

Value system evolution towards a cognitive radio era: Implications of underlying market dynamics

Thomas R. Casey

Aalto University

School of Electrical Engineering

Otakaari 5, 02150

Espoo, Finland

Timo Ali-Vehmas

Nokia Corporation

Keilalahdentie 2-4, 02150

Espoo, Finland

Abstract — This paper 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 Cognitive Radio and Dynamic Spectrum Access technologies. Using a combination of systems thinking tools and platform theory four value system configurations around the future radio platform are introduced and the corresponding underlying dynamics are characterized. Based on this a feedback model using system dynamics and agent based modeling is built, 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 radio platform paths. The results show how the value system could continue on established evolution paths but also how it could transition to a so called complex adaptive system. Furthermore, for policy makers, the results point out threats of winner-takes-all and fragmentation type of scenarios, and highlight the possible importance of aligning the underlying market dynamics with the natural allocation and assignment cycle of spectrum frequency bands.

Keywords – CR, DSA, value system, systems thinking, platform theory, system dynamics, agent based modeling

I. INTRODUCTION

Cognitive Radio (CR) and Dynamic Spectrum Access (DSA) technologies have the potential to disrupt the current value system and usher in a new era in wireless communications. Under the new paradigm the management of radio resources would be decentralized to the edges of wireless networks where devices would together collaborate and provide wireless services [1]. The paradigm shift could potentially direct the market towards a horizontal and open structure enabling many new service applications and entrants [2] and could thus fundamentally change the underlying dynamics of the market. However, established path dependencies on current spectrum management models are strong and it is uncertain whether they can, or even should, be broken. Therefore, as it relates to the deployment of CR and DSA, there is a need to understand the underlying dynamics of the market in addition to the technology itself.

When it comes to the question of how actors in the current value system around the radio spectrum resource are organized one can distinguish different models. Historically,

for a long time, spectrum licenses were given to one actor who was in charge of service provisioning and network deployment and controlled the whole value system from infrastructure to devices (e.g. government monopoly operators) which in turn led to inefficient legacy allocations [2]. Improvements have been made e.g. after telecommunications liberalization with the introduction of digital cellular mobile communications where licenses have been assigned to a group of operators and where ownership of devices and selection of network (i.e. with the help of SIM-cards) have been given to the end-users [3][4]. This in turn has fueled competition between operators and has forced them to use the spectrum resources more efficiently and improve the availability of their networks (both in terms of coverage and capacity). On the other hand, the usage of harmonized technology standards, as was done in Europe following the GSM Memorandum of Understanding of 1987 [5], has enabled large international economies of scale, device circulation and roaming which in turn has been a key ingredient that has enabled the more than 6 billion mobile subscriptions we currently have in the world¹. As mobile operators around the world are converging to LTE and LTE-A, CR and DSA technologies could be naturally embedded to this technology path.

As it relates to wireless computer networking, the unlicensed model has diffused widely where access points and base stations can be deployed and services can be provisioned by anybody, provided they follow a simple spectrum etiquette. Wi-Fi certified IEEE 802.11 has become the de-facto standard whose origins can be traced back to FCC's 1985 decision to allow the unlicensed use of spread spectrum techniques on ISM bands [6][7]. Subsequently, many private enterprises and households have become wireless service providers where the cumulative number of Wi-Fi chipsets sold has surpassed the 1 billion mark² and the installed base of Wi-Fi access points is already in the order of hundreds of millions.

On the other hand public Wi-Fi has remained somewhat limited where e.g. roaming solutions are still rather fragmented and typically proprietary. Furthermore, given the limitations of the scalability of the IEEE 802.11 MAC

¹ <http://www.gsma.com/> (accessed on 27th of March, 2012)

² <http://www.wi-fi.org/> (accessed on 27th of March, 2012)

protocol the unlicensed model is able to scale and grow in a bottom-up manner only up until a point. Since most of the demand arises from indoor locations [8], more co-ordination and spectrum is needed to enable bottom-up type of growth for which CR and DSA in turn could provide a solution. An example of bottom-up type of infrastructure growth can be observed e.g. with the wide spread diffusion of the Internet Protocol (IP) which has become the generic protocol to interconnect all computers [9]. In a similar manner CR and DSA could enable roaming and mobility between all devices on all possible frequencies which in turn could lead to an open and global network of wirelessly connected devices through which everyone could provide and receive public wireless services on any access point (AP) or device.

As it relates to the future of CR and DSA various scenario studies have been conducted [8][10][11][12][13]. In many of these the core question is to what degree the future system (e.g. CR spectrum database structure) is a centralized or decentralized one and to what degree an open (i.e. horizontal) or closed (i.e. vertical) one, a typical pattern that has been identified also on a more generic level [14][15][16]. However, while static descriptions have been made, the underlying dynamics of these scenarios have not been described.

Given the introduction of CR and DSA technologies, the purpose of this paper is to explore the possibilities of how the value system around wireless access provisioning could be organized in the future and what would be the underlying dynamics. Due to the interdependent nature of the problem we take a holistic approach by using a combination of systems thinking tools and platform theory to understand the underlying structures. Based on historical evolution and prior scenario analysis work we introduce four value system configurations around radio platforms and characterize the underlying dynamics for each. Based on this we build a feedback model using qualitative system dynamics and quantitative agent based modeling (ABM), configure it with historical data and use it to evaluate future evolution possibilities both for GSM based mobile cellular and Wi-Fi based wireless local area radio platform paths.

The rest of the paper is organized as follows. In section II we introduce four value system configurations and the corresponding underlying dynamics. In section III we build a feedback model and configure it with historical data. In section IV we use the model to explore how the value system around wireless access provisioning could evolve in the future both in terms of GSM based mobile cellular and Wi-Fi based wireless local area radio platform paths. In section V we discuss the implications of our results and then finally in section VI draw conclusions.

II. FRAMEWORK FOR UNDERLYING STRUCTURE OF VALUE SYSTEMS

A. Value system configurations

Systems thinking studies, how things influence one another within a whole, where a core principle is that underlying structure gives rise to observed trends, patterns and events

[17]. The structure between actors and their business (and technical) interfaces can be described as a value system [18]. A value system in turn can be characterized as being organized around a mediating technical platform [19][20][21] operated by a platform manager [22][23]. Here we define a radio platform (e.g. a mobile network) as being managed by an operator that provides a wireless service and mediates interactions (facilitated e.g. by a database) between two user groups: end-users using devices and entities hosting base stations (BS) (or access points) who both can create affiliations to the platform. The service itself is delivered through technical interfaces and components (devices and access points) and therefore the other side of the platform (e.g. BS host) might not be directly visible to the other (e.g. end-user).

Based on historical evolution and prior scenario analysis work we define four value system configurations around radio platforms. The platform typology follows the closed or open and centralized or decentralized categorization as depicted in Figure 1.

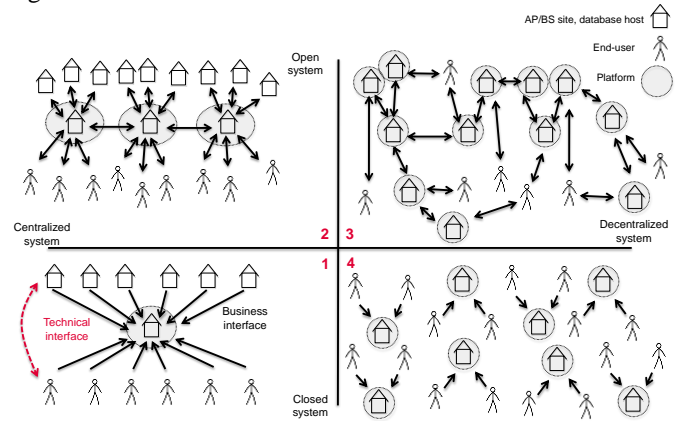


Figure 1. Four value system configurations around radio platforms.

Firstly, in the centralized and closed value system configuration the radio platform is centered around one actor that controls the spectrum resource and the interactions (and signaling) between end-user devices and base station or access point sites, which would e.g. correspond to old government monopoly operators. In such a system there is only one platform manager with whom everyone has to collaborate since there is no other platform to switch to.

Secondly, in the centralized and open value system configuration the value system consists of a small set of connected radio platforms managed by a small group of platform managers that both collaborate and compete. The platform managers control the spectrum resource and the interactions between end-user devices and BSs or APs (typically operators operate the BSs and site owners only provide horizontal and value system independent resources for site space and electricity etc.). Since a standardized technology is used the platform users can rather easily switch between platforms. This would e.g. correspond to the competition and collaboration model of mobile operators using GSM based technologies where the end-users can use the same device and switch between mobile networks.

Thirdly, in the decentralized and open value system configuration the value system consists of a large set of small connected radio platforms. Anybody can become a radio platform manager and start providing wireless services for other users. There exists a great heterogeneity of technologies and services with plenty of local innovation and competition. However, actors also collaborate, technologies are made interoperable and radio resources are quickly reassigned between platforms so that valuable services that have high demand are able to flexibly scale bottom-up. End-users can freely switch and roam between platforms and can easily become wireless service providers themselves. Such radio systems do not currently exist, although some open Wi-Fi roaming solutions bear some resemblance (e.g. Eduroam and openWTS³). Still, examples of decentralized and open systems exist in other fields, such as e.g. IP networks in computer networking.

Fourthly, in the decentralized and closed value system configuration the value system consists of a large set of small radio platforms that are isolated from each other where all compete over the radio resources and no (or very limited) co-ordination exists. Isolation and intense competition can lead to the erosion of radio resources where nobody is able to scale their services bottom-up. Anybody can start providing wireless services, but typically only for a closed user group. This would e.g. correspond to private Wi-Fi deployments and fragmented roaming and authentication solutions.

B. Underlying dynamics of value systems

Next we will describe the underlying dynamics of each value system configuration using basic concepts from dynamical systems theory [24]. A dynamical system can be characterized with an attractor, whose type can roughly be divided into four groups: fixed point, limit cycle, strange and no attractor.

Firstly, centralized and closed value system can be seen as being directed by a fixed point attractor which evolves towards a static state (like a damped pendulum). Secondly, centralized and open value system can be seen as following the dynamics of a limit cycle attractor which produces periodic and somewhat regular change (like a continuously swinging pendulum). Thirdly, decentralized and open value system can be seen as following the dynamics of a strange attractor which produces deterministic irregular change and functions on the edge of chaos. Fourthly, decentralized and closed value system can be seen as being characterized as a system that does not have an attractor that would give it structure and thus exhibits complete disorder and random behavior.

The market share of each operator, i.e. radio platform manager, in each value system configuration is depicted in Figure 2. The dynamics are influenced by the adaptation speed of the actors and the system overall, i.e. how often decisions about platform switches are made, how often resources are re-

allocated and re-assigned, and how quickly competitors respond to market changes.

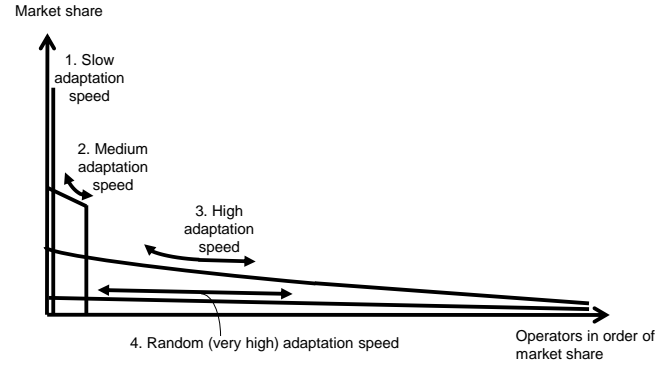


Figure 2. Operators in order of market share in each value system configuration.

In a centralized and closed value system configuration following the fixed attractor dynamics, one actor carries all traffic, as was the case with government monopoly operators. The system is very slow to adapt to changes with long resource allocation and assignment delays where users cannot switch to another provider and can overall be seen as corresponding to the inefficient legacy spectrum assignment model.

In a centralized and open value system configuration following the limit cycle attractor dynamics, few actors carry the traffic, as is typically the case with mobile operator competition today. Here the system adapts to changes cyclically where end-users are able to switch to more valuable networks thus inducing competition and more efficient use of resources. Overall the system allocates and assigns resources in a cyclical manner.

In a decentralized and open value system configuration following the strange attractor dynamics, traffic is carried by many actors. The value system is quick to adapt to changes with short delays for resource allocation and assignment and low switching costs for end-users. Here actors form a long tail distribution where actors from the tail can quickly grow and reach the top and vice versa. Such a value system corresponds to the observations of Anderson [25] who states that a long tail distribution results when the tools of service production and distribution are democratized and supply and demand are connected. Overall, the value system would correspond to a so called complex adaptive system [26] where a large number of agents interact using simple rules and which is characterized by self-organization, emergence, and scale-free network structures with long tail distributions [27]. This has been observed e.g. in the Internet in terms of routers [28] and web pages [27]).

Finally, in a decentralized and closed value system configuration following the no attractor dynamics, traffic is carried by many actors but no actor is able to get ahead of others, get more resources and scale up. There is no delay for resource allocation and assignment (as is the case with the unlicensed spectrum licensing), resources do not accumulate and no structure is formed. Overall the system adapts randomly and seems like noise to an outside observer.

³ <http://www.eduroam.org/>, <http://openwrt.org/> (accessed on 27th of March, 2012).

III. FEEDBACK MODEL OF THE UNDERLYING DYNAMICS OF THE VALUE SYSTEM

The above described underlying dynamics are generated by a large set of actors and encompass a large number of feedback connections. Our next goal is to build a model of these underlying dynamics using two feedback modeling tools: qualitative system dynamic modeling [29] and quantitative agent based modeling [30]. As background for the modeling work eight expert interviews were conducted including representatives of device and network equipment vendors, mobile operators, regulators and academia.

As it relates to the modeling approach it is important to make a distinction between detailed and dynamic complexity. Simply put, dynamic complexity is modeled with feedback structure, whereas detailed complexity is modeled by increasing the number of variables [17]. System dynamics focuses more on dynamic complexity and can easily encompass a wide range of feedback effects, but typically aggregates agents into a relatively small number of states [30]. Agent based modeling, on the other hand, puts more focus on detailed complexity where individuals and their interactions are explicitly represented, which in turn makes it more difficult to link model behavior to its structure. Therefore, modelers must trade off disaggregate detail and breadth of boundary [30].

Our goal here is to use a combination of detailed and dynamic complexity, i.e. leverage the strength of both system dynamics and agent-based modeling. We start out by characterizing the underlying dynamics of the value system configurations with simple system archetype feedback structures [31] and after that use ABM to assimilate the large number of feedback relationships between individual agents simultaneously, i.e. integrate detailed and dynamic complexity together [17].

A. Conceptual model of feedback structure

The basic structures for conceptual level feedback modeling are positive and negative feedback loops. Positive feedback is reinforcing (depicted with letter R in Figure 3) and produces reinforcing growth or decline, whereas negative feedback is balancing (depicted with letter B in Figure 3) and produces goal seeking behavior. Combining positive and negative feedback loops Wolstenholme [31] described three system archetypes: 1. Escalation archetype consisting of two balancing loops (e.g. vicious competition between actors), 2. Success to successful archetype consisting of two reinforcing loops (e.g. accumulation of resources to one entity) and 3. Limits to growth archetype consisting of a reinforcing and balancing loop (e.g. saturation of growth). A combination of these system archetypes can be used to characterize the underlying dynamics of the value systems on a conceptual level. For simplicity in Figure 3 the resulting feedback structure is described between two agents.

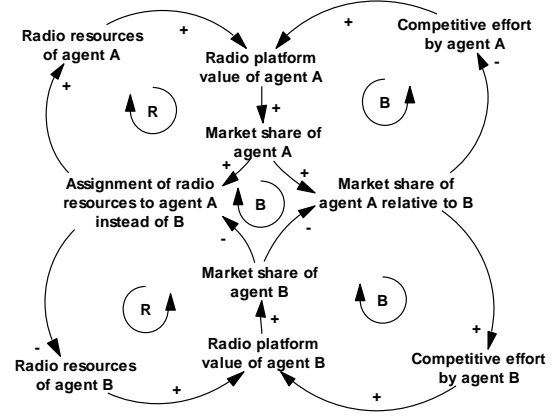


Figure 3. Conceptual level model of the underlying dynamics of the value systems.

The conceptual model describes competition and collaboration between agents where the more resources (radio spectrum, infrastructure, and monetary) an agent has and the more competitive effort (attempts to add value, tailoring of services to local needs, new innovative services, lower prices etc.) an agent puts in the more valuable the radio platform of an agent is. Subsequently, a more valuable radio platform of an agent leads to more end-users affiliating to it and a larger market share of end-users which in turn means that more resources will be assigned to the agent instead of other agent(s). On the other hand the less valuable the radio platform of an agent is, the less end-users affiliate to it, the smaller the market share compared to other agent(s) becomes and the more competitive effort it will put in.

The escalation archetype describes the competition process between the agents. Competitive effort of agent A leads to a larger market share for agent A and subsequently to higher competitive activity by agent B. This leads to a larger market share for agent B which in turn induces higher competitive effort by agent A (here the two balancing loops finally result in a reinforcing loop).

The success to successful system archetype describes the process of resource accumulation, i.e. the more resources agent A has the more valuable the platform and the larger the market share for agent A. This in turn leads to the assignment of even more resources to agent A and an even more valuable platform. On the other hand this leads to less resources to agent B, and subsequently a less valuable platform, less market share and even less resources to agent B.

The limits to growth system archetype 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 it puts in and the less valuable its radio platform becomes⁴.

In a value system characterized by a fixed point attractor the success to successful mechanism is strong and resources

⁴ The model embeds two other limits to growth structures, between reinforcing resource accumulation and balancing competition, and between reinforcing competition and balancing resource accumulation.

and platform value accumulate to one agent. However, because of the resulting low competitive effort of the dominant agent the system overall slows down and becomes dominated by negative feedback. In a limit cycle value system the strength of the success to successful mechanism is rather strong, but some competition is present where resources accumulate to and circulate between few agents. Overall, the system evolves incrementally, i.e. has some positive feedback but is still dominated by negative feedback. In a system characterized by a strange attractor the strength of the success to successful mechanism is low and competition is high where resources are liquid and move around quickly. Overall, the system evolves chaotically, i.e. has some negative feedback but is dominated by positive feedback. In a no attractor system there is no success to successful mechanism and competition is intense. Resources do not accumulate, no structure emerges and overall the system is dominated only by positive feedback.

B. Agent based model

Based on the conceptual level feedback model an agent based model can be built that characterizes the individual behavior of each agent. Agent behavior is depicted in Figure 4 and Figure 5 which show the two possible roles an agent can have: end-user and wireless service provider. An active wireless service provider is here defined as an agent that has at least one user affiliated to its platform (the passive agents in turn can be used as site resources by the active platform managers, e.g. mobile operator femtocells in households).

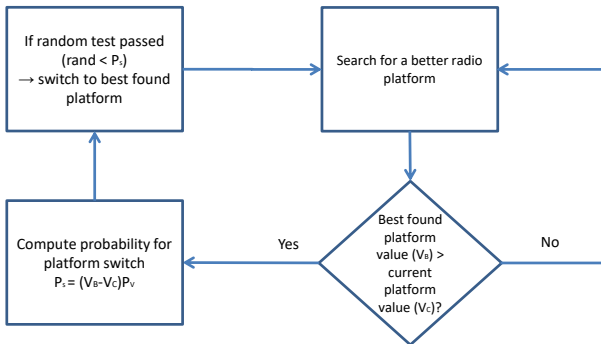


Figure 4. End-user agent logic.

End-users periodically (every quarter of the year) search for the best radio platform and if the value of the best found platform (V_B) is higher than the value of the platform they are currently affiliated with (V_C) they will switch with a certain probability. When perceiving the value of the radio platform agents have individual preferences, i.e. a certain wireless service can seem more attractive to one agent than to another. The final switching probability (P_s) is computed as a function of the value difference ($V_B - V_C$) and a parameter (P_v) describing the switching probability per value unit, which reflects device cost, flexibility and intelligence (e.g. SIM, software defined radio (SDR) and CR capabilities). For simplicity no multi-homing is possible for the end-user agents, i.e. only the main platform affiliation is considered.

Each agent as a wireless service provider, in turn, periodically (every quarter of the year) checks whether more users in total have switched to or from their platform. If in total more users have switched to their platform, they will be assigned with more resources but will also decrease their efforts. If more users have switched from their platform, resources will be removed from them but they will also increase their efforts. The speed at which changes to resources and efforts occur depend on resource accumulation speed (S_R) and competition reaction speed (S_C) parameters. The final value of the wireless service is computed as a function of the radio resources available and competitive effort. Detailed equations for these processes are presented in Appendix A.

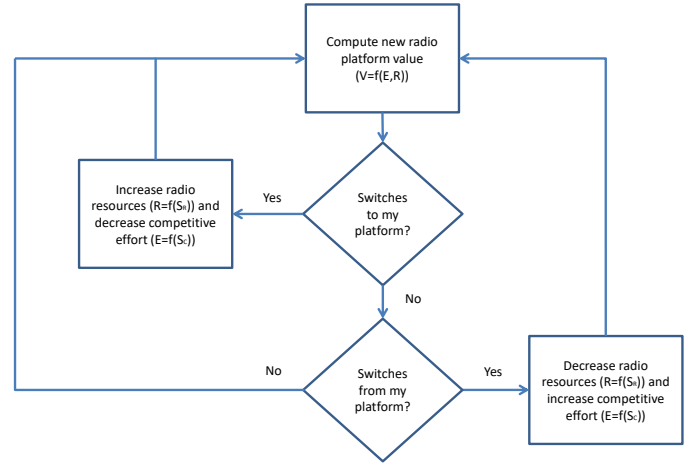


Figure 5. Wireless service provider agent logic.

The agent model logic was implemented using the latest release of Repast Symphony (2.0) which is a Java based modeling system⁵. The model underwent several iteration rounds and was tested thoroughly.

C. Model calibration with historical data

Next the model is calibrated with historical data using a group of 100 agents (reflecting e.g. a geographical area where agents work as a proxy of the whole market) to model the evolution of wireless networks in Finland. We will model both the evolution of mobile cellular networks and wireless local area networks separately and will therefore also consider mobile handsets and computers separately. More detailed model assumptions for both evolution paths are depicted in Table A.1 in Appendix A.

We will start by modeling the evolution of cellular networks, by assigning spectrum licenses (i.e. resources) to selected agents as they enter the market and by increasing the parameter describing the switching probability per value unit (P_v) as device cost decreases (e.g. NMT, GSM technologies introduced) and device flexibility and intelligence (e.g. SIM,

⁵ <http://repast.sourceforge.net>

SDR and CR capabilities) increases⁶. Resource accumulation speed (S_R) is configured to reflect the licensing model at that time and competition reaction speed (S_C) is set low reflecting the operation of large scale infrastructure and the corresponding long term investments.

Figure 6 shows how the model results follow the rise of NMT based mobile telephony in the beginning of the 1980s. The market was essentially dominated by the government monopoly operator which was the only one that had a spectrum license and thus the value system at that time could be characterized as a closed and centralized one and the underlying market dynamics with a fixed attractor.

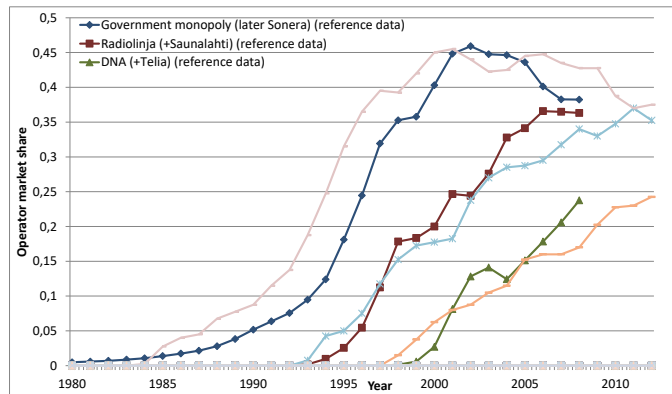


Figure 6. Model calibration with historical evolution of market shares of mobile operators in Finland (reference data source: Ministry of Transport and Communications Finland)⁷.

The situation changed in early 1990s with the telecommunications liberalization, the separation of the government monopoly to regulator and operator entities and the introduction of second generation digital mobile communications system, GSM, for which a new entrant Radiolinja got a license. The introduction of the technology was followed by heavy growth where the mobile networks started experiencing capacity problems mid 1990s after which new spectrum licenses were assigned to existing and new operators. A new entrant operator Telia got a GSM1800 license and later merged with DNA that got a GSM900 license in late 1990s.

As the GSM market grew the value system started to gradually resemble an open and centralized value system where the small group of mobile network operators both collaborated, i.e. used standardized and interoperable technologies, but also competed since end-users were able to switch between networks using the same device, which in turn forced the operators to increase the value of their radio platform and to use the spectrum resources more efficiently. Correspondingly, the underlying market dynamics have started to resemble the dynamics of a limit cycle attractor where the market shares of the three operators have come

⁶ Switches include both first time adoption and switches from one operator to another.

⁷ Mobile virtual network operator Saunalahti was acquired by Elisa and they are thus considered as one entity. Also DNA and Telia are considered as one operator. Multiple subscriptions have been removed from the data.

close to each other and have started to evolve in a cyclical manner.

Next we will move on to modeling wireless computer networking by assigning unlicensed spectrum resources to all agents in the beginning of 2000s (i.e. after the Finnish regulator adopted the regulations set out by FCC) and by increasing the parameter describing the switching probability per value unit (P_V) as Wi-Fi device and AP cost decreases and flexibility and intelligence (e.g. ease of configuration) increases. Resource accumulation speed (S_R) is assumed to be very low since the spectrum is unlicensed and competition reaction speed (S_C) high reflecting local and instantly adaptive behavior and small scale investments.

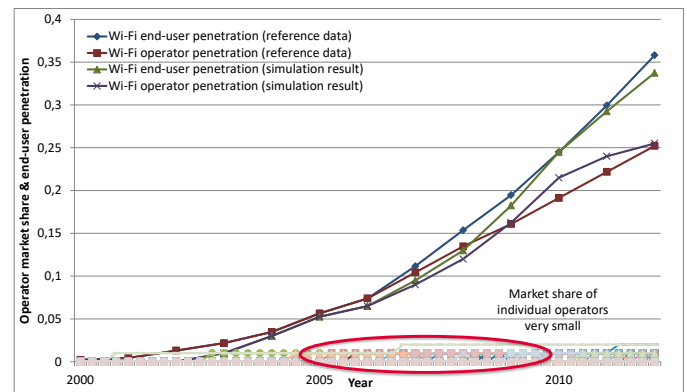


Figure 7. Model calibration with historical evolution of the number of Wi-Fi end-users and operators in Finland including individual market shares of Wi-Fi operators (reference data source: Morgan Stanley⁸).

Figure 7 shows how the model reflects growth in the number of Wi-Fi operators and end-users starting to use Wi-Fi. Although the total number of agents becoming Wi-Fi operators grows substantially over the decade the individual market shares of operators remain small reflecting the limited success of public Wi-Fi solutions which thus far have remained rather fragmented especially in terms of roaming and have not been able to scale up.

Therefore, as the model also shows, the Wi-Fi operator value system resembles a closed and decentralized architecture where the Wi-Fi operators are isolated from each other and where there is no co-ordination between the operators leading to limited or eroding resources. The underlying dynamics follow the no attractor dynamics with no success to successful mechanism (see Figure 3). Therefore no structure emerges and overall the system is dominated by positive feedback.

The current situation is reflected in Figure 8 which shows simulation results from both evolution paths in terms of the top 20 operators in order of their market share in the year 2012. As it relates to mobile cellular networks, three large mobile network operators dominate the value system and compete with each other following the limit cycle dynamics. For wireless local area networking the value system is

⁸ Wi-Fi reference data computed based statistics from Morgan Stanley, http://www.morganstanley.com/institutional/techresearch/pdfs/Mobile_Internet_Report_Key_Themes_Final.pdf (accessed on 23rd of March, 2012).

fragmented with a large number of operators with small market shares sharing the market and following the no attractor dynamics.

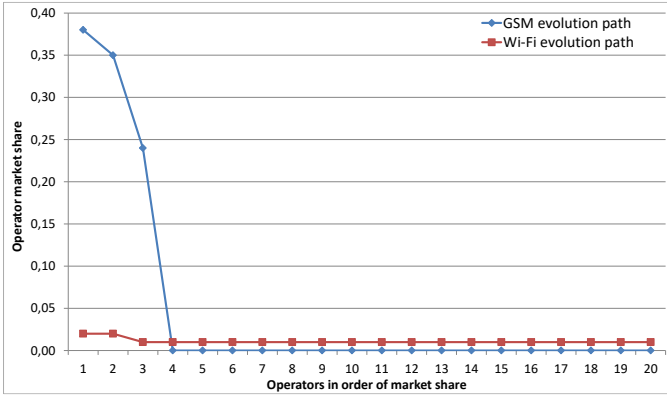


Figure 8. Top 20 operators in order of their market shares in year 2012 according to the simulation results of GSM and Wi-Fi evolution paths.

IV. SIMULATION OF EVOLUTION PATHS

After configuring the model with historical data we will move on to exploring how the value system could evolve in the future both in terms of the GSM and Wi-Fi paths by continuing the simulations for a longer period. The introduction of CR and DSA technologies to devices is modeled by increasing the parameter describing the switching probability per value unit (P_v) to a high value during a 10 year period (2015-2025) thus reflecting the corresponding higher device intelligence and flexibility⁹.

A. GSM evolution path

We start by simulating future scenarios of the evolution of mobile cellular networking. Cognitive radio spectrum licenses to operate mobile networks will be given to all agents during the CR and DSA introduction period (year 2020). We assume that competitive reaction speed (S_c) will remain low since rather long term investments are still needed. Furthermore, we conduct sensitivity analysis by adjusting the resource accumulation speed (S_R) which reflects the overall spectrum licensing model. In the base case it will correspond to regulated exclusive licenses, i.e. the currently dominant licensing model with large spectrum bands and long license times. In the first sensitivity case S_R will be considerably slower and correspond to license-exempt, i.e. unlicensed spectrum. In the second sensitivity case S_R will be only slightly slower and reflect light or secondary licensing, where small bands are assigned dynamically with shorter cycles while ensuring that competition prevents extensive resource accumulation. In the third sensitivity case S_R is considerably faster and corresponds to unregulated exclusive licenses where all resources can cumulate or be assigned to one operator and no spectrum caps are enforced.

⁹ It should be noted that in the model we do not consider the additional costs and uncertainty associated with the deployment of CR and DSA systems.

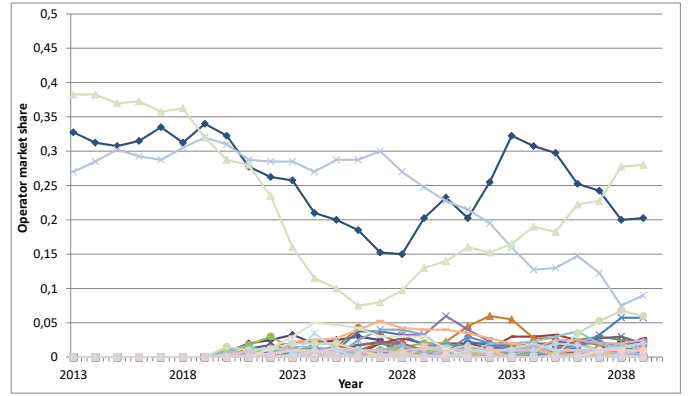


Figure 9. Market shares of agents in the GSM evolution base case.

Figure 9 shows the market shares of agents in the base case. As can be observed, after the introduction of CR and DSA technologies and the entrance of new smaller operators, competition between the large operators intensifies and they lose some market share. However overall, the underlying dynamics of the value system continue to follow the limit cycle dynamics, i.e. although some additional competition is present the majority of resources still accumulates to and circulates between the incumbent operators and the strength of the success to successful mechanism between the agents (see Figure 3) remains rather strong.

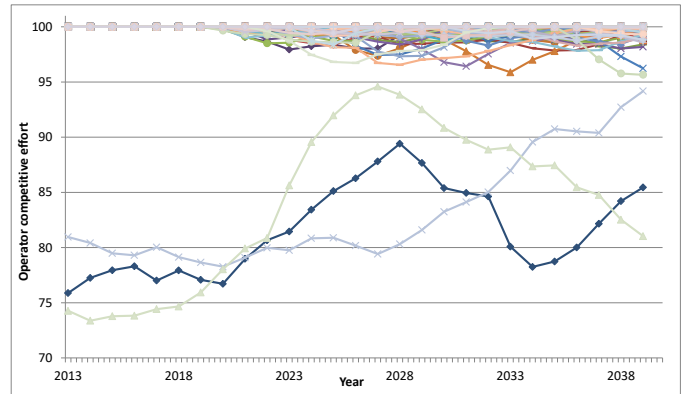


Figure 10. Competitive efforts in the GSM evolution base case.

Changes in competitive efforts are shown in Figure 10 where before the introduction of CR and DSA the competitive efforts of the three large operators are quite close to one another and evolve cyclically (in the model competitive effort ranges from a minimum of 30 to a maximum of 100). After the introduction of CR and DSA and the entrance of new operators, competitive activity between the large operators increases but still, the value system continues to evolve in a cyclical manner, i.e. it has some positive feedback but is still dominated by negative feedback. Nevertheless, this new competition leads to more efficient use of resources and more value overall. One can also observe that the increased possibility for end-users to switch between operator networks increases volatility in the system since the system still remains slow to react to changes.

Figure 11 show results from the sensitivity analysis. As can be observed, introducing an unlicensed model dramatically reduces the market shares of large operators and leads to a situation where the market share of all operators remains small and thus the value system transitions to follow the no attractor dynamics. With a light licensing model incumbent operators are able to sustain some market share but are joined by new entrants who have been able to grow their market share and thus the value system starts transitioning towards strange attractor dynamics. The use of exclusive licenses without regulation leads to a winner-takes-all situation where all resources accumulate to one actor who starts dominating the whole market and thus the value system transitions to follow the fixed attractor dynamics.

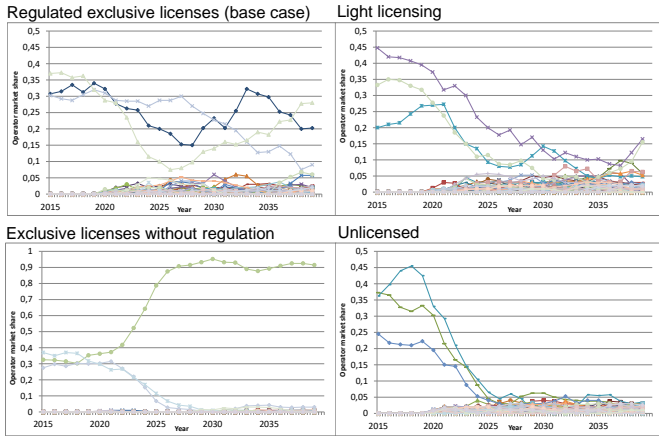


Figure 11. Market shares in GSM evolution sensitivity cases (note different scale in unregulated exclusive licenses sensitivity case)¹⁰.

In terms of competition, with the unlicensed model all agents compete fiercely, resources do not accumulate and the individual platforms remain limited in value. With the light licensing model competition is less intense and resources are directed to valuable services which in turn are able to grow and scale up but not enough to gain a significant share of the market. With unregulated exclusive licenses competitive effort by the dominating agent drops to a minimum value and therefore, although it controls almost all of the resources, the value of the platform does not increase.

Figure 12 shows the top 30 operators in order of market share at the end of the historical simulation (year 2012) and at the end of the simulation in the different sensitivity cases. As can be observed, when comparing the base case to the historical situation the tail of wireless service providers has gained whereas the head has lost some market share.

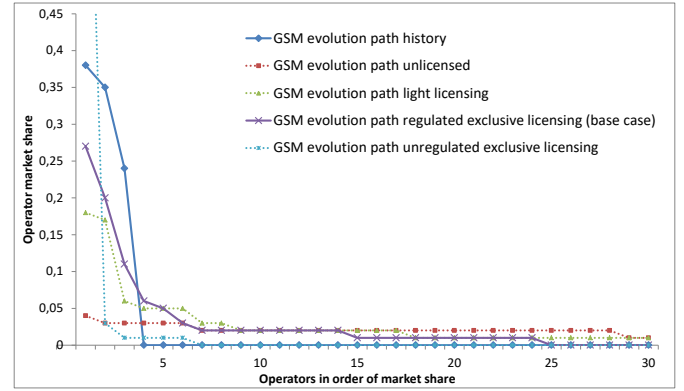


Figure 12. Top 30 operators in order of market share year 2012 and at the end of the simulation in the different GSM evolution sensitivity cases.

With the unlicensed model the tail has become very long where almost all of the market share from the head has gone to the tail. With light licensing more wireless service providers have become active and the tail has gotten longer but the head still serves a large part of the traffic. With unregulated exclusive licenses one agent in the head gets all of the traffic and practically no long tail exist.

B. Wi-Fi evolution path

Next, we move on to simulating future scenarios of the evolution of Wi-Fi based wireless local area access. We assume that all agents have the existing unlicensed spectrum resources and that competitive reaction speed (S_c) will remain the same reflecting local and instantly adaptive behavior and small scale investments. In terms of the sensitivity analysis the resource accumulation speed (S_R), corresponding to the spectrum licensing model, will grow to be somewhat faster in the base case (i.e. light and secondary licensing), and in other sensitivity cases will remain the same (i.e. continuation with the unlicensed model), grow to be still somewhat faster (i.e. regulated exclusive licenses), and considerably faster (i.e. unregulated exclusive licenses).

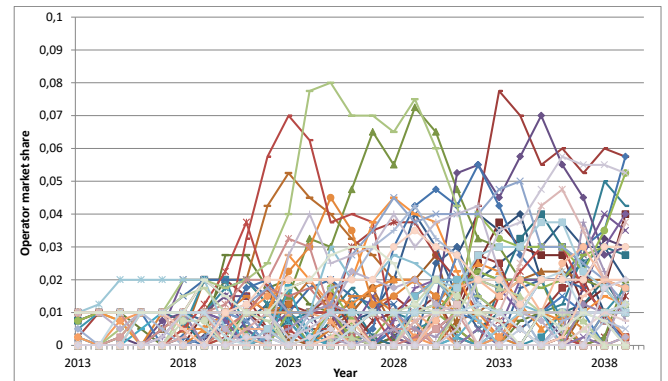


Figure 13. Market shares of agents in the Wi-Fi evolution base case.

Figure 13 shows the market shares of agents in the base case. As can be observed, after the introduction of CR and DSA technologies and light licensing, some operators with valuable services are able to scale up, get more resources and

¹⁰ It should also be noted that the goal here is to only show the overall dynamics of the value system and since many random processes influence the simulation, the results are not a forecast of the exact market shares of operators.

market share. However, the system adapts quickly to changes and resources are re-assigned to wherever new innovations and locally relevant services are created and therefore no single actor or group of actors starts to dominate the value system. Therefore, the value system transitions to follow strange attractor dynamics, where the strength of the success to successful mechanism is low and competition is high (see Figure 3). The value system evolves chaotically, i.e. has some negative feedback but is dominated by positive feedback. Overall, the system can be characterized as a complex adaptive system that operates at the edge of chaos.

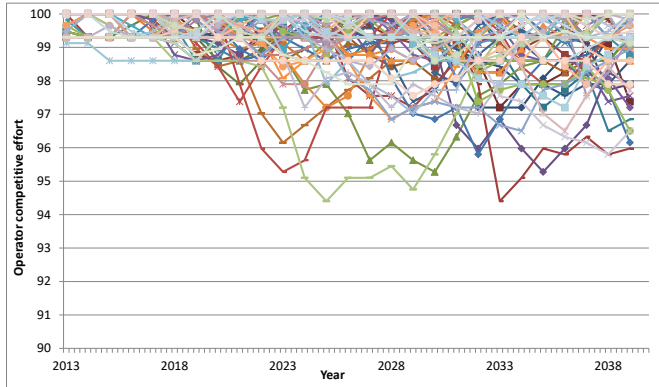


Figure 14. Competitive efforts of agents in the Wi-Fi evolution base case.

Changes in competitive effort are shown in Figure 14 where one can observe that before CR and DSA, and light licensing are introduced competition between agents is fierce. After the introduction of CR and DSA and light licensing, co-ordination increases but competition remains still high fueling new services and local innovation. However, competition is not so intense that resources erode, leading to more efficient use of resources and more value overall as compared to the unlicensed model.

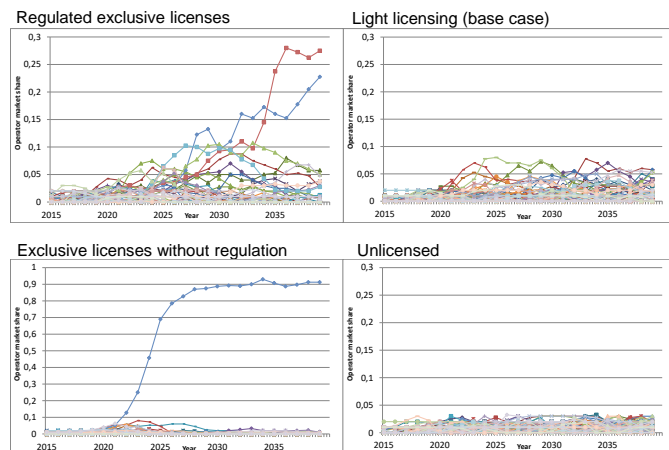


Figure 15. Market shares in Wi-Fi evolution sensitivity cases (note different scale in unregulated exclusive licenses sensitivity case).

Figure 15 shows results from the sensitivity analysis. As can be observed, continuation with an unlicensed model leads to a situation where the market share of all operators remains very small 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 is the case with Wi-Fi roaming and authentication today.

With a regulated exclusive licensing model, resources accumulate so that two operators start controlling the market and thus the value system transitions to follow the limit cycle dynamics. In the case of 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 both of these 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 database and leveraged network externalities arising from elsewhere.

In terms of competition, with the unlicensed model all agents compete fiercely and the individual platforms remain limited in value, with the regulated exclusive licenses model the two dominant actors that get most of the resources slow down and start competing cyclically and with unregulated exclusive licenses competitive effort by the dominating agent drops to a minimum value.

Figure 16 shows the top 30 operators in order of market share at the end of the historical simulation (year 2012) and at the end of the simulation in the different sensitivity cases. When comparing the base case to the historical situation the market shares of wireless service providers especially in the head have increased.

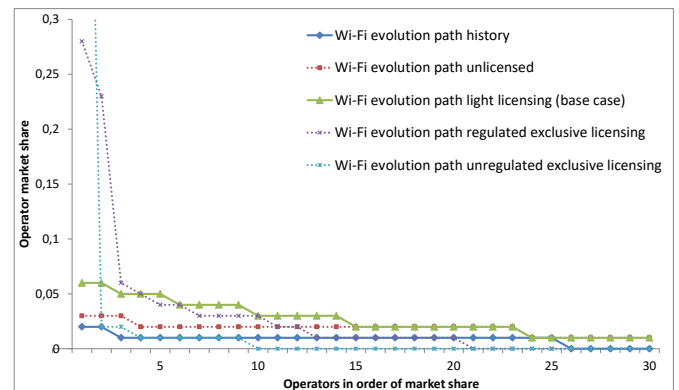


Figure 16. Top 30 operators in order of market share year 2012 and at the end of the simulation in the different Wi-Fi evolution sensitivity cases.

With the unlicensed model the head has also grown slightly but the tail has become considerably longer than with light licensing and the number of active wireless service providers stabilizes to roughly 70 agents. This would correspond e.g. to a situation where most of the agents are operating their smartphones as Wi-Fi access points for themselves. With the regulated exclusive licensing model the two operators in the head have taken most of the market share where the tail in turn has lost market share and most of the operators have become passive. With unregulated exclusive licenses one agent in the head gets all of the traffic and practically no long tail exist.

V. DISCUSSION

The results have general level implications for understanding the underlying dynamics of future CR scenarios and the corresponding spectrum database structure but also highlight issues specifically relevant for policy makers. As it relates to the GSM path, in the base case the value system continues to follow the limit cycle dynamics and to be dominated by few incumbent operators. In such a case CR and DSA technologies are likely to be embedded to the technology standards used by the mobile operators (i.e. LTE-A and its future versions). The possible spectrum databases and indoor sites would also be mostly controlled by mobile operators.

In terms of the Wi-Fi path, in the base case the value system evolves to a complex adaptive system where the CR and DSA technologies would establish themselves as an independent technology standard enabling roaming and mobility between all devices on many frequency bands. The database infrastructure would follow an open and decentralized architecture (resembling that of IP) and be operated by many entities.

Furthermore, as shown in the sensitivity cases, it is also possible that a collision occurs between the two evolution paths and that the overall value system transitions from a centralized to a decentralized one or vice versa corresponding to the more general level descriptions of [14][16]. The value system around the mobile cellular network platform could evolve towards strange attractor dynamics (i.e. entrance of many small operators and a diminishing role for incumbent operators) and vice versa the Wi-Fi path could evolve towards limit cycle dynamics (e.g. Wi-Fi access points controlled by incumbent mobile operators or other large actors).

From a policy maker perspective the results also point out future threats. There is a possibility that CR and the corresponding database technologies will become fragmented, much like Wi-Fi roaming and authentication now, and the roles of CR databases will remain very limited, isolated and local. Yet another threat is a winner-takes-all type of situation where one of the existing operators, or another strong player outside the value system, controls the CR database infrastructure and uses closed proprietary technologies which might in turn slow down diffusion overall.

The results could also have implications as it relates to different spectrum frequency bands and their characteristics. As discussed by [24], dynamical systems tend to naturally synchronize with one another and transition to follow the same dynamics. For example, roughly put, one can say that low frequency bands propagate far and need more centralized co-ordination and long assignment cycles whereas high bands in turn do not propagate far, remain as a local resource (especially in indoor locations) and thus need less co-ordination. Therefore, one could pose a question whether there is a natural allocation and assignment cycle for the spectrum frequency bands and if so, how would these characteristics relate to the described underlying dynamics.

For example in terms of the GSM evolution path, the usage of standardized technologies, cellular network planning and

competition following the limit cycle market dynamics has led to rather efficient use of 900 and 1800 MHz bands. Subsequently, one can question, to what degree should CR and DSA technologies even be used to disrupt these underlying dynamics. Still, one can argue that there exists an upper limit for frequencies after which building cellular networks becomes inefficient. Unlicensed private Wi-Fi deployments, on the other hand, have led to rather efficient use of the 2.4 GHz ISM band and correspondingly one can question are the unlicensed and light licensing models more naturally aligned with higher spectrum bands and short range sites.

Since the policy maker can influence the underlying dynamics of the market 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 allocation and assignment cycle of the radio resources. Following this logic we can hypothesize that on a rough level this alignment could be realized as shown in Figure 17.

Here, fixed point attractor dynamics and traditional command and control licensing would be aligned with very low frequency bands and base stations working on very large sites. This would correspond to utility based applications (e.g. broadcasting and public safety) and be governed by long reorganization periods. Limit cycle attractor dynamics and regulated exclusive licenses, on the other hand, would be aligned with low spectrum bands and base stations working on large range sites where there is some room for value differences in terms of coverage and capacity but which still have long investment cycles and require reliable assets. This would correspond to a few core applications (such as mobile voice, text messages and managed mobile internet connectivity) enabled by mobile cellular technologies and would be governed by cyclical competition.

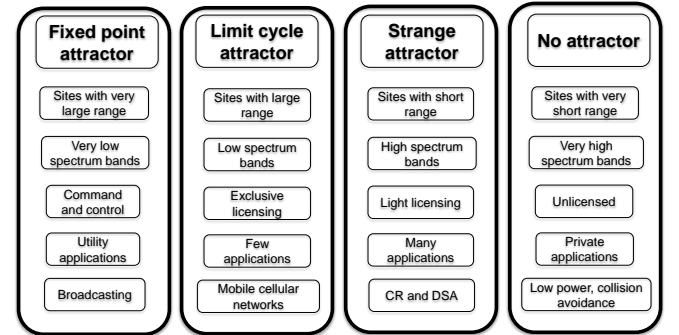


Figure 17. Example alignment of underlying market dynamics, radio resources and technologies.

Strange attractor dynamics and light and secondary licensing models would be aligned with high spectrum bands and base stations and access points working on sites with short range with instantly adaptive behavior and small scale investments needed where somewhat unreliable assets, e.g. light or secondary licenses, would be sufficient. This would correspond to many different types of applications, locally relevant public services enabled by CR and DSA technologies and be governed by chaotic competition with just enough co-

ordination to ensure system operation. No attractor dynamics and the unlicensed model would be aligned with very high frequency bands and with access points and devices working on very short range sites. This would correspond to private and personal use and applications, enabled by low power levels, simple spectrum etiquette and decentralized medium access protocols with collision avoidance mechanisms (e.g. CSMA/CA) but otherwise isolated governance.

In reality such alignment is of course difficult (if not impossible) to reach and therefore the dynamics could work on all frequency bands (such as CR devices on TV white spaces) and on all site types. Nevertheless, as a general rule one can argue that this would be the most natural alignment, which in turn would mean that CR and DSA technologies could reach their highest potential if they were used with short range sites and high spectrum bands.

Furthermore, what is interesting to note is these underlying dynamics might be better aligned with the market characteristics of particular countries. For example the limit cycle dynamics are commonly observed in many European countries with a strong harmonization legacy, such as e.g. Finland, where only GSM based technologies have been used, three network operators compete using the same technology and SIM-card based postpaid subscriptions are common leading to moderate churn rates (e.g. annualized churn typically above 10 % in Finland [32]). Markets in countries such as e.g. India are already more decentralized and follow strange (or no) attractor type of dynamics where many operators are present and pre-paid subscriptions and multi-SIM phones are common leading to very high churn rates (e.g. annualized churn roughly 40 % in India¹¹) which in turn could make the market better compatible with CR and DSA systems as pointed out by [33].

On the other hand, in countries with vertical market structures, such as e.g. Japan, operators have traditionally had tight control of the technologies deployed, each operator having their own application stack, where the operators can internally be seen as following the fixed attractor dynamics with dedicated operator devices and high switching costs leading to low churn rates (e.g. annualized churn well below 5 % in Japan [32]). Although in our simulations it was assumed that CR and DSA increase device flexibility and the probability of switching between operators, this might not be the case if operators are in a position to limit and control the deployment of CR and DSA technologies in the devices.

Overall, these simulations show that only small changes in some parameters might change the market dynamics significantly. Therefore, as it relates to technology standardization, it is important to preserve the opportunity to manage the market dynamics during the entire lifetime of the system technology and to avoid undesirable deadlocks and market failures. Since it is not possible to define all the parameters precisely right today it would be beneficial to preserve flexibility and configurability in standards and

technologies in order to be able to control and adapt to the market dynamics later. The right architectural technology decisions are therefore very important for CR and DSA technologies.

VI. CONCLUSIONS

In this paper we have studied value system evolution around future radio platforms given the introduction of CR and DSA technologies. We have used a combination of systems thinking tools and platform theory to characterize four value system configurations around the future radio platform and the corresponding underlying dynamics and have built a feedback model to evaluate future evolution possibilities both for GSM based mobile cellular and Wi-Fi based wireless local area radio platform paths.

The results showed how the value system could continue on established evolution paths but also how it could transition to a so called complex adaptive system. For policy makers, the results have pointed out threats of winner-takes-all and fragmentation type of scenarios. The results also highlighted the possible importance of aligning the underlying market dynamics with the natural allocation and assignment cycle of the spectrum frequency bands, a hypothesis that could be explored more in future research.

Furthermore, the overall framework introduced here, could in the future also be used to model the evolution of value systems around other technologies and e.g. explore the relationship of CR and DSA to other ICT technologies, e.g. Internet and cloud computing.

ACKNOWLEDGEMENTS

The authors would like to thank Professor Heikki Hämmäinen and Mr. Ankit Taparia for their contributions. This work has received funding from the EECRT project and has also been conducted under the context of COST-TERRA (COST Action IC0905) research framework.

REFERENCES

- [1] J. Mitola, and G.Q. Maguire, "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, Vol. 6, No. 4, pp. 13-18, 1999.
- [2] J.M. Chapin, and W.H. Lehr, "Cognitive Radios for Dynamic Spectrum Access - The Path to Market Success for Dynamic Spectrum Access Technology," *IEEE Communications Magazine*, vol. 45, no. 5, pp. 96-103, 2007.
- [3] A.T. Manninen, *Elaboration of NMT and GSM standards: From idea to market*, Ph.D. Thesis, University of Jyväskylä, 2002.
- [4] D. Steinbock, "Globalization of wireless value system: From geographic to strategic advantages," *Telecommunications Policy*, Vol. 27, No. 3-4, pp. 207-235, 2003.
- [5] F. Hillebrand, *GSM and UMTS: the creation of global mobile communication*, John Wiley & Sons, New York, NY, 2002.
- [6] W. Lemstra, V. Hayes, and J. Groenewegen, *The innovation journey of Wi-Fi: The road to global success*, Cambridge University Press, Cambridge, 2010.
- [7] K.J. Negus, and A. Petrick, "History of wireless local area networks (WLANs) in the unlicensed bands," *The journal of policy, regulation and strategy for telecommunications, information and media*, Vol. 11, No. 5, pp. 36-56, 2009.

¹¹ As estimated by Telecom Regulatory Authority of India, <http://traai.gov.in/WriteReadData/ConsultationPaper/Document/MNP.pdf> (accessed on 27th of March, 2012).

[8] T. Smura, and A. Sorri, "Future Scenarios for Local Area Access: Industry Structure and Access Fragmentation," in *Proceedings of the Eight International Conference on Mobile Business*, pp. 57-63, Dalian, China, June 2009.

[9] B.M. Leiner, V.G. Cerf, D.D. Clark, R.E. Kahn, L. Kleinrock, D.C. Lynch, J. Postel, L.G. Roberts, and S. Wolf, "A Brief History of the Internet," *ACM SIGCOMM Computer Communication Review*, Vol. 39, No. 5, pp. 22-31, 2009.

[10] P. Ballon and S. Delaere, "Flexible spectrum and future business models for the mobile industry," *Telematics and Informatics*, Vol. 26, No. 3, pp. 249-258, 2009.

[11] T. Casey, "Analysis of radio spectrum market evolution possibilities," *Communications and Strategies*, No. 75, pp. 109-130, 2009.

[12] M. Barrie, S. Delaere, and P. Ballon, "Classification of business scenarios for spectrum sensing," in *Proceedings of the 21st International Symposium on Personal Indoor and Mobile Radio Communications*, pp. 2626-2631, Istanbul, Turkey, September 2010.

[13] A. Medeisis, and S. Delaere, "High-level scenarios for the future of cognitive radio business," in *Proceedings of the 22nd International Symposium on Personal Indoor and Mobile Radio Communications*, pp. 2330-2334, Toronto, Canada, September 2011.

[14] P. Anderson, and M.L. Tushman, "Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change," *Administrative Science Quarterly*, Vol. 35, No. 4, pp. 604-633, 1990.

[15] W.B. Arthur, "Positive feedbacks in the economy," *Scientific American*, vol. 262, pp. 92-99, 1990.

[16] C.H. Fine, "Clockspeed-based strategies for supply chain design," *Production and Operations Management*, Vol. 9, No. 3, pp. 213-221, 2000.

[17] P. Senge, *The fifth discipline: The art and practice of the learning organization*, Doubleday, New York, NY, 1990.

[18] M.E. Porter, *Competitive advantage: Creating and sustaining superior performance*, Free Press, New York, NY, 1985.

[19] C.B. Stabell and Ø.D. Fjeldstad, "Configuring value for competitive advantage: on chains, shops, and networks," *Strategic Management Journal*, Vol. 19, No. 5, pp. 413-437, 1998.

[20] M.G. Jacobides, T. Knudsen, and M. Augier, "Benefiting from innovation: Value creation, value appropriation and the role of industry architectures," *Research Policy*, Vol. 35, No. 8, pp. 1200-1221, 2006.

[21] M. Iansiti, and R. Levien, "Strategy as ecology," *Harvard Business Review*, Vol. 82, No. 3, pp. 68-81, 2004.

[22] T. Eisenmann, G. Parker, and M.W. Van Alstyne, "Strategies for two-sided markets," *Harvard Business Review*, Vol. 84, No. 10, pp. 92-101, 2006.

[23] A. Gawer, and M.A. Cusumano, "How companies become platform leaders," *MIT Sloan Management Review*, Vol. 49, No. 2, pp. 28-35, 2008.

[24] S.H. Strogatz, "Exploring complex networks," *Nature*, Vol. 410, No. 6825, pp. 268-276, 2001.

[25] C. Anderson, *The long tail: Why the future of business is selling less of more*, Hyperion Books, New York, NY, 2008.

[26] W.B. Arthur, "Complexity and the Economy," *Science*, Vol. 284, No. 5411, pp. 107-109, 1999.

[27] A.L. Barabási, and E. Bonabeau, "Scale-free networks," *Scientific American*, Vol. 288, No. 5, pp. 50-59, 2003.

[28] M. Faloutsos, P. Faloutsos, and C. Faloutsos, "On power-law relationships of the Internet topology," *ACM SIGCOMM Computer Communication Review*, Vol. 29, No. 4, pp. 251-262, 1999.

[29] J.D. Sterman, *Business dynamics: Systems thinking and modeling for a complex world*, McGraw-Hill, New York, NY, 2000.

[30] H. Rahmandad and J. Sterman, "Heterogeneity and network structure in the dynamics of diffusion: Comparing agent-based and differential equation models," *Management Science*, Vol. 54, No. 5, pp. 998-1014, 2010.

[31] E. Wolstenholme, "Using generic system archetypes to support thinking and modelling," *System Dynamics Review*, Vol. 20, No. 4, pp. 341-356, 2004.

[32] A. Riikonen, T. Kitahara, and H. Hämmäinen, "Comparison of Mobile Internet Usage and Industry Structure: Japan vs. Finland," 18th Biennial Conference of the International Telecommunications Society, Tokyo, Japan, July 2010.

[33] S. Varadarajan, T. Casey, and H. Hämmäinen, "Flexible Spectrum Management for Mobile Broadband Services: How does it vary across Advanced and Emerging Markets?," *Telecommunications Policy*, In press, 2012.

APPENDIX A – MODEL EQUATIONS AND ASSUMPTIONS

Equations (1), (2), (3) and (4) describe how resources and efforts of an individual agent change in the model.

$$R_C = R_C + aS_R\Delta T \quad (1)$$

$$R = bS_R\Delta T + cS_RM + R_C \quad (2)$$

$$E = S_C \left(\left((E_{\max} - E_{\min}) - (E_{\max} - E_{\min})M \right) + E_{\min} \right) - E \quad (3)$$

$$V = ER \quad (4)$$

Here R_C depicts the cumulated resources, S_R resource accumulation speed, ΔT the share of agents that have switched to the platform out of all agents, M market share, E effort, E_{\max} maximum effort, E_{\min} minimum effort, S_C speed of competitive reaction and V platform value of an agent. Parameters a , b , and c are used to calibrate the model. After fitting the model with historical data the calibration parameters are $a = 0.05$, $b = 2$, $c = 1$, $E_{\max} = 100$ and $E_{\min} = 30$. The model is calibrated so that the resource accumulation speed $S_R = 0.02$ corresponds to unlicensed spectrum, $S_R = 0.12$ to light or secondary licensing, $S_R = 0.15$ to regulated exclusive licenses and $S_R = 0.4$ to unregulated exclusive licenses.

Assumptions for simulations of GSM and Wi-Fi paths are depicted in Table A.1. S-shaped growth is assumed when increasing resource accumulation speed (S_R) and switching probability per value unit (P_V) to reach the target value over a specific time period. The total number of agents in the simulation is 100.

Table A.1. Assumptions for GSM and Wi-Fi evolution paths.

	GSM	Wi-Fi
Competitive reaction speed, S_C	0.3	1
Base case (2015-2025), S_R	0.15	0.12
Sensitivity case 1 (2015-2025), S_R	0.02	0.02
Sensitivity case 2 (2015-2025), S_R	0.12	0.15
Sensitivity case 3 (2015-2025), S_R	0.4	0.4
Switching probability per value unit (Cellular: 1982-1990, Wi-Fi: 2000-2010), P_V	0.3	2
GSM (1990-1995), P_V	2	
Mobile Number Portability (~2003), P_V	4	
CR (2015-2025), P_V	10	10

When simulating the GSM evolution path an initial license resource is given to government monopoly operator in early 1980s, to Radiolinja in early 1990s and to Telia (later DNA) in late 1990s. Initial CR cellular license resource is given to rest of the agents in 2020. When simulating the Wi-Fi evolution path initial unlicensed spectrum resource is given to all agents in 2000.