Business Potential of Software Defined Radio Technology

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Abstract

The business potential of software defined radio (SDR) technology is studied by evaluating whether or not its characteristics correspond to those particular to a \emph{disruptive technology}. The maturity of the SDR technology concept is illuminated by analyzing the opinions and perspectives of a selection of representatives for different stakeholders in the wireless communications market. Characteristics as, for example, the degree of consensus about the utility of SDR technology and the awareness of features and limitations are studied by application of the theory of technological frames. This theory helps us understand how and when technology evolution takes place. Finally we describe the value network structures of some potentially viable application areas for SDR and suggest some possible business opportunities based on SDR technology.

This thesis is carried out as a case study and the research data is obtained from secondary sources, such as literature and Internet publications as well as interviews with people well experienced in the field of wireless communications. In particular, we study the perspectives of the personal communication services (PCS) manufacturing industry, the PCS providers (operators), the purchasers of military equipment (defense) and independent observers in academia.

It is concluded that there are several definitions of SDR. Depending on which is adopted the potential for disruptive evolution of SDR is perceived differently. In the military sector, a disruption has already taken place from an equipment perspective. For the manufacturers of PCS equipment, i.e., infrastructure and terminals, SDR is viewed as a possible implementation technology, rather than a radically new and disruptive technology. The transformation of the RF transceiver processing from the analog to the digital and SW domains is seen as a sustaining technology evolution, virtually inevitable due to the need to support multiple air interface standards and cost reasons. However, one plausible trend is the separation of the HW and SW of the wireless communication platforms and this may open up for potential disruptive innovations. In particular, the provisioning of general purpose wireless processors and high-level abstraction SW with detailed knowledge about the RF processing hardware, described as SW primitives, will enable applications and services to be implemented by SW engineers without expert knowledge in wireless communications. There is a belief that this will fuel innovation, particularly in the areas of waveform software, middleware, services and applications. Another, potentially

disruptive, feature that can be enabled by SDR technology is network transparency for services. SDR is also related to the issue of improved spectrum efficiency through the concept of cognitive radio. However, cognitive radio is believed to be more distant in the future than SDR technology.

Several new areas in the networking sector will need to be addressed to achieve ubiquitious connectivity and interesting business opportunities open up when if this is to be enabled with SDR technology. Other areas that will need to be addressed are terminal management, infrastructure management, billing and routing in heterogenous networks.

Unfortunately, the presence of a strong trend towards an increased demand of higher wireless data rates is not unambiguous and no apparent killer application based on ubiquitious connectivity has yet emerged. In conclusion, the maturity of SDR technology is found to be quite low. There is little work made on standardization and the standards that exist are not well known. Moreover, there is not a clear common definition of SDR technology or any \emph{de facto} standard for generic platforms, which is found to be a very important component for the widespread use and success of SDR technology.

NOTE: The thesis is available, below, in LaTex format only. Please contact the author for an Adobe Acrobat compatible file or a paper copy.

\section{\label{sec:TerminologyAndAcronyms}Acronyms}

\begin{description}
\item[ADC] Analog-to-digital conversion is the process of quantizing continuous-valued analog signals into digitized format, i.e., a finite number of discrete signal levels. ADCs are the gateways to the domain of digital signal processing, which is, currently, more convenient than the analog domain in terms of computational power and ability to perform complex operations, storage and delay ability, implementation flow, process portability, prototyping and power consumption.

\item[ASIC] Application specific integrated circuit

\item[BB] Baseband

\item[CMOS] Complementary metal oxide semiconductor\textbf{\ }technology

\item[DAC] Digital to analog converter

\item[DSP] Digital signal processor

\item[FPGA] Field programmable gate array

\item[GPP] General purpose processor

\item[JTRS] Joint tactical radio system

\item[MEMS] Micro electro mechanical systems

\item[MW] Middleware

\item[OEM] Original equipment manufacturer

\item[ODM] Original device manufacturer

\item[PA] Power amplifier

\item[PCS] Personal communication service

\item[RF] Radio frequency

\item[SDR] Software defined radio is the term adopted by the SDR forum in order to describe a radio with software controlled waveform generation in a broad frequency range, for both current as well as evolving wireless communication standards.

\item[SCA] Software communications architecture\textbf{\ }is a development framework that supports modularity and well defined interfaces between the radio frequency (RF), digital processing hardware and software functionality and provides a mechanism to tie them all together. This architecture is open source in order to mitigate the evolution of incompatible proprietary solutions.

\item[WAP] Wireless application protocol

\item[WF] Waveform
\end{description}

\section{Introduction}

\subsection{The Technical Concept of Software Defined Radio}

This thesis\footnote{%
This thesis is carried out at the Institute of economic research at Lund University.} applies the theory of \emph{disruptive technology} \cite{CHR97} to a concept in wireless communication -- \emph{software radio} that emerged in the early 1990's \cite{MIT00}. Software radio targets cost-effective flexible communication platforms through a high degree of programmability and hardware reuse. Ultimately, a software radio digitizes the received signal already after the antenna, thereby enabling reception of any type of radio frequency (RF) transmission through reconfigurable digital signal processing (DSP). In reality, such extreme architectures are not yet compatible with (state-of-the-art) wireless communication technology for mobile terminals due to that enabling functionality such as low-noise amplifiers (LNAs), analogue-to-digital converters (ADCs) and power amplifiers (PAs) are not sufficiently wideband and require too much power to be practical. However, there are several different intermediate degrees of software radios that already exist or are on their way to the market.\ Such radio architectures are usually collected under the name software defined radio (SDR). In particular, these solutions are gaining popularity in the segments of wireless communications that use more mature technology with somewhat less extreme requirements on data transfer rates.

Due to the difficulties to support an ultimate software radio design, it is the authors perception that the whole concept has got an undeserved bad reputation in the industry. For instance, the typical spontaneous reaction of RF designers, with whom I bring up the topic, is to immediately point out that the RF front-end and the ADC of a software radio receiver for conventional personal communications would require an associated nuclear plant to supply power enough to support the necessary wideband linearity characteristics. Regardless of whether such aggressive software radio architectures will become reality in the near future or not, it is the authors opinion that the concept is well worth a serious discussion and, clearly, the interest in SDR technology is growing rapidly at the moment.

Over the last years, the most important development has taken place in the SDR forum, which is an organization committed to promoting SDR concepts and open, modular, communication platform architectures. The SDR forum is dominated by the U.S. defense industry and a number of large U.S. communication network operators. However, recently, several small actors, such as U.S. startup companies Vanu, Sandbridge Technology and BitWave Semiconductors, focusing explicitly on SDR technology have emerged. The technical literature in the area is now virtually exploding. However, to the knowledge of the author, relatively little attention has been devoted to the \emph{economical} impact of the evolution of SDR technology. Furthermore, there exist theory foundations for evaluation of technology potential that have not yet been applied to the concept of SDR technology. It is our hope that such an approach will contribute to systematically judge the potential of this technology and identify the most important business opportunities.

Motivated by this lack of knowledge and methodology, this thesis seeks an answer to the question whether SDR is a disruptive technology and how and where to seek for potential business opportunities. Moreover, the potential benefits from its application and the limiting factors in different markets are illuminated in the context of value network characteristics \cite{CHR97}%
. Analyzing the product ranking criteria of different markets, we try to understand where SDR will find its most important applications.

We use the concept of \emph{technological frames} \cite{ALL03} to judge the maturity of the SDR technology based on the definitions expressed by different stakeholders in the PCS market, the exemplary artifacts associated with those definitions and the state of the standardization work. Finally, in order to give some possible future directions, we suggest and discuss more visionary alternative definitions of SDR technology that may disrupt the wireless communications industry.

In order to understand the most important technology issues as well as some aspects of the cost structure of contemporary radio technology, we will, in this section, take a closer look on the basic building blocks of some common radios. Please confer Section \ref{sec:TerminologyAndAcronyms} for a list of common terminology and acronyms, used in the sequel discussion.

The majority of today's radio chipsets are implemented according to the architecture in Figure \ref{fig:radioarchitecture}. The place of the ADC in the receiver, \emph{i.e.}, the partitioning of receiver functionality among the analog time-continuous and the digital time-discrete domains is very important since it has a direct impact on the extent of flexibility in terms of number of different air-interfaces that are supported through software configuration. For instance, the ultimate software radio performs analog-to-digital conversion at the antenna and the receiver data path contains virtually no analog blocks.

The position of the ADC is determined by design parameters as bandwidth
(data rate) of the radio, power consumption and the choice of semiconductor
process technology for the analog and digital chip implementations. High
bandwidth ADCs are typically associated with very high sampling rates and
high power consumption. The major problem encountered when moving the AD
converter towards the antenna in wideband systems is the high sampling
frequency and the accompanying extreme levels of power consumption.

In Figure \ref{fig:radioarchitecture}, the transmitter and receiver share
the same antenna through an antenna switch. The analog blocks involved in
the transmitter typically consist of a frequency reference (synthesizer), a
reconstruction filter and a power amplifier (PA). The analog part of the
receiver contains selectivity filter, low noise amplifier (LNA), image
rejection filter, mixers, variable gain amplifier (VGA) and anti-aliasing
filters. In addition a number of external components is required. This is
due to technical difficulties to integrate functionality as crystal
oscillators (XOs), high-selectivity ceramic filters, as for example surface
acoustic wave (SAW) filters, balun and others inductive elements as loop
filters on chip. The number of external components required is a significant
driver of cost. Reduction of the number of external components is also
important in order to achieve better integration and smaller area of the
radio circuits. Also very important to the cost is the process yield, \emph{%
i.e.}, the ratio of functional analog or digital chips obtained in
production. Implementation of both the analog and digital radio components
on the same chip is possible with, for example, complementary metal oxide
semiconductor (CMOS) technology. Heavily integrated circuits, so called
system on chip (SoC) implementations, are getting more common and the aim is
to obtain more cost-efficient implementations. SoC solutions may consist of
purely digital or analog circuits, or, alternatively, both digital and
analog circuitry (single-chip solution). However, the challenges are
significant and the final result in terms of cost-efficiency and the
performance depends heavily on successful, robust, design solutions to
issues as signal integrity and analog radio yield.

Today, most digital chipsets for the consumer electronics market are
manufactured in CMOS technology. For instance, the processor industry uses
CMOS technology and also leads the process development. Thus, there is a
strong drive for increasing the clock speed and improving the integration of
this technique, since both extended parallelism and high clock speed enable
faster execution of software instructions.

Particular to mobile radio terminal technology is the requirement for low
power operation. The power consumption of a CMOS circuit can be approximated
by the relation \cite{PAR99}, p. 74%
\[
P=C_{total}\cdot V_{0}^{2}\cdot f\text{,}

\]%
where C_{total} is the total capacitance of the circuit, V_{0} is the supply voltage and f is the clocking frequency. The more sophisticated the circuit, the higher is, in general, its capacitance. The increased sampling frequencies must be compensated by decreased supply voltage -- something that poses tough challenges on the analog radio frequency\ (RF) designer. For instance, lower supply voltage may impose requirements on larger area for a CMOS design compared to a bipolar design and it is therefore not obvious that today's CMOS technology is more efficient than bipolar process technology for analog radio implementation. CMOS technology is also associated with other challenges as higher flicker ($1/f$) noise, substrate noise and signal integrity issues. However, these issues may be compensated for by robust radio design and hopefully reduced by new process technologies as silicon oxide insulation for CMOS.\FRAME{fhFU}{2.9144in}{1.7132in}{0pt}{%
\Qcb{General radio transmitter (TX) and receiver (RX) architecture.}}{\Qlb{%
fig:radioarchitecture}}{radioarchitecture.wmf}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "F";width 2.9144in;height 1.7132in;depth 0pt;original-width 2.8703in;original-height 1.6769in;cropleft "0";croptop "1";cropright "1";cropbottom "0";filename 'Figures/radioarchitecture.wmf';file-properties "XNPEU";}}

Digital implementation of radio functionality introduces robustness to process variations and makes the design process easier since more reliable performance predictions can be obtained in simulations. Other advantages of digital implementation is the possibilities to include self-testing and self-trimming abilities in the radio chip. Perhaps, rather than enabling wideband AD conversion for the most recent, high performance air interfaces through extraordinary sampling rates promoted by the processor industry, the most important characteristic of digital implementation will turn out to be the flexibility obtainable through programmable channel filters, reconfigurable frequency synthesizers and digitally controlled polar modulators, etc. Furthermore, due to physical constraints as clock latency and cooling issues related to high power dissipation in small geometries, the processor industry seems now less confident in increased sampling rates as a means to improve computation capacity \cite{ELN04d}. The use of multi-processor architectures and lower clock speeds seems now to become a real alternative.

It appears that radio development inevitably will pursue the track of increased digitalization of the analog radio front-end components. It is thus tempting to infer that development is rapidly heading towards the fulfillment of SDR technology. However, some people argue that technology breakthroughs are needed for wideband radio front-ends and low-loss antennas and such breakthroughs rarely come as a result of sustaining technology development. Furthermore, it is paramount to promote flexibility and hardware reuse in order not to get stuck with multiple, incompatible digital radio solutions, as is, in many ways, the situation today.

According to Mitola, \cite{MIT00}, p. 23, engineers should avoid to define a new radio platform for each small incremental advance. Instead, one should strive for a generic radio platform. This platform should aim to achieve fundamental new capabilities for the customer and motivate technology investment towards well defined market needs. Mitola's view on the development of SDR is consistent with Christensens view on the evolution of disruptive technology in that it is cultivated in market segments orthogonal to mainstream needs, gains momentum and technical maturity there and eventually turns to the mainstream market segments and causes disruption.

\subsection{\label{sec:ValueProposition}Value Proposition of Software Defined Radio Technology}

There are basically three ways towards increased data rates in wireless communication systems: increased bandwidth, increased transmission power or increased processing to get closer to the Shannon limit \cite{SHA48} for certain bandwidth and transmission power. The cost of a given amount of processing can be expected to decrease over time as integrated circuit design improves towards cheaper, more integrated and less power consuming implementations. On the other hand, the costs associated with allocation of new frequency spectrum likely will increase and the alternative of increased transmission power is limited by interference problems, potential health issues and battery duration in mobile terminals.

In higher frequency bands, more bandwidth is available and higher attenuation of the transmitted signals occur. Reuse of frequency spectrum by short-range radio infrastructure and migration to higher frequencies are thus possible directions towards increased data rates. Given that the cost per unit is sufficiently low, extensive amounts of infrastructure can be distributed over the areas of coverage. The limiting factor to such an approach is not the cost of infrastructure equipment but rather the cost of roll-out and maintenance. In fact, the latter two activities correspond to as much as 85\% of the total cost for the operation of a typical cellular telephony network \cite{AHL04}.

The value proposition of SDR, as presented in \cite{SDR04a}, states that \emph{"SDR concepts form the building blocks to integrate applications over any air interface at any point in time. These building blocks are implemented as adaptable software and flexible open hardware platforms to address the interoperability issues arising from the constant services evolution and technical innovation that defines the wireless industry. SDR is an emerging technology that spans all radio network topologies in the commercial, military and civil government sectors, and enables highly flexible solutions with benefits to operators, manufacturers and consumers."%
}

The use of SDR may contribute to increase the data rates through more efficient use of spectrum bandwidth (see the related concept of cognitive radio), by more advanced processing. Its most attractive features are, however, its suitability to support flexibility, easy maintenance, backwards compatibility and interoperability. In addition, the deployment of more software-oriented radio architectures may contribute to shorten product development cycles, streamlining the design flow and give sustainable economics in infrastructure maintenance and management.

The tremendous costs and the substantial business risks associated with the development of completely new radio air interfaces speak against future wireless communication systems being developed from scratch as was the case for 1st, 2nd and 3rd generation mobile telephony. Instead, the real challenge may be to reach interoperability between numerous different radio systems for short and wide range coverage with a mixture of wideband and narrowband transmission. Another, inevitable, challenge is to reduce the development and maintenance costs in order to meet issues such as dramatic price drops on communication electronics, slow adoption of more sophisticated wireless services, such as video telephony, other high speed data communication services and a receding capital supply as a result of heavy debt in the telecommunications industry.

In conclusion, SDR may become an important tool to obtain improved interoperability between different radio systems and nevertheless improved cost efficiency in both development and maintenance cycles. However, so far, SDR has reached very limited application. For mobile terminals, this is partly due to high power consumption and partly due to that the number of supported standards typically is limited to two or three. For these cases, the most cost efficient implementation has been so called \emph{velcro design%
} -- that is, two different chip sets, each with a standalone radio, simply are glued together. The cost of such an architecture typically reach 125\%
- 150\% of the cost of one single radio interface and this has, up to now, not provided sufficient incentive for widespread use of SDR technology in commercial handsets \cite{MIT03}.

In the military sector, there is a different reality. The military has extensive experience from interconnection problems. Military demands for improved interoperability, which, for instance, has resulted in the so called joint tactical radio system (JTRS) initiative, are expected to accelerate the development of radio systems based on SDR. One of the problems with the military systems has been the need to use dedicated radios for different needs. With new SDR-based systems this will no longer be necessary.

With the JTRS common architecture, it will be possible to use different radios with different characteristics, from portable units to advanced radio systems. The new software-based radio system will offer substantially improved interoperability, lower cost (through standardization), flexibility as well as scalability. The development of JTRS is based on an open architecture, which implies more clearly defined interfaces and modular design so that different components and services can be provided from different suppliers.

To sum up the value proposition of SDR, radios based on such technology offer

\begin{itemize}
\item standard architecture for a wide range of communications products,

\item HW reuse in terminals and infrastructure,

\item non-restrictive wireless roaming for consumers by extending the capabilities of current and emerging commercial air-interface standards,

\item uniform communication across commercial, civil, federal and military organizations,

\item flexibility and adaptability,

\item potential for significant life-cycle cost reductions,

\item over the air downloads of new features and services as well as software patches and

\item advanced networking capabilities to allow truly "portable" networks.
\end{itemize}

\noindent We will discuss the benefits particular to different actors in wireless communication value networks in more detail in Section \ref%
{sec:Analysis}.

\subsection{Problem Definition}

\subsubsection{\label{Sec:TheoreticalQuestion}General Problem (Theoretical Question)}

The fundamental theoretical question we seek to understand better is how to judge the potential of new (wireless communication) technology. In order to identify technologies with strong growth opportunities and understand the evolution of those, several theoretical approaches have been proposed. Among those, we focus on the theory of disruptive technologies \cite{CHR97} and the technological frames concept suggested in \cite{ALL03}. In this thesis, we learn about the utility of those theories and gain some experience with the difficulties and shortcomings encountered when applying them to make inference on the business potential of new technology. We believe such understanding to be of interest in, for example, product management and research organizations of companies active in any kind of technology intensive industrial area. The audience targeted consists of: 1) people with strategic responsibility in wireless communication equipment manufacturing companies and 2) research engineers working on radio related hardware (HW) and software (SW) issues.

In order to assess the utility of the above mentioned theories, the case of SDR technology is particularly appealing since it is a technology that is subject to a rapidly increasing interest while having been asleep for a relatively long time. Furthermore, the value proposition of the technology is relatively different from today's mainstream wireless communication technology (see Section \ref{sec:ValueProposition}) and there are substantial technological challenges ahead in the different application scenarios. Finally, there is a big uncertainty about the potential of the SDR technology in the PCS market.

\subsubsection{\label{sec:Practical Key Issues}Practical Key Issues}

\begin{itemize}
\item[1.] Is SDR a disruptive technology? This issue is studied by benchmarking the technology against the characteristics of disruptive technologies, as outlined in \cite{CHR97}. Will the SDR technology radically change the paradigm of wireless communications of today? Will it make us think about radio architectures and business models in a completely different way?

\item[2.] Which seems to be the most viable application scenarios for the future? If SDR can be considered a disruptive technology, what are the characteristics of the potentially most important markets? This question is addressed by describing different markets as different \emph{value networks}%
. Studying the ranking criteria and the cost structures associated with those value networks will illuminate the potential of software radio technology. The cost structures adhere to the radio architectures of different standards for communication, the partitioning in analog and digital components as well as the partitioning in software and hardware functionality. The present state as well as future directions for SDR technology evolution is analyzed from a socio-technical perspective by adopting the concept of technological frames.
\end{itemize}

\section{Research Methodology and Roadmap for the Application of Theory}

This section gives a summary of the methodical approach of the case study performed in this thesis.

\FRAME{fhFUX}{402.25pt}{230.625pt}{0pt}{\Qcb{Roadmap for the application of theory on the research problem in this study.}}{\Qlb{fig:roadmap}}{Figure}{%
\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 402.25pt;height 230.625pt;depth 0pt;original-width 659.3125pt;original-height 416.9375pt;cropleft "-0.1069";croptop "1.0482";cropright "1.1069";cropbottom "-0.0482";tempfilename 'INDCN800.wmf';tempfile-properties "XPR";}}

Using the theories of disruptive technology and technology frames, we identify a number of key questions that need to be answered in order to draw conclusions about the business potential of SDR technology. The answers to these questions are sought from informations obtained from secondary sources of as literature, press-releases and general observations of the market trends. Furthermore, a number of representatives for different stakeholders in the wireless communications industry, who also can be considered experts in the field are interviewed. Those interviews are carried out as \emph{% structured} interviews (elite interviews \cite{MER94}), where the referees are posed a series of questions, partitioned in indirect and direct questions. By indirect questions, we refer to questions prompted by the theory of disruptive technology and technology frames that do not explicitly focus on the expert's opinions on the actual situation and business potential of SDR technology. The indirect questions are used to make inference about the actual conditions of SDR technology from the theory.

The direct questions are posed to survey the expert's opinion on the actual conditions of SDR technology. In this way, the internal validity (see for example \cite{MER94}, pp. 177-180) of the results and conclusions from the thesis can be strengthened since there is a two-fold triangulation in terms of asking \emph{several} experts about their opinion about actual conditions and, at the same time, we can make our own conclusions about the actual conditions using the response to the indirect questions and the theory.

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\begin{tabular}{|l|l|}
\hline
\textbf{general theoretical problem type} & handling problem \\ \hline
\textbf{methodical\ starting point} & deduction/abduction \\ \hline
\textbf{type of research} & case study \\ \hline
\textbf{data collection} & secondary sources, elite interviews \\ \hline
\textbf{validation} & methodical triangulation \\ \hline
\textbf{interviews} & structured \\ \hline
\textbf{questions} & direct/indirect \\ \hline
\end{tabular}%
\caption{Summary of research methodology.\label{tab:methodology}}%
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A summary of the research methodology used in this study is provided in Table \ref{tab:methodology}.\FRAME{fhFUX}{397.1875pt}{267.875pt}{0pt}{\Qcb{% Performance trajectories of the sustaining technology serving the high-end market segments, the market demand curves and the trajectory of the attacking, disruptive technology.}}{}{Figure}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 397.1875pt;height 267.875pt;depth 0pt;original-width 649.0625pt;original-height 491.3125pt;cropleft "-0.1086";croptop "1.0407";cropright "1.1086";cropbottom "-0.0407";tempfilename 'INDCN801.wmf';tempfile-properties "XPR";}}

\section{\label{Sec:TheoryAndConnection}Theory for Judgement of Technology Potential}

In \cite{CHR97}, the concept of disruptive technology was introduced to describe and identify new technology and/or new applications of old technology that bring about a value proposition radically different to what is available on the market. A disruptive technology, competing along other dimensions of performance than those historically most valued by customers, may become a serious threat to established technologies that compete with improved performance of well-agreed product attributes. One of the main question of this thesis is whether SDR can be considered a disruptive technology or not and whether and when SDR may deliver substantial customer value.

In Section \ref{sec:DisruptiveTechnology}, we recapitulate the distinctive features of disruptive technology, aiming at understanding whether SDR is a legitimate disruptive threat to today's wireless technologies and whether it is an opportunity for profitable growth.

In order to identify potential business opportunities in SDR technology it is crucial to understand the needs driving the evolution of the new value proposition of\ SDR as well as the maturity of the value proposition. For this purpose, we adopt the socio-technical perspective on new technology evolution presented in \cite{ALL03}. The key elements of this theory are discussed in Section \ref{sec:TechFrames}. Finally, in Section \ref% {sec:KeyQuestions}, we formulate a number of questions, based on the theories of disruptive technology and technological frames. The response to those questions is later subject to discussion and analysis in Section \ref% {sec:Analysis}.\FRAME{fhFUX}{398.5pt}{293.1875pt}{0pt}{\Qcb{Characteristics of sustaining and disruptive technologies.}}{\Qlb{% fig:Characteristics_of_disruptive_tech}}{Figure}{\special{language

"Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 398.5pt;height 293.1875pt;depth 0pt;original-width 651.4375pt;original-height 542pt;cropleft "-0.1081";croptop "1.0368";cropright "1.1081";cropbottom "-0.0368";tempfilename 'INDCN802.wmf';tempfile-properties "XPR";}}

\subsection{\label{sec:DisruptiveTechnology}Key Issues of Disruptive Technologies}

\FRAME{fhFUX}{398.3125pt}{272.625pt}{0pt}{\Qcb{Summary of the \emph{% innovators dilemma} as defined by Christensen.}}{\Qlb{fig:InnovatorsDilemma}% }{Figure}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 398.3125pt;height 272.625pt;depth 0pt;original-width 651.4375pt;original-height 500.875pt;cropleft "-0.1082";croptop "1.0401";cropright "1.1082";cropbottom "-0.0401";tempfilename 'INDCN803.wmf';tempfile-properties "XPR";}}In order to understand whether or not a certain technology is disruptive, it is crucial to visualize 1) the trajectories of performance demanded by the market, 2) the trajectories of performance offered by mainstream, sustaining technology and 3) the trajectory of performance expected for the technology under consideration. A performance trajectory describes the evolution in time for a particular product characteristic. For a mobile terminal, some examples of such a characteristic are; wireless data transfer rate, reliability, battery lifetime and user friendliness. Figure \ref{fig:trajectories} gives an example of performance trajectories offered and demanded and their relative evolution in time.

The characteristics of sustaining and disruptive technology are displayed in Figure \ref{fig:Characteristics_of_disruptive_tech}. The performance trajectories are readily graphed as functions of time but the challenge is to chose the relevant performance attributes along the abscissa. Regarding this matter, it is the author's interpretation that Christensen distinguishes two different phases in the disruption process: first, the value proposition of the disruptive technology gains momentum by presenting attractive performance with respect to a new set of attributes, attractive to other than mainstream markets and customers. Later it manages to resolve its initial shortcomings in the mainstream market and finally completely outscores its previously dominating technology. In an example in \cite{CHR97}% , where the concept of battery cars is studied as a potentially disruptive technology, Christensen illustrates this view in the statement (p. 198):

"\emph{the companies that ultimately achieve the advances in battery technology required to put electric cars in mainstream markets will be those that pioneer the creation of new value networks}". Christensen refers to this circumstance as a dilemma for innovators, particularly within incumbent companies. The concept is summarized in Figure \ref{fig:InnovatorsDilemma}.

Drawing up the performance trajectories requires collection of certain informations that are listed below. We elaborate on the implications for the particular case of wireless communications in the small font text below each bullet.\FRAME{fhFUX}{405.0625pt}{267.375pt}{0pt}{\Qcb{Key elements in the analysis of the potential for disruption for a particular technology.}}{\Qlb{%
sec:analysis_of_disruptive}}{Figure}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 405.0625pt;height 267.375pt;depth 0pt;original-width 665pt;original-height 490.1875pt;cropleft "-0.1060";croptop "1.0409";cropright "1.1060";cropbottom "-0.0409";tempfilename 'INDCN804.wmf';tempfile-properties "XPR";}}\FRAME{fhFUX}{404.625pt}{266.875pt%
}{0pt}{\Qcb{Questions prompted by Christensen, for the particular case of SDR as a potentially disruptive technology.}}{\Qlb{fig:QuestionsPrompted}}{%
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224.375pt}{0pt}{\Qcb{Questions prompted by Christensen, for the particular case of SDR as a potentially disruptive technology.}}{}{Figure}{\special%
{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 398.3125pt;height 224.375pt;depth 0pt;original-width 651.4375pt;original-height 404.5pt;cropleft "-0.1082";croptop "1.0497";cropright "1.1082";cropbottom "-0.0497";tempfilename 'INDCN806.wmf';tempfile-properties "XPR";}}

\begin{itemize}
\item[(a)] \textbf{definition of basic functionality requirements and performance measures,}

{\small The most common functionality and quality issues of wireless communication techniques are related to data transmission/reception rate, power consumption, availability (outage probability), roaming and interoperability, manufacturing cost for infrastructure and terminals, reliability, maintenance, support of evolving services, cost of carried data, quality of service, and lifetime of equipment. Depending on the perspective of the market players under consideration, different functionality ranking criteria apply. For instance, a network provider may be more concerned about the spectrum efficiency, in terms of bits/s/Hs/km}$%
^{2}${\small , than the data rate provided to a particular user.}

\item[(b)] \textbf{definition of current mainstream market needs, analyzing rather what customers do than what customers say they do with the technology}%
,

{\small The work related to this definition identifies suitable measures for quantizing the performance requirements of different players on different wireless communication standards. The market share of different wireless communications techniques such as personal mobile communications, military tactical communications, fixed wireless communication links, local area wireless network access, digital/analogue audio/video broadcasting, personal area wireless networks, metropolitan area wireless networks, sensor communications, satellite communications, should be outlined. Also some thought should be given to other, more far-fetched, functionality requirements of potential interest to certain user groups. The informations are collected from secondary sources, mainly through literature studies and interviews.}

\item[(c)] \textbf{evaluation of current technology offerings}

{\small For example, the most widespread wireless communication standards are evaluated in terms of performance of the functionality attributes defined in (a). The technology offering of SDR technology is compared to the evaluated standards.}

\item[(d)] \textbf{surveying the technology potential of the potentially disruptive technology}

{\small Due to the fact that the ongoing (known) activities on SDR technology is limited to business-to-business applications and that a substantial part of the research and development activities is going on secretly. It is difficult to obtain primary information \ about what different players really do with the technology. However, during the interviews, we have posed straightforward questions in order to get as clear a picture as possible.}

\begin{itemize}
\item {\small What is your most optimistic vision of SDR technology?}

\item {\small Where do you think that SDR technology is most useful in your business model? What are its most attractive characteristics?}

\item {\small Have you conducted any study on SDR concepts?}

\item {\small Will SDR technology be most important in order to cut costs or to provide increased value to customers?}

\item {\small Can any group of players be said to loose upon the deployment of SDR technology (for example infrastructure equipment manufacturers)?}

\item {\small Is SDR technology present in your business model?}

\item {\small Do you believe there is a meaning in the SDR paradigm? Is it just an inevitable path of development that can't be avoided?}

\item {\small If the answers to the previous questions were yes and no, which are the competing technologies?}

\item {\small How do you judge the performance of a new technology?}

\item {\small What systematic approaches for judging technology potential are you aware of?}
\end{itemize}

\item[(e)] \textbf{forecasting of the rate of performance improvement of different attributes}

{\small For a selection of the performance attributes outlined in (a), some of the underlying technologies most critical in SDR technology, as field programmable gate arrays (FPGAs), ADCs, DSPs, etc are identified. We turn to literature, such as \cite{WAL99} and \cite{CUM99}, to see what the rate of performance improvement has been in the past and extrapolate. For the traditional wireless communication techniques, we do the same thing and compare the rate of improvements to those of the SDR technology. During the interviews, the technologies identified as critical to SDR will be assessed. Furthermore, the performance attributes with the highest rate of improvements are discussed and potential hard constraints or showstoppers (as for instance the Shannon limit, battery capacity) are illuminated. In addition, we look at silicon production processes and issues as clock speed, integration and power consumption. Some promising future technologies, as, for example, micro electro mechanical systems (MEMS), are also reviewed.}

\item[(f)] \textbf{evaluation of the rate of performance improvement commanded by the market needs.}

{\small The following questions are discussed during the interviews.}

\begin{itemize}
\item {\small Which are the most important and revenue-bringing high-end services today?}

\item {\small How tight is the coupling between performance demand and technology push in wireless communications?}

\item {\small Has marketing been successful to steepen the slopes of product requirement demand curves (see \cite{CHR97}, p. 180)?}

\item {\small Can the HW/SW spiral of the PC industry be replicated in wireless communications?}

\item {\small Will SDR technology improve the conditions for such a scenario?%
}
\end{itemize}

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%BeginExpansion
\noindent%
%EndExpansion
During the work with this study, it was found that the collection and comparison of different performance of circuits required in SDR solutions from secondary sources is very difficult and tedious. Furthermore, experience from similar work tells that attributes as clock speed and dynamic range of ADCs are difficult to predict with accuracy through interpolation of trends. Although Moore's law has proven fairly reliable, it primarily addresses the number of transistors that can be integrated in a certain area, which does not automatically transfer to clock speed or dynamic range.
\end{itemize}

Instead, the work has focused on analysis of the responses to a some specific questions posed to evaluate how well the technology correlates with the typical characteristics of a disruptive technology.

For the sake of completeness, we recapitulate the workflow, suggested by Christensen, in Figure \ref{sec:analysis_of_disruptive}. Christensen identifies the following typical characteristics of disruptive technologies:

\begin{itemize}
\item[(i)] \textbf{The technology appears deficient, i.e., it can't be used according to the performance measures most important in today's mainstream market}

{\small Interview questions:}

\begin{itemize}
\item {\small Are there any showstoppers of SDR technology?}

\item {\small Can SDR technology compete in mainstream markets?}
\end{itemize}

\item[(ii)] \textbf{The performance improvement rates are faster than the demand in terms of those measures, what is governing/limiting market performance demand curves?} \textbf{When will intersection happen?}

{\small The answer would follow from the analysis of the results obtained from (e) and (f) and it will be assessed in the expert interviews. However, the interviews show that it is difficult to distinguish what is the effect and the cause, \emph{i.e.,} decide what is the hen and the egg.}

\item[(iii)] \textbf{Is the new technology smaller, simpler or more convenient to use than the dominating technology,}

{\small The answer will follow from the analysis of the results obtained from (a), (b) and (c).}

\item[(iv)] \textbf{Does it seem to take a technology breakthrough to make the technology competitive in mainstream markets or is sustaining improvements enough?}

{\small Comparisons of the results from (e) and (f) give indications about this.}

\item[(v)] \textbf{Is the sticker price (unit up-front fee) typically lower for the new technology?}

{\small See analysis of cost in connection with the (a) issue.}

\item[(vi)] \textbf{Does the technology offer a set of attributes orthogonal to those commanded in mainstream markets?}

{\small During the interviews, it is discussed whether 1) there are other attractive technologies, alternative to SDR that are not possible to combine with SDR and 2) if there are any other threatening substitutes to SDR functionality across substitute industries (see \cite{CHA99}).}

\item[(vii)] \textbf{redefines the distribution channels?}

{\small The major channels for distribution of equipment and services in wireless communications will be identified and compared to the PC industry. The similarities with the modular SDR and PC architectures is discussed during the interviews.}
\end{itemize}

\FRAME{fhFUX}{398.3125pt}{265.1875pt}{0pt}{\Qcb{Christensen's extension of the theory of disruptive technologies -- \emph{the innovators solution}.}}{%
\Qlb{fig:shaping ideas}}{Figure}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 398.3125pt;height 265.1875pt;depth 0pt;original-width 651.4375pt;original-height 486.0625pt;cropleft "-0.1082";croptop "1.0413";cropright "1.1082";cropbottom "-0.0413";tempfilename 'INDCN807.wmf';tempfile-properties "XPR";}}\noindent A summary of the workflow of the Christensen theory is provided in the expositions of Figures %
\ref{fig:QuestionsPrompted} to \ref{fig:shaping ideas}. In \cite{CHR03},

Christensen et al. elaborates further on the theory of disruptive technologies and argue that few ideas are inherently disruptive or sustaining. Rather, they get shaped in the minds of the innovators and business developers of the industrial companies and may come out as either of the kinds. This thinking is illustrated in Figure \ref{fig:shaping ideas}.

\subsection{\label{sec:TechFrames}Key Issues of Technological Frames}

This section discusses the question: how can we understand the current maturity of SDR technology and where the industry moves or ought to move and addresses the issue of whether and how SDR could disrupt (and disintegrate the wireless industry). In \cite{ALL03}, \emph{technological frames }are defined as "all elements that influence interaction and lead to attribution of meanings to technical artifacts". It is the authors perception that different technological frames, in fact, represent different value network scenarios. Among those, eventually only one or a few will prove viable. Towards the end of this thesis, we identify some possible such value network scenarios

The concept of\emph{\ technological frames} is useful to define technological change, to understand when it has happened and to explain how it happens. In this study, the technological frames concept helps us to map out the maturity of the SDR technology.\FRAME{fhFUX}{405.625pt}{254.0625pt}{%
0pt}{\Qcb{Key elements of the sociotechnical perspective of technology evolution.}}{\Qlb{fig:sociotechnical}}{Figure}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 405.625pt;height 254.0625pt;depth 0pt;original-width 666pt;original-height 464pt;cropleft "-0.1058";croptop "1.0433";cropright "1.1058";cropbottom "-0.0433";tempfilename 'INDCN808.wmf';tempfile-properties "XPR";}}

\FRAME{fhFUX}{398.8125pt}{254.8125pt}{0pt}{\Qcb{Example of technological fram -- the common definition of the PC.}}{}{Figure}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 398.8125pt;height 254.8125pt;depth 0pt;original-width 652.6875pt;original-height 465.25pt;cropleft "-0.1080";croptop "1.0432";cropright "1.1080";cropbottom "-0.0432";tempfilename 'INDCN809.wmf';tempfile-properties "XPR";}}

\FRAME{fhFUX}{400pt}{267.4375pt}{0pt}{\Qcb{Analytic process suggested by the theory of technological frames.}}{}{Figure}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 400pt;height 267.4375pt;depth 0pt;original-width 654.9375pt;original-height 490.5625pt;cropleft "-0.1076";croptop "1.0409";cropright "1.1076";cropbottom "-0.0409";tempfilename 'INDCN80A.wmf';tempfile-properties "XPR";}}

In \cite{ALL03}, Allen claims that radically new (mobile) technology emerges when "established technological communities attempt to impose their own definitions of key problems and solutions on new mobile technology". When this happens, newer players are, in order to compete, forced to provide a total system that completely redefines the application area. In other words, Allen stresses that it is necessary to take control over the total user experience in order to bring about new common definitions.

Similar to Christensen in \cite{CHR97}, Allen stresses the importance of new applications of existing old technology as the driving force behind technological discontinuities. When those new applications gain widespread acceptance, a \emph{common definition of technology problems and solutions} is said to be established \cite{ALL03}. This common definition implies that a variety of stakeholder, such as investors, producers, consumers and regulators engage in sustained social interaction, \emph{i.e.}, a new value network structure is being set up. This is similar to the view in \cite% {CHR02} that new disrupting technology prompts the disintegration of value chains and calls for new partitioning of systems into interdependent subsystems.

In order to judge how far SDR technology has gone towards such a common definition it is crucial to investigate the level of the stakeholders understanding and agreement of what the technology is good for, what it is trying to achieve and what are its most desirable characteristics. As far as the author understand, the most important characteristics of a technological frame are captured by the common definition and the fuel for sustained social interaction that it provides. Typically a technological frame addresses:

\begin{itemize}
\item[(i)] \textbf{the most important problem to be solved by a technology, expressed as a certain dilemma facing some set of customers,}

{\small This corresponds to performance-demand driven issues of different players, but may also be a circumstance that improves competition conditions for manufacturers, as for instance by the provisioning of a modular architecture that facilitates adaptive changes in the value chain structure.
In addition to the facts obtained from these interview questions, they gives information about the degree of concordance on the meaning of SDR, \emph{i.e.% }, how similar the definitions of different experts are.}

\begin{itemize}
\item Which is the most important customer dilemma that SDR technology addresses?
\end{itemize}

\item[(ii)] \textbf{the most important performance criteria for a technology that offers a solution to the problem and}

{\small This question is posed to the respondents.}

\item[(iii)] \textbf{an exemplary artifact, \emph{i.e.}, a prototype that can give an idea of what a practical implementation of the technology would be}

{\small Current and past research and developments in academia and the industry are surveyed through literature studies. Questions to the respondents concern their knowledge on the deployment of SDR technology in practical systems, research projects, prototypes and testbeds for SDR.}
\end{itemize}

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\noindent%
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In order to analyze new technology evolution (and outline potential value network scenarios) Allen suggests the following phases:

\begin{itemize}
\item[(a)] \textbf{Make an inventory of existing social interaction. Identify the relevant social groups and their corresponding existing definitions of the most important problems and solutions with respect to the new technology.}

Questions for the interviews are:

\begin{itemize}
\item What is the current situation of the SDR industry?

\item Which are the major technical barriers against widespread deployment of SDR technology?

\item What technologies are currently under development?

\item What are the major strengths and weaknesses of SDR technology?

\item Will SDR be confined to military applications or transcend also the other areas of wireless communications such as personal mobile communications?

\item In what applications is SDR technology used already today?

\item Which applications are closest to be launched to the market?

\item Who are the leading suppliers of commercial hardware and software components?

\item Who are the major actors on the markets?

\item Which traditional telecommunication companies and what new entrants are active in the SDR development?

\item How are the industry standards evolved and what is the current state of them?

\item Who are the primary customers of SDR hardware and software?

\item What are the key product success criteria driving different groups of users of the SDR technology?

\item What are the ranking criteria of the customers?
\end{itemize}

\item[(b)] Search for a common definition. Analyze the attempts to establish new common definitions specifying a problem, solution requirements and an exemplary artifact.

This phase contains a categorization of SDR research and development efforts on traditional wireless communications industry and startup companies. The interviews are used to gain knowledge about the different players, but detailed inventory of research and development activities is left out due to time limitations. Question to experts are:

\begin{itemize}
\item Who do you think will come up with a redefining totality solution (as for instance Palm within the personal digital assistant (PDA) industry)?

\item Who is best prepared to capture the growth opportunities in SDR?
\end{itemize}

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%EndExpansion
Finally, we note the point where Allen says that the aspect of technology evolution that is most difficult to appreciate is the notion that the common definition of a new technological frame is only obvious in retrospect. This means that new technology applications does not have a success criteria ready as soon as they emerge. Rather the success criteria is defined through a process of discovery and so should be expected also for the SDR technology.
\end{itemize}

\FRAME{fhFUX}{409.5pt}{265.5625pt}{0pt}{\Qcb{Questions prompted by Allen for the specific case of SDR technology.}}{\Qlb{fig:QuestionsSocioTechnical}}{%
Figure}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 409.5pt;height 265.5625pt;depth 0pt;original-width 674pt;original-height 486.8125pt;cropleft "-0.1046";croptop "1.0412";cropright "1.1046";cropbottom "-0.0412";tempfilename 'INDCN80B.wmf';tempfile-properties "XPR";}}

A summary of the workflow of the technological frames theory is given in the expositions of Figures \ref{fig:sociotechnical} to \ref%
{fig:QuestionsSocioTechnical}.

\begin{example}
In \cite{ALL03}, Allen identifies the following three phases in the search for a common definition of the application of a new technology:\ A) initial extension of existing definitions, B) excitement and disappointment and C) first established definition. For the case of the personal digital assistant (PDA), Allen gives the following line of events as an example.

\textbf{A. Initial extension of existing definitions:} Minor PC companies apply existing PC definitions to the use case of PDAs. The main problem addressed is how to provide PC functionality supporting the needs of existing PC users, but in a smaller unit. The performance criteria are very similar to those of the PC industry, e.g., processor speed and memory. Battery life-time, however, is a new performance parameter. Most new products come from existing PC companies that are not market leaders, but radical innovation comes from even more peripheral players.

\textbf{B. Excitement and disappointment:} Two major definitions emerge -- the pen-based computer and the wireless communication assistant for mobile professionals. There is a battle between major players in the computer and telecommunications industry, who, respectively, support either one of those definitions. Incumbents as Apple, IBM, Microsoft and Motorola are the driving force. The pen-based computer is able to attract non-PC users through it's new input method and it's user friendliness. Examples of the wireless communications assistant are the personal communicators introduced by Motorola and Nokia. In general, well established players persist with the existing technological frames.

\textbf{C. First established definition:} The PDA is redefined as a personal information manager that act as a companion to the PC. The Palm company make a radical departure from previous definitions and achieve commercial success. New key performance criteria are organizer functionality and easy connectivity with a PC. Within two years almost all PDA products share this basic technological frame. This marks the end of the search for a sustainable new PDA application and industry competition starts around a

widely shared technological frame.
\end{example}

It should be noted that the first established technological frame originated from a startup company that was not a PC producer, nor a telecom or a consumer electronics company. The most successful palmtop PDA producers were Palm and Psion -- also a startup. An interesting circumstance is that both Palm and Psion began as pure application SW companies. In order to develop their most promising applications, they needed to come up with a whole new solution including new HW and a new operating system (OS).

A key learning from the PDA example is that experiments with new definitions require the creation of an entire user experience. Probably, much of the success of Palm and Psion was due to the use of the application SW as a starting point. One may, however, ask where those companies stand today?\
The author rarely see anyone using a Palm pilot PDA those days and so called smartphones seem to have taken over most of the digital assistant functionality, the calender synchronization with the Microsoft Outlook program being the dominant application. A couple of years ago, there were some initial attempts with PDA's that contained cellular modems, but these seem to have vanished from the markets. One reason might be the difficulty to manage the complexity of radio modem technology and the challenges of component integration and battery lifetime.

\subsection{\label{sec:Creation of New Market Space}Creation of New Market Space}

This section will concentrate on the issue of how to judge the potential of new technology, ultimately aiming at evaluating the business potential of SDR technology. The business potential is driven by the \emph{segmentation} and \emph{differentiation} strategies that can be enabled by this technology. We will take a rather technological perspective and strive to use quantitative data to assess the business potential and possible marketing strategies for SDR technology. The main components of marketing strategy are segmentation, differentiation and positioning\footnote{%
Positioning is a communication strategy to influence the customer to believe and remember the superiority of the company's value proposition.} \cite%
{AND97}. We will leave out the issue of positioning from the discussion, focusing on the segmentation and differentiation opportunities opened up by SDR technology.

The identification of high potential technologies is related to the segmentation activity, where a company determines what customers to address and how to allocate resources to put together an attractive value proposition for those customers. The innovator's dilemma discussed in \cite%
{CHR97} highlights the circumstance that market segments with potentially very high growth opportunities are difficult to identify with traditional

sensible management, if not special attention is directed to the creation of \emph{new value networks}. A similar point of view, focusing on the necessity on looking across conventional boundaries of competition , \emph{% i.e.}, over performance attributes and the projected evolution of their value to customers over time, is presented in \cite{KIM99}. This implies that an equipment manufacturer or a service provider should analyze how customers make trade-offs between substitute products or services and see whether there are any decisive, irrevocable and clear trends that will change these trade-offs in the future.\FRAME{fhFUX}{396.9375pt}{253.4375pt}{% 0pt}{\Qcb{Considerations to make in order to identify a new value curve.}}{% \Qlb{fig:creation_of_new_value_curve}}{new_value_curve.wmf}{\special% {language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "F";width 396.9375pt;height 253.4375pt;depth 0pt;original-width 6.6556in;original-height 4.0023in;cropleft "-0.0130";croptop "1.0434";cropright "1.0130";cropbottom "-0.0434";filename 'Figures/new_value_curve.wmf';file-properties "XNPEU";}}% One way of thinking about these trade-offs is illustrated in Figure \ref% {fig:creation_of_new_value_curve}.

\begin{example}
Home Depot is the name of a company that has revolutionized the do-it-yourself market in North America. Home Depot analyzed the existing industries serving home improvement needs and identified two major customer choices: 1) people could hire subcontractors or 2) they could buy tools and materials from a hardware store and do the work themselves. The key issue to understand in this case is why customers would choose one substitute over another. Home Depot pin-pointed one decisive advantage of the first alternative -- contractors have specialized know-how that most home-owners lack. Another important circumstance is the lower price of the second alternative. With lower prices than other hardware stores, Home Depot is delivering the decisive advantages of both substitute industries and eliminating all costly features as central location, nice looking shelves, etc. Similar ways of thinking could be applied to the wireless equipment manufacturing industry by identifying substitute products (including SDR based technology), identifying the performance attributes and pin-pointing the motivation for certain customer preferences.
\end{example}

The differentiation activity is the process where a company makes up its mind regarding how it will conquer and govern a market segment and how it will assemble offerings that differ from its competitors. For example, the SDR architecture may highly impact the flexibility/rigidity of the wireless equipment manufacturing value chain and the corresponding potential opportunities for differentiation. For instance, in \cite{CHR02}, it is claimed that the ability for companies to capture attractive profits is highly dependent on their ability to swiftly move operations to the value chain locations where the immediate customers are not yet satisfied with the

functionality of the available products. Particularly interesting in this respect are the modularity of the SDR architecture, the flexibility of the product compositions the possibility to have a differentiated offering (value proposition) that is extended in time\footnote{%
-- through the opportunity to continuously download service packets with altered or added functionality.} well beyond the initial delivery of the communication platform to the customer. In Section \ref{sec:Analysis}, we also discuss the issue of differentiation in relation to the impact of the potentially disruptive SDR technology on the strategic alternatives for competition according to the view presented in \cite{CHR97}, p. 180.

\begin{example}
Let us draw on the previous example and limit the scope of substitute to products or services that can be hosted by a mobile phone. Consider a typical mainstream application as telephony and reflect on the individual needs that can be fulfilled by a phone call. Entertainment, consolation, safety, need for planning, emergency assistance or self-assertion are basic human needs that can be satisfied by a phone call. Now try to find alternatives to the phone call that can satisfy those needs and then reflect on the performance attributes that make those alternatives less attractive than the phone call. The idea is that those insights should lead to the creation of new value propositions and new value networks, i.e., new market space.
\end{example}

The possibilities to create new market space for services enabled by a mobile terminal, can be analyzed with the substitute-thinking suggested in %
\cite{KIM99} and discussed in Section \ref{Sec:TheoryAndConnection}. The following example, based on the \emph{user-focused reference model} \cite%
{CRI04} that adheres to Maslow's hierarchy of human needs, indicates that most of the conceivable substitutes for a voice-call can only be provided through the addition of new functionality in the mobile or enhancement of the services provided over the network.

\begin{example}
Some potential reasons for a person to make a voice call from a mobile terminal may be: a) having a boring time, b) seeking consolation, c) organizing a meeting, d) seeking directions or e) being in an emergency situation. Instead of solving those problems with the voice call, a) could be addressed with some amusement functionality/service, b) could be handled with a direction to the closest chocolate store, c) by an automatic meeting synchronization application, d) with an electronic map and e) with an emergency button, a first-aid manual or the directions to the nearest hospital. In conclusion, it is difficult to imagine a substitute product/service that is not associated with increased functionality in the mobile terminal or enhanced services.
\end{example}

According to \cite{ARB04}, there is a common understanding between academia and industry that personalization, ambient awareness and adaptability are crucial elements of future mobile communication networks. Furthermore, rather than being a result of a research-and-development trajectory towards a coherent technological system, future communication systems should be made up by various technologies configured around specific user requirements, identified by the market. Due to decreasing coordination of infrastructure investment of established operators and new entrants, the network environment will be very heterogenous and interoperability will be a crucial success factor for new wireless business models. Moreover, \cite{ARB04} states that "capturing value from information goods, widely perceived as public goods, will remain an important challenge for any such business model. Services tailored to specific needs or initiated by the user him/herself seem to increase their value to the customer".

Market forecasts indicate that the growth in the personal communication service (PCS) market is expected to exceed 40\% per year until 2007, reaching about \$150 in 2006 \cite{SDR03a}. Ultimately, the corresponding revenue streams comes from the end customers and the market actors strive to maximize their share of the revenues by encouraging the end customers to use more billable units and higher value services. It is also critical to enroll more customers.

\subsection{\label{sec:KeyQuestions}Summary of Questions Prompted}

In order to understand whether or not SDR is a disruptive technology, Sections \ref{sec:DisruptiveTechnology} and \ref{sec:TechFrames} lead us to pose a set of questions. Below, a list of questions is provided, where each question is related to one or more of the categorization criteria outlined in Sections \ref{sec:DisruptiveTechnology} and \ref{sec:TechFrames}.

As discussed in Section \ref{Sec:TheoreticalQuestion}, the questions are partitioned into two groups: indirect questions and direct questions. The indirect questions aim to produce data for analysis in the theoretical framework in order to make inference about the key questions of the thesis. The indirect questions are coupled to the issues described in Sections \ref%
{sec:DisruptiveTechnology} and \ref{sec:TechFrames}. The direct questions concern the key issues of this, thesis, presented in Sections \ref%
{Sec:TheoreticalQuestion} and \ref{sec:Practical Key Issues}. The responses to the direct questions provide a consistency check on the conclusions drawn from the theoretical analysis.

\subsubsection{Indirect Questions}

The questions prompted in Sections \ref{sec:DisruptiveTechnology} and \ref%
{sec:TechFrames} are collected here.

\begin{itemize}
\item[i.1] Which are the basic functionality requirements and performance measures of SDRs?

\item[i.2] Which market needs are to considered as mainstream?

\item[i.3] Where do you think that SDR technology is most useful in your business model? What are its most attractive characteristics?

\item[i.4] Have you conducted any study on SDR concepts?

\item[i.5] Will SDR technology be most important in order to cut costs or to provide increased value to customers?

\item[i.6] Can any group of players be said to loose upon the deployment of SDR technology (for example infrastructure equipment manufacturers)?

\item[i.7] Is SDR technology present in your business model?

\item[i.8] Do you believe there is a meaning in the SDR paradigm? Is it just an inevitable path of development that can't be avoided?

\item[i.9] If the answers to the previous questions were yes and no, which are the competing technologies?

\item[i.10] How do you judge the performance of a new technology?

\item[i.11] What systematic approaches for judging technology potential are you aware of?at they say they do with the technology?

\item[i.12] Do you agree with the presented forecasting of the rate of performance improvement of different attributes?

\item[i.13] Which are the most important and revenue-bringing high-end services today?

\item[i.14] How tight is the coupling between performance demand and technology push in wireless communications?

\item[i.15] Has marketing been successful to steepen the slopes of product requirement demand curves (see \cite{CHR97}, p. 180)?

\item[i.16] Can the HW/SW spiral of the PC industry be replicated in wireless communications?

\item[i.17] Will SDR technology improve the conditions for such a scenario?

\item[i.18] Are there any showstoppers of SDR technology?

\item[i.19] Can SDR technology compete in mainstream markets?

\item[i.20] The performance improvement rates are faster than the demand in terms of those measures, what is governing/limiting market performance demand curves? When will intersection happen?

\item[i.21] Is the new technology smaller, simpler or more convenient to use than the dominating technology,

\item[i.22] Does it seem to take a technology breakthrough to make the technology competitive in mainstream markets or is sustaining improvements enough?

\item[i.23] Is the sticker price (unit up-front fee) typically lower for the new technology?

\item[i.24] Does the technology offer a set of attributes orthogonal to those commanded in mainstream markets?

\item[i.25] Does the technology redefine the distribution channels?

\item[i.26] Which is the most important customer dilemma that SDR technology addresses?

\item[i.27] What is the current situation of the SDR industry?

\item[i.28] Which are the major technical barriers against widespread deployment of SDR technology?

\item[i.29] What technologies are currently under development?

\item[i.30] What are the major strengths and weaknesses of SDR technology?

\item[i.31] Will SDR be confined to military applications or transcend also the other areas of wireless communications such as personal mobile communications?

\item[i.32] In what applications is SDR technology used already today?

\item[i.33] Which applications are closest to be launched to the market?

\item[i.34] Who are the leading suppliers of commercial hardware and software components?

\item[i.35] Who are the major actors on the markets?

\item[i.36] Which traditional telecommunication companies and what new entrants are active in the SDR development?

\item[i.37] How are the industry standards evolved and what is the current state of them?

\item[i.38] Who are the primary customers of SDR hardware and software?

\item[i.39] What are the key product success criteria driving different groups of users of the SDR technology?

\item[i.40] What are the ranking criteria of the customers?

\item[i.41] Who do you think will come up with a redefining totality solution (as for instance Palm within the personal digital assistant (PDA) industry)?

\item[i.42] Who is best prepared to capture the growth opportunities in SDR?
\end{itemize}

\subsubsection{\label{sec: Direct Questions}Direct Questions}

\begin{itemize}
\item[d.1] Will SDR technology disrupt the wireless communications industry?

\item[d.2] Which seems to be the most viable application scenarios for the future?

\item[d.3] Where is the greatest growth expected?

\item[d.4] When will a potential disruption occur?
\end{itemize}

\section{\label{sec:Analysis}Analysis}

We start out our analysis by identification of some major stakeholders and value network relations of the PCS market. We also discuss the military market for wireless communication equipment for defense purposes as it has been the major driver of SDR technology since a number of years. In fact, this is one of the last equipment segments where dedicated military solutions are ahead of commercial of the shelf (COTS) equipment in terms technology sophistication and innovation.

\subsection{Stakeholder Definitions of SDR Utility}

\subsubsection{Major Stakeholders of the PCS Market}

\FRAME{fhFU}{401pt}{259.5pt}{0pt}{\Qcb{Business connections between the actors in the personal communication services market (value network). The picture has been borrowed from \protect\cite{SDR03a}.}}{\Qlb{%
fig:value_network}}{Figure}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "T";width 401pt;height 259.5pt;depth 0pt;original-width 399pt;original-height 257.4375pt;cropleft "0";croptop "1";cropright "1";cropbottom "0";tempfilename 'INDCN80C.bmp';tempfile-properties "XPR";}}

Adopting the perspective on the market for PCSs, outlined in \cite{SDR03a}, the market actors can, with some modifications, be cathegorized in the following groups:

\begin{itemize}
\item[APs] \textbf{Application Providers} with the role to supply and package their specific applications for use in mobile terminals. Examples of such applications are weather forecasting, stock quoting information, gaming, dating or gambling services. Taking a somewhat visionary view, in the direction of the PC-market evolution for SDR, it is possible to imagine more sophisticated applications for enhancing the performance of the mobile terminal, as software for memory-management, virus-control and other kinds of hardware maintenance.

\item[CPs] \textbf{Content Providers} that make available various kind of information from databases, music/video downloads or streaming video or audio content for instance, TV or radio shows. The access to this information may be an important part of an application offering. The content provider may connect with the application provider or the multimedia manager to packetize such an offering. In the future, one can imagine CPs to provide geographical data and information about infrastructure location that will allow terminals to improve the quality of their wireless connections.

\item[MMs] \textbf{Multimedia Managers} that packetizes the applications and content with the branding touch desired by the service provider. The aim is to give a look and feel that is consistent with the service providers branding program to make sure that the user does not need to learn several different interface styles.

\item[WUs] \textbf{Wireless Users} who are the individual subscribers to the PCS services, which benefits from their use. Wireless users typically obtain a terminal and subscribe for a service that provides them with a telephone number and potentially an IP address.

\item[NOs] \textbf{Network Operators} who run the radio infrastructure necessary to reach out to the wireless users. The network operator is

concerned with the challenge to offer adequate levels of capacity in
different coverage areas and handling the dynamics introduced by growing
demand, new service offerings and new technology (as for example SDR). The
network operator may be a cost center within in service provider
organization or and independent profit center that may provide service to
customers of several service providers. The network operator may support
several different air interfaces.

\item[SPs] \textbf{Service Providers} that can be seen as the motor of the
PCS market as they aggregate and offer the major part (today) of the
services and establishes branding of the offering to the wireless users.
Frequently, the service provider supplies the wireless user with the
terminal. An important characteristic of the SP is that it has the financial
responsibility for establishing the credit of the user and means of payment
for the services consumed. The service provider is also responsible to
maintain secure links between the wireless users and the financial
institutions. In case of a problem with any kind of services, it is the SP
that the user will turn to for a resolution.

\item[FDs] \textbf{Function Developers} who develops or acquires software to
run on network nodes and determines network functionality. As a supplier of
functionality that may effect the RF spectral characteristics of the system,
the\ FS should be a trusted organization who must operate within the
constraints imposed by regulatory bodies and the security policy of the
system, for which the SP is the chief responsible. The FD also provides
system interfaces that can be used by the APs to deliver system applications
content. In contrast to the\ APs, the FDs are concerned with details of
system performance and functionality.

\item[RPs] \textbf{Regulators and Politicians} that impose legal constraints
on the competition with the aim to control and tap off the revenue streams
in the PCS market. As pointed out in \cite{NOA01}, a fundamental reason for
regulation is the democratic societal circumstance that there will always be
a majority that want something from a minority. Despite the event that
future SDR based, cognitive, radio systems have the capability to coexist
without any kind of spectrum regulation, this circumstance makes it
plausible that regulation will continue to exist in one way or another. In
the light of the research findings (rendered the Nobel prize in economy
2004), one may argue that the society would benefit from regulation becoming
an institution isolated from political influence in line with the evolution
of the central banks in many countries. One step in this direction,
important for the realization of SDR systems is to limit regulations to
spectrum characteristics rather than detailed specification of equipment to
be used in particular bands.

\item[OEMs] \textbf{Original\ Equipment Manufacturers} and system providers
who design and manufacture the equipment used to provide the PCSs, including

network routers, links for physical interconnection, network database functionality, base stations and mobile terminals. OEMs are responsible for the reliability and performance of their product offerings. For this reason, as well as competition, they are typically reluctant to open up their systems to third party solutions and functionality.

\item[WLs] \textbf{Wireline Operators} that often provide the communications for traffic and network management to the\ NOs. Furthermore, they provide a channel for the SPs to provide the WUs with branded services over the fixed network. Potentially, other market actors may use the WLs to reach out to the WUs with their product and service offerings. For example, an\ FS could use this channel to provide a WU with enhancements in terminal functionality or performance.

\item[RNs] \textbf{Roaming Network Operators}

\item[PANs] \textbf{Wireless Personal area Networks}

\item[AAs] \textbf{Academia and Independent Analysts}

\item[IAs] \textbf{Illegal Actors}

\item[MIL EMs] \textbf{Military equipment manufacturers} do not (yet) act on the PCS market but might soon enter, for example, when ready with the SCA standard.

\item[MIL USERs] \textbf{Users of military equipment}, \emph{i.e.}, national defense and safety organizations are neither on the PCS market. However, there is an increasing interest for COTS equipment (from the PCS market) as a platform for development of specific applications.
\end{itemize}

\subsubsection{\label{Sec: Definition of the Dilemma Solved by SDR}%
Definition of the Dilemma Solved by SDR}

The participants in the interviews of this study belong to PCS operators (including SPs and NOs), MIL EMs, MIL USERs, PCS OEMs and Academia (AA). Different stakeholders have quite different opinions about the most important problems addressed by SDR. There seems to be three major definitions of SDR and the dilemmas addressed by the technology. Basically, these definitions are connected to different layers in the OSI stack and consist of

\begin{itemize}
\item[Def. 1] layer 1 and 2 -- platform communication hardware and software,

\item[Def. 2] layer 3 and 4 -- middleware, transport layer and network functionality and

\item[Def. 3] layer 5 and 6 -- applications.
\end{itemize}

\noindent This partitioning is shared between the PCS operators as well as the manufactures and users of military communications equipment. However, the manufacturers of equipment for personal mobile communications (PCS OEMs) seem to be more geared towards viewing the SDR technology as an implementation technology that is required to obtain more effective and less costly production of equipment. The most important definitions of the dilemmas solved by SDR for these groups is illustrated in Figure \ref%
{dilemma_solved_by_sdr}.

\FRAME{fhFU}{5.1119in}{4.4356in}{0pt}{\Qcb{The definitions of the dilemma solved by SDR from from the perspective of different stakeholders.}}{\Qlb{%
dilemma_solved_by_sdr}}{dilemmasolvedbysdr_1.wmf}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "F";width 5.1119in;height 4.4356in;depth 0pt;original-width 7.3898in;original-height 6.4074in;cropleft "0";croptop "1";cropright "1";cropbottom "0";filename 'Figures/DilemmaSolvedBySDR_1.wmf';file-properties "XNPEU";}}

Figure \ref{dilemma_solved_by_sdr} illustrates that PCS OEMs are highly concerned with cost-driven issues as development time, reuse of HW and production yield. There is, however, also a common definition between PCS OEMs and PCS operators that SDR is about upgrades of air-interface related functionality and applications. This is valid for both the terminals and the infrastructure. Specific for PCS operators is the view that SDR enables better support for naive or impaired terminal users and simplifies the access to advance services for those users. The PCS operators also make a connection between the graphical user interface (GUI) and SDR as a way to support a common look and feel of the services provided to different terminals.

Common to all three groups, active on the market, is the view that SDR technology can be used to provide network-independent services. Network independency implies that a service will be perceived the same to the end users, regardless of whether the physical interface is GSM, WCDMA, WLAN or even fixed, wireline, communications. Particular to the MIL EMs, MIL Users, PCS Operators and Academia is the definition that SDR paves the way to unbundling of HW and SW.

The PCS Operators seem to focus on the third party provisioning of applications, while the MIL EMs and MIL Users have the more radical view that SDR is about the separation of HW and SW for air-interface functionality. This SW is denoted \emph{waveforms} and the idea is that third parties should be able to develop and qualify different waveforms that can be plugged in and run on generic HW platforms and enable interoperability with equipment based on other HW and even SW from other parties, supporting the same standardized waveform.

An alternative way to illustrate the spread of different definitions of the application of SDR technology is to take a value-chain perspective, starting with research and equipment manufacturing issues and ending with the convenience of the end-users of different wireless services.\FRAME{fhFU}{% 5.5166in}{1.286in}{0pt}{\Qcb{Example of value chain activities where the PCS OEMs and PCS Operators make a strong connection to SDR.}}{\Qlb{% SDR_value_chain}}{valuechain_1.wmf}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "PICT";valid_file "F";width 5.5166in;height 1.286in;depth 0pt;original-width 6.8614in;original-height 1.0482in;cropleft "0";croptop "1";cropright "1";cropbottom "0";filename 'Figures/ValueChain_1.wmf';file-properties "XNPEU";}}Figure \ref% {SDR_value_chain} illustrates major activities that the PCS OEMs and PCS Operators relate to SDR technology. The spectrum efficiency part is related to the choice of adequate access-modes depending on the quality of service (QoS) requirements of different services, for example to cathegorize services after latency requirements and avoid to waste high bandwidth access on narrow-band, non-latency sensitive services as for example E-mail. Spectrum utilization is also addressed the concept of cognitive radio (see for example \cite{TUT02}), which addresses intelligent radios that adapts and tunes to available frequency bands depending on the present traffic situation in different areas.

The focus of the PCSs OEMs are in the first sequence of the chain and the main interest of the PCS Operators is naturally on the last part. One can argue that virtually all areas of the PCS industry value chain can be related to SDR technology. In this sense, there is not a strong consensus on the utility of SDR between the different actors considered in this study.

\FRAME{ftbpFU}{5.2053in}{5.2918in}{0pt}{\Qcb{Summary of major technological frames related to SDR technology.}}{\Qlb{fig:SDRtechframes}}{% proposedsdrtechframes.wmf}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "F";width 5.2053in;height 5.2918in;depth 0pt;original-width 6.9038in;original-height 7.018in;cropleft "0";croptop "1";cropright "1";cropbottom "0";filename 'Figures/ProposedSDRTechFrames.wmf';file-properties "XNPEU";}}

Figure \ref{fig:SDRtechframes} illustrates some major technological frames of SDR technology. From the beginning in the early 1990's much of the focus was directed towards issues of highly digital radio transceiver front-ends and discussions about the possibility to sample at already at the antenna. Highly digital radio transceivers is still a hot topic and there are strong incentives to reduce the amount of HW in PCS radio transceivers due to that the number of cellular bands that needs to be supported is growing steadily. Sampling at the antenna is by many perceived as completely unrealistic, particularly for mobile terminals due to high power consumption it brings. From a business point of view, this discussion seem to be less of an important issue.

The concept of cognitive radio has also been widely discussed. There is, however, a clear consensus among the referees that it is quite distant in the future. On the other hand, the definitions of SDR meaning generic HW and\ SW platforms, transparent networks and cost and time reducing implementation technology are more popular.

In conclusion, the evolution of the SDR concept is in the first of the technology evolution phases defined by Allen and described in Section \ref%
{sec:TechFrames} (see Example 1). There is an interesting connection between SDR technology and the PDA example since the definition of the PDA as a wireless assistant never succeeded. Given the success of the definition where radio processing HW and\ SW separates and radio technology becomes more easily available, this definition of the PDA may experience a renaissance. Whether or not the PDAs will be able to compete with the smart phones in this segment is unclear. Another interesting observation is that the successful Palm PDA company started out with development of application SW. This prompts to the definition of SDR as new applications and services built on ubiquitious connectivity as a possible starting point for new businesses opportunities related to SDR technology.

\subsubsection{Definition of the Major Weaknesses of SDR Technology}

There is not a strong consensus on the weaknesses of SDR technology between different stakeholders. One exception is power consumption and area issues that are identified as weaknesses by the PCS OEMs and PCS Operators as well as the Academia. For mobile terminals, this is reflected in battery lifetime and form factor, which are extremely important ranking criteria for the end-users. The military sector is less concerned with these issues. On the other hand, SW failure may have catastrophic effects and dependability (to avoid "bluescreen of death") is a critical issue.

\FRAME{fhFU}{5.0168in}{3.7101in}{0pt}{\Qcb{The weaknesses of SDR technology as perceived by different stakeholders. The expression "bluescreen of death" refers to the fatal consequences a failure in the radio communication SW of a military unit may have in a combat situation.}}{\Qlb{%
sdr_weaknesses_3}}{sdr_weaknessis_3.wmf}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "F";width 5.0168in;height 3.7101in;depth 0pt;original-width 7.1278in;original-height 5.2607in;cropleft "0";croptop "1";cropright "1";cropbottom "0";filename 'Figures/SDR_weaknessis_3.wmf';file-properties "XNPEU";}}

Figure \ref{sdr_weaknesses_3} displays the major concerns of the different stakeholders and illustrate that these are quite different for the PCS and the military market. It should be emphasized that issues as power and area apply mainly for PCS terminals. For basestations and civil vehicle-based wireless communications, as for example in cars, power and area are less important issues. Interestingly, the life-cycles of cars are much longer than PCS terminals, however, the standardization for wireless communications in cars is in an early stage and much work remains.

The standardization work on SDR is entirely driven by the military sector, in particular the U.S. department of defense. Due to the specific nature of the military platforms for communication equipment, this work cannot be straightforwardly inherited by the PCS industry. The fact that the standardization and qualification work is essentially limited to the U.S. defense industry makes it even more difficult to assimilate for the PCS industry, which has its centre of gravity in Europe or maybe Asia.

An interesting aspect is the interest conflict in that the MIL EMs and MIL Users, request more detailed standards, while PCS OEMs are afraid of over standardization and too detailed regulation that prevents cost-effective implementations. Another aspect is that the SW standardization, \emph{i.e.}, the SCA initiative, requires very high power for implementation of the software stacks. Therefore, SCA does not apply directly for PCS. However, the SCA light initiative allows ASIC implementation of SCA stacks, which makes it more geared to the PCS industry.

Interestingly, there seem to be some conspiracy theories around, telling that the U.S. government and military wireless communication industry aim at retaking the lost initiative in the PCS infrastructure and terminal market from European and Asian OEMs, by exploiting their strong position in the SDR (SCA) standardization and the SCA light initiative. This circumstance,\emph{%
\ i.e.}, the wish/hope of North American OEMs that SCA light has potential to disrupt the PCS equipment market, could be one reason why OEMs, as Motorola, seem more agressive in the field, compared to European PCS OEMs who are somewhat pending to SDR concepts, despite the similar value networks of military communication platforms and PCS infrastructure.

\subsection{Impact of SDR on Value Networks and Cost Structures}

The question whether SDR technology is about cost-savings or addition of value-increasing functionality was discussed during the expert interviews. The majority of the experts interviewed found that cost-benefits were paramount to manufacturers and that these primarily stem from decreased development times and the possibility to decrease the number of hardware platforms supported thanks to the configuration flexibility of SDR. It was also argued that life-times of infrastructure subsystems as PA, RF and baseband\ blocks could increase with SDR.

The design flow for the RF parts was not seen to be radically different with SDR. However, the design flow for the digital parts can be finalized much earlier with an SDR-oriented design flow. In fact, it is possible to start verifying the design, already after the indispensable first steps -- algorithm and SW implementation. The possibility to define special standardization languages, which, in an UML-like fashion, are able to map specifications on HW\ implementations was also mentioned. The use of such a language in the standardization process of a new air-interface could imply that an implementation is virtually ready as soon as the specification is frozen. Another interesting point is made by Giuseppe Caire who says; "Many big mistakes have been made in standardization. With SDR, they will be possible to correct in retrospect."

With respect to the end-customers of PCSs, most experts see no dramatic changes as a result of the SDR technology. Mainly the support of multi-standard functionality and increased convenience due to automated configuration and connection to multiple air-interfaces and less focus on technology were mentioned. According to Tony Ottosson, the end user should not notice that certain functionality is implemented with SDR technology. He says, "If they notice, one has made a mistake." However, there is a fear that end-users will notice SDR in terms of more frequent product releases, upgrades or even software patches. In this latter respect, the example of the patch frequency of the operating system Windows is taken as a possible, undesirable, development.

The operators stress that simpler and more transparent\footnote{% Transparent services are such that they appear the same or very similar to the customers regardless of the access technology or network over which they are conveyed. Ideally, the access technology, \emph{e.g.}, GSM, WCDMA, WLAN, should not matter for the provision of a particular service and, in this sense, if there is only one configuration of a particular service, it may be more relevant to talk about network transparency.} services as well as extended possibilities for personalization of the terminals will be brought about by SDR to the end-users. It is also suggested that SDR could enable more upgradeable terminals with prolonged life-time. However, the PCS Operator representatives point to the case of lap-tops of which the majority has practically the same life-time as a mobile phone today, despite the possibility to upgrades of SW (as well as HW). The life-time of a mobile is said to be governed by form-factors as design and convenience factors as battery lifetime.

A few of the experts has a radically different view on the utility of SDR for the end-users. The high potential for new applications in consumer products that will be released as a result of open platform architectures and third party provisioning of radio SW is identified as utterly exciting.

Christer Wik points to the \emph{network-effect}, \emph{i.e.}, the fact that more different terminals can be supported in the same network, which creates a larger base of potential customers and users of the network. The network effect denotes the situation where the value of a network to its participants grows with every additional participant. This reasoning has an interesting connection to the \emph{theory of increasing returns}, introduced by W. Brian Arthus. This theory states that economy of scales are increasing, for example for some high-tech products that need to be compatible with a network of users \cite{BRI96a}. Typical characteristics are high upfront costs in terms of R\&D expenses, network compatibility requirements and the ability to groove in customers, \emph{i.e.}, to heighten exit barriers through the investment needed on initial training in order to be able to manage the products or services. Operating systems, Internet services, flat-rate or free voice over IP services in fixed broadband networks are example of products and services where returns are increasing with scales.

According to Brian Arthur, market instability, multiple potential outcomes, unpredictability and possible predomininance of inferior products are hallmarks of products and services with the increasing returns characteristics.

For some parts of the wireless communications industry, the theory of increasing returns apply, for others not. According to Prof. Early-Adopter, cellular telephony has week network effects, while the emerging ad-hoc networks have strong network effects. Prof. Early-Adopter continues; "The cases where the \emph{theory of increasing returns} apply makes it much more difficult to predict technology evolution, even with tools as Christensens theory of disruptive technologies and time-series studies of technology performance trends." The support of more different terminals and the emergence of new services and applications building on ubiquitious connectivity, provided by SDR systems, may indeed, in the light of the theory of increasing returns, have strong network effects\footnote{%
For network products, network effects as well as product characteristics as design, technical performance, and user friendliness, matters. When the network of users grows sufficiently large, the network effects dominate over the product characteristics.}.

An interesting observation is that most experts that believe in no firm advantages for the end-users, neither cathegorize SDR as a radically different approach to radio engineering nor a disruptive technology. On the other hand, those that see clear advantages for the customer also believe SDR to have the potential to become disruptive in the PCS sector.

If SDR is about cost-efficiency for the manufacturers, it is about added-value for the operators. However, the operators may be able to capture a minor part of the cost-reductions created in the manufacturing process.

The possibility of easy addition of functionality and less dependence on manufacturers, due to Microsoft-style open platforms, is pointed out. The operators view downloads of games, ring-tunes and over-the air configuration as the early stages towards SDR.

Transparency of networks towards different services is important for the operators. It is pointed out that the initial HW cost for infrastructure equipment is minor, compared to the maintenance costs, and that the life-time can be extended with SW upgrades. Also the potential to improve the spectrum utilization, ultimately through cognitive radio is mentioned. Bertil Thorngren suggests that SDR opens up for trading of frequency spectrum. For example, new operators could, in the future, lease spectrum from other operators or from the military. Today, most of the spectrum is unused and statically allocated, for example by the military.

Ultimately, instantaneous frequency trading can be imagined. There are however, many tricky pricing issues to resolve, particularly when users are roaming between different networks. In connection with this discussion, Bertil Thorngren points to the emergence of new pricing models. One such example is to attach the equivalent of a letter stamp to every data-packet upon transmission, thus unifying billing and making the price more predictable.

\subsubsection{Military Platform Communications}

\FRAME{ftFU}{5.1275in}{3.3814in}{0pt}{\Qcb{Example of value network of military communications platforms built on SDR technology.}}{\Qlb{%
fig:mil_value_network_5}}{mil_value_network_5.wmf}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "F";width 5.1275in;height 3.3814in;depth 0pt;original-width 6.3754in;original-height 4.1909in;cropleft "0";croptop "1";cropright "1";cropbottom "0";filename 'Figures/mil_value_network_5.wmf';file-properties "XNPEU";}}

An example of some key components and ranking criteria of military platform communications is given in Figure \ref{fig:mil_value_network_5}. Similar to the value networks of the Christensen theory, the leading suppliers are listed for the midmost chain of components.

The demand for SDR solutions in the military sector is enforced by the trend towards \emph{network centric warfare}. General cost characteristics of these value networks are that HW unit prices are less of an issue as series are relatively small and the life-times are long. Particularly, for some exotic waveforms common between only a few countries, the series are very small. The research and development costs are substantial, but due to the small series the production costs are less important.

The public safety sector has value network characteristics similar to military platform communications (see for example the RAKEL initiative in Sweden).

\subsubsection{PCS Terminals}

\FRAME{ftFU}{5.1275in}{3.9228in}{0pt}{\Qcb{Example of current (non SDR-based) value network of PCS terminal platforms.}}{\Qlb{% fig:PCSterminalValueNetwork}}{pcs_value_network_6.wmf}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "F";width 5.1275in;height 3.9228in;depth 0pt;original-width 6.3754in;original-height 4.8689in;cropleft "0";croptop "1";cropright "1";cropbottom "0";filename 'Figures/pcs_value_network_6.wmf';file-properties "XNPEU";}}

An example of a value network for PCS terminals is illustrated in Figure \ref% {fig:PCSterminalValueNetwork}. Very large series, in the order of hundreds of millions of units are produced per year. Although WCDMA will not be a global standard, it will have a wide coverage taking into account a few dialects with minor differences. Due to design issues as form-factor, GUI and the rapid evolution of features as camera and external memory, terminals can be expected to have short life-time. Given the high-volume, the research and development costs are probably less important than the production costs and the costs associated with configuration and maintenance.

One can argue that the shorter product life-cycles require more rapid design flows and prototyping possibilities, thus making a case for SDR technology. On the other hand, there is no need to spend vast resources on improving the speed of the communication circuits unless there is clear market demand for improved data rates. The majority of the persons interviewed in this study argue that the PCS market already today is over-served in terms of the data rates available compared to those required by most applications. Given a PC-industry scenario where the applications continuously require higher data transfer rates, the benefits of the faster development times that SDR can offer becomes more clear. It should, however, be noted that higher data transfer speed over radio is radically different in nature to the requirements of PC applications, which typically seek for more and more processing power and memory to improve perceived value delivered to customer. The value of wireless communications to this group is more difficult to address.

As illustrated in Figure \ref{fig:PCSterminalValueNetwork}, some major OEMs and ODMs in the PCS terminal market are Qualcomm, Texas Instruments, Ericsson, Nokia and Samsung. Among the most important performance ranking criteria of the physical layer components is power consumption, size/integration, convenience, production yield/cost and standard compliance.

\begin{example}
January 24, 2005, Texas Instruments (TI) and Nokia announced that Nokia will incorporate TI's single-chip digital RF Processor (DRP) in its future mobile phones, targeting high-volume, high-growth, entry markets as China and India % \cite{NOK05}. TI claims to have integrated the bulk of handset electronics on a single-chip, including digital baseband, SRAM, logic, power management and analog functions. The DRP technology is said to target cost, size and power reduction as well as performance optimization. \textbf{Analysis:} Note that nothing is said about performance improvement. This is due to that the sub-sampling method used to down-convert radio frequency in the DRP is a noisy technology that compromises the sensitivity (signal quality) of the receiver. The press-release brings about a smell of disruptive technology as it signals an attack on the low-end market segments of cellular communications in markets with relatively low penetration. Furthermore, the DRP seems to support only conventional GSM voice-calls and no high-end functionality as EDGE modulation or WCDMA video telephony. On the other hand, the DRP-enabled Nokia phones bring about no new functionality and address markets where competition from other ODMs has already entered. For the end-users, the DRP technology gives no added-value. The only advantage is a potential reduction of cost for the handsets. Indeed it is difficult to argue that the DRP technology is a sustaining technology in the sense of receiver sensitivity, as it actually trades worse sensitivity for increased integration and cost reduction. On the contrary, along the dimensions of integration and cost (given that the production yield is improved compared to separate analog and digital chips), the DRP technology can be considered sustaining. These latter dimensions may be the most important from a competition point of view if you believe the market to be over-served in terms of performance and that the competition basis has shifted to size, reliability or price, cf. \cite{CHR97}, pp. 171--172. The DRP technology should not be confused with SDR technology, but the roadmap clearly indicates that TI aims to successively include more and more air-interfaces, ultimately reaching a SDR chip in 2008. According to a TI sales representative, "the SDR chip is very much in an early phase of research now." Over the last years, TI has made extensive marketing to point out the DRP technology as a technology revolution where all RF modules are included on a single-chip in a purely digital production process without any, costly, special process features required. According to Dr. Jan-Wim Eiekenbroek, senior system design engineer at Bruco Integrated Circuits, this is, however, not completely true as TI used a coil (a process feature) and an off-chip suppression filter, at least for the Bluetooth version of the DRP. The definition in \cite{CHR97} leads us to conclude that the DRP is not a disruptive technology but that TI strives to market the DRP in such a context.
\end{example}

\subsubsection{PCS Infrastructure}

\FRAME{ftFU}{5.1232in}{3.9686in}{0pt}{\Qcb{Example of current (non SDR-based) value network of PCS infrastructure units.}}{\Qlb{% fig:PCSinfrastructureValueNetwork}}{pcs_infrastr_value_network_7.wmf}{% \special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "F";width 5.1232in;height 3.9686in;depth 0pt;original-width 6.3702in;original-height 4.9268in;cropleft "0";croptop "1";cropright "1";cropbottom "0";filename 'Figures/pcs_infrastr_value_network_7.wmf';file-properties "XNPEU";}}

Figure \ref{fig:PCSinfrastructureValueNetwork} shows an example of a value network for PCS infrastructure. Despite the relatively small series, compared to PCS terminal and the consumer electronics industry, PCS infrastructure manufacturers have become very concerned with production costs. During 2004, some manufacturers of infrastructure equipment managed to capture substantially larger profits than during previous years, despite marginally increased turnarounds. This can be explained by the focus on reduction of production cost.

There are indications that the end-users are unwilling to pay a lot more than today for wireless communications services in the future (see for example \cite{ZAN97}). If this is true the reduction of production cost must continue. According to Peter Olanders, the telecommunications industry must become as efficient as the car manufacturing industry -- something that calls for a dramatic conversion of the current operations.

Ways to decrease the production costs are, for example, to decrease the number of external, off-chip, components, replacing FPGAs with ASICs and merging multiple small ASICs into one large ASIC. Some major players in the PCS infrastructure market are Ericsson, Nokia and Lucent. Key performance attributes are roll-out speed, scalability, life-time, maintenance and backwards compatibility. In conclusion, ranking criteria of PCS infrastructure are quite similar to those of the military communication platforms.

\FRAME{ftFU}{5.2537in}{4.0724in}{0pt}{\Qcb{Example of value network of PCS operator and service providers.}}{\Qlb{fig:PCSoperatorsValueNetwork}}{% pcs_operator_value_network_8.wmf}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "F";width 5.2537in;height 4.0724in;depth 0pt;original-width 6.5319in;original-height 5.0548in;cropleft "0";croptop "1";cropright "1";cropbottom "0";filename 'Figures/pcs_operator_value_network_8.wmf';file-properties "XNPEU";}} For completeness, an example of a value network of PCS Operators is provided in Figure \ref{fig:PCSoperatorsValueNetwork}.

\subsubsection{SDR\ Implications for PCS Market Value Networks}

One may ask what happens when the terminals partly or fully take over the work of the infrastructure, as for instance in so called \emph{ad-hoc} networks. This would make PCS systems look more like military systems. Clearly, the issue of power consumption in the handheld units becomes more accentuated for equipment that combines infrastructure and terminal functionality. Given that no substantial enhancements of battery lifetime are at hand, this can be seen as an argument against the deployment of SDR in PCS systems.

The question whether any particular players could be pointed out to loose upon the deployment of SDR technology was posed during the expert interviews. A fairly general opinion is that manufacturers with proprietary solutions risk to loose market shares when new players based on generic platforms enter. Given that the operators continue to behave as they do now,% \emph{\ i.e.}, protecting proprietary solutions and going for patents, they will loose customer interest. The development of WAP vs. iMODE was pointed out as an example where the ability to be able to open up communication (SW) platforms for application development has been a critical success factor for iMODE, while WAP has been a failure in terms of customer utility and air-time generation. Ralf Schuh points out that the contracts between the operators and manufacturers are long term and that there is virtually no manufacturer portability. Partly due to this, there are actually not many Asian or Chinese providers of infrastructure equipment and no dramatic elimination of cellular infrastructure providers is to be expected due to the entrance of SDR technology.

Suppliers of certain filtering equipment, for example ceramic filters and IF filters as well as analog construction companies may disappear from the market. Another view is that SDR updates in order to support substandards, as for example EDGE, may be of limited value as these are not widespread.

Bertil Thorngren says; "The seemingly hopelessly conflicting technologies WLAN and cellular are now merging together". This development may be dangerous to traditional operators that have acquired spectrum for cellular communication who may loose market shares to WLAN operators that popping up in virtually every corner.

In the view of Jan-Wim Eikenbroek, SDR is not implemented suddenly as it is based on sustaining component development. Jan-Wim Eikenbroek continues; "The evolution has been going on for years and SDR will be implemented over years."

Given that the big manufacturers of PCS equipment are not prepared for the separation of platform HW and SW, they may end up as big losers. Companies with a strong focus on delivering the whole box are inclined to loose unless they get ready for a shift towards the new applications implied by SDR. Tony Ottosson says; "The number of suppliers of integrated circuits for mobile communications is now decreasing dramatically. The winners will be the manufacturers of good enough general circuits in larger production series, see the PC industry." Considering the military sector, the companies that were not able to participate in the JTRS cluster, for example ITT\ and Raytheon, have drawn a blank.

Prof. Forward takes as an example the computing world, where 18-36 months means one or two generations whereas, in the traditional telecommunications world one generation is about 15-20 years long. The long generation life-times creates a pressure to make the very best decisions on technology before the implementation starts and this creates an enormous inertia. Companies like Worldcom, using computer technology, \emph{i.e.}, IP, instead of traditional telecommunication protocols were able to innovate much faster than the incumbents. Prof. Forward continues; "SDR really speeds up this process a lot. Spectrum allocation issues previously took many years. Now you can imagine to do it every 10 ms".

Pursuing the line that SDR is not a disruptive technology, Michael Faulkner has an interesting comment to the question about potential losers on a shift towards SDR technology; "Take WLAN that is the opposite of SDR. It is disruptive but not flexible. WIMAX will be the same. It comes in with cheap, simple stuff -- then, features such as handover and security are added along the way."

\subsection{Technology Maturity and Projected Evolution}

This section illuminates the maturity of the technologies considered to be enabling for SDR.

\subsubsection{Enabling Technologies}

The following question was posed to the referees.\textbf{\ "Which are the enabling technologies for SDR hardware and software concepts (in particular for mobile phones), ADCs, DACs, DSPs, MEMS, or what?"} The notion of enabling technologies implies that the functionality supported, can be viewed as (today) some kind of system bottleneck.

According to the responses, the enabling technologies for SDR hardware and software components can be cathegorized as

\begin{itemize}
\item[(i)] \textbf{SoC architectures with different coprocessors} (HW accelerators).

\item[(ii)] \textbf{Power efficient, flexible GPP HW}. Programmability and power efficiency are usually contradictory. For instance HW accelerators in FPGAs are difficult.

\item[(iii)] \textbf{Primitives for radio communication processing}, \emph{% i.e.}, matrix multiplications, FFTs, etc, are to be implemented in efficient ways that allows for reuse and dynamic assembling according to the algorithms of different air interface standards. A language that uses abstractions for HW peripherals is needed. In connection with this, Jonas Vasell states; "Here it is easy to start talking about low-power, ASIPs, configurable HW, etc., but these issues are obvious. What is really needed is software architectures that are knowledgeable about the HW."

\item[(iv)] \textbf{DSP processing power} needs to increase. Possibly, ARM-style processors should be used instead of DSPs. The distinction between the GPP and DSP domains is blurred. For example, a conventional PC CPU of today support vector instructions today. HW circuits like FPGAs get more programmable. However, FPGAs do not apply for SDR today.

\item[(v)] \textbf{AD\ converters needs to lower power consumption and increase resolution}. Low-power DACs is, by some, said to be no issue and there is no clear consensus that ADCs and DACs are the limiting components for mobile terminals. To a large extent this depends on the bandwidth of channels. The supported standard with the highest data rate is dimensioning the system. There is not happening much in ADCs. Sigma-delta technology in AD converters is not expected to make a huge step forward. MEMS can be considered a complement to high performing AD converters. Both are needed. The need for improvements of the AD converter is dependent on the definition of SDR, \emph{i.e.}, where in the receiver the transition to digital takes place. ADCs is actually only an issue if 3G BB can be included in the SDR transceiver. Now, more than 5 MHz BW must be supported, for 4G, more than 20 MHz. MEMS can be a bit disruptive on the analog side.

\item[(vi)] \textbf{Flexible subblocks} -- for example flexible BB, wideband RX, wideband TX and multi-carrier TX are needed.

\item[(vii)] \textbf{Submicron type evolution of processes}. More gates are required to support flexibility. Real flattening of the clock speed has not yet been observed. HF capabilities of processes evolves (see for example SiO CMOS). Wee see evolution to 5 GHz frequencies. State-of-the art processes can support 5 GHz. Process technologies from numerous foundries in order to have radio functionality in CMOS, not GaAs or other exotic technologies are required. You can imagine sorting of radios according to performance in the same way as processor chips and similar evolution of commoditization.

\item[(viii)] \textbf{Little is done in antennas for 2MHz - 2 GHz}. Antennas are not driven by Moores law, rather Maxwells equations. Mixers and filters are stressed by wideband radio. The radio technology of SDR itself, does not pose any exceptional requirements but ability to innovate in order to achieve wideband radio communication is required.

\item[(ix)] \textbf{Security} -- a number of aspects on infosec are becoming accentuated and acute. The discussion about this has been very limited.

\item[(x)] \textbf{Management infrastructure}, which can be described as a system for version control, that makes sure that networks with SW are properly configured and that the SW is distributed in the right way.

\item[(xi)] \textbf{Dynamic networking}. If you look at SDR as an enabler of ubiquitious connectivity, dynamic networking, which is a technique that enables change of access modes, is important. The control part is essential to SDR and the aim should be to be always best connected (ABC). In fact, for GSM and WCDMA, ABC functionality is already implemented without SDR. There are no really general enabling technologies, they are architecture dependent.

\item[(xii)] \textbf{Software architectures that meet real-time constraints}%
. A lot of effort will need to be spent on software architectures that handle real-time constraints, impact of bugs, security and general complexity issues. Problems on the software side can now cause the whole radio to fail, while, previously, failure due to bugs was mainly limited to certain applications. Christer Wik elaborates on the need for new SW architectures; "For example, violation of radio protocols are not acceptable in the event of failure in an another application, such as Microsoft Word. Typically software architecture is, to a large extent, neglected in similar projects to SDR. With SDR, everybody who are able to start a C-compiler can (attempt to) generate waveform code. There is a risk that this causes poor functionality and a lot of security problems, if not due to pure system security, due to bugs in the code."
\end{itemize}

The radio front-ends will look approximately the same in the next 6 years, but they will be smaller and require less power. There will be no combination of cellular and WLAN in mobiles in the next 6 years. It is not a requisite with simultaneous operation of cellular and WLAN. It makes no market sense, compare the address book problems. For example, do we see WAP and cellular speech simultaneously today?

Dr. Antenna and Michael Faulkner stress the importance of wideband antennas. As Michael Faulkner puts it; "Wideband antennas are required, and lots of them.". Michael Faulkner recites Dr. Hardware who says; "Design HW for the SW" and "Do not worry about HW optimization". According to Michael Faulkner, this is the right approach.

Prof. Forward has a pragmatic view on the enabling technologies of SDR; "First enabler is simply CPU speed. Processors clocked at 3 GHz makes 1.5 GHz radio not an issue. Second, memory, storing all SW needed for all large amount of standards in the memory from the beginning, is required. More can be completed later." In fact, already today, Samsung has a mobile phone with a 1.5 GB harddrive. Prof. Forward predicts that handheld terminals will soon have more than 10 GB of memory. This, he says will imply that downloading of SW over the air -- being the "wet dream for 3G" becomes meaningless. The phone will be one huge IPOD and there will be no need to download any music over 3G.

At least from the software point of view, this opinion is confirmed by the operators who are sceptic to waveform download over the air and seem to believe the harddrive scenario, with pre-loaded air-interface software, to be more likely.

\subsubsection{Leading Companies in\ SDR and SDR-enabling Technologies}

The following discussion is focused around the question;\ \textbf{"which are the leading companies in these technologies?"}.

The picture of the companies leading in SDR is unclear, although there seems to be some consensus that Analog Devices (AD) is leading in ADCs. TI is leading the DSP development, followed by Motorola, Intel and STM. Some argue that the ARM-style processors are better alternative than the TI DSPs.

On the system and integration side, the picture is even less clear. Most of the efforts in the military sector are going on in the U.S., propelled by the DoD and the JTRS initiative. In the military sector no company has stepped forward as leading among the big ones. The big ones on SDR include Rockwell-Collins, Harris and Boeing. In Europe, the french defense research establishment, Thomson \& German EADS are prominent. Also Motorola is doing a lot of work on SDR and cognitive radio (see the EU research program E2R). The Finnish defense research establishment has a SW demonstrator together with Electrobit and the University of Oulu, but it is difficult for the Finnish to find cooperation partners. FMW wants the JTRS software architecture standard. In Sweden, for example Saab and Generic Systems are active on SDR systems.

For the military and the PCS infrastructure sectors, FPGA implementation is an attractive alternative. Leading FPGA suppliers as Xilinx and Altera are directed towards configurable system solutions. MEMS is mainly driven by military companies as Northrop Grumman, Fairchild-Raytheon and ST Microelectronics. Wideband RF modules are driven by RFMD, ST and Qualcomm. On the academic arena examples of advanced European research institutes are Dresden University and the Eurecom institute.

Returning to the system suppliers, rather than SDR, the main interest is now directed to the evolution of the WIMAX systems and their competition with 3G cellular systems. There seem to be little consensus about the future success of the WIMAX solutions. Some argue that Flarion, in the lead of the WIMAX arena, will be successful but others think that WIMAX is not innovative enough from the air-interface perspective. Prof. Coding says, "Flarion is very smart and competitive but has a very hard time to succeed." Also Asian players as Samsung are very strong on WIMAX. Flarion might succeed to become an option to 3G but there are doubts that they will operate networks. Flarion can run Voice over IP but this is also true for UMTS.

WLAN manufacturers seem to take the lead in configurable baseband processors. A natural reason for this is the plethora of dialects of IEEE 802.11 that nowadays exist and need to be supported. Other leaders in radio focused processors are Steinbreckers who started it, Vanu, targeting SDR basestations and chip vendors, several of which who tried to do Bluetooth , WLAN on one chip. According to Prof. Forward, SDR WLAN solutions with most of IEEE 802.11x implemented in DSP exist already. On the other hand, the cellular industry is slow due to regulation latency and standardization issues.

In conclusion, the success of the WIMAX concepts and its implications for the evolution of SDR technology is not clear. It is difficult to tell the system side leaders in SDR. Probably it would be easier if there was some consensus about what applications will require and use future SDR based systems.

\subsubsection{Basic Functionality Requirements and Performance Measures}

This discussion is based on the following question \textbf{"which are the basic functionality requirements and performance measures of SDRs and it's components?" }and aims for an inventory over the functional requirements and performance measures considered most relevant to SDR technology.

\begin{itemize}
\item[(i)] \textbf{ADCs - dynamic range}, bits (10-12 bits) depending on the RF-chain and the variety of standards it should support. For basestations you need as many bits as you get. Dynamic range is much more important for SDR than for other kinds of radios.

\item[(ii)] \textbf{Processing speed, for DSPs - gigaflops}. Floating point (FLP) is required for more demanding algorithms. The relevance of the flops measure depends on the time-to-market. If relaxed, fixed-point-operations may be more relevant. For instance, for MIMO applications, FLP processing is useful. However, FXP processing is more power efficient. According to Ralf Schuh, MIPS is a joke. "Benchmarking for certain radio functions, like FFTs is more relevant and more frequently used measure. Processing time and power to perform a certain radio processing function should be used", he says. Ralf Schuh points to the ARM processor as more optimized for general purposes. Flops is a relevant measure for fast time to market. For conventional CPUs, a test called SPECmarks is used to do benchmarking. A similar test should be used to compare DSPs.

\item[(iii)] For terminals \textbf{- power consumption}.

\item[(iv)] \textbf{Programmability in the context of a GPP architecture}

\item[(v)] \textbf{Reliability, availability, roaming everywhere}. It should preferably not deviate from traditional radio specification requirements. Examples of traditional radio specification points that still apply are spurious, sensitivity and bandwidth. Sensitivity is not paramount in jamming environments (military applications). Also for PCS equipment, sensitivity might be possible to relax.

\item[(vii)] Qualification of waveforms and new requirements on plug \& play support are entering for SDR. Issues as replacement of HW, property rights of waveforms that touch on the world of law. For instance, is it OK to load certain own waveforms in a radio manufactured by somebody else? U.S. DoD has the ambition to own all waveforms for U.S. military. According to Dr. Antenna, the qualification of waveforms will be even more important than the qualification of HW, for the PCS standard air-interfaces as GSM and\ UMTS. Dr. Antenna says, "Information security -- how well protected is my communication when I go between different waveforms." "Dependability -- how reliable is the SW?" "Development principles for the waveform SW needs careful attention as buginess also affect the information security."

\item[(viii)] Traditional radio performance measures with different trade-offs, for example flexibility vs. power as well as the level of standardization.
\end{itemize}

Christer Wik argues that an important issue is that the functionality is completely determined by the waveform software in today's (military) SDR implementations. In general, the performance requirements are stated in protocol specifications, specific to each waveform and these are difficult to read and interpret. All of a sudden it has become ever more important to "look under the hood" and understand the time constraints for different functions. For example, with today's SW development methods for waveform functionality and verification, it is not possible to do the equivalent of HW synthesis to understand the latency requirements of the SW components. The definition of time budgets is much more of a challenge in SW development. For example, having a particular SW running within the desired timing constraints on one particular platform does not mean that it will work as well on another platform. With respect to this, it is critical to come up with middleware that makes the HW of different platforms more similar towards the SW. In addition, the variety of platforms needs to be ordered in different categories in order to reduce the design space. These categories should, for example, imply certain support for non-functional behavior, as different kinds of real-time aspects, \emph{i.e.}, protocol violations if response is not obtained in time or if the power consumption limits are violated. Also platforms classes for reliability and security are required.

Prof. Forward puts it this way; "What we'll see as basic issues are about BW, frequency range, DR, noise and, maybe most important, power. The difference to traditional radio is fixed BW and fixed operating frequency. Now it is a parameter space instead of a set of numbers. See for example Graychip that takes a whole 23MHz band, digitizes it and pulls out various cellular standards. For most cellular systems they cover all operator bands." Michael Faulkner points to the fact that the design is made for the worst parameter. He continues; "And sensitivity is a selling argument. Multiple antennas is the solution to a lot of problems, but not disruptive though."

\subsubsection{Technology Maturity}

In this section, we discuss the following question about technology maturity. \textbf{"According to your view, what is the level of maturity of these technologies (for each enabling technology, on a scale from 1 to 10, where 10 means ready to deploy in mobile phones with performance and convenience factors, as battery and size, equivalent to the 3G phones of today)?}

The aim is to obtain maturity numbers for some key technologies (mean value): ADCs, DSPs, analog front-ends, management infrastructure, security, dynamic networking, SW architecture. We seek also a general number and a predicted year for SDR terminals with performance comparable today's 3G phones. The result is illustrated in Figure \ref{fig:SDRmaturity}.

According to Prof. Platform, GSM models can be done in power efficient DSPs today, UMTS almost, but not quite. Probably, he says; "UMTS-TDD mode will soon be OK with today's technology". Giuseppe Caire find this hard to tell, but says; "From an algorithm point of view we are about ready. From a HW perspective some work needs to be done. Generally, the implementation of algorithms in SW is very natural, typically the 2nd step in any design flow (for HW implementations)" Giuseppe Caire continues; "Specifically for SDR, the implementation should be much closer to the theoretical definition than the case of traditional radio development. The distance between ideas at algorithm and Matlab stages and the running practical implementation will be much shorter."

\FRAME{fhFU}{3.41in}{4.2454in}{0pt}{\Qcb{Levels of maturity for SDR enabling technologies and general SDR system technology.}}{\Qlb{fig:SDRmaturity}}{%
sdr_enabling_tech_maturity_9.wmf}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "F";width 3.41in;height 4.2454in;depth 0pt;original-width 4.2272in;original-height

5.2728in;cropleft "0";croptop "1";cropright "1";cropbottom "0";filename 'Figures/SDR_enabling_tech_maturity_9.wmf';file-properties "XNPEU";}}

For basestations the SDR enabling technology seems to be mature, given that FPGAs fit into the definition of SDR. For mobile technology, ARM style processors are required and there is some consensus that the enabling technology is expected to mature in about 6 years.

Tony Ottosson believes that it will take TI and Motorola 3 to 5 years to come out with DSPs\ that support 3G as efficiently as today's ASIC implementations. One problem, though, he continues, is that the radio processing language required for SW implementations on this kind of DSPs is that new standards always comprise new processing instructions that needs to be added. The DSP industry must focus and make DSPs more specific for the mobile communications industry. This is happening right now but, as pointed out by Giuseppe Caire, the Intel Centrino for mobile communications is not yet here.

In some sense, it seems that the technology is already mature, although the UMTS-FDD and 3G+ modes as for example HSDPA are difficult to support with SDR technology. However, only the first samples of those mobile terminals has come out to the market and their use is still very limited. The question is, says Jan-Wim Eikenbroek, "Do we want it -- that is, do we want to pay for it?"

In WLAN implementations, SDR is the solution of choice. Peter Olanders claims that it might become an alternative to cellular in some few years, based on the WLAN architectures and latter relaxed specifications. He continues, "Once the problem is clearly given, technology always solves it."

Glancing at the military technology arena, the time for the deliverance of the JTRS cluster 5 (handheld) terminals is 2008-2009. This may imply that the first SDR enabled PCS terminals show up at the same time. However, Dr. Antenna comments that the JTRS project has discounted the development of technology not known today for batteries and radio performance. Dr. Antenna continues; "In order to address (open up for) the deployment of SDR in personal communications in Europe, within the framework of the U.S. military de facto standard, they are now proposing JTRS light, with some relaxed requirements, for instance the SCA stacks may be permanently burned in ASIC implementations instead of re-programmable processors."

Tony Ottosson points to the correlator operation in a RAKE receiver that is one of the more power consuming operations and the fact that a DSP is itself an ASIC. He argues that the development time for a DSP with a correlator is longer and therefore DSP radio processing will always come out later than ASIC counterparts.

Another aspect is that many people are numismatists. The technology is quite mature and we know pretty well what is required for SDR but the important thing is to be able to put it into practice. Pretty much, the practical SDR development is driven by U.S. interests. Dr. Antenna puts it; The U.S. industry is producing, not doing research.\ The rest of the world is trying to understand what is going on in the U.S., but there is nothing magic about it." In the opinion of Prof. Forward, the technology may take off any moment, which is illustrated by the fact that investors and other actors apart from the manufacturers are now willing to start taking bets on it.

\subsubsection{Major Technical Barriers Against Widepread Deployment of SDR Technology}

In order to probe whether there are any technical breakthroughs required for the deployment of SDR technology in PCS equipment, we ask:\ \textbf{which are the major technical barriers against widespread deployment of SDR technology?} The resulting discussion gives at hand the following conclusions.

\begin{itemize}
\item[(i)] There is a consensus that \textbf{the power consumption} is one of the more important barriers with respect to mobile terminals. Peter Karlsson encourages us to think about how many MIPS are required for SDR? When can we run this number of MIPS with less than 50 mW power? This kind of reasoning was introduced for multimode terminals, already three years ago, in \cite{SCH03}. SDR terminals will not be built until the power consumption is as low, or lower, than that of today's terminals. This customer requirement must be satisfied before flexibility issues are addressed. In terms of ADC evolution, not that much has happened over the last two years according to Ralf Schuh. Ralf Schuh believes there will be a uniform, continuous flow towards SDR and points out; "SDR is already deployed in mobiles and, particularly, in basestations." Ralf Schuh continues; "Basestations are so complex, which makes ASICs be too risky compared to FPGAs."

\item[(ii)] According to Giuseppe Caire, an important barrier is definitely \textbf{the lack of good hardware platforms} with RF and ADC/DAC functionality. SDR-oriented chipsets need to be made available for development, \emph{cf}. the software-based ADSL modems, which exist already. A challenging issue is the identification of rudimentary operations that are required in all future standards and their efficient implementation."If we would know which these are, we would be ready now" says Tony Ottosson. According to his view, this is, however, not very possible to solve and there is always some more power efficient implementation. We need to show what functions are required for communications. Clearly it is hard to know what operations are required in future standards. However, in fact, some of the existing standards, as for example GSM, already now have most processing in DSP.

\item[(iii)] Jan-Wim Eikenbroek feels that is not so much of a real problem. It is more of a mental issue. "You can implement SDR and use it now if you want. People are scared because it is not well known from a security and reliability point of view." Jan-Wim Eikenbroek, however, admits that there might be some remaining issues to solve related to the power consumption for current conventional radio implementations.

\item[(iv)] Apart for the issue of broadband antennas, Michael Faulkner do not see many technical barriers. "MEMS can solve it". Michael Faulkner does not see that disruptive stuff is coming into play in the SDR evolution for the radio front-ends.

\item[(v)] Standardization suitable for consumer equipment. Military standards are not applicable for consumer equipment.

\item[(vi)] Michael Faulkner points to the issue of cost. For example, GPP-based and DSP-based BBs are more costly than ASIC implementations. When it comes to availability of sophisticated digital HW (ADCs/DACs/DSPs), Christer Wik is hopeful and says; "When the price drops, SDR will be the natural way, intentionally or unintentionally."
\end{itemize}

Although cost is not primarily a technical barrier, it is certainly one of the most important factors that affect the adoption of SDR technology in radio front-ends. See the discussion about the TI DRP in Example 4. Another, somewhat surprising, outcome from this discussion is the feeling that there are no really high technical barriers to break through. It seems that mainly sustaining technology developments are required for most relevant parts of the analog and digital parts of the physical layer of wireless communications for PCS.

\subsubsection{\label{sec:performance improvement rates}Performance Improvement Rates in Relation to Demand Increase}

\FRAME{fhFU}{4.5385in}{4.4365in}{0pt}{\Qcb{Model of product evolution and shifts in basis of competition. The uppermost curves illustrate the traditional basis of competition in wireless communications, while the lowermost curves suggest an alternative product evolution in an application focused market.}}{\Qlb{fig:product_evolution_model}}{buying_hierarchy_10.wmf%
}{\special{language "Scientific Word";type "GRAPHIC";maintain-aspect-ratio TRUE;display "USEDEF";valid_file "F";width 4.5385in;height 4.4365in;depth 0pt;original-width 5.962in;original-height 5.8271in;cropleft "0";croptop "1";cropright "1";cropbottom "0";filename 'Figures/Buying_hierarchy_10.wmf';file-properties "XNPEU";}}According to

Christensen, there is an opportunity for disruptive technologies when traditional concepts overshoot the market demand. This led us to ask the expert's opinion about the relation of market demand and technology improvement for wireless communications,\emph{\ i.e.}, \textbf{"do you think that the performance improvement rates are faster than the demand in terms of those measures, what is governing/limiting market performance demand curves?"} We also ask: "\textbf{when will intersection (SDR feasible for infrastructure or/and terminals) happen?}".

As there seem to be a quite strong interdependence between technology development and demand, it is a tricky task, already to judge what comes after the other and there is no clear agreement among the referees, although many seems to believe technology is overdoing for the moment. Theory tells us that the demand of customers is continuously changing. Instead of giving a firm answer about whether technology is overdoing or not, we will take a closer look on the performance attributes that matter for customers and how these might evolve over time.

Figure \ref{fig:product_evolution_model} illustrates the \emph{product evolution model}, also denoted the \emph{buying hierarchy} but its creators, Windermere of San Fransisco (see for example \cite{CHR97}, pp. 170--172). The uppermost curves illustrate how oversupply according to certain performance parameters, as, for example, data rate, size, battery, etc., can explain a shift in the basis of competition in the PCS market. When all performance attributes valued by the customers are played out, commoditization and price erosion follows. Sustaining technologies are used to lower the costs more and more. The questions is; in which of the uppermost curves do PCS manufacturers compete today and where are the new performance attributes that keep the industry away from the price erosion domains?

The lowermost curves describe an alternative product evolution path, based on the assumption that applications are more important than high data rates in some partly new or emerging segments of the PCS market. In the Christensen framework \cite{CHR03}, this is denoted \emph{new market disruption}. The competition between conventional, ASIC, technology and SDR along the uppermost evolution path is denoted as low-end disruption by Christensen. Below, we will discuss the role of SDR and its potential for low-end and new-market disruption. It should be noted that the upper and lower curves are by no means exclusive. For example, one can imagine that widespread adoption of certain applications, as for example the iMODE and\ FOMA concepts, can revive the need for higher data rates due to more demanding applications or more difficult coexistence issues due to interference.

There is a believe that the separation of HW an SW, which is one possible definition of SDR, will fuel the innovation and speed up the development as it decreases the impact of standardization procedures and undermines the power of the incumbents that deliver HW and SW solution bundled. There seem to be two major paradigms for the competition in wireless communications: 1) \emph{high data rates} vs. 2) \emph{application functionality}. The application functionality paradigm can be seen as an alternative to the product evolution chain of the high data rates paradigm.

As mentioned above, an interesting question, difficult to sort out, is whether the market needs are driving the technology development or whether it is the other way around. This issue seems to be very related to the pricing of wireless services. This can be illustrated by a remark by Ralf Schuh: "Why is not UMTS taking off? 1) no nice mobiles, 2) from a speech point it makes no difference, 3)\ data communication is mainly used at home, there are few locations left were you want to use it." On the other hand, he continues, "users wants everything if it is free."

In a technology driven market, SDR can earn a competitive position if it speeds up the R\&D lead times and comes out as a true alternative to ASIC solutions for new standards. An other alternative is that SDR brings about very cost efficient solutions that enable high data rates at more attractive prices. This is a step towards a demand driven market. None of these scenarios seem likely in the short term perspective. On the other hand, as there are indications that current wireless technology over-serves the market, SDR would be more competitive if there came a focus on applications and convenient services. It appears more likely that such services could be subject to a stronger market demand than the high data rate oriented services. The latter scenario can be viewed as a demand driven market, where higher data rates are driven by the needs of applications demanded by the end-users, \emph{cf.} the PC industry.

There seem to be two major different views of the performance development of SDR technology relative to established technology; a) new wireless standards will always be introduced using a)\emph{\ established ASIC technology} and b) \emph{SDR technology}, followed by ASIC technology for mass-market production. We consider first the performance-oriented paradigm that has high data rates as the primary basis of competition in the early stage of the market evolution. There is no consensus about this between the experts. However, two major scenarios can be distinguished: 1.a and 1.b. The different views on performance development are reflected by the following comments during the interviews.

\begin{itemize}
\item[1.a] "Performance improvement rates are proportional to demand." "SDR always will implement something that was done in the path with dedicated hardware." "SDR will never have better performance than traditional technology, except if very complex algorithms are used." "SDR will not take the lead in isolated standards with high performance." "It

appears very doubtful that SDR will leapfrog ASIC technology and be first to support new standards in mobile terminals. This might be the case for basestations though." "At least from a performance point of view it is uncertain whether ASIC will be driven out of the market by SDR."

\item[1.b] "Partly, there is no demand for high-end services today." "The questions is -- what is the hen and what is the egg?" "The first products out may be implemented with SDR, however, the quality of those first products will be low and I doubt that the subsequent mass-market production should be addressed with SDR." "If the definition of processing primitive instructions for wireless communications can be solved, then the DSP implementations will be leading over ASIC implementations for the introduction of new wireless communication standards. "We do not see the low-end market for SDR emerge yet because of the high price tag of SDR." "Vanu is selling for high-end (basestations), low-end is considered \ in terms of price-tag." "Right now most SDR solutions are targeted to WLAN." "SDR will take lead over HW implementation for new standards. After production of huge volume ASICs enters." "SDR - yes, but it will take time." "WLAN now supports 50 Mbit/s with SDR technology." In basestations, SDR is first in FPGAs, everyone is prototyping that way." " I can imagine that SDR comes first."
\end{itemize}

Peter Karlsson says; "I think SDR will catch up around 2009". He continues; "one may say that there are separate SDR systems that support single standards, as GSM, WCDMA and WLAN, but not one SDR system that simultaneously supports all of these modes." Ralf Schuh points out the circumstance that you do not enable all promises in the standards at once, see for example UMTS. From the operator perspective you limit users for capacity reasons, \emph{cf.} HSDPA. This statement can be seen as some supporting evidence that the market is demand driven in that the applications need to catch up with the data rates supported before higher data rates are enabled in the standard. This way of getting the market used to new standards with small steps seem to be well supported by SDR solutions.

If we look at the functionality competition paradigm, the implementation technology of the air interface is less significant, being it SDR or conventional ASIC. Therefore a) and b) can be merged into a single scenario. This application scenario prompts some interesting business potential for SDR as an enabling technology for new services and applications.

\begin{itemize}
\item[2.a,b] "However, in multimode solutions, SDR has the lead." "A speculation is that the existence of SDR can affect the evolution of wireless communication standards." "There will come a paradigm shift towards functionality. If performance, itself does not limit the basis of competition, one definitely need to imagine the scenario that SDR leapfrogs

traditional ASIC technology". "Compare to traditional telephony -- it is based on a protocol on the terminal side that makes it very difficult to introduce new services. The so called "plus services" are OK to implement but not much more. The situation is similar in current PCS systems and SDR is a remedy. "The SMS service is an example of a nice-to-have feature that became incredibly popular and revenue bringing, quite unpredictably" "When it will be possible to add more sophisticated services in GSM we might see GSM competing with TETRA, supporting for example true preempt and priority, \emph{i.e.}, when connections are broken in order to obtain transmission capacity."
\end{itemize}

Giuseppe Caire believes that there is a great opportunity now as current technology is overdoing in terms of data rates supported. He says; "More bandwidth is available than people use, for example numerous TV channels, ADSL, UMTS broadband links. More friendly technology in sense of mobile connection to the internet is needed". As an example, being one of the leading researchers in mobile communications in the world, Giuseppe Caire mentions that he gave up E-mail with mobile. "It should be that you connect once and the phone learns the environment", he concludes.

A difference can be observed in the views of the representatives of the manufacturing industry of PCS equipment and the other stakeholders. For example, Peter Olanders believes that demand will always increase faster than the solutions at hand, which evolve according to Moore's law. However, Moore's law is more true for the PC than the wireless communications industry. It is also more true for the terminal than for the infrastructure manufacturing. Peter Olanders gives as an example that the move from analog to digital cellular systems gave about an order of magnitude increase of processing. The move from 2G - 3G about 10 - 50 times more processing and the move from 3G - 4G is expected to give about 100 times more processing. According to Peter Olanders, humanity always stretch. He further believes that\ SDR will be able to crossover the demand curve although use and reuse are cost driven.

On the other hand, the military actors have no extreme requirements on radio performance. Several experts share a lack of understanding about who consumes the high data rates in personal mobile communications. According to Jan-Wim Eikenbroek, "The industry is probably over-serving the market right now. This is very related to the economy of different countries, \emph{i.e.}%
, the level of living and the willing to spend money. It seems that the industry is creating this need. Potentially, the situation is different in Japan."

The question is; are extreme data rates a requisite for creation of the most attractive applications? Probably not, at least not initially. Therefore it is not so essential whether the SDR or traditional ASIC technology will take the lead in the introduction of new wireless air-interfaces. This is the reason why we do not distinguish between the categories 2.a and 2.b.

The success of the iMODE and\ FOMA concepts in Japan supports the business potential of Scenario 2.a,b and, given the above discussion about SDR as an enabling technology for those services, we conclude that SDR technology as such should inherit some of this business potential.

\subsubsection{State of Industrial Standards for SDR}

A crucial element of the Allen theory of technological frames is to consider the maturity of the standardization of a technology, being it a collectively worked out standard or a de facto standard. Allen states that the early stages of technology evolution are characterized by many new technology definitions. In order to understand the state of the industry standards related to SDR and to probe the awareness of the standardization work, we ask: \textbf{how are the industry standards evolved and what is the current state of them?}

In general, the existing work on standardization of SDR technology is unknown to the experts interviewed. Less than 25\% of the experts are aware of the standards although the existence of the SDR Forum is known to most of them. Particularly, it is known that the SDR Forum works on standardization of open interfaces, addressing mainly the higher layers. Only the referees associated with the military sector have taken active part in the standardization work.

It should, however, be noted that standardization work related to SDR technology is not limited to the SDR Forum. However, for example in 3GPP, SDR is viewed as an implementation issue and not specifically addressed. Peter Karlsson says; "All standardization organizations work towards terminals that function in different networks. SDR is a small enabler of this. It is implied that this will require an open architecture."

On the component side, de facto standards exist, \emph{i.e.}, for DSPs, but with respect to maturity and stringency. However, today, there is no general industrial standard for SDR. The only document that exists and looks as something like a standard is SCA.\ SCA has not reached the goal, in particular it lacks an industrial place of residence. Previously, SCA was hosted by the U.S. department of defense (DoD). Now, there are two candidates: OSG and SDR Forum. The DoD do not want to own the standard, only define it. Currently, the SDR standards that exist are limited to military applications. Standards for SCA and plug \& play radio have been developed by the U.S. defense industry on commission of the DoD. Version 3.0 of SCA is ready and next version 3.1 is anticipated during spring 2005.

According to Dr. Antenna, the problem now, addressed in version 3.1, is the lack of APIs for smart antennas. The SDR standardization work is more and more taken over by the Object Management Group which is an, impartial, independent group of software developers in the world that promotes common standards. In conclusion, the SCA standard is as mature as one can expect it to become but it will have to be sharpened in a number of areas. According to Christer Wik, the SCA standard does not even solve all steps needed to realize a radio on a rudimentary level. On a scale from 1 to 10 of maturity, the current maturity of SCA gets a level 3.

In the manufacturing industry, there is a fear that over-ambitious type approval procedures promoted by the SDR standardization organizations may become a showstopper for the SDR technology. Peter Olanders explains that type-approval is something between the manufacturer and government representatives and thus there is no necessity to open up to third part.

The difference to the PC\ market is striking since there is no control (type approval) at all in the PC industry. A potential showstopper of SDR is standardization in the wrong direction, for example standardization of implementation in the sense that the SDR architecture is standardized, and also the interconnection procedures. In general, initiatives taken by organizations as the SDR forum have very wide mandate may have severed impact For example, the over-standardization of cordless telephony, CT1 (analog 900 MHz cellular system standardized by CEPT), led to that it was not possible to make cost-effective implementation for years. To some extent this is also true for GSM. These concerns, about over-ambitious type approval and standardization of implementation are reasons for the personal communications manufacturing industry to stay out of standardization work on SDR. It seems most likely that the dominating definitions (see the technological frames theory) will emerge as de facto standards imposed by the largest players in terminal platforms.

A couple of years ago, there was the belief the SDR technology would have a large impact on the personal communications infrastructure. However, during the downturn of the telecommunications industry around 2001, dominating companies as Nokia and Ericsson shut down their SDR infrastructure development units due to slow commercialization. Due to the price erosion and the pressure for shorter product development cycles and more configuration flexibility, one thought is that SDR, as an implementation technology, may be adopted earlier in the terminal industry.

\subsection{Market Opportunities of SDR}

As discussed in Section \ref{sec:DisruptiveTechnology}, one of the characteristics of a disruptive technology is that it offers value to customers in dimensions complementary (orthogonal) to the mainstream markets. The flexibility that SDR offers is seen by many as such orthogonal value and an important complement to the mainstream offering of today. Few believe that SDR will radically change the end user experience. There is a consensus that it will take a couple of years for SDR to be an established technology in the PCS market. Below, we give some of the answers received to the question; "\textbf{do you think that SDR technologies offer a set of attributes orthogonal to those commanded in mainstream markets?}"

According to Prof. Platform, SDR is not competing at all in mobile communications today. Giuseppe Caire points to quality as a very important matter. He continues; "Services as seamless migration will be offered in more rational ways with SDR."

Operators and manufacturers agree that SDR is an implementation technology for the air-interface layer and that it will not change much from a functional operation perspective at this level. On the service and application levels, the situation is different. Ralf Schuh says that SDR is a tool to provide maintained value of the terminals. He refers to the pocket calculator as an example on the projected price erosion of mobile terminals; "Some 20 years ago they were very expensive and had the same functionality as those you get for free today." "The same evolution will be see for mobiles if not more applications are added."

Bertil Thorngren do see certain interesting niche markets for the mobile terminals that can be supported by SDR. For example, services with different requirements on coverage and real-time. Bertil Thorngren says. "For less time-sensitive services, WLAN, and even the fixed network are good alternatives". "The absence of differentiation between the tasks of cellular, local area and fixed to support download of everything leads to a misdirected competition between technologies." Compare the case of trucks, where different kind of throttling of the same engine gives advantages of scale in the manufacturing. Compare the need for efficiency with respect to the battery in mobile terminals? When it gets crowded in the radio networks, new pricing will emerge, and different kinds of throttling of terminals is one ingredient in this scenario that can be solved with SDR technology.

The concept of prolonging the life time of mobile terminals with SDR technology is scrapped by Jan-Wim Eikenbroek who says; "This is not attractive to customers -- it is a throw-away community in the western world". Dr. Antenna argues that the SDR technique is not applicable for personal mobile communications in the short term and that the notion that battery capacity is increasing significantly is a chimera.

Tony Ottosson has the somewhat unusual but interesting view that the number of air-interface standards to support is decreasing. He argues; "It seems that UMTS will cover a larger part of the world than GSM and this will lead to fewer standards to support." The attractiveness of the value proposal of SDR will depend on the number of standards to support.

Most optimistic about the market opportunities of SDR are Jonas Vasell, Christer Wik and Prof. Forward. Jonas Vasell says; "The ability to release services, as SMS and voice, from specific cellular standards, as GSM and WCDMA, gets more important as data communication, generated from other sources than voice, becomes a more significant feature in communications. The wireless communications industry has not made use of the possibility to build other applications than voice. The operators do not make use of the potential."

Prof. Forward states that the best example to understand the competitiveness of SDR is to contrast the classical Ericsson model -- technical excellence in specifications and being 2dB better than competitors to SDR, offering some worse sensitivity but gaining on flexibility. He continues;\ "Gaining 2dB on sensitivity may generate enormous problems with SDR but the flexibility overcomes the need to always reach optimal performance. SDR can be good enough".

The question "\textbf{what kind of emerging, new, markets for SDR applications, do you see?}", turned out to be tough to answer for the experts. These were some of the comments obtained:

\begin{itemize}
\item Private mobile radio. Safety. Remote area access. Cars - power consumption is less on an issue, life cycles are longer. "Perhaps generic radio front-end in PCs - however, it takes significant processing power away from the PC." "Intel's view of this is to have a coprocessor for radio, in particular wireless GSM."

\item "The goal is to have terminals that adapt to the environment, roaming from system to system." "The evolution of standards goes towards a heterogenous environment which makes SDR a need, not just an option as it will hardly be possible to integrate 4 - 5 standards in the same device." "SDR as an option depends on the willing of the operators to unbundle."

\item Updates of the terminal GUI. "Download of Java scripts for different applications - for example, fetch E-mail in the background. Telia connect that supports change between WLAN, 2G and 3G."

\item "DSPs, in general, are used to address smaller markets. a) niche markets, as for example military communications. b) industrial applications as for example process control in factories, where only a limited units are manufactured and ASIC therefore is too costly."

\item "I mainly see ways to build in SDR in existing markets in order to obtain improvements: a) telematics and management of vehicle fleets, b) private safety (blue-light operations), c) flexible data communication terminals and d) billing and routing for operators. This is exciting!"

\item The middleware market and the waveform software market. "There is a market for integrators of these components. Application developers, based on that appropriate middleware and waveform software are available exist already. The most interesting development issue now is to solve the implementation issues in middleware and the certification of waveform software. When this is done, we can go ahead with a civil version of SCA."

\item "Circuit providers are now seen to climb the value chain and provide substantial parts of the SW of the air-interface of WCDMA." For example, several DSP manufacturers already have substantial parts of the functionality required to run WCDMA implemented in SW. The quality of this SW and the ability of these manufacturers to assemble the whole application is, however, an open issue.
\end{itemize}

In \cite{CHR03}, Christensen urges us to think about situations where new technologies compete against non-consumption, in order to identify disruptive applications. Some reflections on the question "\textbf{does SDR compete against non-consumptions in those markets, i.e. can these markets only be served with SDR technology (due to better availability, more convenient use, reliability, flexibility, simplicity or cost)?}" are provided below.

\begin{itemize}
\item "Wireless local loop in the 3rd world."

\item "It may create longer air-time for some users, with chatting functionality, etc. Adding features will keep prices up, \emph{cf.} cars and the development with increased number of mobiles per person. By the way, the calculator in mobiles is not good, Matlab is much better."

\item "Not really. SDR is mostly an implementation technology. I do not see that SDR brings about new services."

\item "The operators are victims of the own success. This is not the case in Sweden or similar countries. One application is fishermen far out at sea and how to know where to land the fish. Coverage is difficult. Farmers and applications related to the harvest organization is another group to target."

\item "I do not think that SDR will lead to extreme user-friendliness -- see the case of Windows. SDR will only mean a gain for manufacturers and operators. The provisioning of cheap units could open up new markets but SDR will still be relatively expensive and apply mainly for B2B markets. Markets where dedicate HW does not make sense, as for instance outside commercial bands, but this means really small markets."

\item "This is very very difficult.\ What are the limits where I think that
the applications fulfil my needs? Many applications will be possible with
SDR."
\end{itemize}

A general conclusion is that it is difficult to imagine low-end markets
segments where SDR is competing with traditional technology. Basically, the
only viable examples obtained in response to this, from the question "%
\textbf{are you aware of any low-end segments of main-stream markets where
SDR technology is competing with traditional technology?}" were related to
WLAN and GSM applications.

\begin{itemize}
\item WLAN (modems but not radio).

\item "No dedicated HW is always cheaper in low-end segments. Cars may be
one such market, but the absence of an agreement of standards is a problem."

\item "GSM and all variations of standards for the ISM bands, for example
Bluetooth, ZigBee. The basebands can be DSP implemented in those systems."
\end{itemize}

\subsection{Opportunities and Potential New Value Networks}

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equipment, seen from the manufacturer perspective.}}{\Qlb{%
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'Figures/Evolution_scenarios_4.wmf';file-properties "XNPEU";}}This section
relates to the theory of new market space creation, outlined in Section \ref%
{sec:Creation of New Market Space}. The focus is on identification of
business opportunities for small and medium size companies with limited
capital investment resources. For example, development and offering of RF
digitalization ASIC technology is very capital and labour intensive and
requires close access to semiconductor process technology. Such business
opportunities are likely reserved for the dragons in the semi-conductor
industry and consequently they receive less attention here. On the other
hand, as the development costs for new ASICs, both for the RF and baseband
processing domains reach very high levels of capital expenditure and risk,
there are strong incentives to separate the HW and SW according to one of
the scenarios painted in Figure \ref{fig:evolution_scenarios_4}. For
example, on the basestation side, Ericsson and Analog Devices, who
manufactures the Tiger-Shark DSP family has a close cooperation and

substantial parts of the functionality required for UMTS and HSDPA is already implemented as software stacks (waveforms) running on those DSPs. For dragons as Ericsson, some incentives to separate SW from HW consist of the opportunities to reach new customers with SW only and to be able to reduce risk by purchasing HW platforms from other manufacturers vendors. On the negative side are the complexity and difficulties associated with integration of HW and SW from different vendors, the risk of pirating of the SW. The links of interdependency between the HW and the SW may still be too strong for this separation to make sense and the coordination benefits of a "one-stop shop" for both HW and SW the paramount issue.

Particularly interesting, on the mobile phone side, will be to monitor Samsung's concept, where the radio HW is purchased from Silicon Labs and the software comes from an external supplier. As Christensen gives as a bedrock principle in \cite{CHR02}; "Those who control the interdependent links in the value chain capture the most of the profit". Christensen argues that companies should "skate" to the points in the value chain, where complex, non-standard integration needs to occur. It is not clear whether the interface between the HW and SW in mobile phones is sufficiently well defined and standardized to allow for this kind of modularization. It is plausible that Samsung's separation of HW\ and SW leads to worse performance than the case of an integrated HW and SW design. However, the important question is whether it results in a performance degradation that matters to the purchaser or not.

Another aspect is that less and less ASIC development projects are initiated. Putting new ASICs on the market typically requires enormous development costs. There is a recent example, where a100+ MUSD ASIC project was cancelled due to that the development projects were deemed to risky, although the necessary venture capital was already gathered. Part of the problem is that manufacturers seem to lack adequate cost models that takes into account the research and development activities. Instead, the focus is on the manufacturing costs. Certainly, those are important for the case of mobile terminals but the story may be different for infrastructure as well as military platforms.

One possible dynamic for the platformization scenario, \emph{i.e.}, the separation of HW and SW, illustrated in Figure \ref%
{fig:evolution_scenarios_4}, could be the following:

1) The function developer (FD) may origin as a SW unit within the organization of an OEM. Due to the tremendous costs and risks associated with ASIC development, the FD breaks out from the OEM organization in order to be able to address also other manufacturers of HW platforms for communications. This may also be a response to another OEM coming up with a superior HW platform or even a GPP solution.

2) The FD addresses directly the network operator (NO) and the service provider (SP) and, in the extension, the SP or NO requires the suppliers of HW platforms to its phone suppliers to use the waveform SW of the FD.

3) The\ FD teams up with application providers and content providers to have a strong base for competition with other FDs and offer bundled SW packages for personal mobile communications to SPs. The FD might also team up with broadcast operators or fixed line operators in order to reach out to the end-consumers, bypassing the SPs.

Following the reasoning about product evolution in Section \ref%{fig:product_evolution_model}, the author suggests that we are now in an application competition situation, where SDR may have an important role. This will eventually revive the need for higher data rates. The possibility that SDR, by this time, is mature enough to compete with traditional ASIC technology, even in the spearhead technology implementations, should not be excluded.

In order to identify a new value curve Kim and Mauborgne encourages us to look for complementary product and service offerings that provide new value to customers. They also stress the time dimension and the need to identify decisive, clear and irreversible trends that will change the way customers value different offerings in the future and understand what preparations are required to address the resulting, new, value ranking.

Assessment of the business opportunities of SDR according to the framework of Kim and Mauborgne, first requires us to determine whether SDR is something more than an inevitable direction of technology development. If it is not, most other manufacturers in the industry will follow the same technology path and business opportunities should be sought in other technology directions. Secondly, we need to understand what are the radically different, orthogonal, value that SDR technology offers. To address the first question, these two questions were posed to the referees: \textbf{do you believe there is a meaning in the SDR paradigm? Is it just an inevitable path of development that can't be avoided?}

Most of the referees agreed that SDR is a natural evolution, at least at the physical layer. For example, more and more functionality is continuously moved to DSPs. Prof. Platform says; "Technologies will merge into the SDR path."\ Ralf Schuh points to that a 10 to 20\% improvement of cost or performance is not worth the risk to take substantial technology jumps, for instance to SDR. This reasoning is perfectly in line with the arguing of Brian Arthur in \cite{BRI96a}, p. 106, that a new product often needs to be twice or even three times better in some dimension in order for a customer to switch technology. The military industry might be different due to that more money is involved and that there is a need to always be on top. Ralf Schuh continues; "It is a continuous flow, not like the case with Facit typewriters or analog and digital cameras. The software is already in there, supporting about 40-50\% of the functionality."

Other, dominating views, mainly from the people with an air-interface technology background are:

\begin{itemize}
\item "It is doubtful whether SW for air interfaces will be downloaded on the fly. An alternative is to load the majority of the necessary SW on a harddrive from the beginning of the terminal lifetime." "An opposite product would be a thin client with a minimum of memory but the memory development is fast and the plausibility of such a product is uncertain." "Over the air downloads require a lot of power." "SDR for us is to use different networks in order to download services".

\item "The evolution analog to digital to SW is cost driven and inevitable." "Everywhere, the amount of SW increases. The amount of HW will be approximately the same or decrease in radio communications."

\item "SDR is inevitable due to manufacturer cost cutting and optimization of use of scarce spectrum." "Manufacturers are always looking for cost-effectiveness "Physically there is enough spectrum, but the problem is that it is an economically interesting good to trade, which associates strong economic forces." "Programmable HW exists already today. It is only a question about the ratio of SW."

\item "There will always exist waveforms, with high instantaneous BW, which are difficult to design and define in SW, for instance WCDMA and military spread-spectrum waveforms." "Very cheap, low-end terminals will not be cost-effective with SDR technology. For instance, the military will need to equip certain troops with this kind of throwaway radio." "Co-location problems are getting worse. Active suppression, as for example interference cancellation, is needed."

\item "The ADC will approach the antenna but not reach it."

\item "If somebody comes up with a better way to develop HW that gives shorter lifecycles, this can never be worse than SDR. For example, this could be extremely simple HW which can be thrown away when it gets outdated." "The big difference is the upgrading of basestations but it might become the case that generic basestation HW does not manage to support new standards anyway." "Fast roll-out and patching to fix problems is the largest application. See the operation of Microsoft and the car industry for examples of this behavior."

\item It is a natural way of going. It is slowly forced on everybody. It is not disruptive at this stage, but if it takes a jump forward, with for example, sampling at the antenna, it may be disruptive.

\item "I see it as a vision. From a user and market perspective it is an inevitable development."
\end{itemize}

In general, referees, focused on software architecture, middleware, application and service layers, more loosely connected to the physical layer technology, have a radically different view. Jonas Vasell states; "Definitely yes! SDR is indeed particularly exotic -- not only that the radio is written in SW -- it implies a clear separation of HW and SW. Today, there is a strong connection between the appearance of the platform and the applications it support."

Prof. Forward believes; "It is a paradigm shift in that it commoditizes radios. Just as GPP processors, same thing will happen for radio. Can it be prevented? Sure, by legislation, making SDR transmitters illegal. I do not see this happening." He continues, "Certain countries have very significant problems with spectrum regulation. For example, in France, the regulation process that dealt with WLAN took a lot of time." France like to be able to control and many others. Sweden interestingly has in the last four decades gone quite the other way in the sense of allowing receivers to listen virtually everywhere. This was illegal in the U.S. for example. The reason was that the content was not encrypted in cellular systems and there was a fear that politicians could be eavesdropped by journalists.

Given that SDR is not an avoidable direction of technology development, one wonders what are the alternatives. This was addressed with the question --%
\textbf{if the answers to the previous questions were yes and no, which are the competing technologies?}

The option to use terminals with extensive harddrives that enables support of most air interfaces was mentioned. This, however, should probably be viewed as SDR technology. In general, there were few answers to this question, but the following directions were mentioned.

\begin{itemize}
\item "I am not aware of any clear competitor to SDR, but certain waveforms, implemented in HW, can always compete." "The paradigm shift is quite stealthy. However, for dedicated monolithical manufacturers, it is an unequalled paradigm change. However, their customers are probably somewhat cowards and will continue to by traditional monolithic radios for a while"

\item "Alternatives exist. There is a good bunch of companies that push for patents." "SDR addresses particularly interoperability" "SDR should have open architecture." "Wireless (Linux-based) equipment from 3rd party developers should be welcomed." "See the GNU radio project and the Linux radio."

\item Patented proprietary solutions

\item "For example, in-house wireless networks at Berkely (see the article about motes in \cite{ROS04}) supporting a configurable living environment and security systems and sensor-networks." "For very low power transceivers, configuration features may not apply. Examples are statistically based dataflow - sensor information diffusion with a lot of units spread out. This technology advertises that the band 2-6 GHz is enough to do whatever you like. This is not quite true. There is a lot of spectrum but spectrum should be available all over the world, uniformly and spectrum rationing is a substantial source of government income."

\item "A very efficient way to develop HW but this development progresses slowly. See for example the research on verification of HW, for instance Safelogic AB."

\item "There are technical alternatives, multicore processors, where on the same chip you can have many many different CPUs. This can be imagined also for radio, with lots of specialized radios. Ultimately the PCS industry will go for either of those approaches." "The advantage of specialized radios is lower power. For handsets, this might cover most of what you need, shorter lifecycles will replace."
\end{itemize}

Towards the end of the interviews, we gave some concluding questions from the list of direct questions prompted by theory (see Section \ref{sec: Direct Questions}). \textbf{Will SDR technology disrupt the wireless communications industry?}

Again, the physical layer people are pessimistic about the disruptive potential of SDR technology, while the software, service and application level referees are more optimistic. Comments from the former group were:

\begin{itemize}
\item "No, incumbent companies will adapt."

\item "Certainly no."

\item "If SDR makes it, emphasize on standardization will decrease." "A PC style situation would put standardizations on emphasize on system and applications instead." "People will change phones anyway, as with PCs. The design is basically everything."

\item "No, big companies will buy small ones. Maybe one out of hundred will reach a success like Cisco."

\item "Industry must become more efficient. The telecommunications industry must become as efficient as the car industry. SDR might be one technology to use to achieve this."

\item "Some companies will fail, while some will adopt the technology and gain on it."

\item "No. Not within 5-10 years at least."
\end{itemize}

Comments from the believers were:

\begin{itemize}
\item Yes, the potential is definitely there.

\item Yes, already happened.

\item "Yes, in the sense that SDR breaks a structure that implies that you can only have access to a radio under conditions stipulated by the dragon manufacturers." "In the future, it will a module based system. For example, we agree about SCA and make open source code of WCDMA and certify the implementations that qualify. All integrators that are certified may then connect to the network. How do you think this will affect the dragons?"
\end{itemize}

According to Dr. Antenna, SDR has made a revolution on the military side but its utility is not well understood on for civil communications. It depends on the desire of the customers , operators, to influence their own equipment functionality. For basestations we must expect that the operators will take larger control of its equipment and request independent HW/SW implementations. The wireless communications in general must be very open to new business models. After the fall of the Berlin wall, SDR is, in fact, the only area in communications where the military has been leading the development. The civil industry is leading in all other areas of communications.

A conspiracy theory that has been proposed is that the failed efforts in mobile telephony standardization in the U.S. calls for the U.S. to retake the initiative by promoting the separation of HW and SW with SCA light and be able to recover market shares. However, none believes that it makes sense to implement SCA in mobile terminals due to the extensive amount of middleware required. There is an ongoing initiative with an SCA version of WCDMA, where all software is to be manufactured in the U.S.

\textbf{Which seems to be the most viable application scenarios for the future?}

\begin{itemize}
\item "Roll-out phase of basestation equipment." "802.16 safety."
"Wireless local loop, connecting RNCs together."

\item "Applications like Telia-Go. Those are more of a sustaining
technology kind."

\item "Multi-standard indoor basestations. For example, it can be foreseen
that single-mode GSM basestations will, in a few years, be replaced by WCDMA
nodes at indoor office locations. This would be easiest if it would be a
reconfigurable GSM - WCDMA basestation." "One reason for this is that
indoor dedicated systems are small islands with special users (office
people) who have quite often early advanced telephones, (\emph{e.g.} in
Ericsson's OnePhone project) which means you could foresee at a earlier
state that all users may have WCDMA compatible terminals."

\item "A few years ago SDR was obvious to use in basestations. Now, there
are signs that it starts in the mobile phase, for instance the use of direct
conversion. Direct conversion was predicted to start in basestations but
actually started in phones. Nobody believed something else than that it
would start i basestations."

\item "What will the future business models look like? What pricing models
can be legitimated?" "One alternative is that Vodafone \& Co. dominates
more and more. Small start-ups form a broker-organization and act
together." "Another example is best-effort markets".

\item Connecting networks for end-user. Decreasing cost.

\item "Laptop computers with small SDR enabled radio cards." "An
important issue is the backwards compatibility of new waveforms with old HW.
What is the situation in 2012, will those waveforms run in HW from 2006? The
users are expecting this to be OK."

\item "True ubiquitious communication -- the perception that all wireless
communication needs always are satisfied"

\item "Basestations will benefit the most."
\end{itemize}

\textbf{Where is the greatest growth expected?}

\begin{itemize}
\item Software suppliers to mobiles, based on open platform architectures.

\item "The way, in the mobile one writes SMS on a very limited keyboard. A more sophisticated UI is needed. What has happened in terms of keyboard and screen evolution? Not much" "I see laser-enable keyboards that are closer to PC-style keyboards." "In about 100 years, we probably have a chip in the brain that allows for more sophisticated UI interaction."

\item "Support of a different kind of network use. Help to separate the services from the access type will be an area for growth."

\item "Cellular is huge market."

\item "Sweden has no manufacturers of military radio equipment (since decades ago). Last Swedish radio was troop radio 8000 from ERA, ordered in 1980 and delivered in the middle of the 1990s (10000-12000 stations)"

\item "We start virtually from zero. We will see completely new things. High potential in new markets, with new approaches to routing and billing operators." "Twenty years ago, mobile communication was aimed for some percentages of the market. Now we see much larger." "Look at the price erosion of cameras and consumer electronics. All electronics should cost per kilo, silicon is cost driver".

\item "Consumer electronics. Cars can be viewed as a kind of consumer electronics"
\end{itemize}

\textbf{When will a potential disruption occur?}

\begin{itemize}
\item "There will be no disruption"

\item Probably never.

\item "A disruption has already happened at the military side. ITT and\ Raytheon are losers."
\end{itemize}

Jonas Vasell thinks that this is a not completely common opportunity, but he is also pretty sure there is a window. He believes; "if too long time passes from today, the whole SDR concept will bury itself. Other ways will be sought. SDR may show up anyway, but not as a disruptive technology." Maybe the window is about three years from now. This is based on that the market gains momentum when the first product can be displayed to the market. Access to the technical components comes in this time frame, the right analysis, with respect to business cases, however, need to be done. This is not only a matter of technology.

Many of the questions during the interviews were related to physical layer aspects of mobile communications. This is, however, not necessarily a big application for SDR. As discussed in the introduction to this section, SDR offers new applications in 3 levels: 1) HW, 2) applications and 3) middleware level.

In conclusion, there seem to be two major competition scenarios for the PCS market and they are not mutually exclusive. The first one is that the need for high data rates of mobile users will continue to increase steadily and the second that competition will occur on the basis of new functionality and services that not necessarily require the high data rates (see scenarios 1.b and 2.a,b in Section \ref{sec:performance improvement rates}).

In the first scenario, one can argue that SDR enables high data rates by solving the problem of multi-standard compatibility and rapid development of new standards. Assume that an irrevocable trend is that the need for mobile wireless personal communications increases. The difference to the fiber networking scenario of the Cisco Systems example in Section \ref%
{sec:Creation of New Market Space}, is that wireless communication links have to be squeezed in a shared media -- the radio channel, while the capacity of fiber communication can increase by digging down more fiber. Thus interoperability between different standards ought to be ever more important in the case of wireless communications. Consequently, interoperability is a valid and important driver for wireless communications and, given that the trend of increasing demand for mobile wireless communications is valid, a company with a strong SDR focus could potentially become a new Cisco systems. Compare Flarion and the WI-MAX standard. Cisco did not come up with a new standard that solved the interconnectivity issues, as opposite to Flarion.

Below, we give some examples of applications and services belonging to the second scenario.

\begin{itemize}
\item \textbf{Mesh networks with automotive or laptop size platforms.} Potentially very large series of infrastructure Large series of equipment. Limit between terminal and infrastructure blurred. Virtually no power limitations in units attached to poles or automotive platforms. Relaxed power constraints on laptop-size terminals. See the discussion of the available alternatives for increasing the data rate in mobile communications systems in Section \ref{sec:ValueProposition}. Mesh networking increases the data rates available to consumers by using extensive amounts of relatively low cost infrastructure. Managing and maintaining mesh networks is inclined to be substantially more complex than the management of cellular basestations. The use of SDR technology could facilitate the maintenance and the upgradeability of mesh networks. In \cite{CAS05}, mesh network technology is pointed to as a winner project in wireless technology that could potentially show to leapfrog cellular as well as WIMAX systems during

2005. Moreover, the mesh network technology builds on the concept of ad-hoc networking, which, of some of the referees in this study is said to have more disruptive characteristics than SDR.

\item \textbf{New innovative technologies for routing, billing and infrastructure management} are required for mesh networks. These technologies can also be considered enabling technologies for SDR. Mesh networks will not necessarily use SDR technology but the evolution of those might pave the way for other SDR-based systems.

\item \textbf{Remote monitoring of the health} of elderly people is an interesting way to tackle some of the challenges that comes with an aging population. Worldwide population of those over 65 is predicted to reach 761 million in 2025. This is more than double what it was in 1990 \cite{ROS04}. Meeting the needs of this population is labor intensive and costly for the society. In \cite{ROS04}, a scenario where small wireless sensors, called motes, monitor the health and daily behavioral patterns of people. The motes currently have matchbox size, but the idea is to make them so small that they can be integrated in virtually anything. The information is collected by a PC and monitored remotely by, for example, a doctor or a relative, who can also perform caregiving and give intervene remotely. The motes organize themselves in networks and communicate with each others and with computers in the area. The PC can also communicate with the TV or other displays in the house to facilitate the daily life of disabled or elderly people.
Although the communication of the motes has a narrowband character, due to power and size limitations, SDR technology may not apply for motes in the near future. One can, however, imagine SDR technology as an enabler of interconnection between different wireless devices as PDAs, PCs and other home hardware in order to assist disabled or elder people. For example, a group including General-Electric, Hewlett-Packard and Intel anticipates a smarthome scenario where wireless remote monitoring help older people to live longer on their own and tries to jump-start this market.

\item There is a broad agreement among researchers in the telecommunications sector that technology developments will lead to fixed and mobile service convergence (FMC) and the breakup of old value chains \cite{YAN04}. This is driven by the cost pressure on fixed-line and mobile operators, the fact that mobile services still are very expensive and slow. Operators see fixed and mobile service bundling as a means to keep revenues from falling. In %
\cite{YAN04}, the FMC is made up of three different levels;\ network convergence (networks are designed for fixed and mobile services), commercial convergence (for example marketing and customer service is shared between fixed and mobile operator departments) and service convergence (seamless delivery of fixed and mobile services irrespective of the underlying technology). Similar to the case of mesh networks, issues in billing and routing clearly needs attention in order to allow this seamless delivery. Protocols and air interfaces supported by SDR technology might be

a requisite in order to provide seamless service delivery. The operators interviewed in this study see SDR as an important enabler of network-independent services. The development of \textbf{services that exploits the FMC} might be one of the most appealing business opportunities related to SDR.

\item One example of value chain break-up, described in \cite{YAN04}, is that manufacturing firms approach end-users directly. For instance, one can imagine that a manufacturer can sell waveform software directly over a fixed Internet session, to a customer that wishes to update a PDA to get more efficient wireless communication.

\item Design and delivery of \textbf{SDR prototyping platforms} with HW\ and SW for research, design and demonstration purpose.

\item Development of \textbf{SDR radio platforms for satellite or remote area radio infrastructure}.

\item Development of \textbf{SW versioning management systems for wireless infrastructure and terminals} that keeps track of release versions and upgrades sent to different units.

\item \textbf{Basestations for rapid roll-out in conventional cellular networks.}

\item Manufacturing of \textbf{generic PCMCIA PC cards} or standard PC companion chips with ADCs and DACs that can accommodate waveforms downloaded over fixed Internet sessions.

\item Upgradeable, \textbf{generic communication platforms for platforms with long life-time}, as, for example, cars (automotive) and aeroplanes.

\item \textbf{Toys that interact with wireless devices} using various wireless communication standards.

\item Systems for \textbf{self-calibration, verification and monitoring of wireless chipsets} when in shipping or operation. Potential benefits are shorter production times and manufacturer access to real-life, on-line, operation performance measurements and quality control of wireless communication platforms / chips.

\item Wireless communication platforms for \textbf{robots that need to adapt to different environments}.

\item RFID applications, identification, tracking of goods, \textbf{wireless payment communicating with machines using different air-interface standards}.

\item \textbf{Future proof home electronics?}

\item Control of lamps and other electronic home equipment via any kind of wireless terminal.

\item \textbf{Traffic control systems to operators for balancing capacity in wireless (and fixed) networks dynamically.} Service scheduling tools that performs downloads of the data required by a personal user during, for example, a day, using the most adequate connection (always best connected). For, example, if I read the newspaper on Internet everyday on the bus, this information is downloaded over a fixed connection, before I leave home in the morning.

\item Development of \textbf{communication platform design tools for SDR} that speeds up prototyping and design.

\item \textbf{Broadcasting receivers} that support several protocols as DVB-T, MBMS and other short-range broadcasting protocols for audio/video, for example in shopping malls. With emerging deployment of broadcast services as DVB-H and MBMS in mobile terminals, broadcast operators and cellular network operators compete about carrying the services and collecting the revenues. The business models are not yet well-defined and one can imagine that additional broadcast standards will emerge. Development of an SDR-based receiver chip that can upgrade to new broadcast standards might bring about business opportunities for some kind platforms.

\item Within the JTRS framework, a standard geared towards the power constraints of personal mobile communications -- SCA light is under definition. In contrast to the SCA standard, it allows some parts of the protocol stacks to be burnt in ASIC. Exploring the feasibility of providing optimized SW with HW IP for SCA light might prompt some interesting business opportunities.
\end{itemize}

\section{Conclusions}

In this thesis, we have studied the utility of the theories of disruptive technology and technological frames for judgement of technology potential and technology evolution. In our experience, the collection of comparable data about specific performance attributes of enabling component technologies, which is a key element in the identification of a disruptive technology, is a challenging and very tedious task. Determination and prediction of the evolution of the demand for certain performance attributes and the actual level of supplies are other challenging issues. For the personal communication services (PCS) market, it is hard to separate the cause and the effect in this respect.

The main practical question we seek to answer is whether or not software defined radio (SDR) is a disruptive technology. In conclusion, there are several definitions of SDR. Depending on which is adopted the potential for disruptive evolution of SDR is perceived differently. In the military sector, a disruption has already taken place from an equipment perspective. For the manufacturers of PCS equipment,\emph{\ i.e.}, infrastructure and terminals, SDR is viewed as a possible implementation technology, rather than a radically new and disruptive technology.

The transformation of the RF transceiver processing from the analog to the digital and SW domains is seen as a sustaining technology evolution, virtually inevitable due to the need to support multiple air interface standards and cost reasons. However, one plausible trend is the separation of the HW and SW of the wireless communication platforms and this may open up for potential disruptive innovations. In particular, the provisioning of general purpose wireless processors and high-level abstraction SW with detailed knowledge about the RF processing hardware, described as SW primitives, will enable applications and services to be implemented by SW engineers without expert knowledge in wireless communications. There is a belief that this will fuel innovation, particularly in the areas of waveform SW, middleware, services and applications.

Another, potentially disruptive, feature that can be enabled by SDR technology is network transparency for services. SDR is also related to the issue of improved spectrum utilization through the concept of cognitive radio. However, cognitive radio is believed to be more distant in the future than SDR technology.

In conclusion, the maturity of SDR technology is found to be quite low. There is little work made on standardization and the standards that exist are not well known. Moreover, there is not a clear common definition of SDR technology or any \emph{de facto} standard for generic platforms, which is found to be a very important component for the widespread use and success of SDR technology.\pagebreak

\section{Acknowledgment}

This thesis has been carried out under the supervision of Prof. Allan T.\ Malm at the Institute of Economic Research at Lund University in Lund, Sweden.

The author would like to thank the following persons for their participation in the study and interesting discussions about the business potential of SDR technology and other issues of wireless communications.\bigskip

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\textbf{Prof. Giuseppe Caire} was born in Torino, Italy, on May 21, 1965. He received the B.Sc. in Electrical Engineering from Politecnico di Torino (Italy), in 1990, the M.Sc. in Electrical Engineering from Princeton University (USA) in 1992 and the Ph.D. from Politecnico di Torino in 1994. He was a recipient of the AEI G.Someda Scholarship in 1991, has been with the European Space Agency (ESTEC, Noordwijk, The Netherlands) in 1995, was a recipient of the COTRAO Scholarship in 1996 and a CNR Scholarship in 1997. He has been visiting the Institute Eurecom, Sophia Antipolis, France, in 1996 and Princeton University in summer 1997. He has been Assistant Professor in Telecommunications at the Politecnico di Torino and presently he is Professor with the Department of Mobile Communications of Eurecom Institute. He served as Associate Editor for the IEEE Transactions on Communications in 1998-2001 and he is presently Associate Editor of the IEEE Transactions on Information Theory since 2001. He is co-author of more than 50 papers in international journals and more than 80 in international conferences, and he is author of three international patents with the European Space Agency. His interests are focused on digital communications theory, information theory, coding theory and multiuser detection, with particular focus on wireless terrestrial and satellite applications.

\textbf{Dr. Jan-Wim Eikenbroek} received the M.S. degree and the Ph.D. degree in electrical engineering from the University of Delft, The Netherlands, in 1984 and 1989, respectively. His dissertation was on the subject of an integrated AM short-wave upconversion receiver front-end. In 1989, he joined Ericsson Eurolab Netherlands, Emmen, The Netherlands. Till 1998 he designed low-power radio front-ends for paging receivers and worked on the system aspects of single-chip paging receivers. From 1999 to 2003, he worked on the rf system aspects of single-chip Bluetooth-chips in CMOS technology and was involved in the development of future extensions of the Bluetooth standard as a Senior Specialist in radio system design. In 2003 he joined Bruco Integrated Circuits B.V. Borne, the Netherlands where he is currently working as a Senior System Design Engineer in the fields of low-power radio-systems and automotive systems. His main interests are in the field of RF radio-system design and frequency synthesizers. He holds several patents.

\textbf{Prof. Michael Faulkner} received the B.Sc.(Eng) from Queen Mary College, London University, UK, in 1970, the M.E. degree from the University of New South Wales, Australia in 1978, and the PhD from University of Technology Sydney in 1993.

From 1972 to 1975 he was with STC (now Alcatel) Australia. From 1975 to 1977 he was with the University of New South Wales, and since then as a lecturer and now professor at Victoria University, Melbourne, Australia where he is director of the Centre for Telecommunications and Micro-electronics. Between 1988 and 2004 he spent five periods at Lund University, Sweden. He was co-recipient of the IEE's 1997 IERE prize for a paper on amplifier linearisation. His current interests are, signal processing, radio technology, radio systems and MIMO/OFDM.

\textbf{Dr. Peter Karlsson} received both his M.Sc. and Ph.D. from the Lund Institute of Technology in 1988 and 1995 respectively. In 1995 he joined the Radio System Group at Telia Research AB (Malm\"{o}, Sweden), working on design, analysis and trials with high capacity mobile and fixed broadband radio communications systems. He has been contributing to the standardisation of WLANs in ETSI BRAN and IEEE 802.11 focusing on the physical layer, channels models and range extension with smart antennas. Peter Karlsson chaired the HiperLAN2 Global Forum (H2GF) regulatory group 1999 to 2001 aiming at global allocation for WLANs in the 5 GHz band. During year 2000 he was a research fellow at University of Bristol in combination with a half time position at Telia Research working with adaptive antennas both for cellular and WLAN systems. He has written and co-authored some 50 conference and journal papers on antennas and propagation and mobile and fixed radio systems. Peter Karlsson was area manager of the Mobile System Innovation projects at Telia Research AB in 2001. He was then appointed expert in radio communications and holding the expert position at TeliaSonera Sweden, Mobile Network R\&D until 2004. Peter is now manager of long-term university and European IST 6th framework research cooperation at TeliaSonera Corporate R\&D functions. (Email: peter.c.karlsson@teliasonera.com).

\textbf{Dr. Peter Olanders}, Research Manager at Ericsson AB in Kista, Sweden.

\textbf{Prof. Tony Ottosson} was born in Uddevalla, Sweden, in 1969. He received the M.Sc. in Electrical Engineering from Chalmers University of Technology, G\"{o}teborg, Sweden, in 1993, and the Lic. Eng. and Ph.D. degrees from the Department of Information Theory, Chalmers University of Technology, in 1995 and 1997, respectively. Currently he is a Professor at the Communication Systems Group, Department of Signals and Systems, Chalmers University of Technology. During 1999 he was also working as a Research Consultant at Ericsson Inc, Research Triangle Park, NC, USA. From 1995 to 1998 he participated in the European FRAMES (Future Radio wideband Multiple Access System) project both as a co-worker and during 1998 as activity leader of the area of coding and modulation. Dr. Ottosson has served as

Associate Editor for IEEE Vehicular Technology from 2000 to 2004. His research interests are in communication systems and information theory. Specific topics are modulation, coding, CDMA, multiuser detection, combined source-channel coding, joint decoding techniques, synchronization, cross-layer interaction and scheduling. Dr. Ottosson has published more than 90 journal and conference papers, and holds several patents.

\textbf{Dr. Ralf Schuh} is currently working at TeliaSonera AB, Sweden. He led an internal project dealing with distributed antenna systems (radio over fibre) regarding indoor coverage for GSM and WCDMA. Formerly at GMD FOKUS, the German National Research Center for Information Technology in Berlin, he was involved in two European projects dealing with fibre radio. Dr. Schuh received his Ph.D. in Electronic Systems Engineering from the University of Essex, UK in 1998. His recent activities are on GSM/GPRS and WCDMA planning for indoor coverage and capacity.

\textbf{Prof. Bertil Thorngren} received his first degree (Civilekonom) in 1963, his second degree (Lic.Econ) in 1967 and his Doctor%
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s degree in 1972 all at the Stockholm School of Economics (SSE) ,where he also was appointed Associate Professor in 1974. This was followed by assignments as Acting Professor and Head of the Departments of Business Administration at several other universities. BT has also substantial experience from the telecommunications industry, e.g. as senior VP in charge of Corporate Strategy at Telia ,and from serving as a Board Member at private as well as governmental organizations.

On his return to academic life Bertil Thorngren was 1997 appointed Head of the Center for Information and Communications Research (CIC) at SSE.BT is since 1993 an elected member of the Royal Swedish Academy of Engineering Sciences (IVA). For more see http://www.hhs.se/cic and http://www.teldok.org.

\textbf{Dr. Jonas Vasell} has a background as researcher in computer architecture and real-time systems, and as a consultant specialized on computer system architecture and parallel and distributed systems. He has practical experience in a wide variety of fields ranging from microprocessor architecture, via middleware and platform architectures for software defined radio (JTRS SCA), peer-to-peer computing, and distributed service infrastructure, to architectural design methodology for complex systems.

\textbf{Christer Wik}, M.Sc. Applied Physics. Christer is currently working as an independent technical specialist/technical consultant at Generic Systems Sweden AB. Christer has mostly worked with system architecture for complex technical systems. Christer has worked in a number of fields such as medicine technology, telecommunication, middleware for service distribution (OSGi), Conditional Access (CA) for Digital Video Broadcast (DVB), PKI based container seals and Software Defined Radio (SDR), specially JTRS SCA. Christer often combines pure technical work with other positions such as project management or business development.

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\section{Appendix A -- Interview Template}

Below, the question template used during the expert interviews is provided. Due to time limitations, not all questions could be answered by every referee.

\subsection{Background}

Conditions for the study and the interview:

\begin{itemize}
\item Thesis in business economy at the Institute of Economic Research at Lund University. Advisor: Professor Allan. T. Malm. Thesis corresponding to 10 credits (10 weeks of work)

\item Interviews may be anonymous if preferred. (I would, however, like to be able to quote from interviews.)

\item No financial backing from Ericsson Mobile Platforms Inc.

\item Report will be made official and openly distributed. All participants will have a copy.
\end{itemize}

\subsection{Value-proposition of SDR}

\begin{itemize}
\item[v.1] Which is the most important customer dilemma that SDR technology addresses?

\item[v.2] What do you think is the technically most attractive characteristics of the SDR concept?

\item[v.3] What are the major weaknesses of SDR technology?

\item[v.4] Is SDR mainly about cost-savings or addition of value-adding functionality?

\item[v.5] What features do you think will be most valuable to

a) manufacturers?

b) operators?

c) end users?

\item[v.6] Can any group of players be said to loose upon the deployment of SDR technology (for example infrastructure equipment manufacturers)?

\item[v.7] Do you believe there is a meaning in the SDR paradigm? Is it just an inevitable path of development that can't be avoided?

\item[v.8] If the answers to the previous questions were yes and no, which are the competing technologies?

\item[v.9] Do you think that SDR technologies offer a set of attributes orthogonal to those commanded in mainstream markets?
\end{itemize}

\subsection{Technology}

\begin{itemize}
\item[t.1] Which are the enabling technologies for SDR hardware and software concepts (in particular for mobile phones, ADCs, DACs, DSPs, MEMS)?

\item[t.2] Which are the leading companies in these technologies?

\item[t.3] Which are the basic functionality requirements and performance measures of SDRs and it's components?

\item[t.4] According to your view, what is the level of maturity of these technologies (for each enabling technology, on a scale from 1 to 10, where 10 means ready to deploy in mobile phones)?

\item[t.5] Which are the major technical barriers against widespread deployment of SDR technology?

\item[t.6] Do you think that the performance improvement rates are faster than the demand in terms of those measures, what is governing/limiting market performance demand curves? When will intersection (SDR feasible for infrastructure or/and terminals) happen?

\item[t.7] Are there any showstoppers of SDR technology?

\item[t.8] How are the industry standards evolved and what is the current state of them?

\item[t.9] When do you think that it is possible to produce and bring a cost-efficient SDR based mobile phone to the market? (direct conversion receiver, low-complexity RF-frontend, generic baseband, supporting multi-band WCDMA, GPRS, GSM, HSDPA)?

\item[t.10] Do you believe it makes sense to integrate cellular standard air interfaces, as WCDMA, GSM and short-range air interfaces as WLAN and Bluetooth in the same SDR-based receiver chip?

\item[t.11] Do you think the most significant challenges of SDR are in hardware or software?

\item[t.12] In terms of complexity (design efforts), what is the percentages of the complexity of the required hardware and software?
\end{itemize}

\subsection{Market}

\begin{itemize}
\item[m.1] Which market needs would you characterize as as mainstream?

\item[m.2] Can SDR technology compete in mainstream markets?

\item[m.3] What applications are you aware of, that use SDR technology already today?

\item[m.4] Which applications are closest to be launched to the market?

\item[m.5] What kind of emerging, new, markets for SDR applications, do you see?

\item[m.6] Does SDR compete against non-consumptions in those markets, i.e. can these markets only be served with SDR technology (due to better availability, more convenient use, reliability, flexibility, simplicity or cost)?

\item[m.7] Are you aware of any low-end segments of main-stream markets where SDR technology is competing with traditional technology?

\item[m.8] Who are the major system actors on the SDR markets? Which traditional telecommunication companies and what new entrants are active in the SDR development?

\item[m.9] Do you think that an emerging SDR technology redefines the distribution channels?

\item[m.10] What are the key product success criteria driving different
groups of users (manufacturers, operators, end-users) of the SDR technology?

\item[m.11] What are the ranking criteria of the customers?

\item[m.12] Who is best prepared to capture the growth opportunities in SDR?
Who do you think will come up with a redefining totality solution (as for
instance Palm within the personal digital assistant (PDA) industry)?

\item[m.13] Christensen Test I: Can you think of any large population of
customers who historically have not had the money, equipment or skill to
utilize radio communications, and as a result have gone without it
altogether or have needed to pay someone with more expertise to do it for
them?

\item[m.14] Christensen Test II: Can you identify some kind of customers
that need to turn to an inconvenient, centralized location to use radio
communications?

\item[m.15] Do you see any group of customers at the low end of the radio
communications markets who would be happy to purchase a SDR based product
with less (but good enough) performance if they could get it at a lower
price?
\end{itemize}

\subsection{Research}

\begin{itemize}
\item[r.1] Have you conducted any study on SDR concepts? What was the focus
of the investigation?

\item[r.2] In your opinion, where is the research focus in SDR technology
today?

\item[r.3] What would be an interesting topic for future research in this
area?

\item[r.4] What is your most optimistic vision of SDR technology?
\end{itemize}

\subsection{Judgement of Technology Potential}

\begin{itemize}
\item[j.1] How do you judge the performance of a new technology?

\item[j.2] What systematic approaches for judging technology potential are you aware of?

\item[j.3] What do you perceive as common practice in Industry in order to judge the potential of new technology?

\item[j.4] Do you agree with the presented forecasting of the rate of performance improvement of different attributes?

\item[j.5] Do you think that Moore's law applies for the technology evolution that enables SDR? Why? Why not?

\item[j.6] Do you think that the HW/SW spiral of the PC industry be replicated in wireless communications?

\item[j.7] Will SDR technology improve the conditions for such a scenario?

\item[j.8] What do you think are the most important and revenue-bringing wireless services today? Are they high-end or low-end?
\end{itemize}

\subsection{Concluding Questions}

\begin{itemize}
\item[c.1] Will SDR technology disrupt the wireless communications industry?

\item[c.2] Which seems to be the most viable application scenarios for the future?

\item[c.3] Where is the greatest growth expected?

\item[c.4] When will a potential disruption occur?
\end{itemize}

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