Evolution of wireless access provisioning

Understanding and managing value system structures and dynamics

Thomas R. Casey





DOCTORAL DISSERTATIONS

Evolution of wireless access provisioning

Understanding and managing value system structures and dynamics

Thomas R. Casey

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Aalto University School of Electrical Engineering Department of Communications and Networking

Supervising professor

Prof. Heikki Hämmäinen

Thesis advisor

Prof. Heikki Hämmäinen

Preliminary examiners

Prof. Pieter Ballon, Vrije Universiteit Brussel, Belgium Prof. Gary Madden, Curtin University, Australia

Opponent

Prof. Luís M. Correia, Technical University of Lisbon, Portugal

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Abstract

The value system around wireless access provisioning consists of a large group of collaborating and competing economic actors, and a complex set of business roles and technical components, where the interactions of parts may cause the emergence of important behavior that we might not be able to see when looking at the parts separately. This thesis examines the evolution of wireless access provisioning by studying the underlying structures and dynamics of the surrounding value system. The thesis takes a systems thinking approach to the problem where one tries to find explanation to complex phenomena by examining the linkages and interactions of elements of a system rather than the individual details, and studies the historical evolution of GSM and Wi-Fi technology tracks and future evolution towards intelligent wireless local area access points and flexible spectrum use.

A two stage approach is used where the focus is first put on value system structures in terms of generic scenarios, concurrent modeling of technical and business architectures of the value system and high level forces driving the structure. The second stage of the research models the value system dynamics caused by endogenous feedback structure and interactions between the economic actors and technical components.

The results of this thesis show how the value system around wireless access provisioning has evolved until now and how it could evolve in the future. The thesis also enhances existing and develops new methods and frameworks for modeling and understanding the structures and dynamics of value systems.

Overall the results of the thesis highlight the importance of understanding dynamic complexity in the management of wireless access provisioning. The results stress the importance of understanding the overall feedback structure of the value system and support the notion that more research is needed to understand dynamic complexity and endogenous feedback structure around wireless access provisioning and ICT services in general.

Keywords	Wireless access p	provisioning,	GSM,	Wi-Fi,	value system,	systems t	hinking
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Tiivistelmä

Toimiala langattomien liityntäverkkojen ympärillä koostuu laajasta joukosta kilpailevia ja yhteistyötä tekeviä taloudellisia toimijoita sekä joukosta toimintarooleja ja teknisiä komponentteja. Näiden vuorovaikutus voi johtaa sellaisiin systeemitason ilmiöihin, joita ei pystyttäisi havaitsemaan, jos kyseisiä systeemin osia tutkittaisiin erillään. Tässä väitöskirjassa tarkastellaan langattomien liityntäverkkojen evoluutiota tutkimalla niitä ympäröivän toimialan perimmäisiä rakenteita ja dynamiikkaa. Väitöskirja tarkastelee langattomien liityntäverkkojen toimialaa systeemiajattelun näkökulmasta, jossa kompleksisia ilmiöitä pyritään selittämään systeemin linkitysten ja vuorovaikutuksen perusteella, ja fokusoituu GSM- and Wi-Fi-teknologiaperheiden historialliseen evoluutioon sekä tulevaisuuden kehitykseen kohti älykkäitä langattomia paikallisia tukiasemia ja joustavaa radiospektrin käyttöä.

Tutkimus etenee kahdessa vaiheessa, missä ensimmäisessä keskitytään toimialan rakenteisiin tarkastelemalla yleisiä skenaarioita, liiketoiminnan ja teknisten arkkitehtuurien rinnakkaista mallintamista sekä korkean tason trendejä, jotka osaltaan vaikuttavat toimialan rakenteeseen. Tutkimuksen toisessa vaiheessa mallinnetaan toimialan dynamiikkaa tarkastelemalla eri toimijoiden keskinäistä vuorovaikutusta sekä toimialan takaisinkytkentärakennetta yleisemmin.

Väitöskirjan tulokset osoittavat, kuinka toimiala on kehittynyt tähän asti kyseisten liityntäverkkojen ympärillä, ja kuinka se voisi kehittyä tulevaisuudessa. Väitöskirja myös parantaa olemassa olevia sekä kehittää kokonaan uusia menetelmiä ja viitekehyksiä toimialamallinnukseen.

Kokonaisuudessaan väitöskirjan tulokset korostavat dynaamisen kompleksisuuden ymmärtämistä langattomien liityntäverkkojen hallinnassa. Tulokset painottavat takaisinkytkentärakenteen ymmärtämisen tärkeyttä ja lisätutkimuksen tarvetta, jotta langattomiin liityntäverkkoihin, sekä ICT-palveluihin yleisemmin, liittyvää dynaamista kompleksisuutta ja takaisinkytkentärakenteita voitaisiin ymmärtää paremmin.

Avainsanat Langattomat liityntäverkot, GSM, Wi-Fi, toimialarakenteet, systeemiajattelu

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Preface

Looking back, this thesis process has been a great adventure and I feel very lucky for having had the opportunity to collaborate with a large group of talented and passionate people. First of all, I would like to thank Professor Heikki Hämmäinen, who gave me a one of a kind opportunity to do a doctoral thesis. Heikki has a deep understanding of many of the key issues in our industry and has also a unique ability to interact with people and identify important possibilities and avenues of research. I feel privileged that I was able to spend this time in his team.

I would also like to thank my co-authors who have all played an important role in this thesis process. I would like to thank Timo Ali-Vehmas for bringing a strong industry point of view to the work and for helping me see the bigger picture. Timo is truly a one of a kind systems thinker and has a rare ability to identify underlying structures in all walks of life. I learned a great deal from him and enjoyed the many discussions we had. I would also like to express my gratitude to Professor Juuso Töyli. Juuso possesses a combination of sharp academic thinking and encouraging personality that is very rare. During difficult times he was able to keep my spirits up and at the same help me in raising the bar in terms of scientific rigor. Furthermore, I would like to thank Dr. Timo Smura for providing guidance especially in the beginning part of the thesis process and for his excellent research work in the area of techno-economic modeling of wireless networks that provided a great platform upon which I was able to build my own work. I would also like to thank my other co-authors Dr. Varadharajan Sridhar, Dr. Mikko Heikkinen and Dr. Antti Sorri for our fruitful collaboration.

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Last, I would like to thank my friends and my family. It is great to know that there is a group of people with whom you can relax and from whom you will get support whenever needed. Finally, Tuija and my little dude, Leo, this one is for you.

Thomas Casey, Espoo, 4th of March 2013

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List of publications

- I M. V. J. Heikkinen, T. Casey and F. Hecht, 'Value analysis of centralized and distributed communications and video streaming', The journal of policy, regulation and strategy for telecommunications, information and media (INFO), vol. 12, no. 5, pp. 42-58, 2010.
- II T. Casey, T. Smura, and A. Sorri, 'Value network configurations in wireless local area access', in Proceedings of the 9th Conference of Telecommunication, Media and Internet Techno-Economics (CTTE), pp. 1-9, Ghent, Belgium, June 2010.
- III T. Casey, 'Analysis of radio spectrum market evolution possibilities', Communications and Strategies, no. 75, pp. 109-130, 2009.
- IV T. Ali-Vehmas and T. R. Casey, 'Evolution of wireless access provisioning: A systems thinking approach', Competition and Regulation in Network Industries, vol. 13, no. 4, pp. 333-361, 2012.
- V T. R. Casey and J. Töyli, 'Mobile voice diffusion and service competition: A system dynamic analysis of regulatory policy', Telecommunications Policy, vol. 36, no. 3, pp. 162-174, 2012.
- VI T. R. Casey and J. Töyli, 'Dynamics of two-sided platform success and failure: An analysis of public wireless local area access', Technovation - The International Journal of Technological Innovation, Entrepreneurship and Technology Management, vol. 32, no. 12, pp. 703-716, 2012.
- VII T. R. Casey and T. Ali-Vehmas, 'Value system evolution towards a cognitive radio era: Implications of underlying market dynamics', in Proceedings of the 2012 IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), pp. 77-88, Bellevue, WA, USA, October 2012.
- VIII V. Sridhar, T. Casey and H. Hämmäinen, 'Flexible spectrum management for mobile broadband services: How does it vary across advanced and emerging markets?', Telecommunications Policy, vol. 37, no. 2-3, pp. 178-191, 2013.

Author's contribution

- I Heikkinen was the head author of the article and wrote the bulk of it. Heikkinen and Casey constructed the analysis framework and did the analysis. Casey reviewed and edited the article. Hecht assisted in the analysis of video streaming services and reviewed the article.
- II Casey and Smura together developed the framework and did the analysis. Casey wrote the first version of the article and Smura and Sorri edited it.
- **III** The author is the sole contributor to this article.
- IV The original ideas for the developed framework came from Ali-Vehmas. Ali-Vehmas and Casey together further developed the framework and did the analysis. Ali-Vehmas and Casey together also wrote and edited the article.
- **V** Casey conducted the interviews, did the analysis and wrote the first version of the article. Töyli provided comments to the analysis and edited the text.
- **VI** Casey did the analysis and wrote the first version of the article. Töyli provided comments to the analysis and edited the text.
- **VII** This article continued the work of Publication IV. Casey developed the first version of the model to which Ali-Vehmas provided comments. Casey and Ali-Vehmas together did the analysis. Casey wrote the first version of the article. Ali-Vehmas added text, further developed some of the conceptual ideas and edited the article.
- VIII Sridhar, Casey and Hämmäinen together formulated the main contents of the article. Sridhar and Casey together did the modeling part. Sridhar gathered most of the data, conducted the interviews and wrote a major part of the article. Casey wrote few sections of the article and edited the rest. Hämmäinen commented and edited the article.

List of abbreviations

2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
3GPP2	3rd Generation Partnership Project 2
4G	Fourth Generation
ABM	Agent-Based Modeling
ACE	Agent-Based Computational Economics
AP	Access Point
ASA	Authorized Shared Access
ANDSF	Access Network Discovery and Selection Function
BS	Base Station
CAS	Complex Adaptive System
CEPT	European Conference of Postal and Telecommunications
	Administrations
CPC	Cognitive Pilot Channel
CR	Cognitive Radio
DSA	Dynamic Spectrum Access
(D)AMPS	(Digital) Advanced Mobile Phone System
DVB-H	Digital Video Broadcasting - Handheld
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDD-LTE	Frequency Division Duplex LTE
GDP	Gross Domestic Product
GSM	Global System for Mobile Communications
GSMA	GSM Association
HIPERLAN	High Performance Radio LAN
HSPA	High-Speed Packet Access
ICT	Information and Communications Technology
iDEN	Integrated Digital Enhanced Network
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMT	International Mobile Telecommunications
IP	Internet Protocol

ISM	Industrial, Scientific and Medical
LA	Local Area
LSA	Licensed Shared Access
LTE	Long Term Evolution
LTE-A	LTE Advanced
MAC	Media Access Control
MNO	Mobile Network Operator
MoU	Memorandum of Understanding
NMT	Nordic Mobile Telephone
NTT	Nippon Telegraph and Telephone
PAWS	Protocol to Access White Space Database
PM	Platform Manager
PMR	Professional Mobile Radio
PDC	Personal Digital Cellular
RF	Radio Frequency
SIM	Subscriber Identity Module
SMS	Short Message Service
SON	Self-Organizing Network
SUR	Spectrum Usage Rights
TACS	Total Access Communication System
TD-LTE	Time Division Duplex LTE
UMTS	Universal Mobile Telecommunications System
VO	Venue Owner
WA	Wide Area
WAP	Wireless Application Protocol
WBA	Wireless Broadband Alliance
WCDMA	Wideband Code Division Multiple Access
WECA	Wireless Ethernet Compatibility Alliance
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WS	White Space

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1. Introduction

This chapter first provides background information for the research work and elaborates on why it is being conducted. The chapter then moves on to describe the research questions, goals and scope of the work and is concluded with an outline of the contents of the thesis.

1.1 Background and motivation

Over the last few decades we have witnessed remarkable growth in wireless communications and as a result wireless networks have become an indispensable part of our society. Wireless networks have so far had a tremendous effect on our lives and the way we interact, and have also become a major contributor to economic growth.

When observing the underlying structures around this evolution, one can see that these advancements have been driven on one hand by technological progress, such as the shift to digital communications, mobile cellular network planning, and new radio technologies, but on a broader level by a value system consisting of a group of collaborating and competing economic actors and a complex set of business roles and technical components. The value system around wireless access provisioning is highly interdependent and features a mix of actors ranging from end-users to retailers, from small wireless local area operators to large mobile network operators and from device to infrastructure vendors, not to mention the various regulatory, technology creation, standardization and certification bodies.

Successes and failures in wireless access provisioning

Overall, this growth has so far been spearheaded especially by wireless access to the telephone network and to the Internet where the major successes of GSM- and Wi-Fi certified IEEE 802.11-based technologies have been leading examples. International harmonization based on the GSM family of technologies has led to a globally interdependent value system of actors with large device circulation, economies of scale and international

Introduction

roaming. It has, for example, been estimated that mobile cellular networks already cover 80 percent of the world's population and serve over 6 billion subscriptions where the share of GSM-based technologies is well over 80 percent¹. Mobile communications has become by far the most important application of the radio spectrum in developed countries² and has also had a remarkable effect in developing countries where many have better access to mobile phones than to other basic utilities such as electricity or heating.

As it relates to Wi-Fi, its growth has also been driven to a large degree by an interdependent collaboration network of actors where e.g. the total number of Wi-Fi chipsets sold has surpassed the 1 billion mark³, household Wi-Fi penetration in most developed countries is well over 50 percent (Strategy Analytics, 2012) and the installed base of Wi-Fi access points (AP) is already in the order of hundreds of millions. It has been estimated that in 2011, Wi-Fi accounted for more than 40 percent of all Internet traffic⁴ and thus, one can observe, that especially private Wi-Fi deployments have become an instrumental part of the overall wireless infrastructure.

While we have had such growth, we have also witnessed the failure or modest success of some technologies such as 3G WCDMA with overvalued spectrum auction prices and slow deployment of networks, DVB-H-based mobile television with a limited availability of compatible handsets and public Wi-Fi with fragmented authentication, roaming and mobility solutions.

Interdependencies that exist in the value system, such as direct and indirect network effects, device and infrastructure economies of scale, and compatibility issues in terms of roaming and mobility that in the case of GSM and private Wi-Fi have led to virtuous cycles and self-sustaining growth have in these cases led to vicious cycles of decline or stagnated growth. Furthermore, what has been interesting to note is that in some cases technologies that have not succeeded in some markets have been a success in others (e.g. mobile TV in Japan).

Many of the laws that govern the value system often follow a winnertakes-all type of dynamics where the high stand-alone value of a technology or a service is not sufficient and where orchestration of a viable overall value system and reaching a critical mass for self-sustaining growth is a

¹ www.gsm.org (accessed 24th of August, 2012). GSM-based technologies include e.g. GSM, WCDMA, HSPA and LTE.

² As shown e.g. by studies in Denmark (Falch and Tadayoni, 2004) and the U.K. (Ofcom, 2006) of radio spectrum contribution to GDP.

³ www.wi-fi.org (accessed 24th of August, 2012).

⁴ Cisco Visual Networking Index,

http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns8 27/white_paper_c11-481360_ns827_Networking_Solutions_White_Paper.html (accessed 3rd of March, 2013).

necessity. Since synchronization and collaboration are often required between the different actors, a holistic view point is needed where the entire value system of economic actors, business roles and technology components is examined and their interdependencies are taken into consideration.

Narrow minded thinking in management of wireless access provisioning

Nevertheless, one can argue that narrow minded thinking, isolated decision making and reductionism are still dominant in the strategic management of wireless access provisioning and also on a broader level in other fields. Most companies still create and evaluate business models in isolation, and often do not realize that its success or failure depends largely on how it interacts with models of other players in the industry and on whether it can be designed to generate self-reinforcing virtuous cycles (Casadesus-Masanell and Ricart, 2011). Furthermore, managers often underestimate the importance of deciding early on between pursuing a product or a platform strategy (Gawer and Cusumano, 2008) where it can be difficult to distinguish the underlying logic of the industry.

In general it has been observed that our ability to perceive the interconnections and feedback structures around us is limited (Sterman, 2002). We typically have a tendency to focus on events and explain things with exogenous factors coming from outside instead of focusing on the feedback structure of the system we are a part of and trying to find an endogenous explanation of how the observed event arose from within the system. Luck and coincidence are a typical part of successes and even in hindsight it is hard to reach a commonly agreed understanding of the factors that have caused successes and failures.

Furthermore, our ability to place events within the context of a larger time horizon is also limited. When we do not have a wide enough time horizon, important lessons learned from history are often quickly forgotten and established path dependencies overlooked. Adding yet another hurdle to the management challenges is that, although a need for a change is recognized, it is very difficult to change the mental models of not only individuals but also the collective mental models of institutions. Since established mental models are rigid and since such changes take a long time, temporary insights are often eventually forgotten and no permanent change happens.

Future of wireless access provisioning

Yet, as we move towards the future it seems that interdependence and complexity around wireless access provisioning will become even greater, making it increasingly difficult for actors to position themselves in the value system. The telecommunications and Internet worlds are colliding on the level of wireless access provisioning and it is quite unclear what will be the outcome. Furthermore, on a global level, the varying characteristics of different countries in terms of market structure and stage of evolution, make it even more challenging to understand the value system as a whole.

Overall, the importance of and demand for wireless access seems to be accelerating even further in the future driven especially by wireless and mobile access to the Internet. Since the rapidly growing demand most likely cannot be purely met by improving the spectrum efficiency of radio technologies, wireless access provisioning will have to on one hand evolve towards smaller cell sizes, increased number of base stations (BS) and the introduction of intelligent wireless local area (LA) access technologies such as self-organizing networks (SON). On the other hand it will also have to evolve towards more flexible use of the radio spectrum with more liberal spectrum licensing schemes and new technologies such as cognitive radio and spectrum databases.

These changes are likely to increase the degree of decentralization and openness in the value system that could enable the entrance of new innovative actors or existing strong players that have thus far not been involved in wireless access provisioning. Overall, it has been observed that such deconstruction (Li and Whalley, 2002) or platformization (Ballon, 2009) of the value system is creating enormous complexity for all the players involved which in turn calls for developing new conceptual frameworks for understanding the current changes in the telecommunications and related industries (Li and Whalley, 2002).

Need for a systems thinking approach in wireless access provisioning

One potential approach in trying to understand the complexity of the value system is to use a systems thinking approach. Systems thinking examines a system by studying the linkages and interactions between the elements of a system (Ackoff, 1971). A core idea of systems thinking is that the interactions of parts of a system may cause the emergence of important behavior that we might not be able to see when looking at the parts individually. Such approach could apply well to understanding and managing wireless access provisioning (and also to other fields in Information and Communications Technology (ICT)) where many of the phenomena can be explained by studying the linkages and interactions of the elements of the surrounding value system.

Furthermore, while the opposite approach of using reductionism and reductionistic methods that isolate technologies and economic actors from each other and study them in more detail, is useful in many cases, it is not always the best approach and an appropriate balance between these two approaches is needed. Often a distinction is made between detailed and dynamic complexity (Senge, 1990) where the former tries to explain phenomena by increasing the number of exogenous variables and detail in a model, and where the latter tries to explain phenomena by modeling the endogenous structure of the system, that is, the linkages and interactions of the elements of a system and the corresponding feedback structure.

Sterman (2000) argues, on a more general level, that there are many issues where dominant theories and approaches are exogenous, event oriented and static rather than endogenous, structural and dynamic. Although some limited work exists, one could argue, in a similar manner, that most of the approaches in wireless access provisioning (and interdisciplinary ICT research in general) are still exogenous, event oriented and static and that an endogenous systems thinking approach to understanding and managing the surrounding value system structures and dynamics is needed.

1.2 Research questions and scope

Motivated by the research gap above, the purpose of this thesis is to examine the underlying structures and dynamics of the evolving value system around wireless access provisioning. On a general level the thesis aims to answer the following research questions:

Q1: How has the value system around wireless access provisioning evolved until now and how could it evolve in the future?

Q2: What kind of underlying value system structures and dynamics can be identified around wireless access provisioning?

Q3: How could value system modeling methods following a systems thinking approach be enhanced to improve the understanding and strategic management of wireless access provisioning?

The simplified technical architecture in Figure 1 shows the scope of this research. As it relates to historical evolution the focus is put on examining

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the evolution of GSM and Wi-Fi certified IEEE 802.11 family of technologies, i.e. the Telecommunications (Telecom) and Internet tracks respectively. Other technology tracks of cellular wide area and wireless local area networks (WLAN)⁵ are not studied extensively.



Figure 1. Simplified technical architecture of wireless access provisioning.

In terms of future evolution the scope is limited to two important trends: firstly, the evolution towards smaller cell sizes and intelligent wireless local area access technologies and secondly, the evolution towards more flexible use of the radio spectrum and liberal spectrum licensing schemes. Finally, as it relates to mobile and wireless services overall, the research is mostly limited to wireless access provisioning and does not study other parts of the value system in detail (e.g. fixed access provisioning or service applications).

As terminology in the existing literature is diverse and can in some cases even be contradictory, in this thesis some frequently used important terms are defined as follows:

Evolution: change (in a value system) over time

Wireless access provisioning: the process of providing wireless access to other networks (e.g. to the telephone network or Internet)

Value system: a set of interlinked economic actors, roles and technical components (including both a business and technical architecture)

⁵ Such as (D)AMPS, iDEN, CDMA (3GPP2), IEEE 802.16 (WiMAX), FlashOFDMA (IEEE 802.20), HIPERLAN and HomeRF.

Value system structures: linkages of the elements of a value system Value system dynamics: interactions of the elements of a value system Business architecture: a set of interlinked economic actors and their business interfaces

Technical architecture: a set of interlinked technical components and their technical interfaces

1.3 Outline of the thesis

This thesis consists of this overview and eight publications. The outline of the thesis is depicted in Figure 2. Chapter 2 provides substance background in terms of the historical evolution of GSM and Wi-Fi and future evolution towards intelligent wireless local area access and more flexible spectrum use. The dualism between the Telecom and Internet tracks continues throughout the thesis. Chapter 3 provides an overview to relevant value system modeling methods and theories that follow a systems thinking approach.



Figure 2. Outline of the thesis.

In Chapter 4 the research methods used in this thesis are introduced in terms of the general research approach, modeling process and research process. In Chapter 5 the results of the research are presented following a

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two stage structure where first, results related to underlying structures and second to underlying dynamics of the value system around wireless access provisioning are presented. Finally, in Chapter 6 the results are summarized, their significance and limitations are discussed, and proposals for future work are made. The original publications are included in the appendix.

2. Evolution of wireless access provisioning

This chapter gives an overview to the historical and future evolution of wireless access provisioning. It begins with a short description of the historical evolution of GSM- and Wi-Fi-based technology tracks⁶ and then moves on to describe future evolution in terms of intelligent wireless local area access and flexible spectrum use. Figure 3 depicts the general structure of this overview and some of the topics discussed.



Figure 3. Simplified evolution of GSM and Wi-Fi tracks.

⁶ For a more elaborate study of the historical developments around GSM and IEEE 802.11-based Wi-Fi the reader can refer to Funk and Methe (2001), Manninen (2002) and Hillebrand (2002) in terms of GSM and Lemstra et al. (2010) and Negus and Petrick (2009) as it relates to Wi-Fi.

2.1 Historical evolution

2.1.1 GSM track

The origins of cellular mobile communications can be traced back to 1947 when Bell Labs introduced the concept of cellular networks to resolve capacity constraints of mobile systems through the geographical re-use of frequencies (Manninen, 2002). During the first steps of commercial deployment of analogue mobile cellular networks in the 1970-1980s the cellular networks were usually operated by government monopolies that controlled the entire value system from technology design and manufacturing to operation of infrastructure and ownership of devices. As a result technologies were typically incompatible between neighboring countries where e.g. at one point in time Europe alone had over 20 different systems (Manninen, 2002). An exception to this were the Nordic countries which had a long history of promoting open exchange of capital, products and services, and ideas (Steinbock, 2003) and together designed and deployed the NMT (Nordic Mobile Telephone) system. The NMT system provided open interfaces between the different technological components of the system which in turn led to a rather vibrant value system with multivendor solutions, roaming between the Nordic countries and end-user ownership of devices.

Later on, as the shift from analogue to digital technologies was ongoing, Europe decided to create a common second generation (2G) standard as a response to the existing technology fragmentation and deploy a harmonized pan-European mobile network. The NMT system, with its established processes and market provided a good basis for the introduction of open interfaces and other critical functionality such as the SIM-card and roaming that in turn enabled large scale interoperability, multi-vendor and multioperator solutions and new services such as the Short Message Service (SMS). An important milestone was reached on 7th of September 1987 when 15 operators from 13 countries signed the GSM Memorandum of Understanding (MoU) stating that they would deploy GSM on the 900 MHz spectrum band (Hillebrand, 2002). Later on in Europe, as the telecommunications industry was being liberalized and spectrum licenses were given to new entrant mobile operators, the technology and spectrum harmonization policy continued and only GSM technologies were used by the operators who subsequently joined the GSM MoU. The GSM MoU later on evolved to the GSM Association (GSMA) that to this day serves as one of the core pillars of the GSM technology track along with the 3rd Generation Partnership Project (3GPP⁷) that has taken the responsibility of standardization (formerly held by CEPT and ETSI).

Although the technology and spectrum harmonization approach has diffused globally and GSM-based technologies are now present in almost all countries in the world there still exists some debate to what degree harmonization should be enforced and to what degree should we follow a technology based competition policy and let the markets choose the best technology, a policy that has been common e.g. in the U.S. Proponents of the latter question that, as long as the networks are interconnected, whether mandated standards are more beneficial than standards determined by the market and whether compatibility matters for the adoption of mobile communications (Gandal et al., 2003). Nevertheless, others have found that standards competition between technologies hinders diffusion (Rouvinen, 2006; Sabat, 2005) and that compatibility between neighboring countries is important (Funk, 1998; Jang et al., 2005).

Overall, GSM-based technologies have been deployed differently in different parts of the world where some countries have continued deploying a mix of incompatible technologies (in addition to GSM e.g. PDC, D-AMPS, iDEN and CDMA including its 3rd generation versions specified by 3GPP2). Countries such as Japan and South Korea have only adopted third generation (3G) GSM-based technologies (i.e. 3GPP WCDMA) and the U.S. and most of the Americas have deployed GSM on different spectrum bands than Europe and most of the rest of the world⁸. Furthermore, especially in emerging markets, such as India, pre-paid subscriptions and multi-SIM phones have become popular and have enabled mobile communications for the poorest demographics, although the quality of networks can vary considerably due to ad-hoc and market driven spectrum management (Sridhar and Prasad, 2011). The traditional GSM markets in Europe, on the other hand, mostly follow a post-paid model with single-SIM phones that are often SIM-locked.

Although the GSM-based systems have gained global dominance their large scale has also led to considerable inertia and rigidities which in turn have made it challenging to introduce new innovations and services, which has been the case e.g. with WAP- and 3G-based data services. This in turn has led to the commoditization of mobile voice and SMS services and fierce price competition in some markets⁹. More recently low cost high bandwidth

⁷ www.3gpp.org (accessed 24th of August, 2012).

⁸ What is rather remarkable is that today one can use a single phone equipped with a chip supporting GSM on 850/900/1800/1900 MHz and WCDMA on 2100 MHz bands, roam to almost any country in the world and use mobile voice services. ⁹ See Smura et al. (2011) for an example of the Finnish market.

connectivity to the Internet and its rapidly growing applications and contents has become the main driver for the deployment of new mobile technologies such as HSPA and LTE where operators are increasingly refarming the traditional GSM spectrum bands for next generation cellular technologies (e.g. WCDMA on 900 MHz and LTE on 1800 MHz)¹⁰. Operators are also increasingly outsourcing the operation of their networks to infrastructure vendors who are able to leverage global level economies of scale.

Finally, as we move towards fourth generation technologies we are witnessing a global convergence to LTE (and its future version LTE-A). Although in third generation systems the GSM-based 3GPP (WCDMA and HSPA) has met some competition from 3GPP2 (CDMA) (and to some degree from IEEE 802.16 WiMAX) now all operators seem to be migrating to FDD-LTE (or to TD-LTE in the case of WiMAX). Furthermore operators are increasingly shaping their networks towards a more flat architecture and smaller cell sizes.

2.1.2 Wi-Fi track

The foundations of wireless local area access can be traced back to the 1940s and to the invention of spread spectrum technologies which have become a key enabler of decentralized radio communications and also to the invention of the ALOHA protocol in the 1970s which provided a simple collision avoidance scheme for wireless nodes to co-exist and be less greedy on using the wireless channel (Lemstra et al., 2010).

In terms of regulatory policy, a major milestone was reached in 1985 in the U.S. where the national regulator, the Federal Communications Commission (FCC), decided to allow the unlicensed use of spread spectrum technologies in the bands designated for industrial, scientific and medical (ISM) applications (Lemstra and Hayes, 2009). Subsequently, this new opportunity led to a large number of competing technologies and applications (Negus and Petrick, 2009) ranging from wirelessly connecting cash registers to university wireless local area networks (e.g. HomeRF and WaveLAN systems and later on HIPERLAN in Europe). The systems were, however, mostly incompatible and as concerns were raised about incompatibility problems, standardization began in IEEE 802.11¹¹. Standardization, however, was still internally somewhat fragmented which finally led to the formation of the Wireless Ethernet Compatibility Alliance (WECA), which today is known as Wi-Fi Alliance, that provides a multi-

¹⁰ The term refarming is sometimes used solely to refer to the deployment of new services on a given spectrum band. In this work the word refarming is also used for deploying new technologies on a given spectrum band.

¹¹ www.ieee802.org/11 (accessed 24th of August, 2012).

vendor interoperability certification mechanism for the IEEE 802.11 standards (Negus and Petrick, 2009).

As it became easier to deploy and configure Wi-Fi access points, Wi-Fibased systems started expanding from enterprises to households where the driving use case was private access to the Internet (Negus and Petrick, 2009) and as volumes grew a large group of network equipment, device and chipset manufacturers started to gradually endorse Wi-Fi.

Although private Wi-Fi deployments in enterprises and households, working on the 2.4 GHz ISM band, have spread widely, public Wi-Fi deployments have remained fragmented with no common authentication or roaming functionality in place. Venue owners, such as coffees shops or airports, offering public access (e.g. to attract customers) are typically either distributing access keys themselves, use the global credit card network or leave the access point unencrypted thus making it available for all. Furthermore, the scalability of the IEEE 802.11 media access control (MAC) protocol is limited and as the number of devices and the density of access points exceeds a certain limit throughput drops and the unlicensed spectrum band can become highly congested.

In terms of the relationship between Wi-Fi and mobile networks it has been unclear whether they are substitutes or complements (Lehr and McKnight, 2003; Lemstra and Hayes, 2009). Although many interworking solutions between WLAN systems and mobile networks have been specified thus far none have diffused widely and the networks have remained isolated from each other.

However, as dual mode handsets and laptops supporting both Wi-Fi and mobile broadband are becoming available, we are starting to witness a collision of these isolated technology tracks. For example laptops, which have traditionally used Wi-Fi access points to access the Internet, are starting to use mobile networks and vice versa mobile devices, which have traditionally used mobile networks for wireless connectivity, are gradually starting to use Wi-Fi access points. Furthermore, mobile operators are increasingly trying to off-load traffic from their mobile networks to Wi-Fi access points and on the other hand end-users are increasingly turning their devices into Wi-Fi access points and backhauling the aggregate traffic through the mobile networks.

2.2 Present and future evolution

As discussed in the above section, one can argue that the Telecommunications and Internet tracks are currently colliding on the level of wireless access provisioning where the use case driving the increasing demand for more bandwidth seems to be wireless and mobile access to the Internet. Recently many mobile operators, for example, have seen substantial growth in terms of data traffic in their wide area networks fueled especially by an increasing number of laptop users and by the diffusion of flat rate pricing. Such growth is expected to continue as the number of connected devices and high bandwidth consuming applications increases which in turn presents significant challenges to the existing wireless infrastructure and its ability to scale up in order to meet the rising demand cost-efficiently.

Roughly speaking one can distinguish three ways to cater to the increasing demand:

- 1. Increase the spectrum efficiency of radio technologies,
- 2. Increase the number of base stations and access points, or
- 3. Increase the availability of spectrum e.g. by enabling more flexible access to unused spectrum bands and usage of already allocated spectrum bands more efficiently.

The first option is mostly an engineering issue where some argue that the efficiency of most recent radio technologies (e.g. LTE, LTE-A) is getting close to the theoretical limit and cannot be improved much while others argue that there is still plenty of room for improvement.

The second and third options could involve the entrance of new economic actors such as smaller wireless access and spectrum database operators and major reforms in regulation. Therefore, in addition to studying the corresponding new technical enablers such as self-organizing wireless local area networks and cognitive radio, there is a need for a broader point of view that takes into consideration also the business and regulatory aspects. These latter two options are also tightly connected to the collision of the Telecommunications and Internet tracks. The following two subsections conduct an overview to both of these evolution trends.
2.2.1 Intelligent wireless local area access

Serving traffic with wireless local area access points and base stations residing closer to the end-users makes sense on many fronts. Deploying a denser wireless infrastructure by increasing the number of access points and getting the transmitter and receiver closer to each other is a sure way to increase the system capacity of a wireless link (Chandrasekhar et al., 2008). Furthermore, it has been identified that most wireless traffic originates from indoor locations (Markendahl, 2011) since people typically spend most of their time either at home or work. Additionally, wall attenuation presents a major challenge for the wide area cellular networks to deliver broadband speeds¹² (Markendahl, 2011) which further motivates placing base stations and access points to indoor locations.

However, from a business model point of view considerable uncertainty exists over who will control these wireless local area access points. As there are many interested actors in a position of taking control of them and coupling them to their existing platform, the resulting value system can become rather complex and diverse.

As it relates to technological evolution towards intelligent self-configuring wireless access points two technology tracks are typically identified: firstly, the Telecom track where 3GPP-based intelligent femtocell access points, self-configuring networks and distributed antenna systems¹³ enable mobile operators to extend the coverage and capacity of their wide area (WA) cellular networks and secondly, the Internet track where wireless access points are based on the IEEE 802.11 family of standards.

Overall, the 3GPP-based intelligent femtocell access points are more centralized, work on licensed spectrum, can be more tightly integrated to the cellular network and support the business model of mobile operators better. Therefore, using such intelligent access points is an attractive option for the mobile operators to extend coverage and offload traffic from the cellular wide area network.

However, the model has also some drawbacks. Mobile network costs are proportional to the number of base station sites, meaning that mobile operators prefer sites with larger coverage¹⁴ and in turn avoid increasing the number of access points that can result in high deployment, operation

¹² The recent trend of building more energy efficient houses will make it even more challenging for radio signals to penetrate building walls and windows.

¹³ These base station and access point solutions have many forms and the

terminology is diverse featuring terms like self-organizing networks, heterogeneous networks (hetnets), femtocells, picocells, metrocells and small cells.

¹⁴ Developing A Fully Inclusive Mobile Broadband Strategy: Bringing Mobile Broadband To Remote And Rural Areas. Presentation at Mobile Broadband World, Dr. Eetu Prieur, Elisa, London, September, 2009.

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and maintenance costs. This can be the case especially if existing mobile operators all try to deploy their own infrastructure and do not co-operate e.g. by using multi-operator access points or with roaming. Also, the use of licensed spectrum on femtocells might interfere with the wide area network and lead to inefficient spectrum use in the form of dead zones and coverage holes (Markendahl, 2011). Currently the installed base of such femtocells is still relatively low and driven mostly by coverage, but the number could grow as capacity becomes the major driver.

The Wi-Fi track, on the other hand, has already now a large installed base of private Wi-Fi certified IEEE 802.11 access points using the 2.4 GHz unlicensed band. As opposed to femtocells deployments which work in a more top-down manner, and are controlled by operators, Wi-Fi access point deployments are a more bottom-up type of a process, where enterprises and households themselves acquire, deploy and operate the access points. For the venue owner the process is very simple since practically no co-ordination in terms of spectrum licenses is needed as long as the equipment used conforms to the specified spectrum etiquette (e.g. in terms of power).

One can argue that already the existing base of Wi-Fi access points could be used more efficiently. Many of the Wi-Fi access points currently operating in private mode are located in places with a large number of potential users (e.g. downtown areas in cities), have plenty of excess capacity and could thus also provision public access to a broader user base if the technical architecture and business models were in place. During the recent years, different kinds of public Wi-Fi models have already emerged (Markendahl and Mäkitalo, 2007) ranging from municipal Wi-Fi (often powered by partner infrastructure operators like The Cloud) and Wi-Fi communities (e.g. FON and eduroam) to commercial Wi-Fi aggregators (e.g. iPass and Boingo)¹⁵. Most, however, have had only limited success and the numbers in terms of users have remained relatively modest. Also on a technical level public Wi-Fi solutions have remained fragmented where the systems have been based either on different proprietary (e.g. iPass and Boingo) or open solutions (e.g. eduroam and openWRT). Overall, as it relates to community efforts, there is a need for scale, and for central coordination that are not easily achieved by the ad-hoc nature of many community efforts (Middleton and Bryne, 2011) and it has been questioned whether a decentralized, cooperatively run communication infrastructure can be a significant alternative to the centrally driven, commercial systems (Sandvig, 2004).

¹⁵ www.thecloud.net, www.fon.com, www.eduroam.org, www.ipass.com, and www.boingo.com (accessed 24th of August, 2012).

On the other hand existing large actors such as mobile operators could also aggregate and connect existing Wi-Fi access points to their networks (e.g. using a proprietary solution or a standardized technology such as 3GPP's ANDSF or Wi-Fi Alliance's upcoming Passpoint certification¹⁶) and enable some form of SIM-based roaming. Additionally, large service application providers (such as Apple, Google, Amazon, and Microsoft) have shown interest in spectrum where wireless local area access could be a natural entry point for them (Smura and Sorri, 2009). For example, Google is an investor for FON and the Microsoft owned Skype already now provides a Wi-Fi authentication mechanism to 1 million access points globally¹⁷.

Furthermore, the decentralization of wireless access provisioning is already reaching end-user devices where end-users are increasingly turning their smart phones into Wi-Fi access points by sharing their mobile broadband connection. In the future end-user devices could become intelligent and reconfigurable to the degree of being able to automatically form co-operative ad-hoc type of networks, become wireless relays for others and dynamically share their backhaul access connection with other devices in the proximity. In this case the limit to what is an access point and an end-user device could become vague.

2.2.2 Flexible spectrum use

Another possible way to address the rapidly increasing demand is to increase the supply of spectrum. It has been claimed that the old and rigid command and control type of spectrum licensing has led to inefficient use of spectrum (Olafsson et al., 2007) and that a shift towards a more flexible and market driven approach is needed. In the traditional command and control regime, spectrum licenses are given for a very long time (licenses last for decades) and typically for only one actor to provide a particular service (e.g. a government mobile network operator) that in turn does not necessarily have incentives to make the most of the spectrum. On the other hand, such, rather static, licensing reduces risks and enables long term capital budgeting and investments and roll-out of large nationwide networks by the licensee.

Flexibility in spectrum licensing has nevertheless increased over the years as was the case e.g. when second generation spectrum licenses were issued

¹⁶ GSMA and Wireless Broadband Alliance (WBA) are collaborating to create a solution for Wi-Fi roaming which will be based on Wi-Fi Alliance's Passpoint certification technology (also known as Hotspot 2.0). ¹⁷ corp.fon.com/en/about/investors/,

www.skype.com/intl/en/features/allfeatures/skype-wifi (accessed 24th of August, 2012).

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where the spectrum block allocated for the mobile communications service was divided to smaller, but still relatively large blocks and assigned exclusively to a few competing mobile operators. In some cases the assignments have also been technology neutral and have involved spectrum auctions.

As a whole, compared to the increasing demand, mobile communications still has relatively little spectrum and there is increasing pressure to allocate and assign more spectrum to mobile operators e.g. from the digital dividend released from TV broadcasting. The process however requires international co-ordination and takes a very long time. At the same time strong evidence has been presented that parts of the licensed spectrum is severely underutilized (Olaffson et al., 2007). Such white spaces (WS) can be found from bands assigned e.g. to satellite, radar, professional mobile radio (PMR), military, or broadcasting use. On the other hand these can also be found from bands used by the mobile operators who, e.g., often leave many rural areas unserved or use high frequency spectrum bands, that do not propagate far, only to cover highly congested areas.

This suggests that there is still a need to move towards a more flexible, decentralized and market driven licensing approach by defining spectrum usage rights (SUR) for smaller spectrum bands and geographical areas, by introducing shorter license times (or a secondary market) and by increasing the number of market actors involved. Such a market could also introduce new actors serving as mediating spectrum brokers using either proprietary or standardized solutions (e.g. the mobile operator community driven Authorized/Licensed Shared Access (ASA/LSA)).

Still, there already now exists an established liberal spectrum licensing regime in the form of license-exempt spectrum (i.e. unlicensed spectrum) utilized e.g. by Wi-Fi access points using the 2.4 GHz ISM band. This licensing regime enables anybody to use a license-exempt band and only requires that wireless nodes follow a simple spectrum etiquette. Under such a scheme many different technologies and services are able to co-exist without major transaction or policing costs. However, if the number of devices grows to a high enough value, the unlicensed spectrum band can become highly congested and co-existence is compromised.

Thus, in the long run there might be a need for unlicensed spectrum use to evolve towards a more co-ordinated approach, with better protection and more carefully defined spectrum usage rights, e.g. some form of pooling of spectrum or light licensing where the number of users is limited or registration is required¹⁸. The road towards such light licensing could also introduce new players such as spectrum database operators that would maintain and distribute up to date information about a particular spectrum band. In general, the trend towards spectrum sharing is gaining momentum with governments e.g. in Europe and the U.S. strongly promoting it¹⁹.

Overall, the introduction of new actors could have implications in terms of new business models (Ballon and Delaere, 2009; Barrie et al., 2010) where the market could shift towards a horizontal and open structure enabling many new entrants and a wide range of service applications (Chapin and Lehr, 2007). In addition to mobile broadband connectivity these could be related e.g. to sensor networks, machine-to-machine communications, intelligent transportation systems, smart grids, mobile payments, building automation, local broadcasting, indoor positioning and hospital and logistics applications.

The change towards more flexible use of spectrum is driven to a large degree by advancements in technologies that increase the intelligence and flexibility of radio devices and enable them to use the spectrum more efficiently. Technologies such as cognitive radio (CR) (Mitola and Maguire, 1999) and dynamic spectrum access (DSA) (Chapin and Lehr, 2007) could enable the dynamic identification of and access to unused frequencies, e.g. white spaces in TV broadcasting, where wireless devices could act alone, be assisted by cognitive pilot channels (CPC)(Ballon and Delaere, 2009) or spectrum databases (e.g. IETF PAWS or IEEE 802.22). In the future, driven e.g. by software defined radio (SDR), devices are expected to become highly flexible and capable of communicating using many different radio technologies on several spectrum bands, where only the radio frequency (RF) front-end would still use an analog component (Koch and Prasad, 2009). In principle these software defined solutions²⁰ could significantly

¹⁸ See e.g. CEPT Electronic Communications Committee (ECC) Report 132: Light licensing, license-exempt and commons, Moscow, June, 2009.

www.erodocdb.dk/docs/doc98/official/Pdf/ECCRep132.pdf (accessed 24th of August, 2012).

¹⁹ See related discussions in a European Commission communication and President's Council of Advisors on Science and Technology (PCAST) report in the U.S. Web links respectively:

ec.europa.eu/information_society/policy/ecomm/radio_spectrum/_document_st orage/com/com-ssa.pdf ,

www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf (accessed 24th of August, 2012).

²⁰ See e.g. USRP (www.ettus.com) and WARP (http://warp.rice.edu/) (accessed 24th of August, 2012) for some existing solutions.

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reduce the role of technological harmonization in radio communications and make the development and deployment cycles of radio technologies much shorter, i.e. similar to software development. However, the technological maturity of such solutions is still low and it is uncertain when they could become commercially available in the device base on a large scale.

Standardization activities for such systems are being conducted e.g by ETSI, IEEE and IETF²¹. As an analogy to these developments, it is commonly stated that the Internet Protocol (IP) standardized by the IETF is the "narrow waist" interconnection protocol that connects all computers regardless of the link layer technology running below or application running above the protocol where intelligence resides at devices according to the end-to-end principle (Leiner et al., 2009). Similarly CR, DSA and SDR could become the narrow waist technology that could enable roaming and mobility between all devices on all possible frequencies and lead to an open and global network of wirelessly connected devices through which everyone could provide and receive public wireless services.

²¹ ETSI Technical Committee Reconfigurable Radio Systems (http://www.etsi.org/WebSite/technologies/RRS.aspx), IEEE DySPAN Standards Committee (http://grouper.ieee.org/groups/scc41/), IEEE 802.22 (http://www.ieee802.org/22/) and IETF Protocol to access white space database (PAWS) (http://tools.ietf.org/html/draft-patil-paws-problem-stmt-02). (Websites

3. Value system modeling

The value system around wireless access provisioning is an open and highly interdependent system. In order to understand and model many of the phenomena it produces, a holistic systems thinking view point is needed where the set of economic actors, business roles and technology components and their interdependencies is studied as a whole.

Systems thinking tries to find an explanation by examining the linkages and interactions between the elements of a system²². This process is commonly referred to as *synthesis*, a term whose definition comes from the Greek language and means "to put together". This is in contrast to the opposite approach of *analysis*, where one tries to find an explanation by reducing and isolating a system to smaller and smaller elements. The word analysis comes also from Greek and means "to take apart".

A systems thinking approach has been promoted by many prominent thinkers. Already in ancient Greece Aristoteles pointed out that the whole is more than the sum of its parts (von Bertalanffy, 1972). The developer of the General System Theory, Ludwig von Bertalanffy, noted that classic science has mostly been concerned with one-way causality and has reduced complex phenomena into elementary parts (von Bertalanffy, 1972). Russell Ackoff, another notable systems thinker, stated that there are some properties of systems that can only be treated adequately from a holistic point of view (Ackoff, 1971). Others, like Jay Forrester have stressed the importance of endogenous explanation and using computer simulation in understanding how feedback structure gives rise to observed events and patters (Forrester et al., 1976). Furthermore, some, like W. Brian Arthur, highlight the importance of seeing a system as a large group of interacting and learning heterogeneous agents, where structures emerge on their own and where the system is constantly evolving and unfolding over time (Arthur, 1999).

²² The term systems thinking does not have a well-established definition and is sometimes used interchangeably with terms like systems theory or system science.

This chapter reviews the systems thinking type of value system modeling tools and theories used in this research. It first gives an overview to methods and theories for value system modeling on the level of value system structures, i.e. the linkages of the elements of a value system, e.g. in terms of scenario planning and the modeling of business and technical architectures. The chapter then moves on to introducing methods and theories related to the modeling of value system dynamics, i.e. the interactions of the elements of a value system, e.g. feedback structure modeling based on system dynamics, agent-based modeling and complexity theory.

3.1 Value system structures

A value system in this research consists of a group of collaborating and competing economic actors and a set of business roles and technical components. As a whole, a wide variety of methods and theories exist that can be used to model the structure of a value system on different levels of detail.

3.1.1 Scenario planning

In order to get an overall understanding of the possible value system structures one can use the method of scenario planning. One of the first known applications of scenario planning was conducted by Royal Dutch/Shell in the 1970s. As forecasting had become increasingly difficult, the core idea of the method was that instead of trying to predict the future it is better to accept uncertainty and try to understand it better (Wack, 1985).

Typically a scenario planning process consists of gathering relevant forces driving change, prioritizing and ranking them in terms of importance and uncertainty, and examining their interactions to formulate scenarios e.g. in terms of the possible structures of a value system. Börjeson et al. (2006) divide scenario studies into three categories: normative scenarios which answer the question "how can a specific target be reached?", predictive scenarios which answer the question "what will happen?", and explorative scenarios which answer the question "what can happen?". Some scenario planning methods have a more strategic and business point of view such as the ones by Porter (1985) and Schoemaker (1995) who view it as tool for strategic decision making.

Explorative scenarios, in particular, force managers to consider how they would act under different alternative paths into the future (Senge, 1990) and have the potential to trigger institutional learning, i.e. the process whereby management teams change their shared mental models of their company, their markets and their competitors (de Geus, 1988).

3.1.2 Business architecture

One can get a deeper understanding of the linkages and interactions within the value system by using methods and theories for modeling business and technical architectures. As it relates to the modeling of business architectures, i.e. the individual business models and the business linkages between those, the foundations can be traced back to Porter's (1985) definitions of a value chain describing a single firm and a value system consisting of several individual companies²³.

Later on focus has been put on how actors work together to co-produce value (Normann and Ramirez, 1993; Allee, 2000) and on the different modes of value creation. Stabell and Fjeldstad (1998) present three value creation logics: 1. a long linked technology, where value is created by transforming inputs into products (e.g. wireless network or device equipment), 2. an intensive technology, where value is created by solving unique customer problems (e.g. wireless network planning and deployment), and 3. a mediating technology where value is created by linking customers to each other or to other service providers (e.g. operating a wireless access network).

Out of these three, the logic based on a mediating technology seems especially important for wireless access provisioning. Stabell and Fjelstad (1998) argue that a mediating firm can be seen as a club manager that admits members that complement each other, and excludes those that do not. They also define the value system created by a group of mediating firms as a set of layered and interconnected networks. A similar kind of role has also been identified by Iansiti and Levien (2004) who refer to it as a keystone function and by Jacobides et al. (2006) who point out that some firms can gain architectural advantage by enhancing both complementarity and mobility (i.e. competition) in parts of the value system where they are not active and subsequently attain high levels of value appropriation without the need to engage in vertical integration.

²³ It should be noted that this research understands the term value system as an industry wide system of all relevant value creating roles and actors which also includes the corresponding technical architecture and components.

3.1.3 Technical architecture

A technical architecture consists of a set of technical components and their technical interfaces. Technical architectures have been discussed e.g. in literature related to standardization (Gandal, 2002) and platforms (Gawer and Cusumano, 2008). Gandal (2002) defines three different ways standards get set in practice: 1. de facto standards, i.e. standards set primarily by the market (often proprietary), 2. voluntary industry agreements, where standards are often jointly developed and 3. standards imposed by national standards bodies or agreed upon by regional or international standards development organizations. Funk and Methe correspondingly describe committee (2001)and market based standardization.

Platform theory literature describes platform leaders as organizations that establish their product, service or technology as an industry platform, on which other companies build their products and services (Gawer and Cusumano, 2008) which in turn allows them to exert architectural control over the overall system. Such business actors often become de facto regulators of their platforms (Boudreau and Hagiu, 2008).

The relationship between business and technical architectures is also of critical importance. Tee and Gawer (2009), for example, argue that the structural fit of the business architecture and the underlying platform, i.e. technical architecture, is a key factor for platform success.

3.1.4 Value system structures in ICT

Understanding the overall value system is especially relevant in the telecommunication sector and the ICT industry in general, where industry platformization has increased the importance for firms to be in possession of gatekeeper roles, i.e. the most important "bottleneck" activities (Ballon, 2009). While this means that a closer examination of the business model of a single company is needed to some degree (Chesbrough and Rosenbloom, 2002; Osterwalder et al., 2005; Ballon, 2007) it is also important that the firms understand how their business model is positioned within the value system at large.

Fransman (2010) for example discusses a concept of a new ICT ecosystem that works through symbiotic relationships between a large group of players and highlights that simplified models fail to show the functioning of the ICT ecosystem. The structure of the ICT industry has also been examined with a toolkit developed in the MIT Communications Futures Program that deconstructs the functionalities of a service, identifies control points where (technological or business) management can be applied and evaluates their importance in terms of demand and interchangeability (i.e. coreness), and also examines triggers that cause changes in the value system (MIT CFP, 2005). Furthermore, a holistic approach has been taken e.g. by Odlyzko (2001) who analyzes repeating patterns in the history of communication technologies and by Kilkki (2012) who examines the communications ecosystem as a whole, ranging from user behavior, to issues related to technology, networks, and economics.

As it relates to wireless access provisioning in particular, e.g. scenario planning has been used by Smura and Sorri (2009) who constructed four future scenarios describing the macro level industry structure around wireless local area access technologies based on uncertainties related to the degree of vertical integration and technology fragmentation in the value system. Markendahl and Mäkitalo (2007) have examined business architectures for wireless local area access, and Chapin and Lehr (2007) and Ballon and Delaere (2009) for flexible spectrum use.

3.2 Value system dynamics

When modeling the business and technical linkages of a value system the models are typically static and do not consider two-way interactions and the corresponding feedback structure that is formed. Especially in the case of an open system, such as the value system around wireless access provisioning, it is important to consider the endogenous structure and the resulting dynamics. In the following a review of relevant theories describing network externalities, evolution, change and complexity in the value system is conducted and system dynamics and agent-based modeling tools are introduced.

3.2.1 Network externalities

When it comes to the success of value systems, direct and indirect network externalities between actors often play a key role (Katz and Shapiro, 1985). Many times the value of a platform is directly proportional to the number of other users on the same side (e.g. number of subscribers in a telephone network) or users on the other side of the platform (e.g. number of software developers for an operating system). The phenomena is widely recognized and researched in the telecommunications context (Allen, 1988; Schoder, 2000), although debate is still ongoing regarding the specific formulation (Briscoe et al., 2006). A notable refinement of network externalities is the

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two-sided market theory (Rochet and Tirole, 2003; Parker and Van Alstyne, 2005) which describes how the elasticity of user groups across the market or platform should be taken into consideration in subsidization strategies.

When network externalities (i.e. network effects) are involved platform management can become complex as one needs to focus on one hand on growing the overall value of the platform but on the other hand ensuring that one gets a large enough share of it (Shapiro and Varian, 1999; Iansiti and Levien, 2004; Eisenmann et al., 2006). Furthermore, platforms often face complex co-ordination problems and require the crossing of a critical mass to trigger self-sustaining growth (sometimes referred to as a chickenand-egg or a start-up problem).

3.2.2 Cyclical change

The evolution and change of value systems, both in terms of technical and business architectures, has been researched by many scholars and has a long history of theories. Schumpeter (1942) discussed the concept of creative destruction where innovative entry of entrepreneurs was the force that destroyed monopoly power derived from previous technological and economic paradigms, and sustained long-term economic growth. Later, Arthur (1990) pointed out that industries that are dominated by increasing returns (i.e. where network externalities are strong), can easily become locked into certain technology-development paths. In many cases, once a dominant design or standard has emerged, the cost of switching become prohibitive, and a lock-in persists until an architectural shift or large external shock renders the dominant design obsolete (Sterman, 2000).

Anderson and Tushman (1990) describe a cycle of technological change where technological breakthrough, or discontinuity, initiates an era of intense technical variation and selection that in turn proceeds to the selection of a single dominant design followed by a period of incremental technical progress. Fine (2000) on the other hand introduced a double helix model where the value system follows a cyclical change between a vertical and horizontal configuration. The cyclical process is also closely related to different kinds of innovations (Henderson and Clark, 1990; Christensen, 1997) such as incremental and disruptive innovation.

Some of the cycle theories have also been applied to ICT where e.g. Vesa (2007) used Fine's (2000) double helix concept to model differences in mobile communications markets.

3.2.3 System dynamics

System dynamics was created by Jay Forrester in the mid-1950s to help corporate managers improve their understanding of industrial processes (Forrester, 1961). System dynamics seeks to explain phenomena by modeling the feedback structure of a system and extends general feedback theory (i.e. cybernetics) to computer simulation (Forrester et al., 1976).

Overall, system dynamics takes an endogenous approach (the word endogenous means arising from within), where endogenous structure generates the dynamics of a system through the interaction of variables and actors (and their mental models) represented in the model. This modeling approach differs from methods relying on exogenous variables (variables arising from without) which explain dynamics in terms of other variables whose behavior is assumed (Sterman, 2000).

System dynamic diagrams depict the feedback structure of a system with positive and negative causal links and with stocks, flows and delays. The causal links form reinforcing and balancing loops which are the most basic feedback structures. These can be combined to generic structures known as system archetypes (Senge, 1990; Wolstenholme, 2004), e.g. saturation of growth (typical S-shaped diffusion), resource accumulation (e.g. success feeds success), and escalation (e.g. price wars), and into furthermore complicated structures.

As it relates to system dynamics it is important to make a distinction between two types of complexity: detailed and dynamic complexity (Senge, 1990; Sterman, 2000). Detailed complexity is modeled by increasing the number of variables and detail in the model, whereas dynamic complexity is modeled with, rather simple, feedback structures. Dynamic complexity is present in situations where cause and effect are subtle, where the same action has different effects in the long and the short run, and where an action has one set of consequences locally and a different set of consequences in another part of the system (Senge, 1990). In general, research shows that dynamic complexity and endogenous structure is difficult to understand and that feedback, time delays, and nonlinearity are counterintuitive and poorly understood (Sterman, 1989; 2002). Furthermore, it has been suggested that the real leverage in many management situations lies in understanding dynamic complexity (Senge, 1990).

System dynamics has been used in many fields, where applications have ranged, for example, from logistics and supply chain management to the study of structural changes in the commercial jet aircraft industry (Lyneis, 2000). System dynamics has also been applied in the telecommunications context where e.g. Dutta and Sridhar (2003) used it to model the growth of cellular services in India and Tookey et al. (2006) to model broadband diffusion in remote and rural Scotland. Davies et al. (2008) used system dynamics to examine the case of telecommunications sector regulation in New Zealand and Pagani and Fine (2008) developed a map to analyze the dynamic forces that influence the structure and development of third generation wireless communications value networks and services. Vaishnav (2009) analyzed how a telecommunications regulator can balance regulation with innovation at a reasonable cost by better understanding the dynamic complexity involved.

3.2.4 Agent-based modeling and complexity theory

In system dynamics, individual economic actors are aggregated into homogeneous groups and relatively small number of states (Rahmandad and Sterman, 2010) which in turn can lead to the omission of micro level interactions that might give rise to important behavior. Agent-based modeling (ABM) is a method for simulating the behavior and interaction of a large group of agents where the individual members of a population are represented explicitly rather than as a single aggregate entity (Macal and North, 2010). An agent-based model embeds a feedback structure between a set of agents and is a useful tool, if one wants to increase the level of detailed complexity in the model. However, as detailed complexity grows and as the number of variables is increased and agents become more heterogeneous, linking the behavior of a model to its feedback structure becomes more difficult. Thus there exists a trade-off between disaggregate detail provided by agent-based modeling and breadth of model boundary offered by system dynamics (Rahmandad and Sterman, 2010).

Agent-based modeling can, for example, help in understanding the behavior of so called complex adaptive systems (CAS) (Holland, 2006) that have a large number of interacting and learning agents, are quick to adapt to new circumstances, and are constantly evolving and unfolding over time (Arthur, 1999). Examples of such decentralized systems are stock markets and ant colonies. In a complex adaptive system the individual agents have simple rules and structure emerges in a bottom-up manner as the result of their interaction. The result is typically a scale-free structure that follows a power-law (long tail) distribution²⁴.

²⁴ Scale-free distributions can be found e.g. in the network formed by airline connections (as opposed to the randomly distributed road network), the World Wide Web (Barabási and Bonabeau, 2003) and the Internet router infrastructure (Faloutsos et al., 1999).

Complex adaptive systems are commonly described to be exhibiting spontaneous order and working on the edge of chaos. According to chaos theory such systems can be described with a strange attractor that is not completely random but is still more irregular than the fixed point and limit cycle attractors commonly used in dynamical systems theory which describe goal seeking and cyclical behavior. Furthermore, as it relates to relationships between systems, it has been observed that systems following similar attractor types tend to synchronize with each other (Strogatz, 2001).

Overall, in terms of the relationship between system dynamics and agentbased modeling it is important to recognize the strengths and weaknesses of both tools and use them accordingly. While system dynamics can, for example, be used to simulate a centralized market where two or three actors compete (and e.g. also show limit cycle dynamics) (Sice et al., 2000) it cannot model particularly well the decentralized competition dynamics between hundreds or thousands of economic actors.

In terms of wireless access provisioning, agent-based modeling has been used to evaluate spectrum trading markets (Caicedo and Weiss, 2010; Tonmukayakul and Weiss, 2008; Yoon et al., 2010) where a special form of it called Agent-based Computational Economics (ACE) has been applied. Value system modeling

4. Research methods

This chapter presents the research methods used in this thesis and how the value system modeling theories and methods introduced in Chapter 3 are utilized. The chapter first presents the overall research approach taken, then moves on to describe the process of model construction and the kind of data that is collected, and finally outlines the research process.

4.1 Research approach

This thesis takes a systems thinking approach to modeling the evolving value system around wireless access provisioning, that is, tries to find an explanation to the observed phenomena by examining the linkages and interactions of the elements of the overall value system. The research approach is depicted in Figure 4.

Following the systems thinking approach, this research has a large time horizon and models both historical and future evolution of the value system around wireless access provisioning. In addition to examining future evolution, in terms of intelligent wireless local area access technologies and flexible spectrum use, the research examines established evolution paths and important lessons learned related to the historical evolution of GSM and Wi-Fi tracks that in turn could be taken into consideration when making future policy decisions. The research also takes a holistic approach in terms of different markets and examines how similar technological advancements have taken and could take place differently in different markets.

The research approach does not have a specific stakeholder point of view as such, although some case studies are conducted where an actor, such as a regulator or mobile network operator (MNO), serves as a value system orchestrator. The research findings thus enable all relevant stakeholders to have a better understanding of the value system as a whole and therefore help them in crafting their strategy and in positioning themselves in the value system. The research approach is divided into two stages where the first examines underlying value system structures and the second underlying value system dynamics. In the first stage, reviewed methods and theories for modeling value system structures are applied and new methods are created to examine possible value system structures related to the evolution of wireless access provisioning. Methods and theories, such as scenario planning and different value creation logic's, are used to examine the possible structures of the value system and the technical and business linkages between its elements.

In the second stage, reviewed methods and theories for modeling value system dynamics are applied and new methods are developed to examine value system dynamics related to the evolution of wireless access provisioning. Methods and theories such as system dynamics and complexity theory are used to model the endogenous feedback structure and the interactions between the elements of the value system.



Figure 4. Research approach.

During the course of the research, existing value system modeling methods are enhanced and new methods are created. The created methods draw basis from the reviewed methods and theories related to both value system structures and dynamics where existing similarities are also identified. In this research, the created methods are applied to the value system around wireless access provisioning in order to improve corresponding policy decisions and strategic management. They can, however, also be used more generally, i.e. to model the ICT industry in general.

As a whole, this research gradually moves from examining the (static) linkages of the elements of the value system to examining the interactions of the elements of the system. In other words, as the research

proceeds, the level of endogenous explanation in modeling is increased, i.e. to what degree feedback structure explains phenomena.

4.2 Modeling process

During the research a set of modeling methods are utilized, and they are also enhanced and combined to create new frameworks. In this section, generic processes and principles are outlined for constructing models using these methods. This section also describes what kind of data is collected and used in the modeling process.

4.2.1 Model construction

Although model construction is typically a feedback process and not a linear sequence of steps, this research follows systematic processes and principles when constructing models. As it relates to value system structures, a framework for concurrent modeling of business and technical architectures is created and utilized (in Publications I and II) and combined with the scenario planning method (in Publication III). For scenario planning the structure and steps outlined by Schoemaker and Mavaddat (2000) are utilized. The usage of these two methods is iterative where the results from scenario planning can be fed to the process of constructing the technical and business relationships of the value system structure and vice versa where results from concurrent modeling of business and technical architectures can be fed to the scenario planning process.

The results related to value system structures are used as a basis for modeling value system dynamics where a framework for modeling the dynamics of business and technical architectures is created and utilized (in Publication IV). As it relates to building dynamic models, systematic modeling processes are followed as described by Sterman (2000) for system dynamics (in Publications III, V, VI, VII, VIII) and by Macal and North (2010) for agent-based modeling (in Publication VII).

When constructing system dynamics models a five step modeling process defined by Sterman (2000) is followed (see Figure 5). The first step is *problem articulation*, where the scope of the problem is defined and the purpose of the model is stated (e.g. whether a regulator should pursue a harmonization or technical competition policy as discussed in Publication V).

The second step is the formulation of a *dynamic hypothesis*, where the endogenous structure of the system is depicted with a causal loop diagram, i.e. a conceptual model is constructed that explains the dynamics as

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endogenous consequences of the feedback structure. When developing such a conceptual model existing theories of the dynamic behavior of the system (e.g. network externalities and economies of scale) can be utilized and intermediate modeling tools such as model boundary charts, used to categorize variables as endogenous or exogenous, can be applied. Various subsystem diagrams are also useful, such as the results from the first stage of the research, i.e. from scenario planning and concurrent modeling of business and technical architectures.



Figure 5. Iterative modeling process (modified from Sterman (2000)).

The third step is the *formulation* of a simulation model, where a quantitative model with stocks and flows is constructed, structure and decision rules are specified, parameters are estimated, behavioral relationships formulated and initial conditions defined. In this research Vensim software²⁵ is used to implement the models and run simulations (in Publications V and VI)²⁶.

The fourth step in the process is *testing*, where functioning of the model is verified for example by comparing simulation results to collected reference data (e.g. the penetration of mobile voice service in different markets) or by reproducing key behavior (e.g. vicious cycle of platform discard decisions by end-users). Tests related to boundary adequacy can also be conducted, i.e. checking whether important concepts describing the problem are

²⁵ www.vensim.com (accessed 3rd of March, 2013).

²⁶ The results from these simulations are presented in Chapter 5. As it relates to more elaborate descriptions of the quantitative modeling, i.e. the detailed stockand-flow diagrams, mathematical equations and tables of assumptions feeding system parameters during simulation, in Chapter 5 the reader is directed to the corresponding places in the publications.

endogenous to the model. A number of other tests can also be conducted, e.g. related to dimensional consistency in the model, robustness under extreme conditions, and sensitivity to the integration time step. The fifth and final step is *policy design and evaluation*, where the model is used to understand the reasons for emerging dynamic behavior and the effect of policies.

The process defined by Macal and North (2010) gives general steps to building an agent-based model which can be used to increase the level of detail in the modeling and make the agents more heterogeneous (as done in Publication VII). When constructing the model key questions relate to, for example, what is the agents' environment, how do the agents interact with each other and what agent attributes are calculated endogenously by the model and updated in the agents. Macal and North (2010) highlight that bottom-up, highly iterative design methodologies seem to be the most effective for practical model development. In this research the Repast Simphony simulation toolkit²⁷ is used to implement the model.

Overall, as indicated in Figure 5, modeling itself is a feedback process, not a linear sequence of steps. Finding the appropriate level of abstraction is an iterative process where models go through constant iteration, continual questioning, testing and refinement. Sometimes what is learned from the process of modeling may feedback to alter our basic understanding of the problem and the purpose of our effort (Sterman, 2000)²⁸.

Furthermore, when taking a holistic approach, there is a threat that models become too large and loaded with unnecessary detail where a modeler can lose sight of the embedded feedback structure and dynamic complexity. In an open system, such as the value system around wireless access provisioning, everything is potentially connected to everything else and (almost) nothing is exogenous (Sterman, 2002) and thus, using an appropriate model boundary and abstraction level is important. One will often have to iterate through the steps many times until the appropriate level of abstraction has been reached and, as indicated in Figure 5, iteration can occur from any step to any other step.

Overall, during the research, careful consideration is conducted in terms of what to model endogenously (i.e. include in the feedback structure), what exogenously and what to exclude from the models altogether. Furthermore, when communicating results from dynamically complex models e.g. to policy makers, it is important to use an appropriate level of abstraction so

²⁷ repast.sourceforge.net (accessed 3rd of March, 2013).

²⁸ The author personally experienced this when the work conducted in Casey et al. (2010) helped in formulating a more appropriate problem and model boundary for future modeling work.

that the models are useful and can be communicated to trigger personal and institutional learning and change.

4.2.2 Data

During the research different kinds of data is collected and used which can be roughly divided to hard, written and soft data (Sterman, 2000) as depicted in Figure 6. Hard data describes phenomena with numerical data. In this research hard data consists of snapshots of important variables and short and long time series, where, in some cases, the original time series is further computed to fit the modeling needs²⁹. Public databases, market research documents (published e.g. by regulators) and prior research are used as sources for hard data.

Written data consists of written description of phenomena. In this research written data comes from prior research, industry publications, books, historical and standardization documents, and market research documents.



Figure 6. Classification of different research data³⁰.

Soft data describes the softer parts of the feedback structure, e.g. the beliefs and mental models of actors. Soft data cannot be acquired directly

²⁹ Overall, during the research it was surprisingly challenging to find high quality time series of many important variables. For example, while mobile phone penetration has been well measured (and defined) over the course of history, the systematic longitudinal measurement of e.g. population coverage of mobile networks is virtually non-existent. This suggests that there are important variables that could be measured more elaborately (e.g. by regulating entities) and could be placed in a wider context.

³⁰ Based on a similar conceptualization from www.pegasuscom.com (accessed 24th of August, 2012).

but often has to be elicited through interviews and observations. The softer parts of the feedback structure are typically the hardest to acquire data about which stresses the importance of field study, active participation in seminars, conferences, workshops, and informal discussions with stakeholders. This also means that assumptions and personal judgment are to some degree needed and highlights the need for continual iterative learning. During the research soft data is also collected with stakeholder interviews including representatives of device and network equipment vendors, mobile operators, regulators and academia. The interviews follow a semi-structured format where power point slides of key theme areas to be discussed are used.

Although the softer parts of the feedback structure, such as mental models of individual actors, are the most challenging to understand and acquire data about, they should not be excluded from the models because of lack of data. In fact omitting structures or variables known to be important because numerical data are unavailable could actually be less scientific and less accurate than using your best judgment to estimate their values (Sterman, 2000). When examining system behavior, absolute numerical values are often not necessarily needed and therefore it is more important to identify the general behavioral patterns.

4.3 Research process

The research process is divided into two stages where the first examines underlying value system structures and the second underlying value system dynamics. The research proceeds as presented in Table 1.

4.3.1 Value system structures

The first stage of the research focuses on the underlying value system structures in terms of the technical and business architectures, linkages between the elements and high level forces driving the overall structure. In Publication I the focus is mainly on method development where a value system modeling framework is formulated that enables the positioning of different ICT services and technologies according to their value proposition. The publication integrates existing value system analysis concepts into a holistic theoretical framework that enables the concurrent modeling of technical and business architectures and the connection of these to generic scenarios that have been found repeatedly in prior research.

Publication II enhances the value system modeling framework presented in Publication I in terms visual representation and role analysis as it relates

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to the assessment of role logic and forces driving the importance of a role. The framework is then used to examine possible value system configurations for wireless local area access, the possible actors and forces driving the configurations and how the configurations relate to the generic scenarios³¹. Written data of existing wireless local area access business models is collected.

Publication III examines the possible value system configurations for flexible spectrum use as it relates to the evolution of spectrum markets. It combines the created framework with Schoemaker's scenario planning method (Schoemaker and Mavaddat, 2000) and conceptual system dynamic modeling of the forces driving the structure of the value system. Scenario planning methods typically do not consider feedback structure, and Publication III also demonstrates how the scenario planning method can be enhanced by examining the endogenous structure of forces affecting the evolution, i.e. how they influence and explain the value system structure in the different scenarios³². Data used in the publication is based on prior research in terms of written data and three semi-structured interviews in terms of soft data.

4.3.2 Value system dynamics

The second stage of the research focuses on the underlying value system dynamics and tries to find endogenous explanation by modeling the interactions between elements of the value system. Publication IV develops a qualitative modeling framework of the underlying structures and dynamics of a value system and applies it to the historical evolution of GSM and Wi-Fi³³. The publication enhances the methods created in the first stage of the research and draws basis from prior value system modeling and systems thinking literature to create a framework describing both the underlying structures and dynamics of a value system at different stages and levels of service production. The framework is subsequently used to examine what kind of an effect a structural fit of the business and technical architectures and the alignment and synchronization of the different stages

³¹ Publications I and II were written in the context of MoMI II and IMCOS projects respectively. Publication II is also connected to another article where the author was involved that deals with quantitative techno-economic modeling of some of the identified value system configurations (Katsigiannis et al., 2011) but which is outside the scope of the thesis.

³² Publication III is directly linked to three other publications by the author, that are outside the scope of the thesis. These deal with quantitative level system dynamic modeling of the wireless local area access (Casey et al., 2010), strategic implications of the generic scenarios for network equipment providers (Enqvist and Casey, 2010) and regulatory differences between markets (Basaure et al., 2012).

³³ This publication was written in the context of the EECRT project.

of service production and markets had on the diffusion of GSM and Wi-Fi. Hard data related to GSM and Wi-Fi technology diffusion is collected from various sources (e.g. public databases) and written data from historical documents and prior research. Soft data is collected from 18 semistructured expert interviews including representatives of device and network equipment vendors, mobile operators, regulators and academia.

Publications V and VI have a specific stakeholder point of view and focus on the dynamics of how value systems around wireless access provisioning have been and could be orchestrated. Publication V uses system dynamics to examine the regulator as a value system orchestrator for the diffusion of mobile communications³⁴. This is conducted by modeling the feedback structure of the mobile market and by configuring the model for retrospective simulations of the Finnish market. The publication focuses on evaluating policies used in different countries (e.g. a harmonization policy in Europe versus a technology competition policy in the U.S.) and applies a counterfactual approach to the historical evolution, i.e. what could have happened if the Finnish regulator had e.g. chosen a technology competition policy instead of a harmonization policy when issuing licenses for the 900 MHz spectrum band. Hard data is collected from public databases and regulatory documents, written data from prior research, and soft data from ten stakeholder interviews with representatives from device and network equipment vendors, mobile network operators and regulating entities.

Publication VI models the strategic management of two-sided platforms from the view point of a mobile communications platform manager and elaborates on the dynamics that result in either platform success or failure³⁵. Building partly on the methods developed in the first stage of the research, a framework is created that models the endogenous formation and diffusion process of a two-sided platform and applied to the diffusion of public wireless local area access services. The manager of such a platform could be a mobile network operator, a service application provider or a third party. Hard data reflecting a large European city and platform deployment costs is collected and used for the modeling work. Furthermore hard data from the diffusion of other technology platforms (e.g. DVB-H, GSM and iMode) is used. Written data about historical evolution of other technologies is also utilized.

³⁴ This publication was written in the context of the MoMI II project.

³⁵ This article was written in the context of IMCOS and EECRT projects.

Table 1. Summary of research process ((D) indicates that the publication includes some form of method development).

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Publication	Substance area	Research method	Related theories	Research data	Stakeholder point of view
Value system structures					
Publication I		Value system modeling framework of technology and business architectures, and generic scenarios for value system configurations (D)	Theories on business and technical architectures, different value creation logic's		Generic
Publication II	Possible configurations for wireless local area access	Enhanced version of framework including assessment of role logic and driving forces for role importance (D)	Theories on business and technical architectures, different value creation logic's	Written: publicly available information on existing wireless local area access business models	Generic
Publication III	Possible configurations for flexible spectrum use and spectrum markets	Framework combined with Schoemaker's scenario planning method, and conceptual system dynamics of high level forces (D)		Written: prior research Soft: expert interviews	Generic
Value system dynamics					
Publication IV	Historical evolution of GSM and Wi-Fi	Qualitative modeling framework of value system structure and dynamics (D)	Cycle theories, dynamical systems theory, complexity theory, network externalities	Hard: publicly available statistics on penetration and number of industry alliance members Written: historical documents and prior research on GSM and Wi-Fi Soft: expert interviews	Generic
Publication V	Effect of Regulator policy on historical diffusion of mobile communications	Regulator policy analysis with system dynamics	Network externalities	Hard: publicly available statistics on penetration and availability in Finland, prior research Written: related prior research Soft: expert interviews	Regulator
Publication VI	Platform management and diffusion of public wireless local area access services	Framework to evaluate subsidization strategies of platform managers, system dynamics (D)	Network externalities, platform theory, two-sided market theory	Hard: publicly available data reflecting a large European city and platform deployment costs, statistics on other technology platforms Written: historical evolution of other technologies	Public wireless local area platform manager (e.g. MNO)
Publication VII	Value system dynamics given the introduction of flexible spectrum use	Quantitative formulation of framework developed in Publication IV with conceptual level system dynamics and agent based modeling (D)	Cycle theories, dynamical systems theory, complexity theory	Hard: operator market shares and penetration of GSM and Wi-Fi Written: historical documents Soft: expert interviews	Generic, Regulator
Publication VIII	Deployment of flexible spectrum use in advanced and emerging markets	Conceptual level system dynamics		Hard: publicly available descriptive data about both example markets Written: related prior research Soft: expert interviews	Generic, Regulator

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Publications VII and VIII focus on the long term evolution towards flexible spectrum use. Publication VII explores the possibilities of how the value system around wireless networks could be organized in the future and what would be the underlying market dynamics given the introduction of flexible spectrum use in terms of cognitive radio and dynamic spectrum access technologies. The qualitative level framework presented in Publication IV is further enhanced and formulated to a quantitative feedback model using agent-based modeling³⁶. The model is configured with historical market data and used to evaluate future evolution possibilities both for GSM-based mobile cellular and Wi-Fi-based wireless local area access tracks towards flexible spectrum use. The stakeholder view is generic but focuses also on the spectrum licensing policies of the regulator. Hard data for the work comes from public databases and consultancy reports and written data from historical documents and prior research. Soft data is collected from eight stakeholder interviews including representatives of device and network equipment vendors, mobile operators, regulators and academia.

Finally, Publication VIII compares how flexible spectrum use could be deployed in advanced and emerging markets³⁷. Finland and India are used as examples of a more centralized and decentralized market respectively, and the different policy options and environment for spectrum management are explored for both. As opposed to Publications V and VI, which assume that the value system orchestrator is not part of the feedback structure, in this publication the relevant stakeholders (i.e. regulator, operators) are embedded in the feedback structure to show the path dependency of the policy used in the market and its implications for the deployment of more flexible spectrum use. Descriptive hard data about both example markets are collected and existing written data from prior research is utilized. Furthermore, seven expert interviews are conducted with selected stakeholders in order to collect soft data.

project.

³⁶ This publication is linked to two other publications by the author that are outside the scope of this thesis (Markendahl and Casey (2012) and Taparia et al. (2012)). The publication was written in the context of the EECRT project.
³⁷ A preliminary version of this article was published in another journal article (Sridhar et al., 2012). The publication was written in the context of the EECRT

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5. Research results

This chapter presents the results of this thesis where the evolution of wireless access provisioning, as described in Chapter 2, is examined and modeled using the two stage research approach introduced in Chapter 4. Following the two stage approach this chapter, first, lays out results from the examination of possible value system structures of wireless access provisioning. Second, the chapter continues by presenting results from the examination of underlying value system dynamics of both historical and future evolution of wireless access provisioning.

5.1 Underlying value system structures

The first stage of the research examined the underlying value system structures of wireless access provisioning in terms of the (more static) technical and business linkages between the elements, the high level forces driving the value system structure and the interaction of these forces.

5.1.1 Framework for value system structures

The research process began with the creation of a value system modeling framework shown in Figure 7 which depicts a three level model of a value system. The first level describes the business architecture (i.e. the value network)³⁸ that models the relationship of economic actors, i.e. which roles each actor may take, and the contractual relationships between the actors. In other words, the business architecture consists of economic actors pursuing specific business models (Osterwalder et al., 2005) and having business interfaces and linkages with each other.

The second level in Figure 7 depicts a constellation of roles which describes how roles are configured to enable the production of value³⁹. In

³⁸ This thesis primarily uses the terms business architecture and value network (also value chain in Publication III) to describe the level of economic actors. Other terms such as industry architecture (Jacobides et al., 2006), value web and value net can be found from existing literature.

³⁹ In Publication I the term value production was used for this level of the value system. There are also other terms in the existing literature that can be seen as

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the created framework a role is defined as a set of activities and technical components, the responsibility of which cannot be divided between separate actors. Roles can have three different value creation logics as discussed by Stabell and Fjeldstadt (1998), i.e. transforming inputs into products, solving unique customer problems, and mediating connections between user groups. In particular, a company in possession of an important mediating role can be characterized as a keystone company (Iansiti and Levien, 2004), a platform leader (Gawer and Cusumano, 2008) or a company in possession of a gatekeeper role (Ballon, 2009).



Figure 7. Value system modeling framework (adapted from Publication I). Copyright 2010 Emerald Group Publishing. Reprinted with permission.

Finally, the third level depicts the technical architecture⁴⁰ of the value system which consists of a set of technical components and their technical

being equivalent to the term role. Porter (1985) for example uses the term activity and the Value Chain Dynamic toolkit (MIT CFP, 2005) the term control point, i.e. a point at which (technological or business) management can be applied. ⁴⁰ Throughout the thesis the term technical architecture is primarily used to describe this level. However, Publication I used the term value architecture. Also terms like a "set of interconnected and layered platforms" and "service delivery infrastructure" are used.

interfaces. In the framework a technical component is defined as a collection and realization of technical functionalities. The technical components in turn define roles responsible for operating and maintaining the components.

Furthermore, the framework defines four generic scenarios that can be used to classify different value system configurations based on two dimensions: first, whether the configuration is centralized or decentralized and second, whether the configuration is horizontal (open) or vertical (closed). These two key dimensions have been repeatedly found to be important in prior scenario analysis work (Verkasalo, 2008; Levä, 2009; Smura and Sorri, 2009)⁴¹ and also on a more generic level as it relates to the cyclical evolution of technologies and industries (Anderson and Tushman, 1990; Fine, 2000).

This framework is described in more detail in Publication I and was further enhanced in Publication II by improving the visualization of the different levels of the value system, and by including an explicit evaluation of role logic and role importance. Role importance relates closely to the concept of coreness used in the Value Chain Dynamics toolkit (MIT CFP, 2005) which corresponds to a role that is high in demand but scarce (i.e. has low interchangeability)⁴².

5.1.2 Configurations for wireless local area access

As discussed earlier, considerable uncertainty exists over who will control access to wireless local area access points in the future and as there are many interested actors that could be involved, the resulting value system can become rather complex both on a business and technical level. Motivated by these uncertainties, the created framework was used to examine value system configurations that currently exist or could emerge around wireless local area access in the future⁴³. The study was partly based on the scenario modeling work of Smura and Sorri (2009) and identified important roles, such as wireless local area network and access account operation, which could be taken by an actor leveraging its control over a strategically important adjacent platform. Such an actor could be e.g. a venue owner (or facility manager) controlling the building space, mobile

⁴¹ Interestingly, the shift away from a vertically integrated industry structure was also present in the original scenario planning cases of Shell (de Geus, 1988). ⁴² This has also been highlighted by Jacobides et al. (2006) who stresses the importance of companies becoming the bottlenecks of their industry and Ballon (2009) who discusses gatekeeper roles.

⁴³ In Publication II the term value network configuration was used to depict the level of business architectures. A similar study had been conducted by Markendahl and Mäkitalo (2007) that, however, focused only on the business architecture level and did not include all possible configurations.

Horizontal



Figure 8. Selected value system configurations for wireless local area access (adapted from Publication II). Copyright 2010 IEEE. Reprinted with permission.

operator controlling the cellular wide area network or service application provider in control of the services being accessed.

Figure 8 depicts selected four value system configurations (out of a total of seven) driven by vertically integrated fixed-mobile operators, horizontal mobile operators, venue owners and service application providers, where each configuration is classified based on the generic scenarios.

In a fixed-mobile operator driven configuration (i.e. centralized and vertical) the end-user, in this case a household or an enterprise, has only a single contract with a fixed-mobile operator which provides complete integrated access to both wide area and local area networks and also most of the needed services such as voice calls and video, sometimes referred to as quadruple play. This can also lead to it having tight control of the technical functionalities in the devices which in turn can lead to closed interfaces and proprietary solutions.

In a mobile operator driven configuration (i.e. centralized and horizontal), the mobile operator extends its control to wireless local area access points where the end-user, e.g. a household, conducts the initial deployment and basic physical operation of the access point, e.g. supply of power, and has a contract with a broadband access operator for fixed access. In the case of public access the end-user and venue owner are separate actors that both have contracts with the mobile operator. The femtocell technology is an example of an enabler of this configuration, where the access points are tightly coupled to the mobile cellular network.

The venue owner driven configuration (i.e. decentralized and horizontal) roughly corresponds to the Wi-Fi deployments that are dominant today. In this configuration, a venue owner, e.g. private household, enterprise, coffee shop or city, provides wireless local area access to end-users. This typically includes a direct contractual relationship with the end-user including the provisioning of authentication keys. The decentralized and open configuration allows for more open interfaces and technological heterogeneity in terms of the deployed technologies while also ensuring interoperability between the technical components.

Finally, in a service application provider driven configuration end-users have a single contract with a service application provider which offers wireless access in addition to the services. Various Internet service giants, such as Google, Microsoft and Amazon, have gradually expanded their position in the value system around wireless access provisioning and could eventually also try control wireless access provisioning themselves. The service providers could create a mediating platform through which their service users could get transparent wireless local area access or even become mobile virtual network operators and provide access to cellular

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wide area networks⁴⁴. However, if interfaces are proprietary, there is a threat that users are locked into specific service providers⁴⁵.

The value system configurations are depicted in more detail in Publication II where in addition to these four configurations, others were also identified. These are driven by broadband access operators (such as British Telecom), access aggregators (such as FON or Boingo) and end-users, who are increasingly turning their smartphones to hotspots by sharing their mobile broadband connections with Wi-Fi. Overall, the identified configurations are diverse and range from ones where control over wireless local area access is centralized to ones where it is managed locally in the edges. The configurations were also mapped over the four generic scenarios while still allowing some flexibility in the direction of both dimensions. The results suggest that with small variations almost all of the possible future configurations around wireless local area access can be mapped to one of these.

Overall, the description and identification of the configurations clarifies the possible evolution paths for wireless local area access provisioning and acts as a basis for the design of corresponding future technologies and regulatory policies. In order to leverage existing and future wireless local area access infrastructures optimally, co-operation and mutually beneficial agreements across these configurations are needed. Therefore, corresponding regulatory policies and future technologies should be designed in a way that enables sufficient interoperability and revenue sharing between actors driving the value system configurations.

5.1.3 Configurations for flexible spectrum use

The evolution possibilities for how flexible spectrum use could be deployed in wireless access provisioning involve a great deal of uncertainty. Next, the scenario planning method, coupled with concepts from the earlier created framework, was used to study how a radio spectrum market could emerge around wireless access provisioning.

The study began by utilizing Schoemaker's (Schoemaker and Mavaddat, 2000) scenario planning method which proceeds by gathering relevant

⁴⁴ This scenario relates closely to the findings of Jacobides et al. (2006) who identified that some firms (e.g. service application providers) can conduct value appropriation without the need to engage in (extensive) vertical integration by increasing compatibility (e.g. between end-users and venue owners) and mobility (e.g. competition between wireless access operators) in parts of the value system they are not active.

⁴⁵ An alternative way to interpret this configuration is through small niche providers (often referred to as "verticals") who combine services and access and provide highly tailored services to local needs (i.e. similar to the original WLAN systems, e.g. cash register systems).

technical, social, regulatory and economic forces driving change, by prioritizing and ranking them in terms of importance and uncertainty, and by examining their interactions in terms of correlations. In this work, however, the interaction of relevant forces was studied by examining their causal relations and the resulting feedback structure they form using conceptual level system dynamics⁴⁶. This resulted in a feedback model of relevant trends and uncertainties as depicted in Figure 9.



Figure 9. System dynamics model of forces driving flexible spectrum use⁴⁷ (Publication III). Copyright 2009 IDATE. Reprinted with permission.

The model shows different forces driving the demand for wireless bandwidth (U5) and four ways of catering to, i.e. balancing, the demand: 1. increasing the liberalization of spectrum regulation (B_regul loop), 2. more efficient spectrum use by the incumbent mobile cellular operators (B_incumb loop), 3. increasing the availability of unlicensed spectrum and number of local area operators (B_unlic loop) and 4. increasing the locality of spectrum assignments and markets (B_local loop). Locality of spectrum markets, on the other hand, drives the decentralization of intelligence in wireless networks which in turn fuels locality even further thus forming a reinforcing loop (R_local). The degree of vertical integration is driven on one hand by the reinforcing expansion power of the strongest player(s) of

⁴⁶ The combination of scenario planning and system dynamics relates closely to parts of the Value Chain Dynamics toolkit (MIT CFP, 2005) that discusses so called triggers and their dynamics.

⁴⁷ In system dynamic models a positive causal link (+) indicates that two variables change in the same direction whereas a negative causal link (-) indicates that two variables change in opposite direction. Reinforcing loops (R) have an even number of negative links and balancing loops (B) an uneven number of negative links.

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the value system (R_vert loop) and on the other hand by decoupling forces such as disruptive technologies and regulatory actions (B_horiz loop).

Next two uncertainty forces, Locality of spectrum markets (U1) and Vertical integration in the industry (U2), were used to construct the scenarios as depicted in Figure 10 corresponding to the dimensions used in the generic scenarios of the value system modeling framework and also the prior scenario work of Smura and Sorri (2009). Figure 10 gives a rough description of the presence of each relevant actor group over the technical architecture in each of the four scenarios which are described in more detail in Publication III. As it relates to the endogenous structure of the forces, the system dynamic model in Figure 9 can be used to describe what kind of interaction of forces results in each scenario.

In the cellular operator bundled spectrum scenario, spectrum management and brokering remains centralized where operators hold on to spectrum bands themselves and tie them to their own technologies and services. The B_incub loop in Figure 9 is almost the sole source of supply to the growth of demand and R_vert loop is clearly stronger than B_horiz.

In the centralized spectrum brokers scenario mobile operators take advantage of flexible spectrum use without losing too much control and market to local area operators, i.e. most of the intelligence remains in the network. In Figure 9, the demand is catered mainly by the B_incub loop but is also facilitated by a strong B_regul loop. B_horiz loop becomes stronger than R_vert reducing incumbent cellular operators to being huge, but possibly rather profitable and intelligent, bit pipes. Connectivity and sensing clients, and spectrum databases in this scenario are controlled by the operators, which implies strong presence of LTE-based technologies.



Figure 10. Four scenarios for flexible spectrum use (Publication III). Copyright 2009 IDATE. Reprinted with permission.
In the intelligent devices rule scenario, radio intelligence and control is decentralized to the edges with wireless local area access points and devices themselves actively and independently taking part in the spectrum management process, and collaborating by sensing and monitoring the utilization of the spectrum resource. Ownership of spectrum is also largely decentralized and localized. In Figure 9 most of the demand is met with a strong B_local balancing loop facilitated also by strong B_regul and B_unlic balancing loops and the reinforcing loop R_local. The increased device intelligence leads to the decoupling of services from access and spectrum and hence B_horiz loop is stronger than R_vert. Overall this scenario would correspond to the full realization of cognitive radio where an open, loosely coupled, narrow waist type of, technology would be used for mobility, roaming and spectrum access. Connectivity and sensing clients, and spectrum databases would be implemented with open technologies and be democratized to all.

Finally, in the access and spectrum broker aggregator scenario the decentralized and fragmented access provisioning and spectrum market is aggregated by service application providers who have gained a dominant position in the overall value system. In Figure 9 most of the demand is met with a strong B_local balancing loop (facilitated by B_regul, B_unlic and R_local). The R_vert loop becomes very strong compared to B_horizontal with the powerful service providers re-coupling spectrum and access to their services. Service application providers use closed proprietary technologies for connectivity and sensing clients, and spectrum databases, which in turn becomes the de facto narrow waist technology, and integrate them to their services. This could also lead to a situation where they become de facto regulators of the resulting new radio platform.

Overall, the results highlight the importance of being aware of the endogenous feedback structure of the high level forces driving the structure of the value system and clarify what are the possible evolution paths towards flexible spectrum use. For policy makers the results show the need to be aware of too weak spectrum liberalization but also of a situation where spectrum is liberalized too heavily which in turn could pave the way for other large actors to become de facto regulators of the new radio platform. This has happened to some degree in some existing services e.g in the Internet, where national players and regulators have lost control and services are provided by global Internet players.

The conceptual system dynamics model in Figure 9 illustrates the dynamics of the identified forces and how their interactions could lead to the different scenarios. It should, however, be noted that although the

scenarios reflect plausible value system configurations they represent extreme evolution cases.

5.2 Underlying value system dynamics

After modeling and describing the possible value system structures, still in a rather static manner, the research moved on to examine the deeper endogenous structures and underlying value system dynamics of wireless access provisioning. First, value system dynamics of the historical evolution of GSM and Wi-Fi were examined. Next, two examples of value system orchestration were studied, namely the historical regulatory policy decisions related to the diffusion of mobile communications, and the strategic management of future two-sided public wireless local area access platforms. Finally, value system dynamics related to the evolution towards flexible spectrum use were examined by modeling the underlying market dynamics given the introduction of CR and DSA systems and by comparing advanced and emerging markets using Finland and India as examples.

5.2.1 Historical evolution of GSM and Wi-Fi

As a next step in the research, a framework was developed that can be used to model the dynamics of a value system at different stages and levels of service production. The framework was created by combining a mixture of concepts from cycle theories, dynamical systems theory, complexity theory, and network externalities and built on the prior method development work related to value system structures depicted in Section 5.1.

The framework describes the dynamics of each stage (or subsystem) of a value system both on a business and technical architecture level using basic concepts from dynamical systems theory. Roughly put, the dynamic behavior of a system can be described with four different attractor types: a fixed point attractor, a limit cycle attractor, a strange attractor and a random system that has no attractor at all.

A subsystem directed by a fixed point attractor remains static and consists only of negative feedback, much like a damped pendulum. A subsystem following a limit cycle attractor follows periodic and rather regular change where a system has some positive feedback but negative feedback still dominates, much like a continuously swinging pendulum. A subsystem following a strange attractor produces deterministic irregular change that is highly sensitive to initial conditions (Lorenz, 1963) and can be seen as functioning on the edge of chaos where positive feedback in the system is stronger than negative feedback. A system that has no attractor at all exhibits complete disorder (i.e. is non-deterministic), has only positive feedback and no negative feedback to keep it together. Furthermore, on a broader level, it has been observed that a network of subsystems following the same dynamics can become synchronized (Strogatz, 2001).

Following this division and logic, Figure 11 depicts a value system dynamics notation of, first, a network of *fixed attractor* subsystems dominated by one actor and integrated technical components, second, a network of *limit cycle attractor* subsystems with few tightly coupled actors and technical components, third, a network of *strange attractor* subsystems with many loosely coupled actors and technical components, and fourth, a network of *no attractor* subsystems with many isolated actors and technical components (that can have a fixed attractor structure nested into them reflecting proprietary incompatible systems). For a detailed description of the framework the reader can refer to Publication IV.



Figure 11. A notation of value system dynamics (Publication IV). Copyright 2012 Intersentia. Reprinted with permission.

A subsystem at a particular stage of the value system can transition from one state to another. Figure 12 depicts transitions between the subsystem states, a conceptual level value distribution between the value creating actors at a subsystem level and the overall cyclical process where the value system revolves around a centralized and decentralized structure (Anderson and Tushman, 1990; Fine, 2000).



Figure 12. Dynamics and transitions between the subsystem states (Publication IV). Copyright 2012 Intersentia. Reprinted with permission.

A subsystem transition can come from within the subsystem or through alignment with other subsystems, e.g. adjacent stages in the value system, nearby markets or architectural levels or from other external forces. For example, causes for convergence can come from dominant design selection or industry consolidation and for divergence from regulatory actions or a technological discontinuity.

The created framework was then used to retrospectively model the evolution of GSM-based mobile communications and Wi-Fi-based wireless local area access as described in Publication IV. The left side of Figure 13 summarizes the evolution of NMTand **GSM**-based mobile communications as a transition from a network of fixed attractor subsystems to a synchronized network of limit cycle subsystems. The right side of Figure 13 depicts the evolution of Wi-Fi-based wireless local area access as an ongoing transition from a network of no attractor subsystems to a synchronized network of strange attractor subsystems.

As a whole, over the years, the centralized value system around mobile communications has evolved from a set of national monopoly operators using incompatible technologies to a globally harmonized GSM value system with standardized tightly coupled technical interfaces enabling multi-vendor solutions, end-user device ownership and network selection, mobile operator competition in terms of price and service quality, and international roaming. Here, for example, the harmonization approach used in Europe to deploy GSM on the 900 MHz spectrum (i.e. the GSM MoU in 1987) was a key milestone and trigger in the overall transition towards a centralized and open value system where the actors and technical components could become synchronized.



Figure 13. Evolution of GSM and Wi-Fi paths (modified from Publication IV). Copyright 2012 Intersentia. Reprinted with permission.

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In a similar manner, decentralized wireless local area access provisioning has evolved from a set of fragmented technologies to a global value system of IEEE 802.11-based Wi-Fi certified equipment with loosely defined technical interfaces, large international device circulation and economies of scale, facilitating wireless access to the Internet in private households and enterprises globally. As it relates to the ongoing evolution of Wi-Fi-based wireless local area access, key triggers for the transition were the standardization efforts in IEEE 802.11 and the creation of Wi-Fi alliance to ensure minimal interoperability of equipment which in turn led to a decentralized and open value system where the actors and technical components could become synchronized.

Still, as shown in the upper right corner of Figure 13 some subsystems in the value system around Wi-Fi are still to be synchronized with the strange attractor subsystem network and thus a loosely coupled open roaming network could emerge between the millions of households, enterprises and other venue owners acting as isolated Wi-Fi operators. The same goes for spectrum regulations which could evolve from enforcing a policy where a band is allocated and assigned for license-exempt local use that requires practically no co-ordination from the venue owners to licensing schemes where venue owners, end-users and devices could increase co-ordination and negotiate co-operatively enabling true cognitive radio type of functioning.

As a whole, the results highlight that an important factor in the large scale diffusion of GSM and Wi-Fi has been the structural fit of the business and technical architectures and the alignment and synchronization of the different stages of service production and markets. The results also show that the value systems around GSM and Wi-Fi follow distinctly different dynamics and evolution paths and that they are on a colliding course. As these evolution paths collide, it is unclear if, how, to what degree and in what part of the technical architecture Wi-Fi and cellular network services will convergence.

It is possible that one of the value systems gains a significantly larger role leading to a situation where the other value system becomes a subsystem of the larger one and full synchronization happens. This could be the case if e.g. SIM-based authentication becomes common in Wi-Fi access points⁴⁸. Another possible evolution path is one where the decentralization of radio intelligence to the devices continues and the dynamics of the strange attractor node network extend to the level of wireless access provisioning where decentralized wireless local area access points and devices would

⁴⁸ For example through the possible diffusion of GSMA and Wi-Fi Alliance's recently announced Passpoint certification technology.

become cognitive radios and gain more control over wireless access provisioning.

5.2.2 Regulatory policies for mobile communications

As it relates to the historical transition from a national monopoly operator model to an open multi-operator competition model in mobile communications (i.e. the transition depicted on the left side of Figure 13), regulatory policies varied in different markets. While in Europe a technology and spectrum harmonization approach was enforced, a technology-based competition policy was favored in some markets, such as the U.S. In order to gain insight to the corresponding value system dynamics, Figure 14 depicts a conceptual level system dynamics model of the feedback structure related to the diffusion of mobile communications and the spectrum licensing policy, described in detail in Publication V.



Figure 14. Conceptual model of diffusion of mobile voice technology (Publication V). Copyright 2012 Elsevier. Reprinted with permission.

The model depicts six reinforcing loops that drive the diffusion of mobile communications and two balancing loops that restrict the growth. Selfsustaining growth (or decline) between end-users are modeled with a 'Word-of-mouth' and a 'Direct network effect' reinforcing loop. Reinforcing growth between end-users and mobile operators and the availability of mobile communication services are modeled with a 'Cross-side network effect' and a 'Roaming value' reinforcing loop. The effect of equipment economies of scale is modeled with a 'Mobile handsets economies of scale' loop on the handset side and 'Mobile network economies of scale' loop on

the infrastructure side. The model also shows the licensing policy lever where the regulator can choose between a licensing policy of either enforcing a harmonized standard (and spectrum band) or letting operators freely choose the standard (i.e. technology competition).

Next, a quantitative system dynamics model was constructed and configured for retrospective simulations of the Finnish market where a form of counterfactual history was used to evaluate what could have happened if a different licensing policy would have been chosen in Finland⁴⁹. Figure 15 depicts simulation results related to mobile voice service user penetration with both harmonization and technology competition policies. The simulation results are also compared to historical reference data from the Finnish market and from low diffusion markets as defined by Jang et al. (2005).



Figure 15. Simulation results of user penetration with harmonization and technology competition policies (Publication V). Copyright 2012 Elsevier. Reprinted with permission.

Figure 15 indicates that during the simulation, diffusion of mobile voice occurred faster in the case of a harmonization policy. A harmonization policy enabled end-users to become a part of a larger (worldwide) base of interoperable and affordable handsets and subsequently also led to a stronger 'Direct network effect' reinforcing loop in Figure 14. The harmonization policy also led to larger infrastructure economies of scale and stronger cross-side network effects between the end-users and mobile

⁴⁹ A more detailed description of the quantitative modelling and used data can be found from Publication V sub-sections 3.2.3 and 3.2.4, and Fig. A1.

operators as depicted in Figure 16 where the results are compared to reference data of service availability of Finnish mobile operators.



Share of population with availability

Figure 16. Simulation results of service availability with harmonization and technology competition policies (Publication V). Copyright 2012 Elsevier. Reprinted with permission.

In addition to enabling more rapid network expansion for incumbents, the harmonization policy also makes it more attractive for new mobile network operators to build their own networks in new areas since the active end-users can rather easily switch between networks using the same handsets. With a technology competition policy the strength of the 'crossside network effect' reinforcing loop was weaker because of a longer network expansion delay, more expensive network infrastructure, geographical fragmentation and lack of roaming possibilities to other regions and countries.

All in all, the simulations support the view that enforcing a harmonized standard has enabled a faster diffusion of mobile communications in Finland. On the other hand, it should also be noted that promoting harmonization too extensively can lead to the inability of market actors to differentiate themselves and create new innovative services. In the Finnish market for example, as mobile voice and SMS services became commoditized, fierce price competition resulted where the effect of mobile number portability policy played an important role (the effect of this policy was also modeled in Publication V).

Overall, the results highlight the importance of distinguishing when the majority of value comes from harmonization and interoperability and when from differentiation, innovation and technological competition, and the importance of orchestrating the policies accordingly. In the case of wide

area mobile cellular networks a harmonization approach seems more appropriate whereas with technologies (and resources) that are more flexible and require less co-ordination, a technology competition approach might work better (e.g. in software defined service applications).

5.2.3 Public wireless local area access platforms

While private, e.g. enterprise and household, Wi-Fi deployments have become widely diffused, up until now, public wireless local area platforms have remained fragmented (as indicated earlier e.g. on the upper right side of Figure 13) and have not gained large scale success partly due to a chicken-and-egg type of a problem. Without revenue generating end-users the venue owners have little incentive to join a platform and on the other hand without venue owners offering Wi-Fi access in relevant places, endusers have little incentive to create platform affiliation.

Motivated by these observations, the research proceeded to create a framework that can be used to evaluate platform manager subsidization strategies. The created framework builds on the earlier method development related to value system structures, and models the endogenous formation and diffusion process of a two-sided platform, describing the interplay of strategy levers that platform managers have at their disposal and factors affecting user willingness to create platform affiliation.



Figure 17. A framework for two-sided platform managers (Publication VI). Copyright 2012 Elsevier. Reprinted with permission.

The framework is shown in Figure 17 and Figure 18 depicting a platform manager managing a mediating platform between two user groups (e.g. end-users of a public wireless local area access service and venue owners deploying the access points) and is described in detail in Publication VI. A critical factor for the platform manager is that the net value for user groups on both sides needs to be positive for reinforcing feedback to take place and for growth to become self-sustaining. A core goal therefore is to manage the two-sided platform in a manner that enables all related actors (including the platform manager itself) to gain net value and orchestrate endogenous self-sustaining growth. This can be achieved for example by using direct subsidization (offering equipment or upgrades for free), by using indirect subsidization with revenue sharing or by creating alliances with competing platform managers in order to increase the overall market size.



Figure 18. Conceptual feedback model of the framework (Publication VI). Copyright 2012 Elsevier. Reprinted with permission.

The quantitative formulation of the model was based on a modified version of the classic Bass (1969) model, and modeled adoption through external and internal influence and also platform discards by the users for both sides of the platform⁵⁰. The framework was applied to the diffusion of public wireless local area access services and configured with data reflecting a large European city. Based on the simulation cash flow analysis was also conducted from the point of view of the platform manager taking into consideration revenue sharing, platform management costs for existing users (e.g. authentication servers and other platform functionality) and subsidization costs for new users on both sides of the platform.

First, different direct platform subsidization strategies were evaluated where the strength and length of subsidization on both sides was varied.

⁵⁰ A detailed description of the quantitative modeling can be found from Publication VI in sections 3.3 and 3.4 and in Table A1 in Appendix A. Also as described in Publication VI Appendix B, the configured model is able to reproduce key dynamics observed in the evolution and diffusion of other mobile technology platforms (DVB-H, GSM and i-mode).

The strategies reflected the value system configurations and the corresponding stakeholders identified in the first stage of the research (see Figure 8), where e.g. horizontal mobile operators can more heavily subsidize the venue owners (i.e. have pre-existing relationships to venue owners), service application providers the end-users (i.e. have a large base of end-users, whose devices they partly or fully control) and vertical mobile operators both sides.



Figure 19. Share of platform users with low and venue owner subsidization strategies (Publication VI). Copyright 2012 Elsevier. Reprinted with permission.

Figure 19 shows the share of end-users and venue owners when two subsidization strategies are used where the subsidization lasts for three years. With a low subsidization strategy both sides are subsidized only moderately and with a venue owner subsidization strategy (e.g. by a horizontal mobile operator) the venue owners are subsidized more heavily.

With the low subsidization strategy diffusion is modest, the threshold for endogenous self-sustaining growth is not reached and instead a vicious cycle of platform discards dominates. In this case subsidization efforts should be more intense (or last longer) or alternatively platform affiliation costs should be lower which in turn might not be possible due to the structure of the value system. For example, in Europe, value system structure is typically rather horizontal, which makes it difficult for mobile operators to offer tailored phones for their platforms as opposed to the vertical industry structure e.g. in Japan. With the venue owner subsidization strategy the growing base of venue owners increases the attractiveness for end-users to voluntarily join the platform which in turn leads to self-sustaining growth where no discards occur.



Figure 20. Share of platform users with end-user, short and long subsidization strategies (Publication VI). Copyright 2012 Elsevier. Reprinted with permission.

Figure 20 shows results from three other direct subsidization strategies: a short subsidization strategy where both sides are subsidized heavily (e.g. a vertically integrated mobile operator as a platform manager), an end-user subsidization strategy where end-users are subsidized more heavily (e.g. a service application provider as a platform manager) and a long subsidization strategy where subsidization efforts are low but where the subsidization period is longer (10 years) (e.g. a long term community effort).

A short (and intense) subsidization strategy leads to rather quick diffusion where most users join the platform through external influence but also voluntary, self-sustaining adoption occurs. Since a critical mass is reached on both sides quickly, almost no discards occur. When subsidizing just the end-user side of the platform, it takes a longer time for the cross-side network effect to start working in both directions. With the long subsidization strategy, an extensive incubation period is needed for the cross-side network effects to emerge.

Overall, the simulations highlight that if both sides of the platform are equally dependent on the other side for value, i.e. if the elasticity of demand across the platform is balanced between the user groups, it is important for the platform manager to try to subsidize both sides more equally in order to avoid a vicious cycle of discards and to create a virtuous cycle of selfsustaining growth. This is in contrast to the more exogenous approach suggested by two-sided market theory, where, if the elasticity of demand across the platform is not balanced, it makes sense to enforce heavier and possibly permanent subsidization on one side in order to sustain the crossside network effect and collect profits on the other side.

The results also indicate that one reason why mobile operators in vertically integrated markets, such as Japan, have been successful in deploying mobile platforms is that the mobile operators have been in a position to subsidize both sides of the platform and, thus, to create a virtuous cycle between them. Furthermore, the results point out that in a horizontal industry structure it seems important that either the platform manager is able to subsidize one side of the platform heavily until positive feedback takes place or that a significant base of users exists on one side of the platform.

Indirect subsidization strategies were also examined. Figure 21 shows the effect of different revenue sharing models with venue owners. The ratio where the venue owner (VO) gets 10 % seems best in the short term and break-even is reached the earliest. However, by giving a larger share (e.g. 30 % or 50 %) to the venue owner, the long term cash flow is considerably higher. On the other hand, if the platform manager (PM) shares too much of the revenue (e.g. 50 %), cash flow starts to decline which in turn shows that the effect of a decision can be different in the short and the long run.



Figure 21. Cash flows for different revenue sharing models⁵¹ (Publication VI). Copyright 2012 Elsevier. Reprinted with permission.

Overall, the results highlight the importance of understanding dynamic complexity when managing two-sided (and multi-sided) platforms. As described in more detail in Publication VI, understanding dynamic complexity and endogenous feedback structure seems to play an essential role, when considering subsidization strategies for two or more sides of a platform, when making revenue sharing decisions with the value creating

⁵¹ The venue owner subsidization strategy was used for these simulation cases.

user group of the platform, and when deciding whether to form alliances with competing platform managers.

5.2.4 Value system dynamics in flexible spectrum use

In addition to the possible public roaming platform that could emerge between isolated wireless local area networks operated by venue owners, the value system around wireless access provisioning could also evolve towards flexible spectrum use. Technologies such as cognitive radio, software defined radio and dynamic spectrum access could in principle enable roaming and mobility between all devices on all possible frequencies and lead to an open and global network of wirelessly connected devices through which everyone could provide and receive public wireless services. For this to be realized, the technologies have to be coupled with appropriate spectrum regulations which should be more flexible than the current exclusive allocations but also enable more co-ordination between devices than unlicensed spectrum⁵².

Motivated by the above, the research proceeded to examine the value system dynamics of a set of future radio platforms. Here, an individual radio platform, e.g. a mobile or wireless local area network, is managed by an operator that provides a wireless service and mediates interactions through a database between two user groups: end-users using devices and entities hosting base stations. The value system can be configured in four ways following the open-closed and decentralized-centralized dimensions presented earlier.

Here the research also continued the method development work set out earlier by further characterizing the underlying value system dynamics in each configuration. The underlying dynamics were first modeled with simple system archetype feedback structures (Wolstenholme, 2004) and after that agent-based modeling was used to assimilate the large number of feedback relationships between individual agents simultaneously. Thus, an appropriate balance between detailed and dynamic complexity was achieved by using a combination of conceptual system dynamics and quantitative agent-based modeling as described in Figure 22 and Publication VII.

For simplicity the feedback structure in Figure 22 describes interactions between only two agents (i.e. operators) of the value system. The conceptual model depicts competition and collaboration between the agents

⁵² This would correspond to potential subsystem state transitions from no attractor dynamics to strange attractor dynamics e.g. in terms of devices, wireless local area networks, authentication and spectrum regulation (see the upper right corner of Figure 13).

where the *escalation archetype*, which combines two balancing loops, can be used to model the competition process between the agents. Competitive effort of agent A leads to a more valuable radio platform (e.g. a better quality network), more end-users switching to the radio platform and subsequently to a larger market share for agent A. When agent B perceives that its market share becomes smaller relative to agent A (e.g. if end-users switch from agent B's platform to agent A's platform), it induces higher competitive activity from agent B. This in turn leads to a more valuable platform and a larger market share for agent B which further induces higher competitive effort by agent A. As can be seen here the two balancing control loops result in a reinforcing loop fueling self-reinforcing competition between the agents.

The *success to successful* system archetype which combines two reinforcing loops models the process of resource accumulation. The more resources (e.g. spectrum or site infrastructure) agent A gets the more valuable its radio platform becomes and the larger the market share it gets. This in turn leads to the assignment of even more resources to agent A and an even more valuable radio platform. On the other hand this leads to the assignment of less resources to agent B, and subsequently to a less valuable platform, less market share and even less resources to agent B.

The *limits to growth archetype*, which combines a reinforcing and balancing loop, describes saturation in the system. For example, the more resources accumulate to agent A and the larger its market share becomes the less competitive effort agent A puts in and the less valuable its radio platform becomes⁵³.

⁵³ The model embeds two other limits to growth feedback structures, between reinforcing resource accumulation and balancing competition, and between reinforcing competition and balancing resource accumulation.



Figure 22. Conceptual model of interaction between two agents (Publication VII). Copyright 2012 IEEE. Reprinted with permission.

These feedback structures were linked to the dynamic subsystem states of a value system described earlier. In a value system characterized by a *fixed point attractor* the success to successful mechanism is strong and resources, platform value and end-users accumulate to one agent. However, due to the resulting low competitive effort of the dominant agent the overall system slows down and becomes dominated by negative feedback. In a value system characterized by a *limit cycle attractor* the strength of the success to successful mechanism is rather strong, but some competition is present. Resources, platform value and end-users accumulate to and circulate between few agents, and overall, the system evolves cyclically, i.e. it has some positive feedback but is still dominated by negative feedback.

In a value system characterized by a *strange attractor* the strength of the success to successful mechanism is low and competition is high. Resources and end-users are liquid and move around quickly, and overall, the system evolves chaotically, i.e. has some negative feedback but is dominated by positive feedback. In a value system characterized by a *no attractor* there is no success to successful mechanism and competition is intense. Resources and end-users do not accumulate, no structure emerges and overall the system is dominated only by positive feedback.

Based on the conceptual level feedback model, an agent-based model was built that characterizes the individual behavior of each agent where agents can act as both end-users and wireless service providers (i.e. operators)⁵⁴. The model was then calibrated with historical data using a group of 100 agents (reflecting e.g. a geographical area where agents work as a proxy of

⁵⁴ A more detailed description of the agent-based model and quantitative modelling can be found in Publication VII sub-section III.B and Appendix A.

the whole market) to model the evolution of GSM and Wi-Fi networks in Finland. For the GSM path, historical data of the market shares of mobile operators in Finland was utilized, and for the Wi-Fi path, market data of the number of Wi-Fi end-users and operators was used.

The introduction of CR and DSA technologies to devices was then modeled by increasing device intelligence and flexibility, which makes it easier for end-users to switch between operators, during a 10 year period (2015-2025) and by giving initial spectrum licenses to all agents during the CR and DSA introduction period (year 2020). Sensitivity analysis was conducted by adjusting the strength of the success to successful mechanism (see Figure 22) which in part reflects the overall spectrum licensing model.

Spectrum resource accumulation is weakest in the case of license-exempt, i.e. unlicensed spectrum where no spectrum rights exist, and slightly stronger in the case light licensing, where spectrum licenses are assigned dynamically with short cycles while ensuring that competition prevents extensive resource accumulation. The strength is still somewhat stronger in the case of regulated exclusive licenses, i.e. the currently dominant licensing model with large spectrum bands and long license times, and is strongest in the case of unregulated exclusive licenses where all resources can accumulate or be assigned to one operator and no spectrum caps are enforced. The simulation results are depicted in Figure 23 and Figure 24 and described in more detail in Publication VII.



Figure 23. Operator market shares in GSM evolution path sensitivity cases (Publication VII). Copyright 2012 IEEE. Reprinted with permission.

Figure 23 summarizes the simulations for the GSM evolution path and shows how operator market shares evolve over time in the different sensitivity cases. In the beginning of the simulations three large mobile network operators dominate the value system and compete with each other following the limit cycle dynamics. In the base case of using *regulated exclusive licenses*, after the introduction of CR and DSA technologies, competition between the large operators intensifies and they are joined by smaller new entrant operators. Although the large operators lose some market share, the majority of resources still accumulates to and circulates between the large incumbent operators and overall the value system continues to follow the limit cycle dynamics.

With a *light licensing* model the value system starts transitioning towards strange attractor dynamics where incumbent operators are joined by new entrants who are flexibly assigned with resources and are able to grow their market share. An *unlicensed* model dramatically reduces the market shares of large operators. Here, resources become fragmented, no operator is able to grow bottom-up and the value system transitions to follow the no attractor dynamics. With *exclusive licenses without regulation* the value system transitions to follow the fixed attractor dynamics and leads to a winner-takes-all situation where all resources accumulate to one actor and competition stops.

Figure 24 summarizes the simulations for the Wi-Fi evolution path and shows how operator market shares evolve over time in the different sensitivity cases. In the beginning of the simulation the value system is fragmented with a large number of operators with small market shares and follows the no attractor dynamics. As can be observed, in the base case of *light licensing*, the value system transitions to follow strange attractor dynamics where operators with valuable services are able to scale bottomup and get more resources and market share but where no single actor or group of actors starts to dominate the value system. The system adapts quickly to changes and resources are re-assigned to wherever new innovations and valuable services are created.



Figure 24. Operator market shares in Wi-Fi evolution path sensitivity cases (Publication VII). Copyright 2012 IEEE. Reprinted with permission.

Using an *unlicensed* model leads to a situation where the market share of all operators remains very small, resources remain fragmented and thus the value system continues to follow the no attractor dynamics. This would also correspond to the fragmentation of CR technologies and spectrum databases in a similar manner as with Wi-Fi roaming and authentication today. With a *regulated exclusive licensing* model, the value system transitions to follow the limit cycle dynamics, where resources accumulate so that two operators start controlling the market and competing cyclically. With *unregulated exclusive licenses*, resources accumulate to one actor leading to a winner-takes-all situation and fixed attractor dynamics. The dominant actor or actors in the latter two cases could come from the group of incumbent mobile operators but could also come from outside the value system e.g. if a large Internet player controlled the spectrum database⁵⁵ and leveraged network externalities arising from elsewhere.

As it relates to policy implications, the simulations clarify the possible evolution paths of the two technology tracks and point out how they could continue on existing evolution paths or collide. The results also highlight the possibility of a winner-takes-all and a fragmentation type of scenario. Furthermore, since the regulator can influence the underlying dynamics of the market (e.g. the number of operators) with the spectrum licensing model it could be beneficial if the value system would be orchestrated so that the underlying market dynamics are aligned with the natural characteristics of the radio resources. As discussed by Strogatz (2001),

⁵⁵ The corresponding platform leader would in this case become the de facto regulator of the platform and control the narrow waist of the overall architecture.

dynamical systems following the same dynamics tend to naturally synchronize with one another.

For example, as presented earlier, competition following the limit cycle market dynamics has led to rather efficient use of GSM on 900 and 1800 MHz bands. On the other hand, unlicensed private Wi-Fi deployments, have led to a quite well utilized 2.4 GHz ISM band. Overall, roughly put, one can say that low frequency bands propagate far and need more centralized co-ordination and long assignment cycles whereas high frequency bands in turn do not propagate far, remain as a local resource (especially in indoor locations) and thus need less co-ordination.



Figure 25. Example alignment of underlying market dynamics, radio resources and technologies (Publication VII). Copyright 2012 IEEE. Reprinted with permission.

Following this logic the alignment could be realized as shown in Figure 25. Here, fixed point attractor dynamics and the traditional command and control licensing would be aligned with very low frequency bands and base stations working on very large sites. Limit cycle attractor dynamics and regulated exclusive licenses would be aligned with low spectrum bands and base stations working on large range sites where there is some room for competition and value differences in terms of coverage and capacity, but which still have long investment cycles and require reliable assets.

Strange attractor dynamics and light licensing models would be aligned with high spectrum bands and base stations and access points working on sites with short range, instantly adaptive behavior and small scale investments where somewhat unreliable assets, e.g. light or secondary licenses, would be sufficient⁵⁶. No attractor dynamics and the unlicensed model would be aligned with very high frequency bands and with access points and devices working with very short range sites. Overall, in reality,

⁵⁶ The differences of investment logic for wide and local area operators are examined in more detail in Markendahl and Casey (2012).

such alignment is of course difficult (if not impossible) to reach and the market dynamics can work to some degree on all frequency bands (e.g. CR devices on TV white spaces) and on all site types.

5.2.5 Flexible spectrum use in different markets

Finally, the deployment of flexible spectrum use can also be dependent on cultural issues where certain markets could be better aligned with the deployment of the corresponding systems. For example, while advanced countries have typically used centralized planning and co-ordination to forecast and allocate the associated spectrum blocks to operators, the process is often more ad-hoc in emerging markets dictated by decentralized market forces. Next, the research proceeded to compare these opposite approaches by using the Finnish and Indian markets as examples where the former consists of three rather equally sized mobile network operators with similar network quality, harmonized technologies and mostly a post-paid subscription base, and where the latter features a heterogeneous group of operators, market-based national roaming, a large share of pre-paid subscriptions and wide adoption of multi-SIM phones.

The system dynamics model presented in Figure 26, is based on the shifting the burden archetype (Senge, 1990) and depicts the opposite evolution paths that the Finnish and Indian markets are on. The model is the result of several iteration rounds and is an abstraction of a more detailed model presented in Publication VIII. In the model in Figure 26, the increased disparity of spectrum use in terms of capacity and coverage (e.g. some operators having more spectrum than others) can be handled by enforcing a stronger harmonization policy which subsequently leads to a more equal and efficient initial allocation and assignment of spectrum. This in turn leads to the decrease of disparity and to a balancing loop 'B-Harmonization' which overall roughly corresponds to the spectrum licening policy that has been used in Finland.

On the other hand, efficient centralized allocation means that mobile operators do not need to conduct much market-based sharing (or trading) and that end-users do not have many options as it relates to the different radio access possibilities. This in turn means that secondary market sharing or trading mechanisms between operators (such as national roaming) and cognitive radio type of capabilities (such as multi-SIM functionality) in devices are not required. This subsequently leads to a lower possibility for co-operative trading between operators and opportunistic end-user access and in turn to lower activity in the secondary market. The inability of the market to redistribute the spectrum resources subsequently leads to a reinforcing loop ('R-Efficiency through Centralized Planning') that can lock the market on a path of enforcing a harmonization policy.



Figure 26. Conceptual feedback model of the opposite evolution paths (Publication VIII). Copyright 2013 Elsevier. Reprinted with permission.

Opposite dynamics have been followed by the market in India. Increased disparity in capacity and coverage in India has been handled by the market with co-operative sharing between operators (i.e. national roaming) and opportunistic end-user access (i.e. many data plans and multi-SIM handsets). This has subsequently led to what can be seen as a kind of a secondary market activity and in turn to the decrease of disparity and a balancing loop ('B-Markets'). When the markets tackle disparities in coverage and capacity, it leaves a smaller space for a harmonization policy by the regulator. This subsequently leads to less efficient initial allocation and thus to a greater need of secondary market sharing and trading mechanisms between operators and cognitive radio capabilities of end-user devices, in order to efficiently use and redistribute the radio resources. This in turn leads to a reinforcing loop ('R-Efficiency through Centralized Planning') that works in the opposite direction when compared to the Finnish market and can lock the market on a path of tackling disparity in coverage and capacity via the markets⁵⁷.

As opposed to assuming that the regulator is independent of the feedback structure (which was the case for the central stakeholder in the earlier studies), in this model the regulator is explicitly included in the feedback

 $^{^{57}}$ Overall, this reinforcing loop relates closely to the reinforcing loop R_local described earlier in Figure 9.

structure to show the path dependency of the policy used in the market. The model suggests that matured markets such as Finland that have used centralized and harmonized spectrum planning are likely to continue their ex-ante policies and in the future introduce harmonized LTE-based systems for large mobile operators, whereas the emerging market in India, characterized by market oriented ex-poste regulation, is a good candidate to introduce secondary markets and cognitive radio systems.

For example, the Finnish market has faced similar challenges before in introducing more competition as pointed out by historical examples of temporary competition in terms of new GSM1800 and mobile virtual network operators that eventually resulted in consolidation of the market. On the other hand it can be argued that the harmonization policy used in Finland has led to rather efficient deployment of wide area cellular networks and the corresponding spectrum bands (i.e. 900 MHz and 1800 MHz), whereas the Indian market is suffering from dis-economies of scale, loss of trunking gains and allocative inefficiencies due to a fragmented market (Prasad and Sridhar, 2009). Subsequently, in India it might be challenging to introduce harmonization measures such as co-ordinated refarming of WCDMA on 900 MHz which in the Finnish market happened quite naturally.

On the other hand, regulators and policy makers are continuously exploring ways to improve regulations and it is possible that a tipping point is reached and the self-reinforcing loops are reversed in both markets, e.g. if competition, market-based spectrum license assignment (e.g. with auctions) and open deployment of cognitive radio is strongly enforced in Finland or if careful planning and informed decision making about the trade-offs between competition and industry efficiency is introduced in India.

6. Discussion

This chapter explores the significance of the results. This research makes several practical and method related contributions. Overall, based on the findings and contributions of this research, a thesis can be made that dynamic complexity is essential for the management of wireless access provisioning and that it is important to have an understanding of the corresponding value system structures and dynamics.

In this chapter, first, the contributions are summarized and their implications are discussed. Second, the limitations of the research are discussed and third, recommendations for future work are given.

6.1 Summary of results and implications

This research took a systems thinking approach to modeling the evolving value system around wireless access provisioning. The research was organized around the following research questions:

Q1: How has the value system around wireless access provisioning evolved until now and how could it evolve in the future?

Q2: What kind of underlying value system structures and dynamics can be identified around wireless access provisioning?

Q3: How could value system modeling methods following a systems thinking approach be enhanced to improve the understanding and strategic management of wireless access provisioning?

Accordingly, this research, first, demonstrated how the GSM and Wi-Fi technology tracks have followed distinctively different historical evolution paths and showed their future evolution possibilities given the introduction of intelligent wireless local area access technologies and flexible spectrum use. Second, the research characterized generic value system structures that can be identified in wireless access provisioning and demonstrated underlying value system dynamics of wireless access provisioning by modeling the corresponding deeper endogenous structures. Third, the research also developed methods and frameworks that can be used to model the evolution of value systems, their underlying structures and dynamics. The research contributions are summarized in Table 2 and discussed in more detail in the following.

6.1.1 Value system evolution

In terms of the overall value system evolution around wireless access provisioning both method and substance area related contributions were made as described in Publications I-VIII and summarized in Table 2. During the research a set of methods were developed that can be used to model different aspects of the evolution of value systems. In this research the methods were applied to the evolution of wireless access provisioning but they can also be used to model value system evolution around other technologies, for example in the ICT industry.

In terms of historical evolution the results pointed out the importance of synchronization and alignment in the value system both for the GSM and Wi-Fi technology tracks. The results showed how these two technology tracks have followed distinctively different evolution paths and how they are on a colliding course. The results also highlighted evolution possibilities for how the GSM and Wi-Fi paths could evolve in the future given the introduction of intelligent wireless local area technologies and flexible spectrum use. These possible evolution paths range from centralized to decentralized ones where the value system can have an open or a closed structure. Furthermore, the research has shed light to the reasons why some technological advancements have taken place differently in different markets and has also demonstrated how future technological advancements could happen differently in different markets.

Overall, in terms of practical relevance, the results point out the importance for policy makers to understand the established evolution paths both as it relates to technical and business architectures and how the value system is evolving as a whole. Also, as pointed out by the results, important lessons can be learned from historical evolution, such as the importance of harmonization in wide area networks, which could be taken into consideration when making future policy decisions.

6.1.2 Value system structures

As it relates to value systems structures around wireless access provisioning both method and substance area related contributions were made as described in Publications I-III and summarized in Table 2. This research created a holistic framework for characterizing the underlying structures of ICT value systems. The framework enables the concurrent modeling of both technical and business architectures and the positioning of these to generic scenarios. The framework was also enhanced with an assessment of role logic and forces driving the importance of a role which in turn can be used to evaluate the structure of the value system. The interaction and endogenous structure of high level forces influencing the value system structure were also demonstrated as an extension to the framework and enhancement of the scenario planning method. The created framework helps policy makers to understand the value system as a whole and see how the business models of individual firms relate to the configuration of the entire ICT value system as opposed to many of the current frameworks that focus on a single business model and consider only the business architecture level of the value system.

Using the framework new value system configurations for future wireless local area access were identified and existing ones were formally modeled where the results pointed out the need for co-operation and mutually beneficial agreements across the identified configurations. Subsequently, policy makers could now focus on designing technologies and policies that enable interoperability and revenue sharing between the actors driving these value system configurations.

The framework was also used to model value system structures for flexible spectrum use where the results demonstrated what kind of interaction of important high level forces leads to four distinctive value system structures for flexible spectrum use. The results pointed out that policy makers, especially regulators, need to be aware of a situation where spectrum liberalization is too weak and no progress in terms of more efficient use of spectrum occurs but on the other hand also of a situation where spectrum is liberalized too heavily which in turn could pave the way for other large actors (e.g. Internet players) to become de facto regulators of the new radio platform.

6.1.3 Value system dynamics

In terms of value systems dynamics around wireless access provisioning both method related contributions (Publications IV, VI, and VII) and substance related findings (Publications IV-VIII) were made as summarized in Table 2. Building on the method development work conducted earlier for value system structures, a framework describing both the underlying structure and dynamics of a value system at different stages and levels of service production was created. As opposed to existing work that typically characterizes a value system in a static manner, the developed framework is able to distinctively model the underlying dynamics of a value

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system giving rise to observed events and patterns, while still remaining on the level of conceptual modeling. Furthermore, later during the research, the framework was enhanced and these distinctive dynamics were quantitatively demonstrated using a combination of conceptual system dynamics and quantitative agent-based modeling which seemed to strike a good balance of increasing detailed complexity by using heterogeneous agents without losing focus of the overall feedback structure and dynamic complexity of the model.

Using this framework the research was able to demonstrate relevant transitions, alignments and synchronizations both for the GSM and Wi-Fi evolution paths and highlight the importance of value system alignment, internal structural fit and synchronization in their wide spread diffusion. The results also pointed out potential future subsystem transitions for the Wi-Fi path that have not happened yet, for example related to authentication, roaming, wireless local area access network operation and regulation. Furthermore, by applying the framework to the introduction of flexible spectrum use the research also showed the possible underlying market dynamics given the introduction of cognitive radio and dynamic spectrum access technologies. Using simulations the research was able to demonstrate how the value system could transition to follow different dynamics by varying the strength of spectrum licensing.

Overall, these results enable policy makers to more actively orchestrate the alignment, synchronization and internal structural fit of future technologies. The results also point out threats of winner-takes-all and fragmentation type of dynamic states that policy makers should be aware of, and highlight the possible importance of aligning the underlying market dynamics with the natural, e.g. propagation, characteristics of spectrum frequency bands. In practice, this suggests that a harmonization approach could be favored for wide area cellular networks and low spectrum bands where large and long exclusive spectrum licenses would be granted for few operators conducting long term investments. On the other hand, especially once cognitive and software defined radio technologies are mature enough, a more market driven approach could be used for wireless local area access and high frequency bands where local and short spectrum licenses could be utilized for a heterogeneous set of operators using cognitive radio technologies.

Table 2.	Summary	of con	tributions.
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Wireless access provisioning theme area	Method and theory related contributions	Substance area specific findings	Policy, managerial and practical implications
Value system evolution	A set of methods that can be used to model evolution of value systems	Historical importance of value system alignment and internal structural fit both for GSM and Wi-Fi paths Future evolution possibilities for GSM and Wi-Fi given the introduction of intelligent wireless local area technologies and flexible spectrum use Differences in evolution of different markets	Awareness of important historical lessons that can be learned for future policy making Importance of understanding established evolution paths and their future evolution possibilities
Value system structures	A framework for modeling value system structures in terms of generic scenarios, technical and business architectures, forces driving the structure, and logic and importance of corresponding roles	Wireless local area access: new and existing value system configurations identified	Wireless local area access: need for co-operation and mutually beneficial agreements across identified configurations, i.e. technologies and policies that enable interoperability and revenue sharing
		Flexible spectrum use: Interaction of high level forces driving four distinctive value system structures	Flexible spectrum use: trade-off between spectrum liberalization that is too weak or too strong
Value system dynamics	A framework describing value system dynamics at different stages and levels Quantitative formulation of framework using a combination of system dynamics and quantitative agent-based modeling (i.e. a balanced approach of detailed and dynamic complexity)	Value system alignment and synchronization for GSM and Wi-Fi Possible subsystem transitions related to Wi-Fi path that have not happened yet (e.g. authentication, roaming and regulations) Possible future transitions and dynamic states in the value system given the introduction of cognitive radio	Possibility to actively orchestrate the alignment of a value system, e.g. around a future technology Awareness of winner-takes-all and fragmentation type of dynamic states Possible importance of aligning licensing policy and market dynamics with specific spectrum frequency bands
	A framework for two- and multi-sided platform management strategies Theoretical level importance of distinguishing between subsidization strategies focused on one side and both sides of a platform	Dynamics of subsidization strategies for public wireless local area access platform managers, e.g. how vertically integrated operators seem to be better positioned for platform creation Dynamic complexity in revenue sharing with venue owners	Better awareness of dynamic complexity and endogenous feedback for platform managers
		Effect of harmonized spectrum licensing to important reinforcing feedback structure around mobile communications	A harmonization approach seems more appropriate for wide area mobile cellular networks
		Cognitive radio systems could have better chances of being deployed in emerging markets with a decentralized structure than in advanced markets following a centralized harmonization approach	Challenges of over-harmonization in many advanced markets, e.g. in Europe, and of fragmentation in many emerging markets

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In addition to this, the research developed a framework for two- and multi-sided platform management strategies that models the endogenous formation and diffusion process of a two-sided platform and the corresponding strategy levers. On a theoretical level, using the framework the research was able to demonstrate the importance of distinguishing between endogenous and exogenous growth and the distinction between subsidization strategies focused only on one side and both sides of the platform.

The framework was also able to highlight important issues for potential managers of a public wireless local area access platform. The results for example indicated that operators in vertically integrated markets seem to be better positioned for deploying such a platform since they are in a better position to subsidize both sides of the platform and, thus, to create a virtuous cycle between them. For policy makers the results indicate that understanding dynamic complexity and endogenous feedback structure seems to play an essential role when considering subsidization strategies for two or more sides of a platform, when making revenue sharing decisions with the value creating user group of the platform, and when deciding whether to form alliances with competing platform managers.

The research also examined endogenous feedback structure related to key historical regulatory decisions for mobile communications with quantitative system dynamics where the results highlighted that important reinforcing feedback loops, such as economies of scale and the cross-side network effect between end-user devices and network infrastructure, were stronger in the case of using a harmonization policy as opposed to a technology competition policy. The results therefore showed the importance of using a harmonization approach e.g. when assigning GSM spectrum licenses for wide area cellular networks operating on 900 MHz and 1800 MHz spectrum bands. Thus, the results further support the notion that a harmonization approach could be more appropriate in the case of wide area mobile cellular networks whereas with technologies (and resources) that are more flexible and require less co-ordination, a technology competition approach might work better. This could in turn have direct practical implications e.g. for the licensing of spectrum being released from the digital dividend (i.e. 700 and 800 MHz bands) for future LTE systems.

Finally, as it relates to the introduction of cognitive radio systems in different markets the research showed how the systems could have better chances of being deployed in emerging markets with a decentralized structure and how it might be challenging in advanced markets following a centralized harmonization approach. For policy makers the results point out that advanced markets, e.g. in Europe, often suffer from overharmonization while on the other hand in emerging markets the problem (or opportunity) is often fragmentation. These observations could in turn have implications to spectrum policies in the respective countries.

6.2 Limitations

Although systems thinking can be a powerful approach when examining the complexity of a system it also has drawbacks. For example, when it comes to the level of abstraction that has been used in this research, many details that can seem relevant have been omitted. The reason for this originates from the earlier described trade-off between detailed and dynamic complexity where if the latter approach is chosen one tries to find an explanation by examining the linkages and interrelations of elements of a system rather than the details.

Furthermore, when a system is examined from a broader view point and softer parts of the feedback structure (e.g. mental models of stakeholders) are included, assumptions and personal judgment are to some degree needed. Therefore models are never fully complete and there always remains a possibility that assumptions related to quantitative modeling could be better formulated and that some important feedback structure is not taken into consideration. This in turn highlights the importance of continual iterative learning where the results sometimes serve as better hypothesis for future research. Therefore, many of the findings of this research could be tested and validated further with more formal quantitative modeling and testing methods, e.g. different statistical methods and other methods more focused on detailed complexity. Additionally, this research focused on a limited set of systems thinking tools such as scenario planning and system dynamics, but the applicability of other systems thinking tools or methods close to these could also be explored.

Finally, as it relates to some of the examples discussed during the research, it is often hard to find isolated and pure instances of phenomena since the value system around access provisioning is rather open. When the system is open, macro level issues, such as economic downturns, can have an effect on the evolution, which in turn are not captured within the boundary of the model. Furthermore, many random processes influence the evolution of the value system meaning that risk is always involved and that in the end, e.g. luck can be a deciding factor. Therefore, the frameworks and methods developed during this research can only be helpful guides when making policy decisions but are not the full answer. Nevertheless, although a complex system, such as the value system around wireless access

provisioning, cannot be fully controlled, it can be understood better where the awareness of existing and possible future value system structures and corresponding dynamics enable better strategic management and decisions.

6.3 Future work

Some of the findings of this research point out possible topics for future research. Overall, many of the structures identified during this research could be modeled more elaborately especially in terms of quantitative formulation. Furthermore, the frameworks and methods introduced here could be applied to other fields and used to examine the evolution of value systems around other technologies.

On a practical level, as it relates to policy making, it could be interesting to further examine the possible benefits of aligning the introduced underlying market dynamics with the natural characteristics of radio resources. In other words future research could explore to what degree should a harmonization approach be used for wide area cellular networks and low spectrum bands (i.e. large and long exclusive spectrum licenses for few operators conducting long term investments) and to what degree should a more market driven approach be used for wireless local area access and high frequency bands (i.e. local and short spectrum licenses for a heterogeneous set of operators using cognitive radio type of technologies). Furthermore, the implications of cultural and market differencies in shaping the value system around wireless access provisioning could also be examined in more detail (in addition to Finland and India, implications of the special characteristics of e.g. the Japanese or U.S. markets).

Overall, it could be interesting to examine how the holistic systems thinking approach used in this research could be combined with methods that are more driven by hard data and are more focused on detailed complexity (e.g. different statistical methods). The availability of data is increasing exponentially (sometimes referred to as big data) as new measurement and data collection tools (such as handset-based measurement and sensor networks) and open databases become available, which in turn can increase the focus on detailed complexity and can in the worst case steer us away from the underlying structures and dynamic complexity. Therefore, it is important to find a balance between these two approaches and to highlight the importance of both.

On a more general level, the results found and the policy recommendations made during the course of this research could help trigger individual and institutional learning for relevant stakeholders. However, as it relates to issues that involve dynamic complexity a major challenge is the communication of results (Richmond, 1994). In principle a person must become sufficiently involved in the modeling process to internalize lessons about dynamic feedback behavior (Forrester, 2007). While this might be a challenging task, a possible study for the future is how to improve the communication process of results that have policy implications involving dynamic complexity. Here, system archetypes (Wolstenholme, 2004) and simple conceptual system dynamic models where the detail of a model is revealed incrementally step-by-step, could be a useful way to communicate key insights found from complex models.

Finally, the results of this thesis support the notion that more research is needed to understand dynamic complexity and endogenous feedback structures around wireless access provisioning and ICT services in general. After conducting the research and going through relevant literature one can argue that Sterman's (2000) observation still holds that there are many issues where dominant theories and approaches are exogenous, event oriented and static rather than endogenous, structural and dynamic. One could claim that most of interdisciplinary ICT research takes the former and not the latter approach and that future research could strive towards a better balance. Since the management challenges related to wireless access provisioning, and ICT in general, involve a great deal of dynamic complexity, more research is needed to study the underlying structures and dynamics of the corresponding value systems. Discussion

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The value system around wireless access provisioning consists of a large group of collaborating and competing economic actors, and a complex set of business roles and technical components, where the interactions of parts may cause the emergence of important behavior that we might not be able to see when looking at the parts separately. This thesis examines the evolution of wireless access provisioning by studying the underlying structures and dynamics of the surrounding value system. The thesis takes a systems thinking approach to the problem where one tries to find explanation to complex phenomena by examining the linkages and interactions of elements of a system rather than the individual details, and studies the historical evolution of GSM and Wi-Fi technology tracks and future evolution towards intelligent wireless local area access points and flexible spectrum use.



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