs.

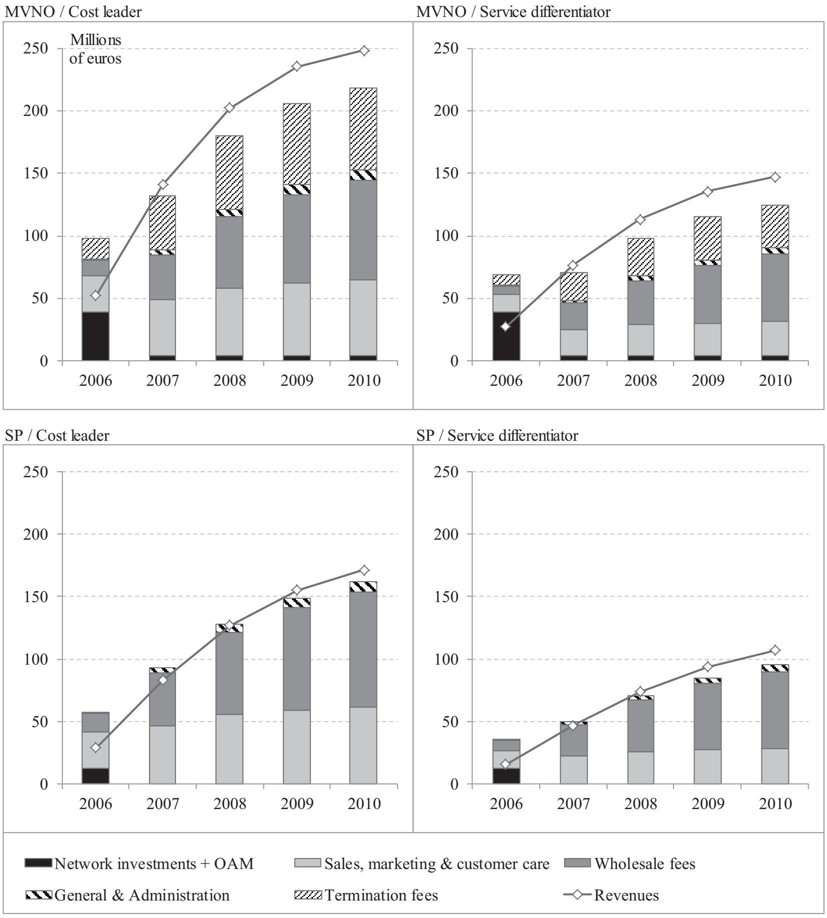


Figure 4.8 Virtual operator study – revenues and costs in the SP / MVNO models and cost leader / service differentiator strategies

In the MVNO model, the revenue margin is sufficiently high in both the cost leader and service differentiator strategies. Because of this, the higher achievable market share of the cost leader strategy makes it more profitable than the service differentiator strategy, although ARPU and per-subscriber revenue margin are lower. In the SP model, the tighter revenue margins turn the positions around, and the service differentiator strategy turns out to be more profitable because of the higher ARPU level.

As shown in Figure 4.8, OPEX clearly dominates the costs of the virtual operator models, whereas investments are less significant. Sensitivity analyses showed that MNO's share of revenue is the single most important parameter in determining the profitability of the models. To be profitable, the SP model requires the MNO's wholesale tariffs to be less than 43% and 47% of retail prices, for the cost leader and service differentiator strategies, respectively. In the MVNO model the respective values are 45% and 42 %. In reality, however, fair wholesale tariffs would be lower for MVNOs than for SPs. By keeping the wholesale tariffs sufficiently high, MNOs can effectively block competition and successful entrance of new virtual operators to the market.

Although the SP model together with a cost leader strategy was found to be the least profitable, most of the virtual operators in the real world belong to this group, and only few MVNOs exist. A possible reason for this is that incumbent MNOs are willing to let low-profitability SPs enter the market more easily than MVNOs, and are thus making the contract terms more favourable for them. Another possibility is that the virtual operators are not willing to move to the more complex MVNO model, e.g. due to lack of technical competence or because the mobile operations are only supporting the company's core business and cross-subsidised by those revenues.

4.3 DVB-H –based mobile television

The third techno-economic modelling study[14] analysed and compared the feasibility of alternative industry architectures for DVB-H –based mobile television service. Similarly to the second study on virtual operators, the technical architecture was fixed, and a DVB-H network was assumed to exist already as was the case in Finland during the time of analysis. Figure 4.9 illustrates the assumed technical and industry architecture in the virtual operator model.

An important decision affecting the industry architecture was made by the Finnish regulator in 2006, when it granted a single license for operating DVB-H –based mobile networks to Digita, also the network operator of the national terrestrial television broadcast networks. The license permitted Digita to act only as a network operator selling wholesale services to other companies, which would then act as service operators and sell retail mobile television and other services to consumers. This decision essentially "fixed" the interface between the network operator and service operator, limiting the range of alternative industry architectures.

[14] The techno-economic model was constructed in 2006-2007 as Tuukka Autio's Master's thesis project (Autio 2007), in which the author was the instructor. The analysis was then extended and published as a peer-reviewed journal article in 2008 (Article II of this dissertation).

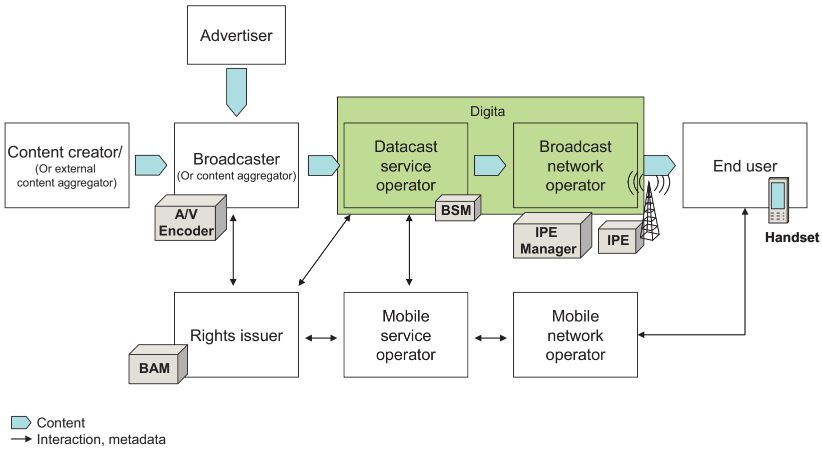


Figure 4.9 **Mobile TV study – technical and industry architecture (Autio 2007)**

Compared to the other two studies where the market was defined more generally, focus in this study was explicitly on the Finnish market. At the time of analysis, in 2007, Digita had already launched its commercial DVB-H network in the capital region around Helsinki and in the cities of Turku and Oulu. The initial population coverage was approximately 25% and in the DVB-H license Digita had agreed to extend the network to at least 40% population coverage by the end of 2007.

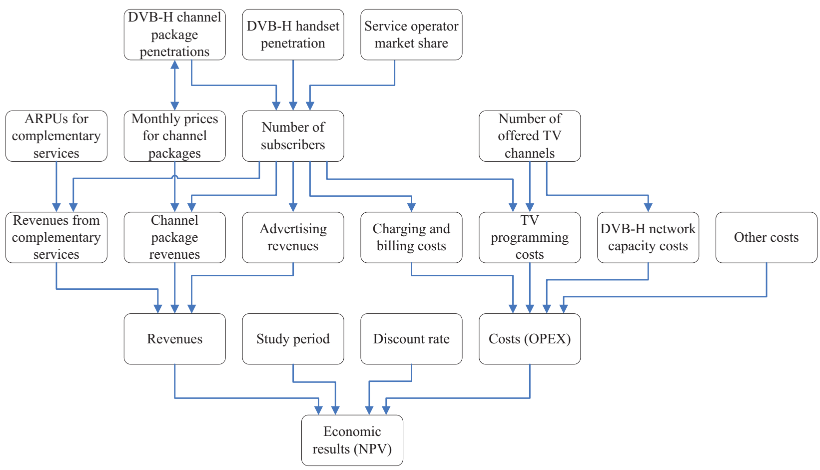


Figure 4.10 **Mobile TV study – logic of techno-economic model**

Figure 4.10 shows the logic of the techno-economic model. The same logic was followed in a total of 42 simulations, separating between seven different industry architectures, three different scenarios regarding service penetration, and two scenarios regarding the availability of free-to-air simulcast content (alongside paid subscriptions). Instead of forecasting the exact profitability of each particular approach, the focus was on comparative analysis between the industry architectures, aiming to find the optimal positions of mobile operators and broadcasters, respectively.

The seven industry architecture scenarios included two mobile operator driven approaches (MNO or MVNO), three broadcaster driven approaches (in-house billing for all channels, outsourced billing for all channels or pay-tv channels only), and two co-operation approached (broadcaster with either MNO or MVNO). A market share of 30% was assumed for a MNO, 10% for a MVNO, and 50% for a broadcaster type of service operator. Whereas mobile operators were assumed to be serving only their own customers, a broadcaster was assumed to sell its services to customers of many mobile operators.

Three forecasts, "optimistic", "average", and "pessimistic" were made for DVB-H handset penetration. The optimistic scenario assumed that the penetration of DVB-H capable handsets would grow at the same pace as the penetration of camera phones in the past, resulting in an S-shaped growth curve with 50% penetration at the end of 2011. Average and pessimistic scenarios assumed 24% and 12% penetration at the end of 2011, respectively.[15]

Due to the high level of uncertainty related to the demand for mobile broadcast services, the simulations were run for a wide range of price / quantity combinations. Three different service bundles or channel packages ("bronze", "silver", and "gold") were modelled, each one offering additional channels over the previous one on a higher price. Based on the model, the number of subscribers and the revenues from channel packages were calculated. The number of subscribers was also used for calculating revenues from advertising and complementary services (e.g. short term pay-TV content).

In the model, the costs comprised purely of different types of operational expenditures. Capital expenditures were assumed to not exist, and e.g. access to required network elements was assumed to be acquired by leasing.[16]

After constructing the model and setting the ranges of variation for the input parameters, a number of simulations were run. More specifically, the

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[15] In hindsight, it is clear that these assumptions were overall far too optimistic. In 2010, only a handful of handset models (Nokia N77, N92, N96, 5330 Mobile TV edition, and LG HB620-T) supported the DVB-H feature, and the total penetration of these devices was insignificant. Finally, in 2011, Digita made a decision to shut down the DVB-H network in March 2012.

[16] For a detailed description of the model and the numeric values of the key input parameters, see Autio (2007).

Monte Carlo method with 1.000 runs was used for each of the 42 simulations. Results of the simulations are shown in Figure 4.11.

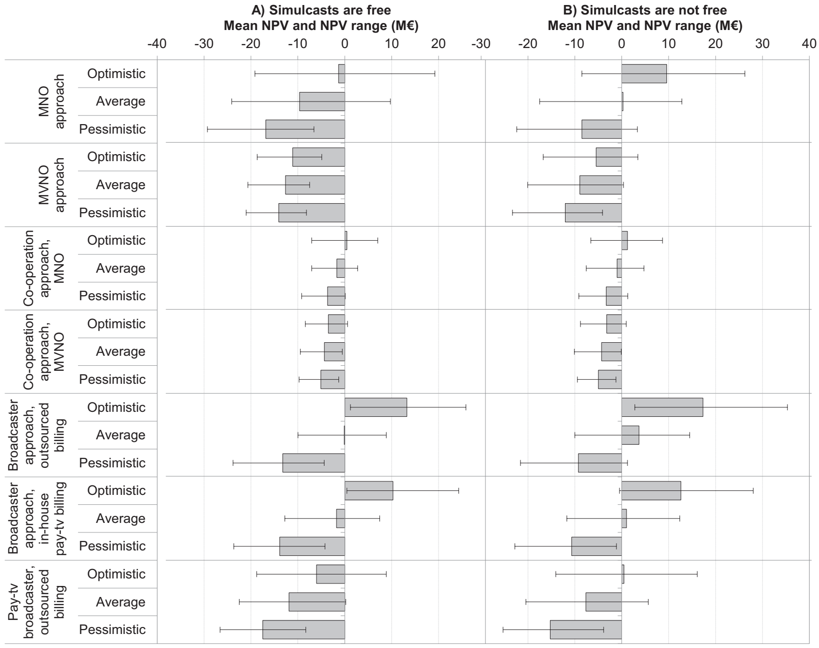

Figure 4.11 Mobile TV study – mean NPVs and NPV ranges for the analysed approaches

Overall, the results show that for MNOs the co-operation approach is the least risky, since broadcasters bear the major risks, i.e. capacity and programming costs. However, also the profit potential of the co-operation approach is limited. The co-operation model seems to be only slightly affected by simulcasts being free or not.

The potential for creating value is higher in the MNO approach, but with a higher risk as well. Here, the simulcasts are in a more important role; if simulcasts are free, the profitability of the MNO approach weakens considerably.

In general, for an MVNO the business case seems worse. Due to the smaller market share, acting as a broadcaster and buying capacity seems unprofitable. Probability of positive net present value (NPV) was low and present only if simulcasts were not free.

The wide spreads in the results for broadcaster approaches show the high risk associated with buying DVB-H capacity and programming for the channel packages. The direct broadcaster approach seems to be slightly more profitable than the indirect one, especially if simulcasts are free. This is due to the high costs of mobile billing compared to alternative methods, such as credit card transactions over the Internet. This indicates a possible conflict of interest between mobile operators and broadcasters, although bypassing mobile operators completely might prove difficult in reality. The pure pay-TV broadcaster approach seems to be very difficult, especially when simulcasts (offered by other players) are free. Market demand might not support buying large amounts of capacity for pay-TV channels.

In conclusion, DVB-H seemed to provide possibilities for viable business but the partially conflicting interests of mobile operators and broadcasters were seen to hinder the formation of mutually beneficial industry architecture. In other markets, some of the complexity related to the linking of two access technologies and related business relationships could be eliminated with a fully integrated vertical industry structure. Finland had chosen a distributed structure to avoid multiple network deployments on a sparsely populated market and at the same time enable service based competition. The overall profitability challenges in the presented scenarios support these policy choices, although the negative effects of increased complexity were also evident.

4.4 Summary of techno-economic modelling studies

In the previous subsections the purpose, logic, and results of three different techno-economic modelling studies were presented. Each of the studies took a somewhat different position regarding their focus on modelling either technical or industry architecture (Figure 4.12).

In Article I, the cost of WiMAX –based fixed broadband access deployments in different geographical area types was in focus. Consequently, the industry architecture was given less attention, and the modelling work simply assumed the existing industry architecture and service characteristics of DSL-based broadband access networks. The value and contribution of the work was in detailed modelling of the technical performance of WiMAX –based systems and the required network investments.

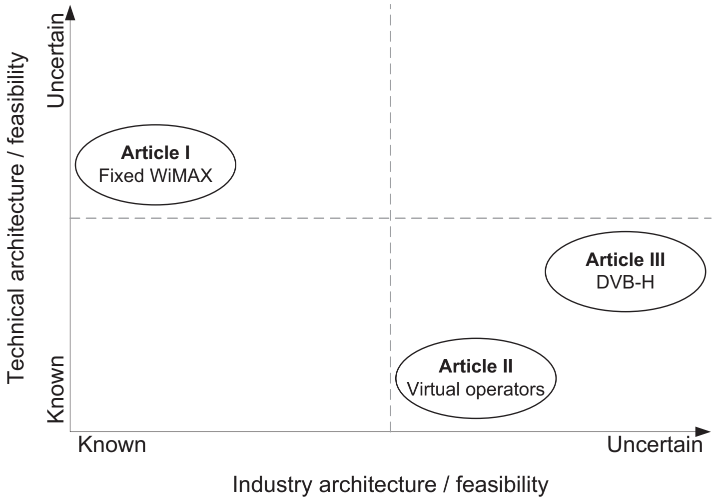

Figure 4.12 Positioning of the techno-economic modelling studies regarding the level of uncertainty and resulting focus on technical and industry architecture

In Articles II and III, the modelling work was more focused on alternative industry architectures and their comparison, whereas the technical architecture and performance of the underlying access networks was not questioned. Article II compared four alternative virtual operator scenarios, assuming a standard GSM/3G network architecture. Article III, on the other hand, analysed and compared seven different industry architectures for DVB-H –based mobile television, assuming the underlying broadcast network was already in place and available for all firms to utilise.

The decision to focus on either the technical or the industry architecture in each of the modelling studies resulted from the respective levels of uncertainty. In Article I (WiMAX) the main uncertainty was related specifically to the technical performance and cost of the systems, whereas in Articles II and III the technology investments were assumed to be mostly made already. Clear focus on either technical or industry architecture also reduced the complexity of the quantitative models to a comprehensible and communicable level. This type of scope limitation may not, however, be always possible, and an exhaustive analysis may require many alternative technical and industry architectures to be modelled and analysed simultaneously. In other words, although the upper-right corner of Figure 4.12 was not covered in this dissertation, this does not suggest that techno-economic modelling work in general should be limited similarly.

5. Results from method development

During the first part of the research, an understanding and experience of the techno-economic modelling methods and practices was reached.[17] Based on the insight and lessons learned during this part, the second part of the research, i.e. method development, focused on improving the quality of inputs to techno-economic modelling work. The following subsections present results from the method development work.

5.1 Methods for measuring and analysing mobile service usage

In techno-economic models, the demand for and usage of services is the basis for both revenue and cost modelling and calculations. For meaningful analysis, reasonable forecasts for future service usage are required. In order to make good forecasts for the future, the present situation must first be understood as reliably and in as much detail as possible. Collecting and analysing data on mobile service usage is, however, becoming increasingly complex as usage diverges between different types of devices and networks. Statistics collected and disseminated by companies, policy-makers, consultants, and academics are often narrow-focused and miss a holistic view on service usage.

The first part of method development work focused on comparing and understanding the relative strengths and weaknesses of different measurement points for mobile service usage data, and applying that experience in developing a framework for analysing the usage of mobile services. The constructed framework was first introduced and demonstrated in Article IV, and then applied for a comprehensive country study of mobile data service usage in Finland in Article VI. The main results of these two articles are presented in the following two subsections.

[17] During the first part, the author actively participated in the European ECOSYS project, in which techno-economic modelling methods were used to analyse both fixed and mobile technology and industry scenarios. During that project, in addition to the three studies presented above as results of this dissertation, the researcher also took contributed to and learned from a number of other techno-economic modelling exercises, including e.g. a WCDMA/HSDPA study and a CDMA-450 study (Harno et al. 2009), and an IMS-based fixed-mobile convergence study (Rokkas et al. 2009).

5.1.1 Framework for analysing the usage of mobile services

The primary purpose of the developed framework is to help in designing mobile service usage research as well as in communicating, positioning, and comparing research results. As such, it improves the quality of mobile service usage studies and the corresponding inputs to techno-economic models.

The framework for analysing the usage of mobile services is depicted in Figure 5.1. The developed framework consists of two layers: measurement points, and technical components of mobile services. The technical components comprise of devices, applications, networks, and content. In addition, the framework presents classifications for each component and the relationships between the components and available measurement points.

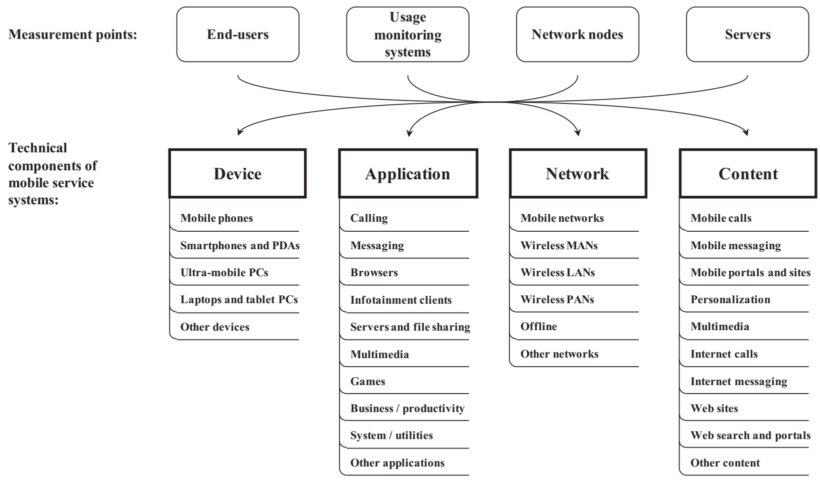

Figure 5.1 A framework for analysing the usage of mobile services

In general, mobile service usage data can be collected from four main sources, as illustrated in Figure 5.2. First, surveys and panels can be used to collect the data directly from the *end-users*. Second, *usage monitoring systems*, including both user monitoring as well as device monitoring, provide data of higher granularity. In mobile handset monitoring, a software agent in a monitored device records what the user does with the device. Third, *network nodes* can be used to collect usage data from a larger user population. Accounting systems registering the usage of chargeable services by individual users are natural sources of information for any service provider. More specific TCP/IP traffic measurements can be also conducted at various network nodes between the devices and servers. Central points of convergence of mobile data traffic should be found to attain comprehensive and representative measurements. Fourth, log files collected by *servers* (e.g. portals and individual Web/WAP servers, search engines, proxy servers) provide an additional source of usage data for the service providers.

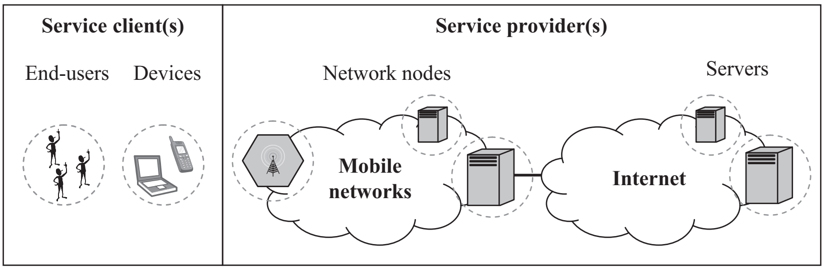

Figure 5.2 Sources of usage data in mobile service systems

Each measurement point can provide data on many of the technical components, but the quality of the collected data differs. In Table 5.1, these differences are presented, separately in two dimensions: data coverage and granularity. Data coverage refers to the proportion of the technical service components and component classes that can be captured by using a certain measurement point. Granularity refers to the level of detail of the collected data. The "+" and "–" signs in the table indicate a relative strength or weakness of data collected from a certain measurement point on a certain component, considering coverage and granularity separately. Regardless of the measurement point, representativeness can be better or worse depending on the properties of the selected sample.

Table 5.1 Coverage and granularity of data collected from different measurement points

	End-users	Usage monitoring systems	Network nodes	Servers
Devices	+ / –	– / +	– / +	– / +
Applications	+ / –	+ / +	– / –	– / +
Networks	– / –	+ / +	– / +	– / –
Content	+ / –	+ / +	– / +	– / +

* In each cell, the first sign refers to the coverage, and the second to the granularity of the data

Data collected directly from end-users has typically good coverage across the service components, as it is possible to ask which devices, applications, and content are used. Detailed information about the usage of different networks is difficult to collect as the network accesses are increasingly transparent to end-users. Granularity of the data collected from end-users is relatively limited compared to the other, technical measurement approaches.

Usage monitoring systems provide accurate, factual information about the used applications and consumed content. Different networks accessed by the monitored devices can be identified, as well as those use cases where no network connections need to be established. Granularity of the collected data is typically good across all the service components. Usage monitoring systems are, however, typically applicable only to one or few of the devices possessed by the end-user, therefore neglecting all the usage that takes place with other devices.

Measurements at network nodes provide accurate and fine-grained data on the usage of the networks and the devices used within them. However, the usage bypassing the selected network nodes and accounting systems cannot be observed, ignoring e.g. WLAN and offline use. This leads to relatively poor coverage of data across the service components. In general, traffic measurements enable the use of more advanced (and more resource consuming) analysis methods than those available in the accounting systems, resulting in better knowledge about e.g. the accessed content.

Finally, measurements done at network servers provide accurate information about the devices and applications used to access the content on those particular servers. Regarding devices, data granularity is rather good, as it is possible for servers to accurately recognise e.g. the operating systems of the devices connected to them. Unfortunately, single server based measurements cannot give a holistic view on the usage of mobile services as the usage is typically fragmented over many servers.

5.1.2 Evaluation of mobile data services usage in Finland

Applying the framework introduced in the previous subsection, the usage of mobile data services in Finland was measured and analysed. The analysis is descriptive by nature and presents detailed information about past market evolution, current market situation, and trends. Furthermore, a number of mobile data market metrics are suggested. Multiple sources of data were utilised, giving complementary viewpoints to the usage of mobile data services and the underlying technical components: networks, devices, applications, and content.

Regarding networks, Finnish operators have made substantial investments into 3G in the past few years, to accommodate the growing data traffic demands. The coverage of 3G networks has constantly evolved, reaching around 80% of the Finnish population in the end of 2008. The increasing coverage and capacity is also clearly visible in the amount of data consumed by the users. During 2008, the volume of packet-switched data transferred in Finnish mobile operators' networks was around 4200 terabytes (TB), corresponding to an eightfold increase to the previous year (Figure 5.3). A major change in the pace of traffic volume growth took place in the fall of 2007, as operators started to aggressively market their mobile broadband subscriptions bundled with HSDPA-capable USB dongles for laptops. Whereas in September 2006, computers accounted for 71% of the total traffic, in September 2008 the share was already 98.5%.

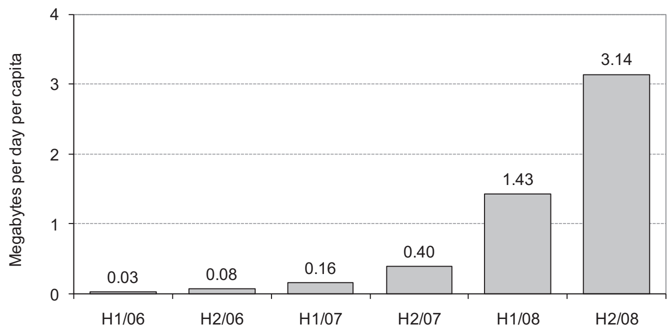

Figure 5.3 **Annual data traffic volume in the Finnish mobile networks, 2006 – 2008 (Article VI)**

Usage of mobile handsets via WLAN networks can be seen as a somewhat reverse development to the growing usage of mobile networks by laptop PCs. This type of usage bypasses the operators' networks, but can be captured by handset monitoring systems, albeit for a much reduced sample of users. In our study, usage of WLAN was not seen to have an adverse effect on the usage of mobile data. On the contrary, WLAN usage correlated clearly with data usage in general, and was minor compared to the usage of mobile networks, as illustrated in Figure 5.4. This increases the validity of the network traffic measurement results, as they can be assumed to have captured a very significant share of all mobile handset usage.

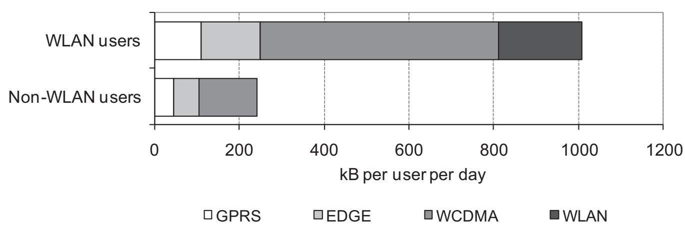

Figure 5.4 **Data usage of WLAN-capable smartphones, Finland 2007 (Article VI)**

In addition to the evolving networks, the mobile handsets of Finnish consumers and professionals have been constantly improving. For instance, in September 2005 the penetration of 3G-capable handsets was less than 1% whereas in September 2008 it had already reached 25%. The penetration of other data service related handset features has also evolved, and almost 80% of Finnish mobile subscribers already have the required capabilities for at least simple data services.[18] However, mobile data capabilities in the networks and devices do not directly lead to mobile data service usage. The percentage of active mobile data users out of all mobile handset users increased from 11.6% in 2006 to 18.0% in 2007, which is significantly less than the penetrations of data capable handsets (e.g. GPRS 66% in 2006, 73% in 2007). This means that in that time period, over 50% of the mobile handset users were not using mobile data even though they had the capability in their handset.

The applications generating mobile data were identified from the mobile network traffic measurements, enabling also comparisons between the profiles of laptop PC and mobile phone –generated traffic (Figure 5.5).

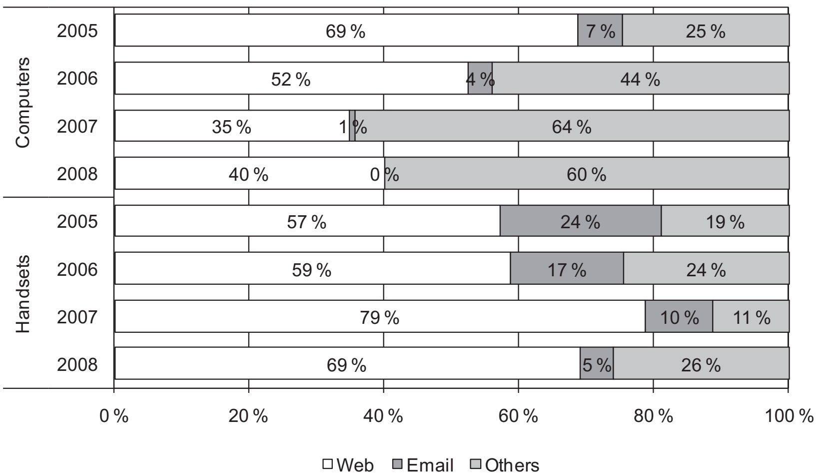

Figure 5.5 **Distribution of traffic between Web, Email, and other traffic types in Finnish mobile networks, 2005 – 2008 (Article VI)**

In the computer generated traffic profile, the share of Web and Email traffic has constantly decreased during the measurement years, whereas the growth of the "Others" category is presumably explained by the growth of peer-to-peer traffic. In traffic generated by mobile handset based on the Symbian OS the share of Web and Email traffic is considerably higher, and the volume of identified peer-to-peer traffic has been insignificant.

[18] More detailed information regarding the diffusion of mobile handset features in Finland is given in Article VII and subsection 5.2.

The usage of individual smartphone applications was identified from the handset monitoring data (Figure 5.6). In the 2007 panel, web browser was found to be the most popular data application among Finnish smartphone-equipped consumers, as 19% of the panellists browsed regularly and 62% at least once during the panel. Internet multimedia applications (e.g. Internet radio or video streaming) and email were less commonly used with only around 20% of panellists using them. Video calls, mobile instant messaging, as well as podcasting were used by very few people. Browsing accounted for 63% of the cumulative packet data traffic, whereas the share of multimedia applications was 25%.

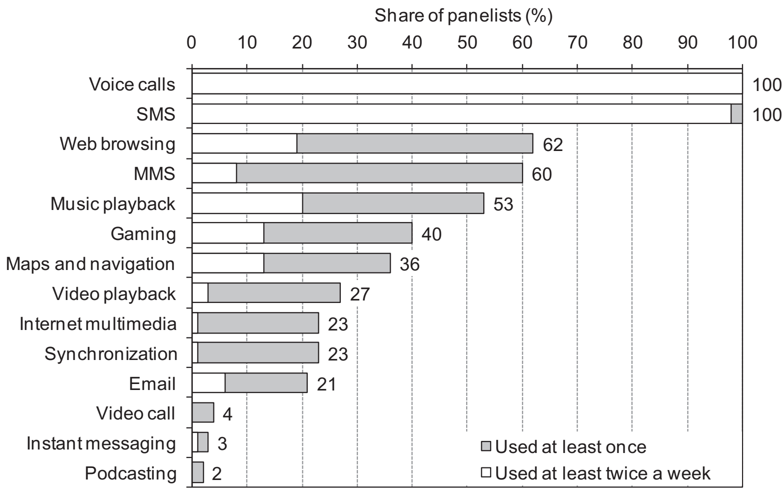

Figure 5.6 Application usage by Finnish smartphone users, 2007 (Article VI)

Finally, the content accessed and consumed with browsers and other applications was analysed utilising data from the mobile network IP traffic measurements. In 2007, the top 15 domains accounted for about a third of the total browsing traffic, whereas the rest of the traffic was distributed over a large number of other web sites. In 2008, the traffic was clearly more fragmented, and the top 15 domains accounted for less than 20% of the traffic. Considering all web sites, traditional Finnish media companies attracted the most usage, followed by social media sites, and adult content. Overall, the share of Finnish web sites was notably high, implying to the importance of local content in mobile browsing.

Although the network traffic measurements covered around 90% of all mobile data traffic in the measured networks, traffic directed to the WAP portals of operators was omitted. A complementary view, including also WAP traffic, was achieved by analysing the domains accessed by the smartphone users of the mobile handset monitoring panels. In the 2007 panel, 90% of all domain accesses were directed to the public Internet, suggesting that the mobile operators' own content is becoming less important as the diffusion of mobile browsing usage continues.

In conclusion, the usage and diffusion of mobile data services in the Finnish market was examined holistically from multiple viewpoints and utilising multiple measurement points, as suggested by the analysis framework developed in Article IV (section 5.1.1). The framework was useful especially in designing and structuring the research, as it facilitated the identification of the relevant viewpoints, the selection of the appropriate data collection methods, and the determination of the scope and limitations of the various research data.

5.2 Approach for forecasting the diffusion of product features

When new mobile and wireless networks are deployed by operators, their usage depends on the diffusion of the respective technologies among consumers, essentially as new features in devices. Forecasting the diffusion of new radio interfaces among the device population is therefore also an important part of many techno-economic modelling studies. Furthermore, other features such as GPS, Java, or HTML browsers act as enablers and platforms for a variety of services and applications, increasing the importance of accurate handset feature diffusion forecasting. In general, however, the diffusion of technology product features has been studied very little. Consequently, as part of the method development work, a new approach for planning and forecasting technology product evolution and the diffusion of new product features was developed in Article VII.

The diffusion of technological innovations and new products is widely discussed in the literature (e.g. Rogers 2003, Mahajan et al. 1995, Meade & Islam 2006). Basic diffusion models, such as the classical model of Bass (1969), use some formulation of an S-shaped curve fitted to historical data to forecast the diffusion and the resulting first purchase sales of new products (Mahajan et al. 1990). As diffusion progresses, first purchase units are replaced by newer units and total unit sales eventually become dominated by replacement purchases. Replacement purchase models (e.g. Olson & Choi 1985, Kamakura & Balasubramanian 1987) decompose total unit sales into first purchases and replacement purchases by making assumptions about the lifetime of sold products (Islam & Meade 2000). In addition, technological substitution models (e.g. Fisher & Pry 1971) have been developed, enabling the evolution of market shares of alternative technologies.

The diffusion of new product features has been previously studied only implicitly. In multigenerational diffusion models, the introduction of a new product feature or a major feature upgrade is seen to result in a significant performance improvement and thereby define a generational change in product evolution, like the transition from monochrome to colour televisions (e.g. Bayus 1992, Islam & Meade 1997). Currently, however, new feature introductions and upgrades are made more often and in higher numbers (e.g. Koski & Kretschmer 2007), and one single feature rarely defines a new generation or a significant performance improvement. Consequently, the boundaries between different generations of technology products have become increasingly vague and an increased level of detail is needed while modelling the diffusion of new features.

The approach for planning and forecasting the diffusion of product features was derived from a formulation of a generic product evolution process. The approach requires three separate phenomena to be modelled, the combination of which enables forecasting of product feature diffusion. First, a product category diffusion model is selected, estimated, and applied in predicting the size of the product population and the numbers of first and additional unit purchases in different time periods. Second, a product unit replacement model is selected, estimated, and applied in predicting the number of replacement purchases in different time periods. Consequently, the unit sales volume of the product is determined by the product category diffusion and product unit replacement behaviour. Third, product feature dissemination model is selected, estimated, and applied in predicting the dissemination share of features among product unit sales in each of the time periods.

The developed approach is not dependent on any specific models for product category diffusion, product unit replacement, or product feature dissemination. A model can be selected, estimated, and applied for each of these phenomena independently. Product category diffusion and product unit replacement have been extensively studied and modelled, whereas product feature dissemination is identified as a previously unexplored phenomenon. The three phenomena as well as the models selected for them in this article are summarised in Table 5.2.

Table 5.2 Models used in planning and forecasting approach

Phenomenon	Product category diffusion	Product unit replacement	Product feature dissemination
Modelling objective	Predict the size of the product population and the numbers of first and additional unit purchases	Predict the lifetime distribution of product units and the number of replacement purchases	Predict the dissemination share of features among product unit sales
Earlier work	E.g. Bass 1969, Mahajan et al. 1990; 1995, Meade & Islam 2006	E.g. Olson & Choi 1985, Kamakura & Balasubramanian 1987	No earlier work
Typically used data	Size of product population	Product category level unit sales data, and assumptions on average and maximum product unit lifetimes	No earlier work
Data used in this article	Size of product population	Product model level unit sales and population data, allowing calculation of unit discards	Monthly sales of product models, product model feature data
Tested models	Bass, Logistic, Gompertz	Weibull, Gamma, Rayleigh, Poisson	Forecasting: analogies, Sensitivity analysis: scenarios
Selected model	Gompertz	Weibull	Forecasting: analogies Sensitivity analysis: scenarios

The developed planning and forecasting approach was used to forecast the diffusion of selected features within the mobile handset population of Finland. The forecasting performance of the approach was also compared to common diffusion models. Two separate feature diffusion forecasts were made, corresponding to notional forecasting situations in September 2007 and September 2008. The diffusion curve of the best fitting benchmark model (Gompertz) and the curve provided by the developed approach for WCDMA (3G) are shown in Figure 5.7.

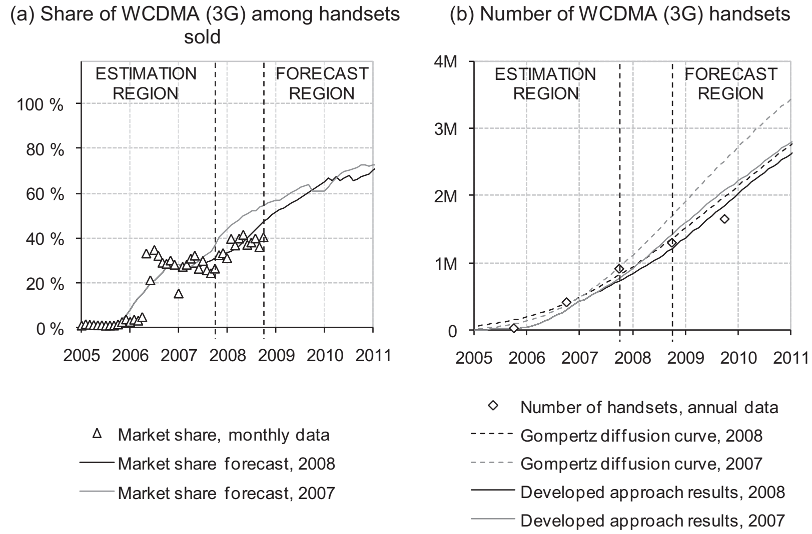

Figure 5.7 Feature diffusion forecasting results. Panel (a): WCDMA dissemination share predictions based on analogies. Panel (b): Resulting WCDMA diffusion curves of the developed approach presented with benchmark model diffusion curves.

The forecasting performance of the developed approach as well as the benchmarking models was evaluated with the available forecast region feature diffusion data for September 2008 and 2009 using root mean square error (RMSE) and mean absolute percentage error (MAPE) as criteria. The developed approach provided better forecasting performance for 14 and 9 out of the 15 compared features for the September 2007 and September 2008 forecasts, respectively. In cases where the benchmark models provided better results, the differences in performance were generally small. The results are presented in more detail in Article VII.

The developed approach also allows a meaningful sensitivity analysis, including the analysis of discontinuous changes in each of the modelled phenomena. Therefore, in addition to forecasts assuming that the underlying processes continue at the prevalent rates, scenarios can be constructed to model changes resulting for instance from supply-side planning and decision-making or major external forces such as new regulations or economic downturns. Consequently, the overall sensitivity of the mobile handset evolution process was studied by evaluating the effects of changes in product unit replacement behaviour and feature dissemination on the diffusion of mobile handset features in 2009 – 2014.

The feature diffusion curves resulting from four different feature dissemination scenarios are shown as the bold solid lines in all panels of Figure 5.8. The evolution of a product population and the diffusion of new product features were found to be fairly slow even in the extreme scenarios. This is particularly noteworthy, as the mobile handset used as an example product in this article is a relatively fast moving technology product. For instance, even if the dissemination share of handsets equipped with the WCDMA feature rose immediately to 100% of unit sales (i.e. Maximum scenario), it would still take four years before their quantity increased from the December 2008 level of 1,300,000 (i.e. about 26% penetration) to 4,700,000 (i.e. about 90% penetration). This slowness results from the nature of the replacement process, where the oldest units are not necessarily replaced first. Similarly, an abrupt end in sales of a certain feature (i.e. Minimum scenario) takes long to affect the total population.

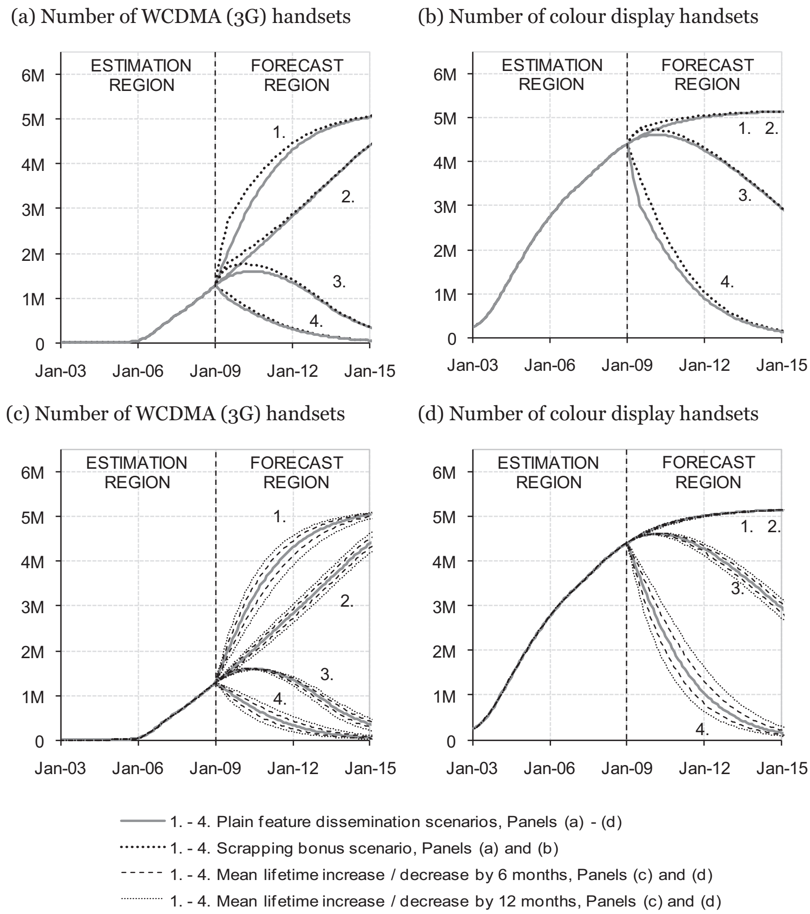

Figure 5.8 Sensitivity analysis results. Panels (a) and (b): Effect of a scrapping bonus campaign on feature diffusion. Panels (c) and (d): Effect of changes in the mean lifetime of handsets on feature diffusion.

The effect of a scrapping bonus campaign on WCDMA feature diffusion is shown in Figure 5.8(a) and Figure 5.8(b). The effect depends heavily on feature dissemination; the higher the dissemination share of the feature, the higher the effect of the scrapping bonus campaign. For instance, during an exemplary six month campaign, the diffusion of WCDMA would effectively increase by 14% points (penetration of 54% instead of 40% in June 2009) under the maximum dissemination scenario, but only 5% points (penetration of 34% instead of 29%) under a more conservative linear growth scenario. However, the effect of the scrapping bonus scenario is also somewhat temporary, as the resulting feature diffusion curves begin to approach the respective diffusion curves without the campaign effects after the campaign has ended.

In case of changes in product unit lifetime (Figure 5.8(c) and Figure 5.8(d)), the resulting effect on feature diffusion was also found to depend heavily on feature dissemination. Overall, the sensitivity of feature diffusion to changes in the replacement model parameters was found to be relatively low, which also implies that small changes in replacement process are not likely to have a significant effect on forecasts made on the diffusion of mobile handset features.

5.3 Scenario planning for techno-economic modelling

Techno-economic modelling methods are suitable for analysing and comparing alternative technology and industry architectures, as concluded in Section 2.4. In many cases the analysed technologies are already standardised, and also the alternative industry architectures may be well known and defined. However, if the objects of analysis are further in the future, uncertainty regarding technologies and industry conditions increases and the modelling task becomes more challenging. Scenario planning methods provide a way to bound this uncertainty and thereby create detailed descriptions of alternative futures that form a basis also for quantitative techno-economic modelling. In this third and final part of method development, the use of scenario planning methods is studied in defining and selecting the technology and industry architectures for techno-economic modelling.

Our issue of interest was initially defined broadly as "How is network connectivity to indoor located devices provided in the future?" Motivation for the study[19] was the common perception that indoor deployments of wireless access points would likely be required to fulfil the future traffic

[19] The study was conducted as part of a research project focusing at local area access systems at Nokia Research Center. After the scenario planning phase documented in this dissertation, the work proceeded to quantitative techno-economic modelling of alternative technical and industry architectures. Results from the techno-economic modelling work have not been published and are also omitted from the dissertation.

capacity requirements. Considerable uncertainty exists, however, about the technologies utilised to provide local area access, as well as the roles of different actors in the industry. In the study, we applied Schoemaker's scenario planning method to identify and analyse key uncertainties and to construct alternative and plausible future scenarios for local area access. The uncertainties and their correlations are presented in Table 5.3.

Table 5.3 Scenario planning for local area access – Key uncertainties and their correlations

Id (Class)	Key uncertainty	Possible outcomes
U_1 (Econ.)	Industry structure	1) Vertical 2) Horizontal
U_2 (Tech.)	Competition between technology substitutes	1) Remain low 2) Increase strongly
U_3 (Reg.)	Spectrum policy and regulation	1) Harmonised 2) Liberalised
U_4 (Reg.)	Role of unlicensed spectrum	1) Limited 2) Significant
U_5 (Tech. / soc.)	Number of connected devices	1) Grow modestly 2) Explode
U_6 (Econ.)	Role of emerging markets in affecting technology choices	1) Minimal 2) Significant locally 3) Significant world-wide

Correlations between key uncertainties

	U_1	U_2	U_3	U_4	U_5	U_6
U_1	1	+	+	+	0	0
U_2		1	++	+	0	+
U_3			1	+	0	0
U_4				1	++	0
U_5					1	0
U_6						1

Based on the list of identified uncertainties, a scenario matrix was formed by selecting U_1 and a combination of U_2, U_3, and U_4 as the two dimensions to be used as the axes. The y-axis of our scenario matrix comprises the industry structure in terms of the level of vertical integration in access and content / applications provisioning. A *vertical industry structure* was defined as one in which network access and content and applications are provided by the same company, bundled, and sold as packages to end customers. The customers make a contract with a single company that satisfies their needs with a complete portfolio containing traditional voice call and SMS applications as well as more advanced data and Internet applications. Bundling leads to a few large players dominating the market and to a lower level of competition in the content / applications market. On the contrary, a *horizontal industry structure* was defined as one in which content and applications are offered individually from access without bundling. Different service components are provided by different players and customers can purchase content, applications, and devices separately from access. From the customer point-of-view, it is easier to switch between access and content / application providers, leading to a higher level of competition in both these markets.

The x-axis of the matrix is defined as the level of technological fragmentation in the access market. In the case of *integrated access* few operators (~3-5) hold the essential spectrum licenses for providing public services. Licenses are granted and restricted to “technology families”, like IMT-2000 and IMT-Advanced for long periods. The number of alternative access technologies remains low and the same technologies are used to serve both outdoor and indoor locations. Unlicensed spectrum is limited to private use by households and businesses. The general level of competition between access technologies and operators is comparatively low. In the *fragmented access* case the number of alternative access operators and technologies and the resulting competition in the access market is high. Usage of licensed spectrum becomes more flexible, as technology neutrality, local licenses, spectrum trading, and more dynamic use of spectrum are required by the regulator as means to induce competition. The role of unlicensed spectrum becomes more significant also in public service offerings.

After deciding on the axes we defined one scenario for each of the cells in our scenario matrix. For each scenario, we provided simple illustrations pointing out the differences between access technologies and their providers as well as content / applications and their providers (Figure 5.9). Wide area (WA) and local area (LA) technologies and four exemplary content / application types (voice, e-mail, maps, and music) are depicted as ellipses and the actors responsible for providing each of these as boxes.

The defined scenarios can be used as a reference when developing technologies and standards for local area networks, to identify bottlenecks of current systems as well as key features required to outperform competing technologies in each of the future scenarios. Furthermore, the scenarios point out local area access provisioning as a potential “gatekeeper role” in the mobile services business more generally.

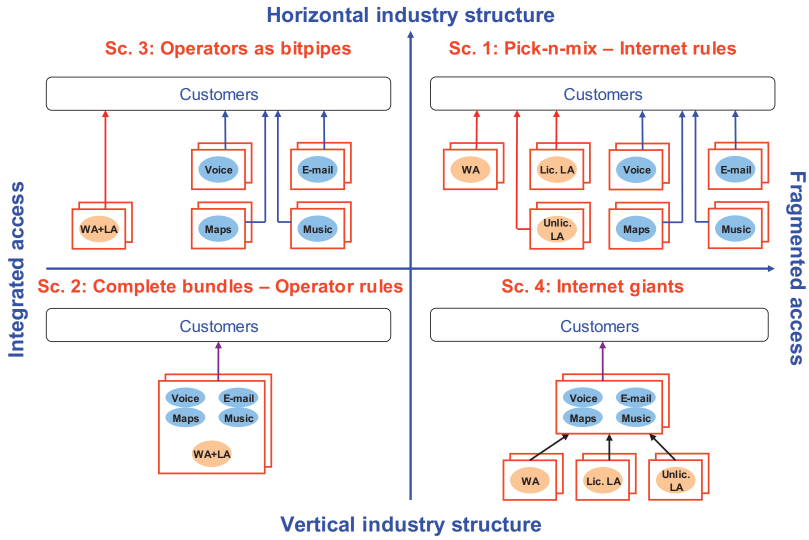

Figure 5.9 Scenario planning for local area access – Scenario matrix

The success of alternative local area access technologies will depend on how well their characteristics and features will match the requirements of the future environment. In the integrated access scenarios (2 and 3) standardised technologies that offer good performance and can scale to different use cases and environments are preferred. Local area networks are deployed and maintained by large access network operators who integrate them tightly into their existing network infrastructure in order to utilise economies of scale in lowering the operational costs. The fragmented access scenarios require somewhat different characteristics from local area access technologies. The access providers may be small and local, and lack the technical expertise for maintaining complex systems. Therefore, installation and maintenance of the networks should be made as simple as possible. Fragmented access may lead to complex deployments where several radio technologies are operating in the same frequency bands including unlicensed bands. This requires that radio technologies have sufficient self-organisation and cognitive capabilities to operate efficiently in heterogeneous radio environments.

Many of the forces identified in our work point out the increasing importance of indoor wireless access networks in the future mobile environment. As a large share of mobile revenues is generated by devices and users located indoors, focusing on local area access might allow new players to enter the access markets and to capture a large share of revenue. Therefore, instead of planning technologies to succeed in each of the potential futures, technology could rather be seen as the means to reach a desired scenario. As none of our scenarios seems to present a “win-win” situation for all the stakeholders, different players are expected to push regulators and standards organisations into different directions regarding local area access development.

The matrix resulting from the scenario planning study combines a technology related dimension as well as an industry architecture related dimension. Although this was not planned when initiating the study, the requirement for using the most important, yet sufficiently uncorrelated uncertainties as the dimensions seems to be naturally met with such a selection. Similar use of technology and industry architecture –related uncertainties as the key scenario dimensions has resulted from some other scenario planning studies as well, including e.g. Levä et al. (2009) and Verkasalo et al. (2009). Although this notion cannot be generalised into a generic guideline for all future scenario planning studies, the combination of technology and industry architecture dimensions has been shown to provide valuable and illustrative scenarios for techno-economic modelling and analysis purposes.

5.4 Summary of method development work

The method development work carried out in this dissertation is summarised by presenting a new framework for techno-economic modelling, illustrated in Figure 5.10. The framework extends and builds on the earlier framework (Figure 2.3) presented by Olsen (1999), which was used as a main reference in the techno-economic models presented in the first part of the dissertation.

The new framework brings forward the methodological contributions of the dissertation. Firstly, the framework identifies *measurements and forecasting* as an essential complementary research domain required for providing the necessary inputs to techno-economic modelling[20]. Within this domain, a separation is drawn between the measurement methods providing factual information about the usage of mobile services and the related technical components, and forecasting methods used to extrapolate this information and to create scenarios for the evolution of markets and services, as well as technical and industry architectures. Devices, networks, applications, and content are explicitly identified as the main technology components of the services. Holistic view of the usage and evolution of each of these components, as well the roles and actors responsible for them are required before advancing to the actual techno-economic modelling.

[20] Earlier, this domain was presented more fuzzily, as a cloud named “Demand for the telecommunications services”, as shown in Figure 2.3.

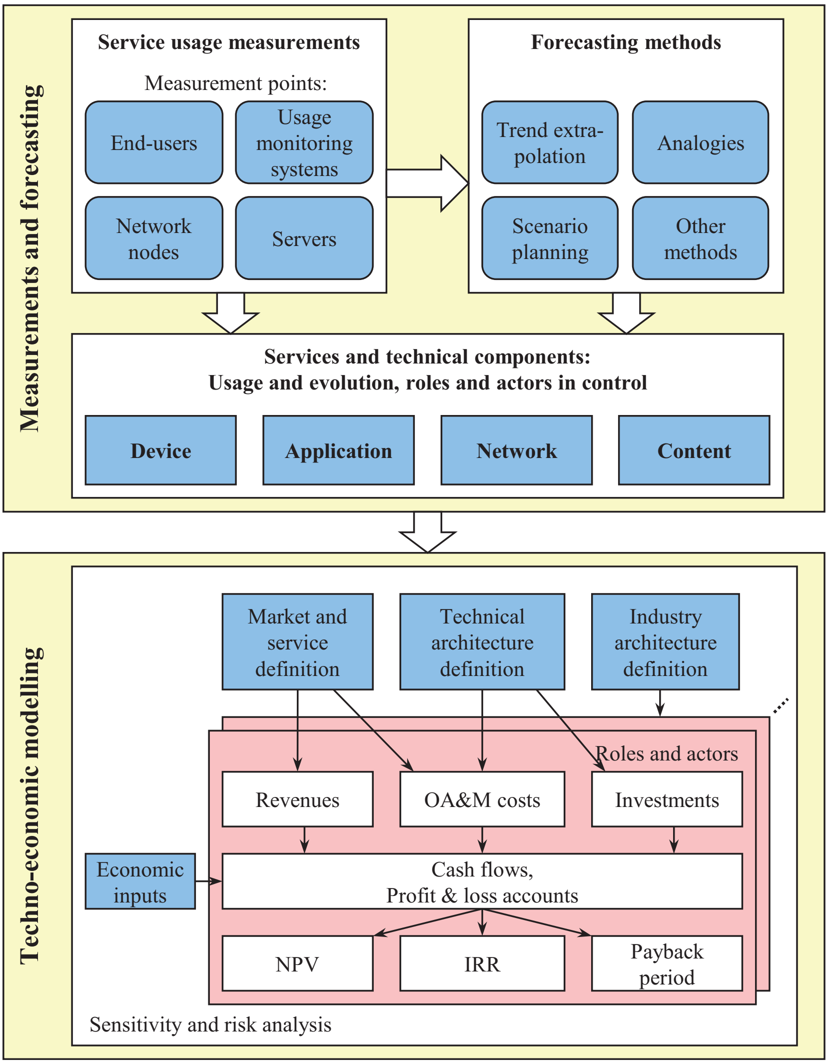

Figure 5.10 **New framework for techno-economic modelling**

Changes are made also within the techno-economic modelling domain. The framework explicitly identifies *market and service*, *technical architecture*, and *industry architecture* definitions as the required inputs for modelling[21]. Addition of the industry architecture dimension highlights the need to define the relevant roles and actors responsible for the different activities and components. Cash flows are then modelled and calculated separately for the key actors of the analysed industry architectures.

[21] In the old framework, "services" and "architectures" were defined (see Figure 2.3), closely resembling the "market and service" and "technical architecture" definitions of the new framework. Industry architecture definition, or any separation between different roles and actors, did not exist in the old framework.

6. Discussion and conclusions

6.1 Summary of contributions

This dissertation makes several contributions to the theory and practice of techno-economic modelling. The dissertation set out to explore how techno-economic modelling methods can be utilised in analysing and comparing the feasibility of wireless access technologies and related industry architectures. The work was organised both chronologically and logically into two parts: 1) techno-economic modelling of selected wireless network and industry architecture scenarios, and 2) development of the techno-economic modelling methods in selected areas.

First, in the field of techno-economic modelling, the dissertation explored the use of the predominantly technology-focused modelling methods in studying alternative industry architectures. Three separate techno-economic modelling studies were presented (Articles I – III and Section 4), analysing the feasibility of fixed WiMAX network deployments, virtual operator models in mobile networks, and industry architectures for DVB-H -based mobile television. In addition to the technology and industry related findings specific to each study, the studies together show how techno-economic modelling methods can be used in analysing and comparing the feasibility of alternative industry architectures. Consequently, a new framework for techno-economic modelling explicitly defining industry architecture as an input and object of analysis was constructed.

Second, the dissertation advances the theory and practise of techno-economic modelling in selected areas (Articles IV – VII and Section 5). A novel approach for planning and forecasting technology product evolution and new product feature diffusion was developed, combining existing models of product category diffusion and product unit replacement behaviour with a previously unexplored phenomenon of product feature dissemination. In addition, a holistic framework for analysing the usage of mobile services was developed, linking available usage measurement points to the four main technical components of mobile services: devices, networks, applications, and content. The framework was also utilised in a study of mobile data service usage in Finland. Finally, scenario planning methods were used to manage and bound uncertainties related to the future of local area access networks, and more generally suggested as a complement to techno-economic modelling in defining and selecting the technology and industry architectures for analysis.

Table 6.1 summarises the key contributions of the dissertation.

Table 6.1 Summary of contributions

<table>
<tr><th>Research topic</th><th>Substance area specific contributions</th><th>Theory and method contributions</th><th>Managerial implications</th></tr>
<tr><td>Fixed WiMAX study (Article I)</td><td>Profitability of 2.5 GHz and 3.5 GHz fixed WiMAX deployments in urban, suburban, and rural areas.</td><td rowspan="3">Expanding the domain of techno-economic modelling from technical architectures to industry architectures.

Explicit definition of industry architecture as an input and object of analysis in techno-economic modelling.</td><td rowspan="3">Explicit definition and application of a systematic techno-economic modelling process, to be used as a guideline and example for practitioners.</td></tr>
<tr><td>Virtual operator study (Article II)</td><td>Conditions for profitable virtual operator business in mobile networks. Comparison of two virtual operator models and two generic strategies.</td></tr>
<tr><td>Mobile television study (Article III)</td><td>Profitability and feasibility of DVB-H – based mobile television in Finland.

Comparison of alternative industry architectures in the Finnish market.</td></tr>
<tr><td>Framework for analysing mobile service usage (Articles IV and VI)</td><td>Factual, holistic description of mobile data service diffusion and usage in Finland in 2005-2008.

Suggestions for harmonised mobile market metrics.</td><td>Framework for analysing the usage of mobile services, linking available measurement points to four technical components of mobile services: devices, applications, networks, and content.</td><td>Supports in designing and interpreting mobile service usage studies. Facilitates selection of appropriate data collection methods, and determination of scope and limitations of various research data.</td></tr>
<tr><td>Mobile handset feature diffusion forecasting (Article VII)</td><td>Factual, detailed description of mobile handset population in Finland in 2005-2008</td><td>New approach for planning and forecasting technology product evolution and new product feature diffusion. Identification and isolation of previously unexplored phenomenon of product feature dissemination.</td><td>A practical tool for planning and forecasting feature diffusion, allowing simulating the effects of managerial and regulatory actions.</td></tr>
<tr><td>Scenario planning for techno-economic modelling (Article V)</td><td>Four future scenarios for future local area access, based on two key uncertainties: access fragmentation and industry structure (bundling of access and services).</td><td>Suggestion to use scenario planning in defining and selecting the technology and industry architectures for techno-economic modelling.</td><td>Suggestion to separately identify uncertainties related to technical and industry architectures when constructing future scenarios.</td></tr>
</table>

The framework for techno-economic modelling introduced by the TERA project (Olsen 1999, Figure 2.3 in this dissertation) was followed and used in the first part of the dissertation. During the course of the work, the need for explicit identification and definition of industry architecture as a main input and object of analysis in techno-economic modelling became evident. Accordingly, the second part of the dissertation concluded with a new framework, in which industry architecture as well as the actors and roles within are explicitly defined.

Service usage measurements are essential in providing the techno-economic modellers and decision makers with invaluable information about the evolution and trends in the services and markets of analysis. Furthermore, the measurements provide information about the comparative performance and positions of different technologies and firms in the market, possibly pointing out strengths and weaknesses in the underlying technical and industry architectures. Together with various forecasting methods (for which the measurements also provide input data), service usage measurements were identified as an essential complement to techno-economic modelling. A number of measurement points and methods were identified and linked to the technical components of mobile services: devices, applications, networks, and content.

Among forecasting methods, diffusion of mobile handset features (and product features more generically) was identified as an unexplored, yet important research field. Handset features can be viewed as enablers for new services and applications, making their diffusion relevant to developers and service providers. A new approach for planning and forecasting the diffusion of product features was developed, combining modelling of three separate phenomena: product category diffusion, product unit replacement, as well as product feature dissemination, which was identified as a previously unexplored phenomenon. The developed approach showed good forecasting performance and was demonstrated to allow a meaningful sensitivity analysis, including the analysis of discontinuous changes in each of the modelled phenomena.

Finally, scenario planning was identified as a method complementing techno-economic modelling especially when the uncertainty regarding technologies and industry conditions is high. The use of scenario planning methods in defining and selecting the technology and industry architectures for techno-economic modelling was studied in the context of indoor deployments of wireless access points. Following the Schoemaker's scenario planning method, the key trends and uncertainties underlying the future evolution of indoor access were identified and used to construct four alternative future scenarios for local area access. The combination of technology and industry architecture dimensions was shown to provide valuable and illustrative scenarios also for techno-economic modelling and analysis purposes.

6.2 Limitations of the research

Some limitations to the present research need to be acknowledged. Firstly, the techno-economic models, as all scientific models, are simplifications of a more complex reality. Defining a suitable scope and level of detail for the models is essential for achieving reliable and relevant results. Correspondingly, the main limitations of the presented techno-economic models result from choices made during the problem definition and modelling process.

In the fixed WiMAX study as well as the virtual operator study, theoretical service areas representing “average Western countries” were assumed. In the mobile television study, the market was even more narrowly defined as the country of Finland. Assumptions regarding e.g. service tariffs, cost of labour, demand for the offered services, and regulation are necessarily very market-specific, thereby also limiting the generalisability of the results.

It should be noted, however, that the potential scope of techno-economic models is very wide, extending from technical to business strategy and policy related areas and issues. Care has to be taken when choosing the right scope for each model, as too many alternative scenarios and degrees of freedom in each of the areas lead to models that are overly complex and difficult to communicate and trust. Special attention should be paid to the trade-offs between scope and complexity; modelling must be detailed and accurate in the focus areas of each model whereas in less important areas unnecessary complexity should be avoided.

The results from the method development work are generally more easily generalised than the techno-economic modelling results. The applicability of the framework for analysing the usage of mobile services (Articles IV and VI) is somewhat limited in time. The general architecture and technical components of mobile services as well as the measurement points are expected to remain the same in the foreseeable future. However, classifications of the service components are less stable and new categories are expected to emerge among each of the components.

The approach developed for planning and forecasting the diffusion of mobile handset features (Article VII) is limited to a sufficiently well-defined product category. In reality, the boundaries of product categories are blurring due to technological convergence and the effect of complementary and substitutive categories on product category and feature diffusion can be significant. Furthermore, the approach essentially applies only to integrated features, and does not take into account features that can be retrofitted or installed to individual units by the end-users.

6.3 Suggestions for further research

In light of the results and experience gained in the process of writing this dissertation, some directions for further research can be suggested.

First, the value of combining technical and industry architecture dimensions in future-oriented technology analysis should be emphasised. Systematic, rigorous, and objective studies analysing and/or forecasting the successes and failures of technologies and standards should be continued, explicitly taking into account these two dimensions and their interplay. Furthermore, it is suggested that combining the design of technical and industry architectures already in the early phases of technology development will increase the probability of success in the market, which should be studied further.

In the field of wireless access networks, the demand for techno-economic modelling of emerging network technologies is evident and increasing, and the on-going evolution towards the future IMT-Advanced systems raises many important questions. When and in which geographical areas should operators start upgrading their existing networks to LTE / WiMAX and later to IMT-A? What are the competitive positions of the different technologies? What is the role of indoor AP deployments, broadcasting networks, new spectrum bands, or cognitive radio in the future network portfolios of operators? Furthermore, in addition to these “what” and “when” types of questions, it is often more important to know “by whom” are the networks deployed and controlled, and the related profits collected. Do new technologies imply changes in the positions of actors within the industry, or vice versa? What are the essential gatekeeper roles in the future network environment, and how will technology developments such as indoor AP deployments, flexible spectrum use, and increasing intelligence in devices change them? Both technology-focused and market-focused studies (i.e. studies comparing technology options widely within a selected market/country) are called for.

In addition to applying the techno-economic modelling methods to new technical and industry architectures, the methods and the “toolbox” around techno-economic modelling can be further developed and extended. Improvements can be made on each of the steps in the techno-economic modelling process. Typically, modelling work is focused on the details of the technical architecture and the investments into network equipment and systems. Methods for analysing operational expenditures therein have been less in focus, albeit their share of the total costs is substantial, meriting further research. Evidently, quantitative modelling and comparison of alternative industry architectures will open many interesting venues for method improvements.

As such, the approach developed for forecasting and planning the diffusion of product features (Article VII) clearly opens many venues for future research. In this dissertation, the product feature dissemination was identified as a previously unexplored phenomenon, yet only the surface of this was scratched. More advanced feature dissemination models can be envisioned, taking into account for instance product unit prices as well as complementary and substitutive nature of specific features. Overall, further research on different markets and product categories is needed to validate the developed planning and forecasting approach.

The service usage analysis framework (Articles IV and VI) focused specifically on the technical components required for delivering mobile services, whereas the industry architecture and mapping of technical components to different roles and actors was left out of the framework scope. Adding this new dimension to the framework and comparing the relative strengths and weaknesses of different measurement points in capturing the usage and users of competing industry architectures can be envisioned. Furthermore, extending the scope of the framework from mobile services to Internet services more generally is possible.

Finally, collecting rich data about mobile users (~ all people) merits further research, related to data collection methods as well as data mining, analysis, visualisation, and interpretation methods. Evolution of measurement systems both in mobile networks (e.g. deep packet inspection, DPI) as well as in devices will enable a new level of detail in usage and user analysis, potentially interesting not only for mobile service providers but to other parties as well. Control over a measurement platform encompassing large numbers of users may become a future gatekeeper role in the mobile industry.

References

Autio, T. (2007) Broadcast Mobile Television Service in Finland: A Techno-Economic Analysis, Master's thesis, Helsinki University of Technology.

Balasubramanian, S., Peterson, R.A. and Järvenpää, S.L. (2002) Exploring the implications of m-commerce for markets and marketing, *Journal of the Academy of Marketing Science*, 30 (4), 48-361.

Ballon, P. (2009) The platformisation of the European mobile industry, *Communications and Strategies*, 75, 15-33.

Barnes, S.J. (2002) The mobile commerce value chain: analysis and future developments, *International Journal of Information Management*, 22 (2), 91-108.

Bass, F. (1969) A New Product Growth Model for Consumer Durables, *Management Science*, 15 (5), 215-227.

Bayus, B.L. (1992) The Dynamic Pricing of Next Generation Consumer Durables, *Marketing Science*, 11 (3), 251-265.

Brandenburger, A. and Nalebuff, B. (1996) *Co-opetition*, New York: Doubleday.

Brealey, R.A. and Myers, S.C. (2000) *Principles of Corporate Finance*, 6th ed., New York: McGraw-Hill.

Cagnin, C., Keenan, M., Johnston, R., Scapolo, F. and Barré, R. (Eds.) (2008) *Future-Oriented Technology Analysis – Strategic Intelligence for an Innovative Economy*, Heidelberg: Springer-Verlag.

Chesbrough, H. and Rosenbloom, R.S. (2002) The role of the business model in capturing value from innovation: evidence from Xerox Corporation's technology spin-off companies, *Industrial and Corporate Change*, 11 (3), 529-555.

Christensen, C.M. and Rosenbloom, R.S. (1995) Explaining the attacker's advantage: Technological paradigms, organizational dynamics, and the value network, *Research Policy*, 24 (2), 233-257.

Coase, R. (1937) The Nature of the Firm, *Economica,* 4 (16), 386-405.

ECOSYS (2005) Evaluation of new business models for emerging mobile network technologies, Deliverable 13. Available at: http://www.celtic-ecosys.org.

Fisher, J.C. and Pry, R.H. (1971) A simple substitution model of technological change, *Technological Forecasting and Social Change*, 3, 75-88.

Gawer, A. (2009) Platform dynamics and strategies: from products to services. In A. Gawer, ed. *Platforms, Markets, and Innovation*. Cheltenham: Edward Elgar Publishing Limited.

Graff, P., Staxen, P., Cleevely, D., Stanislawski, S. and Bailey, R. (1990) Techno-economic evaluation of the transition to broadband networks, Proceedings of the International Conference on Integrated Broadband Services and Networks, 35-40.

Hamelinck, C.N., van Hooijdonk, G. and Faaij, A.P.C. (2005) Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term, *Biomass and Bioenergy*, 28 (4), 384-410.

Harno, J., Katsianis, D., Smura, T., Eskedal, T., Venturin, R., Pohjola, O.-P., Kumar, K. R. R. and Varoutas, D. (2009) Alternatives for mobile operators in the competitive 3G and beyond business, *Telecommunication Systems*, 41 (2) 77-95.

Hevner, A.R., March, S.T., Park, J. and Ram, S. (2004) Design science in information systems research, *MIS Quarterly*, 28 (1), 75-105.

Holmström, B. and Roberts, J. (1998) The boundaries of the firm revisited, *Journa of Economic Perspectives*, 12 (4), 73-94.

Iansiti, M. and Levien, R. (2004) *The Keystone Advantage: What New Dynamics of Business Ecosystems Mean for Strategy, Innovation, and Sustainability*, Boston: Harvard Business School Press.

Ims, L.A., Olsen, B.T., Myhre, D., Lähteenoja, M., Mononen, J., Ferrero, U. and Zaganiaris, A. (1996) Multiservice access network upgrading in Europe: a techno-economic analysis, *IEEE Communications Magazine*, 34 (12), 124-134.

Ims, L.A., Stordahl, K. and Olsen B.T. (1997) Risk Analysis of Residential Broadband Upgrade in a Competitive and Changing Market, *IEEE Communications Magazine*, 35 (6), 96-103.

Ims, L.A. (ed.) (1998) *Broadband access networks, introduction strategies and techno-economic evaluation*, London: Chapman & Hall.

Islam, T. and Meade, N. (1997) The diffusion of successive generations of a technology: A more general model, *Technological Forecasting and Social Change*, 56 (1), 49-60.

Islam, T. and Meade, N. (2000) Modelling diffusion and replacement, *European Journal of Operational Research*, 125 (3), 551-570.

Jacobides, M.G., Knudsen, T. and Augier, M. (2006) Benefiting from innovation: Value creation, value appropriation and the role of industry architectures, *Research Policy*, 35, 1200-1221.

Järvinen P. (2004) *On research methods*, Tampere: Opinpajan kirja.

ITU-R (2003) Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000, Recommendation ITU-R M.1645.

Kamakura, W.A. and Balasubramanian, S.K. (1987) Long-term forecasting with innovation diffusion models: The impact of replacement purchase, *Journal of Forecasting*, 6 (1), 1-19.

Katsianis, D., Welling, I., Ylönen, M., Varoutas, D., Sphicopoulos, T., Elnegaard, N.K., Olsen, B.T. and Budry, L. (2001) The Financial Perspective of the Mobile Networks in Europe, *IEEE Personal Communications*, 8 (6), 58-64.

Koski, H. and Kretschmer, T. (2007) Innovation and Dominant Design in Mobile Telephony, *Industry & Innovation*, 14 (3), 305-324.

Kyriakidou, V., Katsianis, D., Orfanos, I., Chipouras, A. and Varoutas, D. (2011) Business modeling and financial analysis for Metropolitan Area Networks: Evidence from Greece, *Telematics and Informatics*, 28 (2), 112-124.

Lehr, W. and McKnight, L.W. (2003) Wireless Internet access: 3G vs. WiFi?, *Telecommunications Policy*, 27 (5-6), 351-370.

Levä T., Kilkki K. and Hämmäinen H. (2009) Scenario Analysis on Future Internet. Proc. of the First International Conference on Evolving Internet (INTERNET 2009), 23-29 August, 2009, Cannes/La Bocca, France.

Li, F. and Whalley, J. (2002) Deconstruction of the telecommunications industry: from value chains to value networks, *Telecommunications Policy*, 26 (9-10), 451-472.

Lu, K.W., Eiger, M.I. and Lemberg, H.L. (1990) System and Cost Analyses of Broad-Band Fiber Loop Architectures, *IEEE Journal on Seleceted Areas in Communications*, 8 (6), 1058-1067.

Luehrman, T.A. (1997) Using APV: A Better Tool for Valuing Operations, *Harvard Business Review*, (May-June), 145-154.

Lähteenoja, M., Mononen, J., Tahkokorpi, M., Welling, I., Fleuren, F., Drieskens, M., Gieschen, N. and Markatos, S. (1998) Modelling in TITAN. In: L.A. Ims, ed. *Broadband Access Networks, Introduction Strategies and Techno-economic Evaluation*. London: Chapman & Hall.

Mahajan, V., Muller, E. and Bass, F.M. (1995) Diffusion of new products: Empirical generalizations and managerial uses, *Marketing Science*, 14 (3), 79-88.

Mahajan, V., Muller, E. and Bass, F.M. (1990) New Product Diffusion Models in Marketing: A Review and Directions for Research, *Journal of Marketing*, 54 (1), 1-26.

Maggi, W. and Polese, P. (1993) Integrated broadband communications development and implementation strategies, *Electronics & Communication Engineering Journal*, 5 (5), 315-320.

Maitland, C.F., Bauer, J.M. and Westerveld, R. (2002). The European market for mobile data: evolving value chains and industry structures. *Telecommunications Policy*, 26 (9-10), 485-504.

March, S.T. and Smith, G.F. (1995) Design and natural science research on information technology, *Decision Support Systems*, 15 (4), 251-266.

Meade, N. and Islam, T. (2006) Modelling and forecasting the diffusion of innovation - a 25-year review, *International Journal of Forecasting* 22 (3), 519-545.

Monath, T., Kristian, N., Cadro, P., Katsianis, D. and Varoutas, D. (2003) Economics of fixed broadband access network strategies, *IEEE Communications Magazine*, 41 (9), 132-139.

Normann, R. and Ramírez, R. (1993) From value chain to value constellation: Designing interactive strategy, *Harvard Business Review*, 71 (4), 65-77.

Olsen, B.T., Zaganiaris, A., Stordahl, K., Ims, L.A., Myhre, D., Øverli, T., Tahkokorpi, M., Welling, I., Drieskens, M., Kraushaar, J., Mononen, J., Lähteenoja, M., Markatos, S., De Bortoli, M., Ferrero, U., Ravera, M., Balzaretti, S., Fleuren, F., Gieschen, N., De Oliveira Duarte, M. and de Castro, E. (1996) Techno-economic evaluation of narrowband and broadband access network alternatives and evolution scenario assessment, *IEEE Journal on Selected Areas in Communications*, 14 (6), 1184-1203.

Olsen, B.T. (1999) OPTIMUM – a techno-economic tool, *Telektronikk*, 95 (2/3), 239-250.

Olsen, B.T., Katsianis, D., Varoutas, D., Stordahl, K., Harno, J., Elnegaard, N.K., Welling, I., Loizillon, F., Monath, T. and Cadro, P. (2006) Technoeconomic Evaluation of the Major Telecommunication Investment Options for European Players, *IEEE Network*, 20 (4), 6-15.

Olson, J. and Choi, S. (1985) A Product Diffusion Model Incorporating Repeat Purchases, *Technological Forecasting and Social Change* 27 (1985), 385-397.

Pagani, M. and Fine, C. (2008) Value network dynamics in 3G–4G wireless communications: A systems thinking approach to strategic value assessment, *Journal of Business Research*, 61, 1102–1112.

Park. H.-Y. and Chang S.-G. (2004) Mobile network evolution toward IMT-2000 in Korea: a techno-economic analysis, *Telecommunications Policy*, 28 (2), 177-196.

Pike, R. and Neale, B. (2003) *Corporate Finance and Investment, Decisions and Strategies*, 4th ed., London: Prentice Hall.

Porter, M.E. (1985) *Competitive advantage*, New York: The Free Press.

Reed, D.P. and Sirbu, M.A. (1989) An Optimal Investment Strategy Model for Fiber to the Home, *Journal of Lightwave Technology*, 7 (11), 1868-1875.

Riihimäki, V. (2009) Analyzing the WiMAX investment costs and NPV distributions for real option valuation, *Info*, 11 (3), 31-44.

Rogers, E.M. (2003) *Diffusion of Innovations*, 5th ed., New York: Free Press.

Rokkas, T., Varoutas, D., Katsianis, D., Smura, T., Kumar, R., Heikkinen, M., Harno, J., Kind, M., Von Hugo, D. and Monath, T. (2009) On the economics of fixed-mobile convergence, *Info*, 11 (3), 75-86.

Roos, J.P. (1993) 300 000 yuppies? Mobile phones in Finland, *Telecommunications Policy*, 17 (6), 446-456.

Scapolo, F. and Porter, A.L. (2008) New Methodological Developments in FTA, In Cagnin, C., Keenan, M., Johnston, R., Scapolo, F. and Barré, R., (Eds.) (2008) *Future-Oriented Technology Analysis – Strategic Intelligence for an Innovative Economy*. Heidelberg: Springer-Verlag, 149-162.

Shapiro, C. and Varian, H.R. (1999) *Information rules: a strategic guide to the network economy*, Boston: Harvard Business School Press.

Simon, H.A. (1996) *The sciences of the artificial*, 3rd ed., Cambridge: The MIT Press.

Smura, T. (2004) *Techno-economic analysis of IEEE 802.16a-based fixed wireless access networks*, Master's thesis, Helsinki University of Technology.

Smura, T. (2005) Competitive potential of WiMAX in the broadband access market: a techno-economic analysis, in 16th ITS European Regional Conference, September 4-6, 2005, Porto, Portugal.

Smura, T., Kiiski, A. and Hämmäinen, H. (2006) Techno-Economic Analysis of Mobile Virtual Network Operators: Strategies, Investments, and Revenues, in 5th Conference on Telecommunication Techno-Economics, June 8-9, 2006, Athens, Greece.

Stabell, C.B. and Fjeldstad, O.D. (1998) Configuring value for competitive advantage: on chains, shops, and networks, *Strategic Management Journal*, 19, 413-437.

Tahon, M., Lannoo, B., Van Ooteghem, J., Casier, K., Verbrugge , S., Colle, D, Pickavet, M. and Demeester, P. (2011) Municipal support of wireless access network rollout: A game theoretic approach, *Telecommunications Policy*, 35 (9-10), 883-894.

Tee, R. and Gawer, A. (2009) Industry architecture as a determinant of successful platform strategies: a case study of the i-mode mobile Internet service, *European Management Review*, 6 (4), 217-232.

Teece, D.J. (1986) Profiting from technological innovation: implications for integration, collaboration, licensing and public policy, *Research Policy*, 15, 285-305.

Technology Futures Analysis Methods Working Group (2004) Technology futures analysis: Toward integration of the field and new methods, *Technological Forecasting and Social Change*, 71 (3), 287-303.

Tongia, R. (2004) Can broadband over powerline carrier (PLC) compete? A techno-economic analysis, *Telecommunications Policy*, 28 (7-8), 559-578.

Vargo, S.L. and Lusch, R.F. (2004) Evolving to a New Dominant Logic for Marketing, *Journal of Marketing*, 68 (1), 1–17.

Varoutas, D., Katsianis, D., Sphicopoulos, T., Stordahl, K. and Welling, I. (2006) On the Economics of 3G Mobile Virtual Network Operators (MVNOs), *Wireless Personal Communications*, 36, 129-142.

Verbrugge, S. (2007) *Strategic planning of optical telecommunication networks in a dynamic and uncertain environment*, PhD Thesis, Ghent University.

Verkasalo, H., Lindqvist, K. and Hämmäinen, H. (2008) Scenario analysis of the Mobile Voice Services Market, Proceedings of the Asia-Pacific Services Computing Conference, (APSCC '08), Yilan, 9-12 December 2008, pp. 378-384.

Williamson, O.E. (1975) *Markets and hierarchies, analysis and antitrust implications: A study in the economics of internal organization*, New York: The Free Press.

Williamson, O.E. (1985) *The economic institutions of capitalism: Firms, markets, relational contracting*, New York: The Free Press.

Zoulias, E.I. and Lymberopoulos, N. (2006) Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems, *Renewable Energy*, 32 (4), 680-696.

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Rapid innovation in the domains of wireless communications and Internet brings new opportunities and challenges for the industry stakeholders. Increasing uncertainty exists about the role of different wireless technologies and actors providing services in the future network environment. Decision-making and forecasting requires a holistic view, taking into account technology, business, and policy-related aspects. This dissertation applies and develops techno-economic modelling methods for the study of wireless networks and services in the context of evolving industry architectures. The dissertation makes several contributions to the theory and practice of techno-economic modelling. First, the dissertation explores the use of the predominantly technology-focused modelling methods in studying alternative industry architectures. Second, the dissertation advances the theory and practise of techno-economic modelling in selected areas.

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