Radio Spectrum Coexistence Between Military Radars and Radio Access Networks

A Study at Saab Group to Adapt Resources and Capabilities to Increasing Spectrum Scarcity Driven by 5G Capacity Demand

Master's thesis in Quality & Operations Management

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Abstract

Demand for radio frequencies is high due to increasing capacity need for the emerging radio access network, 5G. Hence, the radio spectrum is expected to be more crowded than it is today with users of different radio services. Military radars and radio access networks are two different services that potentially face coexistence. However, interference can occur between users, which undermines the performance of military radars and thereby also national security, which military radar providers, e.g. Saab group, need to address. Hence, the purpose is to investigate how Saab Group can adapt its resources and capabilities effectively, considering a new emerging coexistence environment due to radio spectrum scarcity driven by 5G capacity demand.

The research methodology was split in three main parts. Firstly, a documentary research was performed to investigate the current coexistence situation and feasible methods for coexistence. The second method consisted of a delphi study that involved 14 experts from five different stakeholder categories and aimed at predicting the trend of the coexistence environment between military radars and radio access networks. The third method was to conduct expert interviews with Saab employees to investigate what internal technologies that existed within Saab and assess their coexistence potential with radio access networks.

Findings indicated that currently implemented coexistence solutions are not sufficient and that there is a need for cross-industry collaboration to reach an efficient and effective spectrum sharing method between military radars and radio access networks. The four most feasible coexistence methods were: 1) location-based; 2) resource allocation; 3) cognitive radars; and 4) interference cancellation. At Saab, five internal technologies were found to have potential to contribute to coexistence between military radars and radio access networks.

There are three main resources that Saab can pursue to effectively adapt to the coexistence trends between military radars and radio access networks: 1) competitive technologies for the 4 most feasible coexistence methods; 2) close collaborations with providers of radio access networks to develop common solutions; and 3) extensive insight and involvement in national and international policy development for radio spectrum allocation.
Keywords: radio spectrum, coexistence, spectrum sharing, military radar, radio access network, 5G, wireless communication system, operations strategy, resource based view.

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Johannes Berghult & Alexander Lesser, Gothenburg, October 2018

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List of Abbreviations

CBRS Citizen broadband radio service
CEPT European Conference of Postal and Telecommunications
CORASMA Cognitive radio for dynamic spectrum management program
DFS Dynamic frequency selection
DOD Department of Defence
EDA European Defence Agency
EW Electronic warfare
FCC The US Federal Communications Commission
FMCW Frequency modulation continuous wave
HIPERLAN High performance radio local area networks
IEEE Institute of Electrical and Electronics Engineers
ITU International Telecommunication Union
MIMO Multiple-input-multiple-output
NTIA National Telecommunications and Information Administration
PTS Swedish Post and Telecom Authority
RLAN Radio local area network
TPC Transmit power control
VRIO Value, rarity, imitability & organization
WAS Wireless access system
WLAN Wireless local area networks
WMAN Wireless metropolitan area networks
WPAN Wireless personal area networks
WRAN Wireless regional area networks

1
Introduction

The introduction provides the reader with the necessary prerequisites to the research, covering background, problem analysis, purpose and research questions.

1.1 Background

In the following sections, the meaning of business strategy in a changing market situation is presented along with a the increasing capacity demand from radio access networks that constitutes the main reason for this thesis.

1.1.1 What determines successful firms

What is at the core of success or failure for firms? According to Michael E. Porter, it is determined by industry competition and a firm's competitive strategy for the search of a favourable market position in that industry. As competition determines the performance of a firm's operations, a competitive strategy aims to establish a profitable and sustainable position against forces that drive industry competition [1]. In general, competitive advantage is the ability a firm may enjoy if it creates more economic value than its rival firms [1, 2]. Economic value is what customers are willing to pay for a product or service, and superior economic value is obtained when firms offer lower prices than competitors or offer greater benefits for the same price as competitors [1, 2]. Thus, the size of competitive advantage can be seen as the difference between the economic value a firm is able to create and the economic value its competitors are able to create [2].

In addition, a firm's theory on how to obtain competitive advantage in a single business or industry can also be defined as its business strategy. A good business strategy is a strategy that actually generates such advantages and the opposite constitutes a poor business strategy by failing to obtain any competitive advantage. However, like all theories, a strategy is based on certain assumptions or hypotheses on how industry competition will evolve, and how that evolution may be exploited to reap competitive advantage. The more a firm's assumptions about the future are accurate, the more likely is it that a firm will gain competitive advantage from implementing its strategies. Otherwise, should a firm's predictions fall short, then a firm's strategies are not likely to be a source of competitive advantage. However, it is often very difficult to accurately predict how competition in any industry will evolve, leading to high uncertainty when trying to choose the optimal strategy [2].

Moreover, events or scenarios that inhibit a firm's ability to execute its strategy or reach its strategic objectives are called strategic risks and have been growing a lot in attention during the past ten years [3, 4]. Since the recent global financial crisis in 2008, management teams and board of directors have learned that it is necessary to link strategy with risk management to be able to identify and manage risk in a highly uncertain business environment, to create and protect shareholder and stakeholder value [4]. Strategic risks are the biggest source of value destruction to shareholder value as it explains 86 percentage of firms' significant losses in market value during the last decade [5].

Naturally, strategic risks are of highest concern for many industries today. In fact, a global study by Deloitte grasping the opinions of 300 C-level executives shows that 81 percentage of major global companies explicitly and actively focus on strategic risk management. Rapid-fire business trends and technical innovations such as social media, mobile and big data are exposing companies to strategic risks if companies fall behind on the innovation curve. In addition, 54 percentage of major companies fear that innovative yet disruptive technologies can have negative impact on business performance and long-term business models. Hence, many companies have a broad view on risks with the purpose to optimize long-term positioning and performance [6].

Indeed, one of the most lethal risks to any successful business is technological risks. Many manufacturing firms that once relied on its technology as its primary source of competitive advantage have experienced a transformation where it became a drawback instead. In addition, empirical studies show that mature manufacturing companies struggle with exchanging its core technology for another, leaving them exposed to hazardous consequences. The awareness of such challenges has grown, and many organizations understand that the core problematic is not in the technology itself, but rather in the business model of the firm. Successful transformations have been feasible through commercial use of new knowledge developed from within the firm, and brought to market in which demand exists or will be created. It entails an application push on the market, created by a technical capabilities of the firm. If unsuccessful, it entails developing new technological attributes unwanted by customers or already invented by somebody else [7].

1.1.2 Next generation radio access networks

One major cornerstone of current technological advancement and innovation is the fifth generation (5G) of radio access networks. 5G is expected to enable full connectivity in society and to empower socioeconomic transformations that are not feasible today [8].

It has been predicted that global mobile data traffic will grow eightfold between 2015 and 2020 with a compound annual growth rate of 53 %. During 2012, the monthly amount of global mobile data traffic usage was 820 petabytes and is expected to increase to 30.6 exabytes per month by 2020 [9]. Therefore, the 5G communication systems are foreseen to provide a 1000x to 10,000x capacity increase compared to the 4G predecessor [10]. However, to meet the growing demand of data traffic, 5G networks are needed to provide enhanced characteristics compared to current network technologies. The 5G network must be able to provide much greater throughput volume, much lower latency, ultra-high reliability, much higher connectivity density and increased mobility range. In addition, the socioeconomic of 5G networks are huge. A forecast by Qualcomm predict that the 5G value chain will generate up to 3.5 trillion US dollar in revenue in 2035, and support as many as 22 million jobs. The global GDP will increase by 3 trillion US dollar cumulatively from 2020 to 2035 [11].

Today, the main control variables of global economy are human intelligence, attention, effort and time. That is about to change. The introduction of 5G is expected to underpin the fourth industrial revolution – Industry 4.0, where everything is connected, processed and digitized [11]. Heading into a true digital society and digital economy, machine intelligence will be able to replace many cognitive tasks that humans can or cannot do and improve quality of life. Hence, human labor costs will no longer drive investments and the number of jobs created will be far greater than the numbers lost due to automation [12].

However, to exploit the full characteristics and possibilities of the 5G technology, additional allocation of radio spectrum for radio access networks are needed to widen the amount of available radio frequencies on which the 5G network operates [8]. By increasing the allocation of radio spectrum to radio access networks, it could have a very positive impact on the EU economy and bring additional social benefits to EU citizens. A quantitative assessment based on scenario modelling of the economic impact showed a total net growth in GDP over nine years to 2020 ranging between 200 billions and 700 billions euro when additional 200 MHz respectively 400 MHz are allocated to radio access networks. Although the simulation results should be taken with caution since the margin of error is 50 percent, it is an indication that the impact of such a technological transformation is substantial [13].

As stated, the benefits of the new 5G network technology are enormous. However, there are also challenges that arise as the new 5G network technology emerges. New additional allocation to radio access networks are needed in order to utilize the full potential of 5G technology.

1.2 Problem analysis

Allowing radio access networks additional radio spectrum creates a new problem. Since there is only a limited amount of frequencies in the electromagnetic spectrum, the radio spectrum is a scarce resource [14]. Naturally, there is a competition for the use of spectrum between different users where regulators of spectrum management policies strive towards the most efficient use of spectrum to achieve the highest societal benefit [15].

1.2.1 A more congested spectrum

Besides radio access networks, other services e.g military radar (radiolocation), television broadcasting, aeronautical and maritime radio navigation, and satellite command and control share the radio spectrum in which all have specific allocated frequencies on which transmitting is allowed [15, 16]. However, when there is a new or increased demand for a specific radio service, for example 5G, discussions arise on how radio spectrum should be allocated for the maximized societal benefit. On national level, it is each nation's spectrum management authority that holds the responsibility for reasonable and fair allocations of radio services for the overall maximized socioeconomic gain for the nation. However, to align national differences, international recommendations on spectrum allocations are set [17].

On the international level, it is the International Telecommunication Union (ITU) that decides during World Radio Conferences which users that are allowed to transmit on certain frequencies in the radio spectrum [18, 19]. For the World Radio Conference 2019, a topic on the agenda is to discuss the possibility of additional allocation for radio access networks [20]. Due to the natural competition for radio spectrum, all actors, including the military radar industry want to protect its own interests of having enough allocated radio spectrum to perform radar operations. Since spectrum is a finite resource and allocations are made by political decisions, it is logical that all stakeholders defend the territory for any new rivalry that compete for the same resource.

1.2.2 A new kind of conflict

Conflicts can arise that concern national safety and security when radio spectrum solely allocated for military radars is considered to be shared with radio access networks. Intelligence services and military operations are dependent on the precision and accuracy of a radar system to provide military officials with critical information. Hence, the uncompromised functionality of a radar system is fundamental for national defence. In addition, military radars are not only used during warfare operations, but also to locate any target that needs tracking and provide constant surveillance. During natural disasters, or other critical rescue operations, military radars also provide support during search operations that may not be able to perform without the assistance of the radar. Overall, there are many cases where the functionality of a military radar is uttermost important to enable efficient and successful military operations. Hence, if military radars would share its radio spectrum with other users, the risk for any interference from other equipment must be rigorously studied and avoided.

One of the major players within the military radar industry is Saab Group, a Swedish military equipment provider to the Swedish Armed Forces and to foreign governmental military forces [21]. The military radars are designed for the specific frequencies in the radio spectrum that is allocated to radiolocation services (e.g. radar system with tracking of target) [16]. However, Saab experiences a push from actors within the telecommunication industry to promote increasing allocations for radio access networks in the radio spectrum [22, 23].

The conflict arise when interference between military radar systems and radio access networks occur. To mitigate interference from other systems, a military radar uses an interference suppression function, which purpose is to avoid noise from other transmitters by switching transmitter frequency to another available channel in its allocated band of radio spectrum. Hence, a wider range of available frequencies means that the radar system's interference suppression function have greater conditions to avoid noise. Likewise, should available frequency channels decrease due to more crowded spectrum, the possibility to avoid noise will minimize. If no free frequency channels are available, the radar system will not be able to avoid noise from other transmitters and the function of the radar system is ultimately eliminated [22].

Consequently, regulators increased interest in allocating radio access networks to the same system radio spectrum bands as military radars is of high strategic concern for Saab and other stakeholders of the military radar industry to secure product functionality and competitiveness. By effective strategy creation, much more than just prevent company value destruction can be accomplished; it can also help create value by taking advantage of uncertainty to maximize gains and improve competitive positioning [6]. The ability to adapt resources and capabilities to increasing spectrum scarcity is strategically important to ensure product compatibility and performance. As a provider of military radars, developing optimized products aligned with regulatory conditions is a critical competitive advantage that needs to be addressed. Hence, the objective for Saab is not only to mitigate for eventual downside, but to anticipate and welcome a shift in frequency allocations to maximize its own performance and positioning.

1.3 Purpose

The purpose is to investigate how Saab Group can adapt its resources and capabilities effectively, considering a new emerging coexistence environment due to radio spectrum scarcity driven by 5G capacity demand.

1.4 Research questions

- What are the current coexistence trends between military radars and radio access networks in the radio spectrum?
- What strategic resources and capabilities can Saab Group pursue to effectively adapt to coexistence trends between military radars and radio access networks?

2

Theoretical framework

The following sections include concepts from operations strategy and the resource based view that are applied in this research. The theoretical framework motivates the performed methodology while providing the opportunity for a more rigorous understanding of the findings and their implications.

2.1 Operations strategy

Five decades ago, a gap between corporate strategy and operations was identified, suggesting that closing this gap would generate competitive advantage. A process was proposed to identify how higher level corporate strategy can be supported by a wide set of operations in the company. The concept was named manufacturing strategy [24] and later operations strategy. Conclusions from the research was an emphasis on the strategic value of operations and that there must be some synergistic way of integrating business and operations strategic issues [25]. Operations Strategy was then further developed under a variety of similar definitions [26] and is considered to be operations' next step in maturity after a company mastered industry best practise [27].

Today, the field of operations strategy has developed into more defined working practices, with the same purpose of supporting competitiveness by consciously aligning operations with business objectives in the company. A recent definition is that Operations Strategy concerns "... the total pattern of decisions that shape long-term capabilities of any kind of operation and their contribution to overall strategy, through the ongoing recognition of market requirements and operation resources" [28, p.39]. Figure 2.1 shows how Operations Strategy concerns linking performance objectives with several decision areas to require certain resources and finally result in market competitiveness [28]. The specific performance objectives and decision areas may vary between industries and businesses and therefore calls for customization of the model. However, the process of estimating the decision areas' impact on performance objectives, given the areas' relative difficulty of change, remains an appropriate methodology for operations alignment [28].

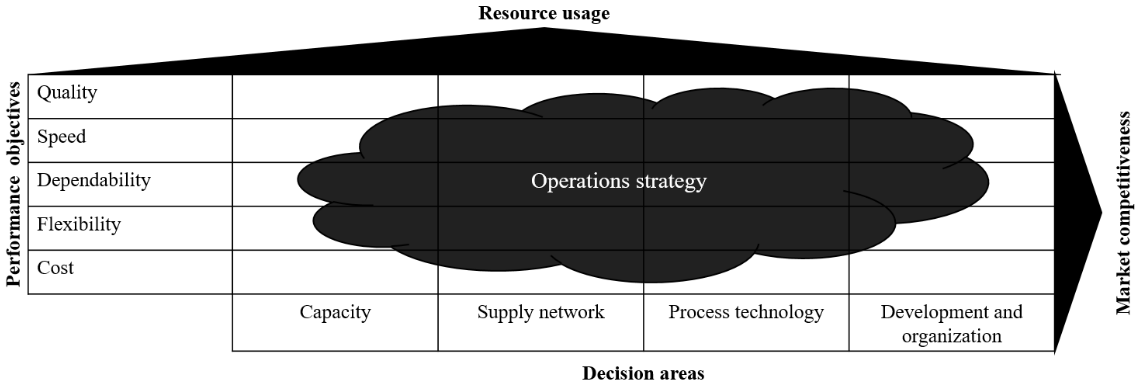

Figure 2.1: Operations strategy matrix [28].

2.1.1 Collaborate or keep internally

When deciding if a process should be performed internally or not, the company should first consider their relative capability position to competitors and the process' contribution to competitive advantage. Based on these two factors, the generic recommendation is to often keep and develop activities that can contribute to a company's competitive advantage, actively considering the process' imitability. When the company's capability position is weak combined with a non-critical process to competitive advantage, the general recommendation is to consider outsourcing and cooperation [29]. A more detailed example of the decision logic when exploring whether to keep an activity in-house is shown in Figure 2.2 below.

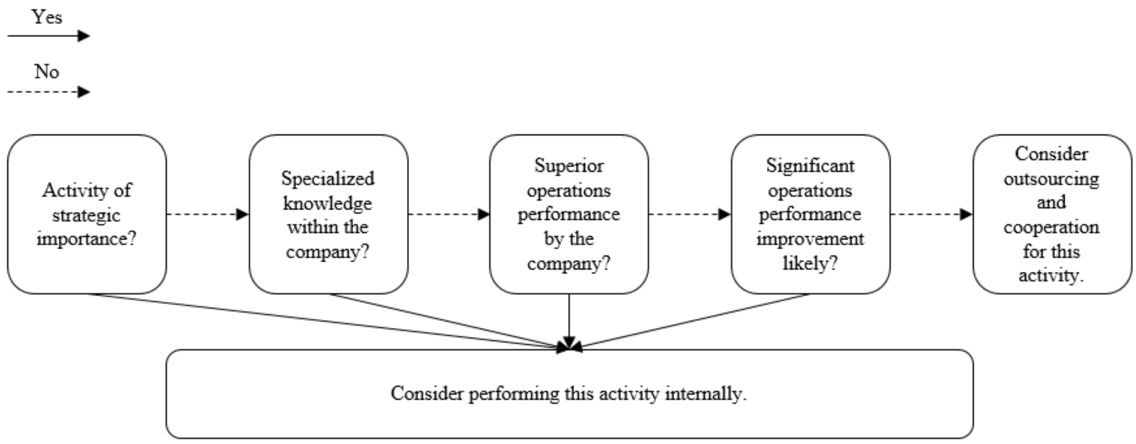

Figure 2.2: The decision logic for whether to keep internally [28].

Historically, collaborating with competitors in strategic alliances and joint ventures to acquire and develop new technologies have shown great results, although failures to build secure defences to protect own interests can have devastating long term consequences [30]. The strategic intents of alliances have traditionally often been knowledge transfer or cost-reduction [30], but more recently also to drive common innovation. Some commentators argue that innovation is no longer the province of individual firms, but depends increasingly on collective action [31]. For collaboration to succeed, each included partner must contribute with something distinctive, such as product development skills, patents, or research. There is a big challenge in transferring enough of these resources to achieve the desired synergies while also ensuring that the company does not give its rivals access to other sources to competitive advantage. It is therefore advised to carefully select desired information to share and build safeguards that prevent any other informal knowledge transfer. One approach to limit harmful transparency is to have a narrow scope of the formal agreement, for example to one specific technology. Another key activity is that top managers should create plans together with their involved internal stakeholders on what information that should not be shared [30].

2.1.2 Shifts in customer preferences

When customers decide whether to buy a certain product or service in a competitive landscape, the offers' factors that affect the customers' choice can be divided into the three categories: 1) delights; 2) order-winners; and 3) qualifiers. Order-winners are the factors that directly and significantly contribute to the customers' choice and therefore constitute the major source of competition between companies. Qualifiers are the aspects that customers require to reach a certain threshold of performance to even consider a product or service. Finally, delights are positive aspects of performance that customers have not yet been made aware of. The absence of delights will not upset the customer since they are not aware of them anyway [28].

Over time, customers' preferences change, driven by new user conditions and increased offered performance. It has been observed that time's impact on competitive benefit is generally resulting in that old delights become new order-winners, while old order-winners become new qualifiers. The relationship is shown in figure 2.3 and stresses the recognition and development of today's delights to enable successful competition with tomorrow's order-winners [32, 28].

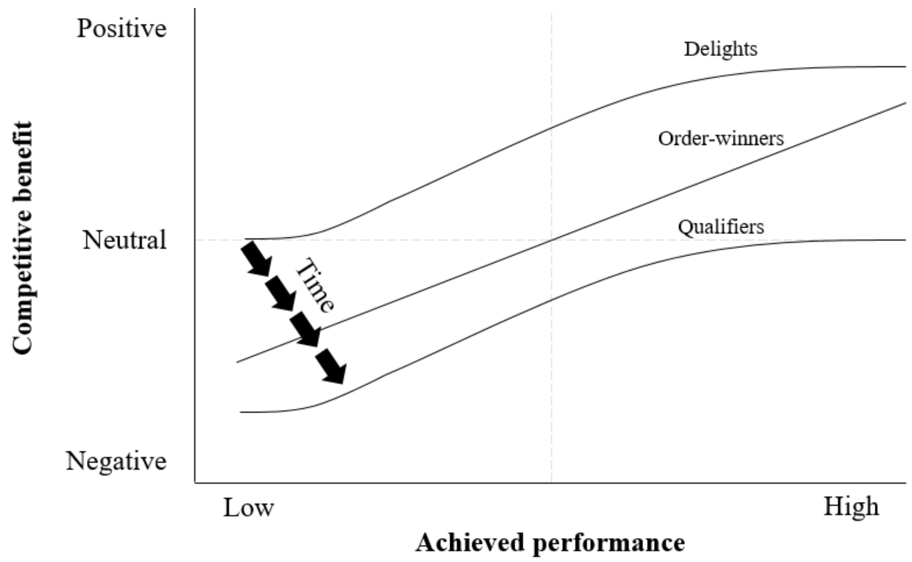

Figure 2.3: Time's impact on factors' competitive benefit [28].

2.2 Resource based view

According to the resource based view, competitive advantage is obtained by superior resources that can perform an activity better or cheaper than the competitors. The approach explains how resources drive companies' performance in a dynamic competitive advantage by combining internal and external analysis for gaining holistic strategic insights. Every company is unique, consisting of a set of physical and intangible capabilities and assets. Because of companies' varying experience, acquired assets and organizational cultures, no two companies can fully get the same characteristics. The resource based view embraces this thought and provides guidelines for how to position and diversify a company for long-term profitability [33]. The assumption of uniqueness in every company's bundle of resources is called resource heterogeneity. Another important assumption of the Resource Based View is resource immobility, which states that valuable resources may be very costly for a firm to acquire or develop certain resource that they currently lack [2].

In the resource based view, resources are defined as the intangible and tangible assets controlled by a company, that can be used to implement and conceive its strategies. Examples of resources are products, customer reputation, factories and manager teamwork. Capabilities are described as a subset of resources possessed by a company, with the purpose to maximize the advantage of the other resources. Therefore, capabilities alone can not be used to implement and conceive strategies but instead to enable a company to use its other resources for the strategic purposes. Examples of capabilities are marketing skills, teamwork and manager cooperation. To understand the different types of resources in companies, the four categories below are sometimes used [2].

- **Financial resources**, including all money from any source
- **Physical resources**, referring to every physical technology that is used by a company, e.g. plant and equipment, geographic location and access to raw materials
- **Human resources**, consisting of relationships, experience, insights, training, judgment, intelligence of individual workers and managers at a company
- **Organizational resources**, describing procedures and attributes of how individuals interact as groups, such as internal and external relations, coordinating systems, reporting structures, culture, planning and reputation

To conclude whether a resource is strategically valuable, Resource Based View uses the three traits named scarcity, appropriability and demand. These three fundamental market forces can be used to determine the value of a resource. If a resource has the characteristics below, it is considered to be strategically valuable. However it is important to consistently invest in upgrading existing resources and to develop new ones since all resources' value depreciate over time [33].

- Difficult to copy for competitors
- Depreciates slowly, i.e. has a long valuable time

- The value is controlled by the company, securing long-term possession
- Cannot be easily substituted
- Better than competitors' similar resources

2.2.1 VRIO framework

Based on the resource based view, a framework named VRIO (Value, Rarity, Imitability, Organization) was created to assess a company's resources and their potential to generate competitive advantage. If all the VRIO attributes are present for a resource, it is considered to constitute a competitive advantage. If it is shown in an analysis that all attributes are not present, the VRIO framework can be used as a guide to develop these traits [34]. Below, brief descriptions of each characteristic is described with key questions to ask in a VRIO analysis. If the answer to a key question is yes, then the resource has that attribute [2].

- **Value**, determines whether the resource is an internal strength or weakness. A way to examine the value is to think of the resource's potential impact on revenues and costs when used
  Does the resource enable the company to neutralize an external threat or exploit an external opportunity?
- **Rarity**, describes that competitive advantage for one company is unlikely to originate from a resource that many its competitor also possess
  Is the resource controlled by only a small number of competing companies?
- **Imitability**, refers to that a resource is not a sustainable competitive advantage for a company if its competitors can develop or obtain the same resource without a cost disadvantage. Cost disadvantages can emerge from unique historical conditions, causal ambiguity, social complexity and patents
  Do companies without the resource have a cost disadvantage in developing or obtaining it?
- **Organization**, emphasizes that a company must organize to exploit a resource to fully realize its potential
  Are procedures and policies at the company organized to support the exploitation of the resource?

2.2.2 Dynamic capabilities

Despite the significance in the resource based view, it has been criticized for being conceptually vague with inattention to the mechanisms by which resources actually create value [35]. To further understand the sources of sustained competitive advantages in today's rapidly changing market environments, the resource based view developed a concept named dynamic capabilities. The concept is intended to explain the gap in the Resource Based View concerning why some firms seem to have an advantage over their competitors when their markets experience rapid and unpredictable change [36]. The dynamic capabilities are shown in a firms ability to integrate, build, and reconfigure external and internal competencies to address a changing environment [37].

Dynamic capabilities are viewed as the drivers behind achieving and exploiting competitive advantage from the creation, evolution and recombination of a firm's resources [38]. The dynamic capabilities are strategic and organizational routines by which managers generate new value-creating strategies from acquiring, shedding and combining resources [39, 40]. The new value-creating strategies are based on new resource configurations as markets evolve, split, collide, emerge and die. Business implications from the dynamic capabilities perspective include that companies should actively manage their processes, such as product development, to promote a rigorous knowledge combination from various key backgrounds to identify new market trends. In short, dynamic capabilities can be summarized as routines to learn routines [36].

2.3 Patent strategy

In the resource based view and VRIO framework, patents are considered to be one of the major sources to limit a resource's imitability and thereby increase its potential competitive impact [2]. In today's business environment, ownership of valuable parts of intellectual property is an important battleground for achieving competitive advantage [41]. However, a patent does not guarantee any type of market monopoly, instead it provides the inventors with the right to exclude others from using an invention for a limited time, according to its boundaries. To be awarded a patent, the invention must make a useful, significant, and novel advance over existing knowledge. Only the novel features are patentable [42].

Since patent protection is often imperfect and unclear [43, 44] in combination with that firms have historically frequently been able to invent around patents [45], successful patent strategies often include building patent fences and investing in active infringement investigations [42]. Furthermore, capabilities that have been shown to be important for the outcome of patent strategies are occurrence of patent attorneys specialized in the concerned technological areas and supportive organizational conditions such as patent knowledge in top management [46] and an optimal cross-functional coordination between technical and legal expertise to effectively translate the respective implications [47]. Research have also shown a correlation between how much of the patent work a firm performs in-house and the development of the firm's own patent strategy-related capabilities. A high degree of outsourced legal work often imply a long-term negative effect on patent strategy performance [48, 49].

Aggressive patent strategies based on strong patents can bring value to a firm in multiple ways. Besides acting as an imitation barrier, it can also facilitate the exploitation of the invention in licenses and alliances with other firms [50, 51]. Furthermore, solid patent protection can help a firm to maximize the benefit from an invention by both commercialization with own assets and by licensing to obtain desired resources owned by other firms [52, 53].

Another area where patents and firms' value creation are closely linked is in the creation of technology standards. By including patents in the development of cooperative standards, the subsequent innovation built on them increases [54]. Thereby, the technological result is likely to be improved with increased possibility to become the industry dominant design. However, there is an obvious trade-off for the included companies since the cooperation commits firms to giving up rights and remedies that was available through their patents. Therefore, companies with clearly superior technology have been shown to be less likely to participate in cooperative standards [55]. Yet, a company with a strong patent position included in the creation of cooperative standards is likely to obtain a favourable network position and high market power [56, 57]. Finally, since a strategic cooperation generally enhances the performance and market deployment of a certain technology and invention, the companies owning the patents can experience wide licensing and commercialization that can benefit the company [58].

3
Methodology

In the methodology chapter, the project's performed steps are presented and motivated. Furthermore, research quality is discussed followed by ethical considerations.

3.1 Research design

The research design provides a framework for how to collect and analyze data. Hence, the choice of research design reflects the level of priority given to a range of different dimensions in the research process. These include the expressing of causal connections between data, the level of generalizing to larger groups than those included in the actual research and understanding social phenomena in its specific context [59]. In this research, a case study design at Saab was attractive to deploy since it was Saab who initiated the research. Thus, it was a natural fit to study the subject of the research through its contextual environment.

To grasp a good overview of the study, the research process can be divided into four main stages: 1) formulate research questions; 2) data collection; 3) data analysis; and 4) writing up and conclusion. The process is inspired by a general six-step approach that is commonly used in qualitative business research. Similar to qualitative research, the process is very iterate where stages are revised several times along the process. Most revision is done between the second and third stages, where collection and analysis of data overlapped each other. Also, formulating research questions was highly iterative, as the scope of the research changed many times along its progress, which is a common trait for qualitative research [59].

1. **Formulate research questions:** The research began with a process of identifying what problems that will be addressed and determine the scope of the research. A preliminary scope for the research was set together with stakeholders at Saab, since the organization had a clear purpose to direct the scope of the study. However, the final research questions were not set until October - the very last weeks of the research process.

2. **Data collection:** The second stage of the research was to find the right kind of methods for extracting the needed data. To do that, both research questions were carefully studied. The main difference between the questions was

the level of generalizability. The first question embraces a larger subject group as it has a broader scope. That leads to a greater ability to generalize the results. The second question is on the other hand more focused on Saab and thus limited to a smaller subject group leading to a lesser degree of generalizability. The broader scope of the first question called for more rigorous data collection methods, since a broader scope was believed to be more difficult to answer effectively. Hence, it was decided that each question should be treated separately with different methods, putting the right amount of resources on each question to efficiently answer both.

A data collection plan was set in early in the project, determining what kind of methods that would be useful to capture the right data in a suitable way. To answer the first research question, it was decided that a documentary research together with a delphi study would be a good choices to deploy. The documentary research generated qualitative secondary data while the delphi study generated primary data of both quantitative and qualitative nature. Both methods were comprehensive to execute and are presented in further detail in section 3.2 and 3.3. To answer the second question, primary data were obtained through semi-structured interviews with technology experts, employed at Saab. More details of the interviews are presented under section 3.4. Additional data that were used for answering the second research question was the outcome from the documentary research and delphi study, in combination with the theoretical framework.

3. **Data analysis:** The output from the first research question gave an understanding of where the trend of coexistence was heading. The findings from the first question were then analyzed and used as input to the second question. The results from the second question were analyzed with the theoretical framework. Hence, abductive reasoning was conducted, as the researchers aimed to arrive at the best explanation given the data obtained from the documentary search, delphi study and interviews with Saab employees. Back-and-forth engagement with the empirical world in combination with literature theory was done as cognitive reasoning has high importance to arrive at a conclusion that most likely explain the studied phenomena [59].

   Saab's internal technologies were analyzed with the VRIO framework to evaluate the technologies potential to create competitive advantage. Cognitive reasoning, considering the findings from the delphi study and possible coexistence methods derived from the documentary research, were used as a basis for assessing Saab's resources and capabilities. The aim was to conclude which resources and capabilities that would prove to be the most valuable for Saab as a competing firm.

4. **Writing up and conclusion:** The research were finalized with a summary of the process of the whole study and the conclusions derived from the analysis. In addition, a check was done to ensure that the research questions had been successfully answered. To match the conclusion with the questions, small changes were made on the research questions. When the questions were successfully answered, two reports were written: one for Chalmers University of Technology and one for Saab, as requested. The reason for two reports was that confidential information in the Saab report are not allowed to be published.

3.2 Documentary research

The main sources of secondary data to the project was the online library at Chalmers University of Technology and University of Gothenburg. The purpose of the documentary research was to map the trend of radio spectrum coexistence and to develop a rigorous understanding of relevant subjects for creating the delphi study. The literature research was further guided by reading tips from delphi and technology experts.

Since coexistence technologies were studied based on a the VRIO framework, a patent search for each technology was performed. The online Espacenet patent search engine was used for this purpose by entering chosen keywords from the technology expert interviews.

To study a selected number of nations' potential differences in frequency allocation compared to the United Nations' radio regulations, the latest published national frequency allocation plan was downloaded from each nation's frequency regulator's webpage. Ten countries were chosen by Saab due to Saab's interest in those countries. The chosen countries were the United States of America, Brazil, United Kingdom, United Arab Emirate, India, Indonesia, Japan and Australia. The allocations 3300-3400 MHz and 5250-5850 MHz includes military radar allocations and were studied for ITU's radio regulations' three world and the selected nations' frequency allocation plans.

3.3 Delphi study

The project's first research question concerns building knowledge for understanding the trend of radio spectrum coexistence. Since the situation is complex and without predecessors, a method for capturing expertise to forecast likely outcomes was desired. For that purpose, the delphi method was chosen. The delphi method has proven to be a powerful tool for organizations when tackling significant decision-making that will affect future directions for a company. The method comprises of an iterative process where experts are selected, asked questions and where the answers are analyzed to reach a prediction consensus as well as capturing where answers deviate [60]. In the following subsections, the different steps in the projects practical usage of the delphi study are presented, from choice of experts to design of questionnaires and collection of responses.

3.3.1 Choice of expert panel

Initially in the delphi study process, expert categories were created to represent the various key viewpoints on the radio spectrum situation, focused on potential coexistence between military radars and radio access networks. The five categories that were created are listed and motivated below.

- **Academic researchers**, were included because of their high degree of expertise and objectivity in research regarding spectrum allocation and development.
- **Telecommunication services** were included since they constitute one of the most affected stakeholders in the coexistence trend's development, with high incentives for effective sharing.
- **Radar equipment providers** were included since they provide a deep understanding of technical challenges and implications from a shared radio spectrum environment.
- **National defence** was chosen as a category because of their knowledge of national security concerns that can affect the future possibilities in radio spectrum coexistence.
- **Regulators** were a natural category since decision-makers at international and national level create recommendations and regulations for how the spectrum should be managed. It is the regulators role to maximize the societal benefit from the scarce frequency natural resource, requiring rigorous expertise of all the various implications of their decisions.

There is no one sample size advocated for delphi studies, instead, the careful selection of appropriate experts is the foundation to reliable results [60]. In this project, two experts were chosen in each category, except for the researchers category where six experts were included. The experts were selected based on their level of expertise within the frequency spectrum field and incentives to contribute to the project. The reason why the researchers category included more experts than any other category was a combination of many willing contributors and their high level of knowledge within the spectrum allocation field. The participating experts in each category are listed below, where anonymous imply that the expert chose not to be named in the thesis report.

- **Academic researchers**
  Martin Weiss, University of Pittsburgh
  Marja Matinmikko-Blue, University of Oulu
  Rob Nicholls, UNSW Business School
  Pierre de Vries, University of Colorado
  Bill Lehr, Massachusetts Institute of Technology
  Anonymous, Technical University
- **Telecommunication services**

Lasse Wieweg, Ericsson
Anonymous, Telecommunication Company
- **Radar equipment providers**
  Magdalena Letsche-Nüßeler, Dr. Christoph Fischer, Hensoldt
  Kjell Harald, Saab Group
- **National defence**
  Hans Sundkvist, Swedish FMV (Defence Materiel Administration)
  Per Nordlöf, Swedish Armed Forces
- **Regulators**
  Jonas Wessel, Swedish PTS and European RSPG
  José Costa, ITU-R

3.3.2 Questionnaire design

The choice for a questionnaire format was made to facilitate the data collection and analysis, as a questionnaire is often faster and easier to manage compared to traditional interviews [59]. One main advantage was that no physical meetings were necessary and the respondents could decide when to answer the questions. Hence, there were no need to book a telephone meeting either.

The questions were developed in collaboration with the main stakeholder at Saab and revised by the supervisor at Chalmers. The questionnaire was then transferred into SurveyMonkey, as it is an easy-to-use platform for managing surveys on the internet [61].

The development of the questions' format was often based on a Likert scale, which is a commonly used format for questionnaires [59]. Hence, the format allowed the respondents to read a statement and then fill in to what degree they agreed with that statement. The levels of agreement were: strongly agree, agree, neutral, disagree and strongly disagree. Hence, the questions were asked in a way that would generate quantitative answers, which would be convenient for the expert panel to answer quick and facilitated the researchers' data analysis. There were also questions that used the Likert scale as a basis to develop similar answer alternatives, such as Very likely, Likely and so forth. However, some questions had an open format which enabled free expression, in cases were a suitable statement was impossible to formulate. Overall, the development process to arrive at final questions that would be sent to the expert panel would take several weeks to complete.

3.3.3 Collection of responses

SurveyMonkey was used as a means to ask the prepared questions and to enable the respondents to answer. The respondents filled in the survey online which means that the collection of answers was made relative easy as every response was automatically collected directly after the respondent was finished with the survey. However, when respondents did not fill in the survey, reminders had to be made by phone calls and e-mails.

When the first delphi round was completed, the input from round 1 was analyzed and new questions were developed based on the findings. The aim was to dig deeper into questions and answers that could have had a different interpretation among the group. In addition, new questions were developed to find the root cause of why respondents answered in a particular way. The questions for both delphi rounds can be found in Appendix A.

3.4 Technology expert interviews

Besides the delphi study, additional data collection was necessary to effectively answer the second research question. The interviews targeted various experts in different engineering areas and radar technology at Saab. The main outcome was an understanding of what internal capabilities that Saab can leverage to effectively adapt to a future spectrum coexistence environment. Hence, the focus of the interviews was to ask questions based on coexistence potential and not include a too technical scope.

The interviews were chosen to be semi-structured with a prepared question sheet to guide the interviewers, but it had not a too narrow focus on the questions. A total of six experts were chosen by the main stakeholder at Saab. Interviews were conducted separately where each interviewee had an own technology area to address. The answers were documented directly during the interviews and a summary of each technology was later written. The summaries were then e-mailed to respective expert to verify that the content was accurate and true.

In collaboration with the main stakeholder at Saab, a total of six technology areas were derived to address:

- **Continuous arbitrary waveform**
- **Orthogonal waveform**
- **Digital radar**
- **Front-end technology**
- **Multifunction system**
- **Adaptive interference suppression**

These areas were chosen to investigate further, based on potential for future coexistence between military radar and radio access networks. The used semi-structured questions can be found in Appendix C.

3.5 Quality of research

Prior, during and after the research, quality of the thesis was assessed and improved guided by the five criteria: 1) credibility, 2) transfereability, 3) dependability, 4) confirmability, and 5) authenticity. The five criteria were chosen since they are suggested by business research literature to provide a complete and rigorous understanding of qualitative research quality [59]. In this section, concerns for each criterion is discussed together with performed effort to promote high quality results.

3.5.1 Credibility

Credibility is about ensuring that the research follows good practice, which is why this research applied respondent validation and data triangulation [59]. Respondent validation was performed by providing all Saab employees that gave input to the project with the opportunity to give feedback and revise the projects usage of their expert knowledge. By its design, the delphi study also gave the panel experts the opportunity to comment on the interpretation of their contribution both in the second round of questioning where the first cycle's findings was summarized and in an e-mail once the delphi study was completed. Data triangulation is also an integrated part of the delphi study since multiple experts with different backgrounds are used to reach a common understanding. The aim with high credibility is to maximize the research's potential to describe events trustworthy and correctly [62], which is aligned with the projects usage of many references to academic literature, often published in high quality journals. One issue for the project's credibility is the evaluation of technologies' potential to aid coexistence since they rely on few individuals' assumptions of uncertain circumstances.

3.5.2 Transfereability

Transfereability concerns the degree that findings from the research can be generalized to other settings which is why thick descriptions are included in the report to provide the reader with the possibility to make own judgments of whether it can be generalized [59]. This research, together with most qualitative research [59], has contextual uniqueness which complicates the development of generic findings that can be used in other environments. It is important to note that the research is closely linked to both Saab with knowledge about the international frequency policy development from a Swedish perspective. It is also important to note that the research was performed between May and October 2018 since the studied system of international frequency management is constantly under development. Finally, as mentioned in the Section 3.1, the first research question is considered to be more generalizable to other settings because it is not specified for one specific stakeholders viewpoint.

3.5.3 Dependability

Dependability refers to the importance of being clear and rigorous in the description of the research process and documentation, thereby maximizing the probability that another research group's attempt to replicate the project would derive similar results [63, 64]. As often experienced in qualitative research, the high level of desired documentation was challenging due to very large data sets [59] and also because of confidentiality. Part of the documentation from the project, especially concerning the technologies and the strategic recommendations for Saab is not be allowed to be shared with external researchers. However, the carefully described research design with its included steps enhances the likelihood of similar replication results of the project.

3.5.4 Confirmability

Confirmability contains how the project group acted to minimize the risk of bias to stay objective throughout the process [65, 59]. Since the project was not only supported by Chalmers University of Technology but also by Saab, there was a risk that the project group's judgment could be influenced by the company's interest of the outcome. However, no such pressure was experienced during the project. In the strive for high confirmability, both researchers were included in all decisions regarding the content in the thesis and close relationship with supervisors at both Chalmers and Saab were maintained. Finally, the theoretical framework was created from many sources on similar topics to mitigate the risk of building on bias from previous research.

3.5.5 Authenticity

Authenticity as a criterion is a wide instrument for reflecting upon the political impact of research. It includes fairness, which concerns whether the research fairly represents the various viewpoints on the studied setting [59]. Since the studied setting in this research comprises of stakeholders of the international usage of spectrum with focus on regulators, military radar providers and radio access networks, it is important that these different viewpoints are included. In the choice of panel experts to the delphi study, an even proportion of representatives from regulators, military radar, national defence, telecommunications was included. By doing this, a fairly representative common understanding could be derived while identifying and capturing where the stakeholders viewpoints deviated. Although the researchers had better insight in the frequency coexistence preconditions for military radar than for radio access networks, it is not believed to have led to any significant compromises in the fairness of the outcome. Viewpoints that are not included in this research that would be interesting are more countries' regulators, other radar and telecommunications companies and more users of radio spectrum that could potentially be included and affected by an increasingly shared spectrum environment.

3.6 Ethics of research

To guide and evaluate the ethics in research, four ethical principles have been used in business research literature: 1) harm to participants; 2) lack of informed consent; 3) invasion of privacy; and 4) deception [59]. The four criteria have been applied in this study as well, where the following discussion evaluates the application and presence of each ethical dimension.

Harm to participants entails not only physical harm but also harm to participants' self-esteem, career prospects or unwanted stress. For most business research, any harm to participants is unacceptable [59] and that is why this study was conducted to avoid any harmful interference with participants to the largest possible extent. Hence, the expert interviewees remain anonymous since their own sensitive opinions, especially regarding Saab's organizations are not meant for others to read, but should remain disclosed to this study only.

Lack of informed consent is an issue within business research that is often debated where the bulk of the discussion is focused on covert observation. Such observations are made when the observer is unknown to the subject which could be an ethical dilemma if the participant does not want to take part in the study. In such cases, it is impossible to inform the subject of the research and thus ask for consent to observe [59]. No covert observations were necessary in this study so the lack of informed consent dilemma was never in question. Instead, all participants were informed that their statements would be collected and used in research purpose. Participants were also informed on the purpose of their engagement or how their input would be managed.

Invasion of privacy for any study has the objective of not giving researchers a special right to intrude on a respondent's privacy nor to abandon normal respect for an individual's values. It is often a bigger issue in covert observations or similar methods were the studied group of people are not aware about the objective of research at all [59]. However, in this study, no covert method was used and no invasion of privacy was done. Instead, the informed consent notion was widely used, which is the act of informing participants about the study and to describe the purpose of the research.

Deception is the last of the four ethical principles and deals with deceiving participants to believe something else, having a hidden agenda or own interests. This is also connected to the morale principles of humans and this research should not thrive to deceive any individual [59]. Hence, any risk of deception should be minimized which was also aimed at in the project. In addition, Saab has a code of conduct, company confidential information and national defence security information that have been respected. Before the research was initiated, a silence agreement on company confidential information was signed between the researchers and Saab Group.
tabu

4

Results

This chapter presents the collected data from the documentary research, delphi study and technology expert interviews.

4.1 Findings from documentary research

In this section, findings from the documentary research are presented. The different subjects are all relevant for understanding the trend of radio spectrum coexistence, since historical data of international frequency allocation and previous research on the subject should be used as a basis for qualified predictions. The section starts by presenting the way spectrum is allocated today in the command & control model, followed by the alternative commons model. After that, the main results from the comparison between national frequency plans and ITU's international recommendations are included. Then, the demand for spectrum coexistence and the currently implemented Dynamic Frequency Selection (DFS) are discussed, before the efforts towards coexistence from the Institute of Electrical and Electronics Engineers (IEEE) Standards Association and the US are summarized. Finally, the documentary research presents different possible methods for radio spectrum coexistence and a recent initiative for coexistence, coordinated by the European Defence Agency (EDA).

4.1.1 Command & Control model of frequency allocations

Spectrum allocation is still managed by the old principles agreed upon 1927 during early international radio regulations. The global level of spectrum management is governed by the ITU, a United Nations special agency. More specifically, the radiocommunication sector of the ITU (ITU-R) is responsible for developing and adopting the radio regulations - a binding international agreement with rules, recommendations and procedures on how radiocommunications should be regulated. The radio regulations are set based on avoidance of radio interference between users of the spectrum and is therefore divided into separate bands of frequencies allocated to a specific kind of radio service. The radio regulations also defines what harmful interference is. The definition of harmful interference is "interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with radio regulations". Furthermore, the problems of harmful interference are to be resolved on the basis of goodwill and mutual assistance [66].

The radio regulations are updated every three to four years at world radio conferences in response to changes in needs and growing demand of radio services [17, 67, 16].

As the radio regulations are an international treaty, national differences in spectrum allocations are allowed. However, should an individual country deviate from the international radio regulations, and allocate some or all of the frequency bands to other radio services, it must secure that no harmful interference is caused to services in neighbour countries that follow the radio regulations. It is the national spectrum management authorities that assigns operating licences to service providers, based on the spectrum allocation plans [17, 67]. In Sweden, the Post and Telecommunication authority (PTS) works with spectrum allocation with the goal of maximizing the societal benefits from radio frequency allocations and to promote a fair market for electronic communication with sound competition [68]

In the traditional command & control model, the spectrum management authority makes all decisions regarding spectrum allocation and spectrum compliance. Hence, this model is commonly referred to as the command & control model due to its bureaucratic approach [17, 69]. The model prevents interference as it divides the spectrum into fixed frequency bands that are exclusively assigned specific kinds of radio services for each band. However, it prevents a more efficient use of spectrum as its design is based on static spectrum management, unable to adapt to changing needs of spectrum usage. As the rights to the spectrum are fully assigned, significant parts are still unused in practice [69].

The main limitation of the command & control model are: 1) parts of the assigned spectrum are hardly used; and 2) the method is slow in responding to changes in market and technology [17]. These shortcomings were accepted during the time when the command & control model was introduced in the late 1920's. As demand grew, there were still unassigned frequencies to use, meaning no real concern of economic efficiency nor resource scarcity existed. However, recent demand has grown very rapidly and has caused spectrum management authorities to run out of usable spectrum to assign for new service and technology providers. Hence, new services need to be introduced at the expense of existing incumbents [17].

4.1.2 Commons model - no licences

An alternative to the command & control model was introduced in the 1980's based on a spectrum commons. A few frequency bands were assigned for unlicensed use by specific types of radio-communication services. These bands were thought to provide open access to all incumbents in the current band given that some rules were followed. Techniques such as reduction of power output level to equal level needed, listen-before-talk, selection of free frequency channels and modulation types robust for interference are all examples that would facilitate a reduction of interference in the commons model [17, 69].

Unlicensed bands became popular for new kinds of radio services, operating with short range and had numerous devices, such as wifi systems. The success of systems operating in a license-exempt environment advocated for an approach where much more spectrum is made unlicensed. Proponents of the approach based on a common share of spectrum relied on that advancement in technology would solve any issue with spectrum sharing, without making spectrum exclusive to specific services. Generally, the commons model has the following two characteristics [17]:

1. Smart radios are used with built-in techniques and rules to reduce interference
2. Everyone can use the spectrum as long as the rules are followed

By implementing shared frequencies in accordance with the Commons model, spectrum can be used more efficiently with overall more used spectrum per time unit. Geographical and timing-based agreements have the potential to be a basis for promoting the spectrum efficiency, resulting in the possibility of more and better services [69].

4.1.3 Sample of national frequency allocation plans

From comparing the selected sample of countries' frequency allocation plans with ITU's radio regulations, it was shown that most nations followed the radio regulations general recommendations to a large extent. The frequency allocation plans in Sweden, United Kingdom, United Arab Emirates, Japan, Indonesia, India and Australia included some minor differences from ITU's general recommendations. However, the radio regulations have footnotes that present deviations for specific countries, where most of the differences from the mentioned countries were listed with the additional allocations. Only a few services deviated, and those services were not fixed or mobile services, which constitutes radio access networks. Hence, most allocations that were analyzed could all be found within the radio regulation document. The full comparison between individual countries' frequency allocation plans and ITU's radio regulations can be found in Appendix D.

4.1.4 The importance of spectrum coexistence

Since the early radio regulations were made, technology and demand for radio services have developed very rapidly. As mentioned in the introduction, a prediction from Cisco shows that global mobile data traffic might grow eight-fold between 2015 and 2020 with a compound annual growth rate of 53 %. The global data usage each month during 2012 was 820 petabytes, which is predicted to be 37 times larger at 2020 [9]. Another prediction, showing the need for more efficient use of spectrum is that the 5G networks are foreseen to provide a 1000x to 10,000x capacity increase compared to the 4G predecessors [10]. The predictions stress the importance of that all existing incumbents make efforts to be more efficient in their use of spectrum, contributing to the overall societal benefit from the scarce frequency resource. Today, radar services have broad frequency bands allocated as primary service [70], while at the same time leaving many allocated frequencies unused at a given time.

The radar frequencies are also desirable for radio access networks and implies that attempts to share frequencies between the services could be beneficial [71].

4.1.5 Dynamic Frequency Selection

In practice, historical attempts of spectrum coexistence between military radars and radio access networks have been primarily managed by the concept of DFS. DFS is a method for primary and secondary users to coexist on the same frequencies, by setting rules for secondary users' behaviour, to ensure that interference with primary services is avoided. Early development of DFS came from the European Conference of Postal and Telecommunications (CEPT) in 1999, when they decided to introduce High Performance Radio Local Area Networks (HIPERLAN) into a total of 455 MHz of spectrum, under conditions of power levels, DFS and Transmit Power Control (TPC). The affected frequencies included 5150-5350 MHz, where the concerned devices were restricted to indoor use only and limited to 200mW equivalent isotropically radiated power. In the range 5470-5725 MHz, outdoor operation was allowed with power levels up to 1 W equivalent isotropically radiated power. For operating in 5250-5350 Mhz and 5470-5725 MHz, TPC and DFS were required [72].

During the coexistence development at CEPT, the European Telecommunications Standards Institute drafted the first DFS conformance specifications. Even though the standard was only intended for HIPERLAN in the beginning, the success of IEEE 802.11 technologies resulted in Europe's first version of a technology neutral standard, EN 301 893, to national voting before ITU'S world radio conference 2003 [72]. The world radio conference 2003 decided that the 455 MHz within 5150-5350 and 5470-5725 MHz bands would allow Wireless Access Systems (WAS) including Radio Local Area Networks (RLAN) with non-interference conditions. Current incumbents in these frequency bands consisted of military, weather and satellite radar. To ensure that WAS including RLAN did not interfere with these users, a DFS mechanism was introduced for detecting radar emissions and changing frequencies. The DFS mechanism require the secondary users to perform a channel availability check continuously to sense if a radar is present and switch channel within 10 seconds if they sense radar activity [73]. Summarized operating requirements for the secondary WAS including RLAN services are presented in table 4.1 below. Further details about DFS can be found in recommendation ITU-R M.1652 [74].

Table 4.1: Summary of DFS requirements for WAS including RLAN

Parameter	**Value**
DFS detection threshold	–62 dBm for devices with a maximum e.i.r.p. of < 200 mW and –64 dBm for devices with a maximum e.i.r.p. of 200 mW to 1 W averaged over 1 μs
Channel availability check time	60 seconds
Non-occupancy period after radar detection	30 minutes
Channel move time	Within 10 seconds

Although the DFS requirements for WAS including RLAN were created to avoid interference with radar equipment, military radars have shown to be more complicated to coexist with, primarily because of limited operation transparency and the radars' frequency hopping. It is often national safety and security reasons that motivate the low transparency regarding how military radars operate. The frequency hopping is a mechanism that makes the radar rapidly and unpredictably switch operating frequencies to make the system more difficult to detect and actively interfere [72]. Since the DFS recommendation was first published by the ITU, it has been revised and updated [75]. However, coexistence problems between radio access networks and radar in parts of the 5 GHz band continues to be reported worldwide. In 2018, there is still a need for developing better coexistence mechanisms between unlicensed users and radars in the 5 GHz band [73]. Discussions considering the existing DFS and future sharing possibilities will be discussed during ITU's world radio conference 2019 [20].

4.1.6 IEEE standardization for coexistence

The IEEE Standards Association is an organization within IEEE that develops global standards in a broad range of industries, by which telecommunication is one industry. These standards are published documents that establish specifications and procedures designed to maximize the reliability of services like wired and wireless communication [76].

Early coexistence standards in 1999 provided methods to measure and mitigate interference through manual coordination. Since then, extensive development have been made to standards related to coexistence between different users [77]. The working groups within IEEE 802 which are developing standards for unlicensed wireless network are [77]:

- IEEE 802.11 Wireless Local Area Networks (WLAN)
- IEEE 802.15 Wireless Personal Area Networks (WPAN)
- IEEE 802.16 Wireless Metropolitan Area Networks (WMAN)
- IEEE 802.22 Wireless Regional Area Networks (WRAN)

The IEEE 802.15 standard was among the first to include coexistence since WPAN protocols required to share the same unlicensed band (2.4 GHz) used by IEEE 802.11 (WLANs). In particular, techniques such as DFS and TPC were developed and standardized to deal with coexistence issues. However, the most important application of coexistence protocols arise when users are incumbents of licensed bands where the primary-secondary user rights apply [77].

The true potential for coexistence schemes were discovered when it was found that large segments of the allocated spectrum are not utilized in different geographic locations. A first attempt in may 2004 when FCC (US) announced the use of unlicensed wireless operation in the analog television (TV) bands VHF and UHF (54–862 MHz). IEEE 802 standards committee created 802.22 working group on WRANs with cognitive radio air interface for license-exempt devices on a non-interfering basis. Hence, the IEEE 802.22 standard for WRANs was the first cognitive radio-based international standard with radio frequencies allocated to its use [77].

As the demand for more frequencies grow, the need for suitable coexistence techniques increases [73, 78]. The IEEE 802.11 standard, commonly referred to as the Wifi standard, has rapidly expanded in the 5 GHz spectrum bands. The 802.11a, 802.11n and 802.11ac devices currently operate in parts of the 5 GHz bands in US. Additionally, the 802.11ax standard is being developed for operations in these bands. As per the radio regulations, unlicensed devices can operate in these frequencies as long as they do not interfere with the incumbent users of the spectrum, e.g. radar systems. Devices must use the DFS mechanism to detect presence of any operating radar and avoid transmission in the same radio channel [73].

4.1.7 US' efforts for radio spectrum coexistence

Already in 2000, the US industry prepared to enter the worldwide market with products designed for IEEE 802.11a standard and the industry was ready for the various possible sharing scenarios and rapidly adopted performance to fulfill potentially varying DFS requirements. The US industry was prepared for emerging requirements and the country was early to implement DFS sharing and thereby promoted the international ITU recommendation of DFS that followed [72].

In 2010, a presidential memorandum named "unleashing the wireless broadband revolution" was issued to make 500 MHz spectrum available over the following ten years on exclusive license base or on a shared access. The National Telecommunications and Information Administration (NTIA) was directed to collaborate with Federal Communications Commission (FCC) to commonly achieve the goal. In 2013, an additional presidential memorandum named "expanding America's leadership in wireless innovation" was created, with the purpose to identify opportunities for sharing spectrum that was currently allocated for federal agencies. Based on the results, the Department of Defence (DOD) issued "a call to action" which led to an auction to license the 1695-1710, 1755-1780, 2155-2180 MHz frequencies to wireless operations which generated more than 42 billion dollars in net profits and required some federal systems to reallocate to other frequencies. In 2015, the DOD expressed strong interest in developing effective spectrum sharing techniques which was later studied by NTIA and FCC, where the 5GHz radar frequencies were included. Recent studies imply that the radar bands 3.55-3.7 and 5.15-5.925 GHz are the main focus areas to share for the overall development towards efficient spectrum usage, where cognitive radio is considered to be a likely enabler [79].

After recent coexistence advancements, the 3.55-3.7 GHz band, called the Citizen Broadband Radio Service (CBRS) band, will allow coexistence. CBRS divides users into three tiers: incumbent access, priority access, and general authorized access. The incumbents access users includes authorized federal and grandfathered fixed satellite service users, which will be protected from harmful interference from other users. The Priority Access tier consists of licenses that will be assigned using competitive bidding within the 3.55-3.65 GHz frequencies. Each license consists of 10 megahertz of spectrum and there are rules limiting the number of licenses per user. Finally, the general authorized access tier is licensed-by-rule and permits open, flexible access to all potential users. Users are allowed to use any portion of the 3.55-3.7 GHz band not assigned to higher tier users and can also operate on unused spectrum held by priority access tier users [80].

4.1.8 Possible methods for spectrum coexistence

Dynamic Spectrum Access is a means to access parts of the spectrum that is currently not utilized. These parts are called white spots and are frequencies assigned to a primary user but are, at a specific time and geographical location, not being used by the primary user. The objective of dynamic spectrum access is to make White Spots available to other users during that time. This implies that secondary users are allowed to operate in that bandwidth as long as no harmful interference is inflicted upon the primary user and the primary user shall always have access priority to the spectrum [17].

There are several general methods that may achieve a primary-secondary spectrum sharing between military radars and radio access networks. These methods can be classified as coordinated or uncoordinated given the level of required information exchange between the radar and radio access network [71]. Seven methods have been recognized as feasible spectrum sharing methods and are summarized in table 4.2.

The following three methods are coordinated methods, meaning that military radars and radio access networks need to exchange a certain amount of information between its system.

- **Location-based methods:** location information exchanges between radar systems and radio access networks may enable a better utilization of the spectrum. Specifically, location information about the radio access network is used by the radar to adjust waveform design, target state estimation and power allocation. Likewise, the radio access network uses location information about the radar system to find spectrum holes more accurately. However, this method relies on the assumption that radar systems permit location information to be known, which may come with safety and security challenges [81].

- **Interference cancellation methods:** permits radars to demodulate interference from radio access networks which enable radars to subtract these signals from the received signals. There are two main methods to do this. The first is serial cancellation, which relies on a cross-correlation function to distinguish reliable signals from interference. However, the disadvantage with that method is that the amplitude attenuation and phase rotation of signals with the same time delay can not be subtracted through correlation. The second interference cancellation method is selective cancellation, which identifies the strongest interference signal. Although only the strongest signal is identified through selective cancellation, experiments show that this is the superior method of the two in terms of radar dynamic range and processing time [82].

- **Joint resource allocation:** integrated system of radar imaging and communications could enhance the possibility to leverage the integration so that spectrum usage efficiency is maximized. Specifically, an example when joint automotive radar and wireless communication operate through the same antenna phase array propose a joint resource algorithm which maximizes the time left (time not used for exchange of radar imaging results) to other vehicular communications. In addition, it also shows that exchange of radar imaging results through vehicle-to-vehicle communications can improve individual radar imaging accuracy [83].

The following four methods are uncoordinated methods. In contrast to coordinated methods, uncoordinated methods do not require any explicit cooperation efforts between radars and radio access networks.

- **Cognitive radio:** can be defined as intelligent spectrum users that are aware of their surrounding environment, and learn from the environment and adapt internal states to the readings by making changes in certain operating parameters, e.g., transmit-power, carrier-frequency, and modulation strategy. The changes are made in real-time, with the aim to perform its tasks with efficient use of spectrum [84]. The applied objective for cognitive radio is to minimize mutual interference between radar systems and radio access networks while also allowing both services to coexist [85].

- **Resource allocation:** a general concept of radio access network coexistence is to maximize the spectrum efficiency subject to interference restrains on radar systems. This is done through resource allocation within the radio access network. An example between cellular systems and stationary radars allocates resources to mobile devices so that the quality of service requirement is met for the mobile applications by extracting the radar-interfering sector assignments from the portion of spectrum that is non-overlapping with the radar operating frequency [86].

- **Null space projection:** to project the radar signal to the null space of the radio access network is called a null-space projection and it is a basic idea that deserves its own mentioning among uncoordinated methods. These kind of methods are also called spatial spectrum sharing [87]. Furthermore, a study indicate that a Multiple-Input-Multiple-Output (MIMO) radar performance can be improved at the cost of non-zero interference at communication receivers, by projecting the radar signal to the null space of the radio access network [88].

- **Waveform design-based methods:** apart from the null-space projection method, there are several other waveform design-based methods. One study proposes an information theoretic waveform design algorithm for MIMO radar to support coexistence with a radio access network [89]. In addition, a mutual information criterion for the joint waveform and power spectrum design may optimize the performance of both systems [90]. Another joint waveform design approach is a pulse position modulation-based waveform design to integrate radar- and communication signals to achieve high-accuracy radar imaging while maintaining high throughput communications [91].

Table 4.2: Spectrum sharing methods for radar-communication coexistence [71, p.70]

Methods	**Pros**	**Cons**
Location-based methods	High spatial spectrum usage efficiency, no mutual interference, fair spectrum sharing	Exchange of sensitive location information, signaling overhead
Interference cancellation methods	Normal radar and communication activities not affected, no coordination operations in radio access networks	Sharing of parameters in radio access networks, military radar systems need to adjust their activities, signaling overhead
Joint resource allocation	Optimal spectrum utilization, higher radar imaging accuracy, radar imaging helps vehicles identify neighbors and establish links	Signaling overhead due to the use of centralized control framework
Cognitive radio	Protection of radar systems, high spectrum reuse efficiency, no information exchange	Sensing overhead in the radio access networks, risk of collision with military radar activities
Resource allocation	Optimal spectrum usage efficiency, no information exchange	Spectrum sensing overhead, possible computing power requirement, sensing errors
Null space projection	No mutual interference, communication activities are not affected	Radar systems adjust their activities, pre-knowledge of radio access networks
Waveform design-based methods	Few coordination operations in radio access networks, high spatial spectral efficiency	Signicant changes to radar systems, pre-knowledge of radio access networks

4.1.9 Cooperation initiatives from EDA

EDA is an European organization that promotes collaboration, initiatives and solutions to improve defence capabilities for its member states. EDA's broad expertise and networks enable the following areas of contribution [92]:

- Harmonizing requirements to deliver operational capabilities
- Research and innovation for developing technology demonstrators
- Training and exercises to maintain and support common security and defence policy operations

In addition, EDA also works towards strengthening the European defence industry and acts as a facilitator and interface between military stakeholders and EU policies that impact the defence industry [92].

Between 2010 and 2013, EDA conducted the Cognitive Radio for Dynamic Spectrum Management (CORASMA) program, sponsored by the governments from the seven nations: Belgium, France, Germany, Italy, Poland, Portugal and Sweden. The program aimed at studying the capability of cognitive radio to support radio access networks for tactical networks operations [93]. The project came to propose a dynamic spectrum management solution at a system level, including changed spectrum policies, etiquette and operations concepts. An analysis was performed to investigate solutions relevant to the CORASMA objectives and implemented in the simulation platform to demonstrate the suitability of new approaches for spectrum management based on cognitive radio. The CORASMA project is expected to result in follow-up projects with similar targets [93].

4.2 Outcome from delphi study

The outcome of the delphi study shows many different opinions and predictions among the experts, and the full result for each question can be found in Appendix B. In order to compare the quantitative results fairly between the different expert categories, the academic researchers' answers were divided by 3, giving all categories an equal amount of votes to distribute.

4.2.1 Today's coexistence performance is insufficient

As mentioned in the documentary research, DFS is currently implemented in the 5 GHz band from ITU's recommendations, with requirements that radio access networks should detect radar transmission and change operating frequency to avoid interfering with the radar. Since the experts are stakeholders with different perspectives on the DFS implementation, they got to rate the performance of it. When asked about how well radio access network providers have been able to exploit the access to frequencies with DFS requirements, the experts which had a perception rated it on average to be poor. Also when assessing DFS performance to avoid mutual interference, the average expert who had a perception rated it to be poor.

Hence, there is certainly a demand for a better coexistence method than the DFS which is implemented today. Interesting responses regarding the DFS performance are listed below.

- Reports from telecom actors to regulators vary in how well they state that they can utilize spectrum with DFS requirement
- DFS functionality experience problems to detect low power radar and radar at long distance
- DFS is extremely spectral inefficient compared to the the theoretical potential of effective coexistence
- The existence of non-complying wifi is increasing, not following the DFS requirement
- In the US, the operating rules for telecom actors are some onerous that operators don not even bother to try operating
- Tests with telecom equipment with DFS close to military radar have shown that the telecom equipment could not operate
- The frequency hopping in military radar is quite high-frequent and irregular, resulting in that telecom equipment is too slow to detect and change frequencies
- DFS works when radar systems transmit at a fixed frequency in conjunction with a high output power

4.2.2 Assessment of possible coexistence methods

Since there is a need to provide more effective and efficient coexistence methods, the experts were asked to assess the feasibility of a set of possible technologies from recent research [71], as presented in Section 4.1.8. The experts selected three methods each and rated them relatively each other based on feasibility for coexistence between radio access networks systems and military radars. The result is shown in Figure 4.1 with weighed votes between 1-3 depending on the relative rating from the experts.

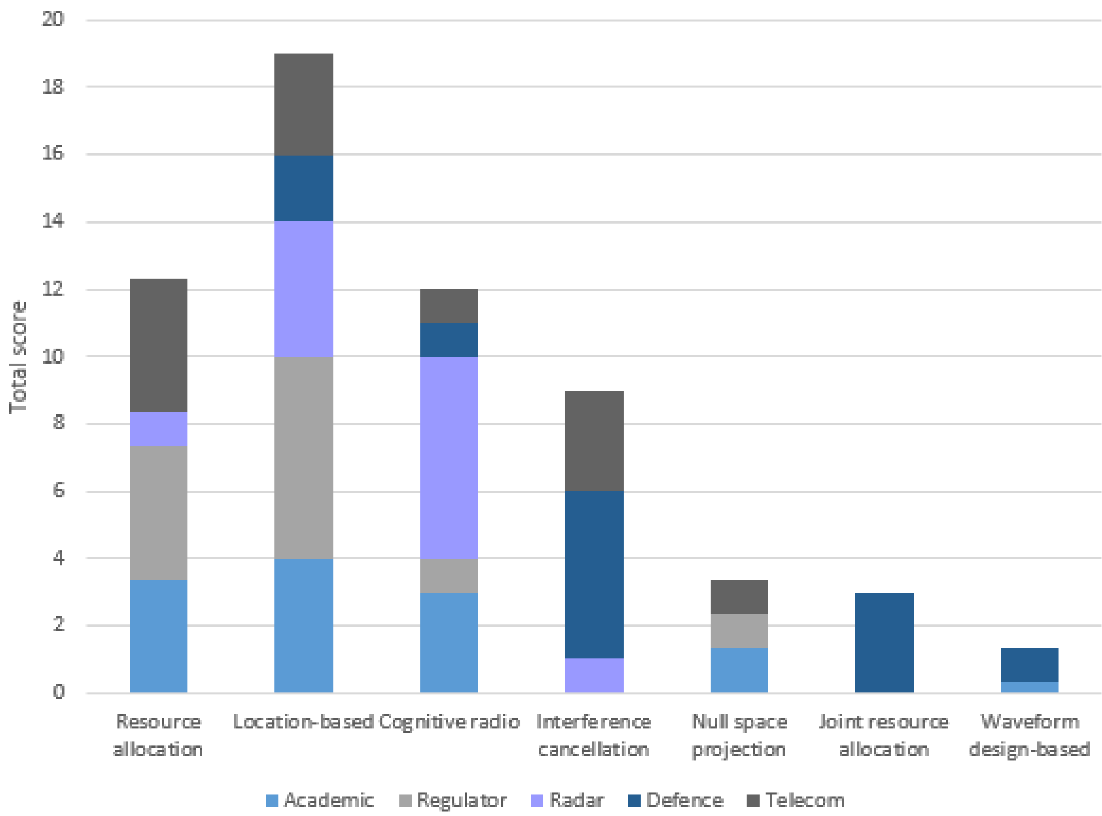

Figure 4.1: Assessment of radio spectrum coexistence methods

It can be seen that location-based, resource allocation, cognitive radio and interference cancellation were rated highest among the methods. The experts also had the opportunity to mention other coexistence methods, where comments were based on the US' CBRS in the 3.55-3.7 GHz band and agreements leveraging shared data bases. Using radio access networks as integrated radar systems was also suggested, as well as using receive-only radar systems.

4.2.3 Main challenges and stakeholders' responsibility

When asked about the main challenges for reaching successful coexistence, the experts' answers emphasized the need for cross-industry coordination, with high involvement from technology, policy and economy. Stakeholders need to realize that the most efficient spectrum solution is to cooperate and solutions should be developed together. When the experts were asked if there is a difference between providers of radio access networks and military radar providers in their responsibility for developing coexistence solutions, the responses showed a similar responsibility, slightly higher for radio access network providers.

The absence of a clear and operationalizable definition of harmful interference was also mentioned as a key challenge to overcome. The fact that old functional equipment without coexistence capabilities will continue to exist for a long time is likely to hinder a rapid transition. Possible solutions that were mentioned for overcoming many of today's challenges were to strive for reducing emissions to a minimum, implement market prices for all private and governmental spectrum users and more cooperation with focus on the political dimension. Finally, if regulations decide to promote any spectrum coexistence method, policy must ensure that equipment not complying with the requirement gets rapid and sufficient consequences, with the purpose to avoid mutual harmful interference.

4.2.4 Predicted spreading and geographical differences

The experts got to express when they believe that radio access networks and military radars will fully coexist in the same frequencies without harmful interference. The responses are shown below in Figure 4.2.

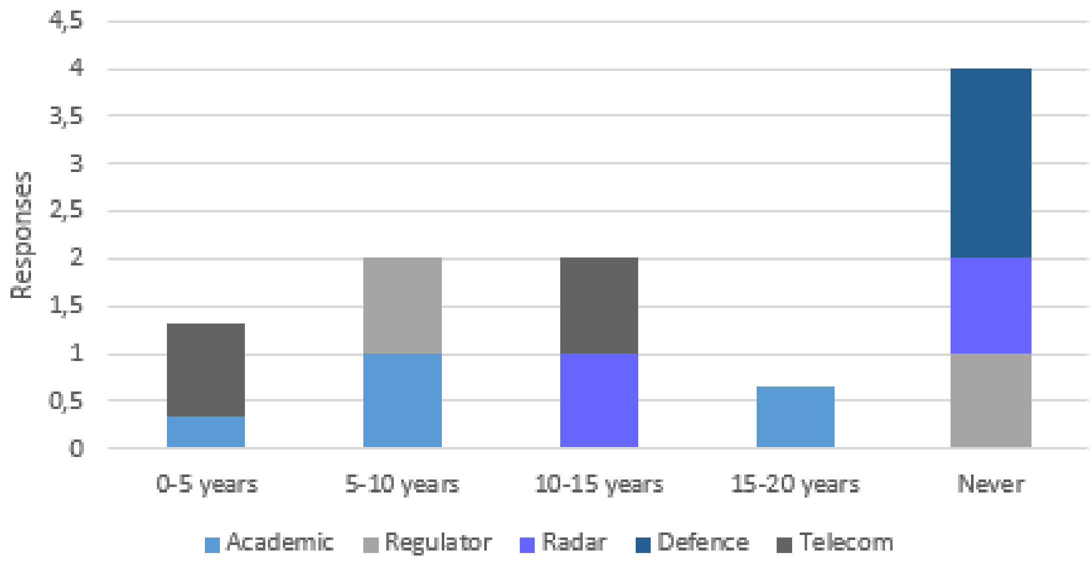

Figure 4.2: Timeframes of when radio access networks and military radar will be able to fully coexist

The answers varied, which beyond differences in opinions could be explained by the lack of a clear definition of the statement "full coexistence without harmful interference". Worth noting is the optimistic timeframe stated by telecommunication experts, where the US' CBRS was again mentioned for showing the progress for coexistence. The first telecom actors are expected to enter the CBRS band (3.55-3.7 GHz) from late 2018 or early 2019, together with the existing military radar. For the definition of harmful interference, experts' formulations ranged from ITU's perspective that both services can access the same band without seriously degrading the performance of another service, to definitions of harmful as a certain economical impact and interference as not complying with the regulations.

Another question that the experts got to answer was whether the development towards coexistence will be driven primarily by international regulations and not the providers of the services. The result is presented in Figure 4.3 below.

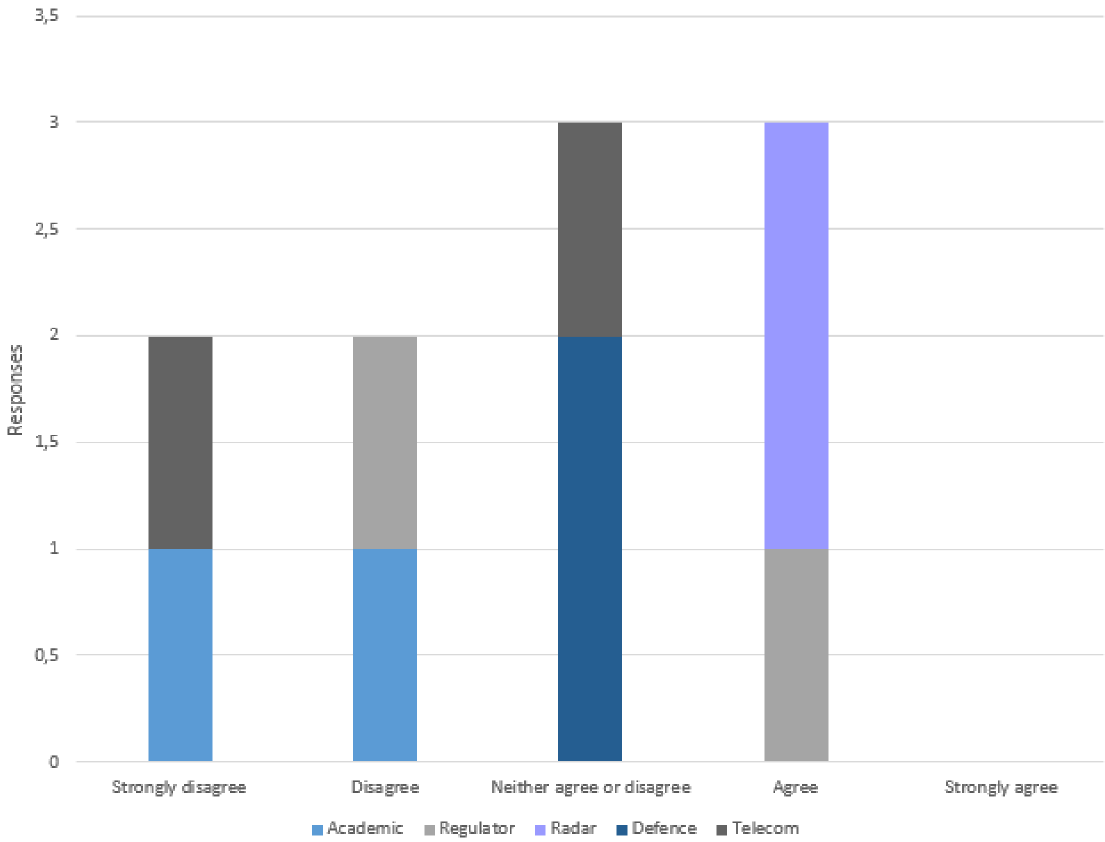

Figure 4.3: If development will be driven by international regulations

Furthermore, opinions were gathered for the likelihood that radar equipment will also get requirements in future coexistence requirements based on cognitive radio. The result is shown in Figure 4.4 and suggested radar requirements will include to base its actions on readings from its environment to ensure performance of secondary users. Further possible requirements can be to provide the necessary data to a shared database, only transmit when needed and to leverage state of the art filter and mitigation techniques. However, requirements that results in compromised radar performance was stated to be unlikely since national safety and security is often prioritized.

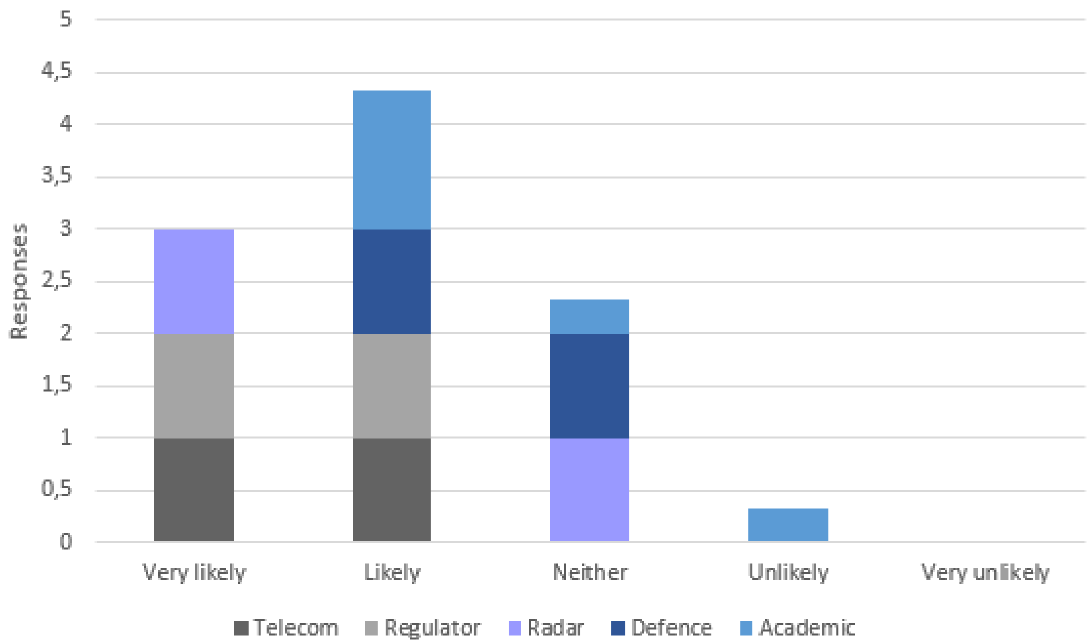

Figure 4.4: Likelihood of radar requirements for future coexistence

Another dimension of the trend towards coexistence is whether different parts of the world will incorporate the same methods and at the same pace. For this purpose, the experts were asked to predict if any of the ITU regions shown in Figure 4.5 will implement coexistence between military radars and radio access networks more quickly than others. The answers are visualized in Figure 4.6.

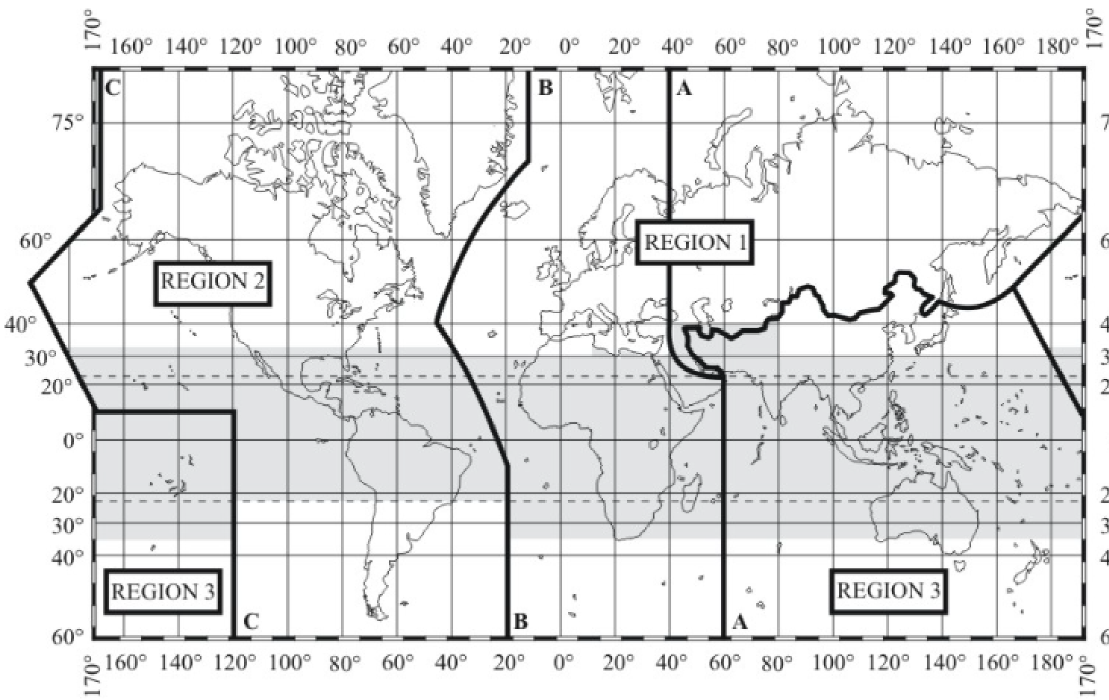

Figure 4.5: The three ITU regions

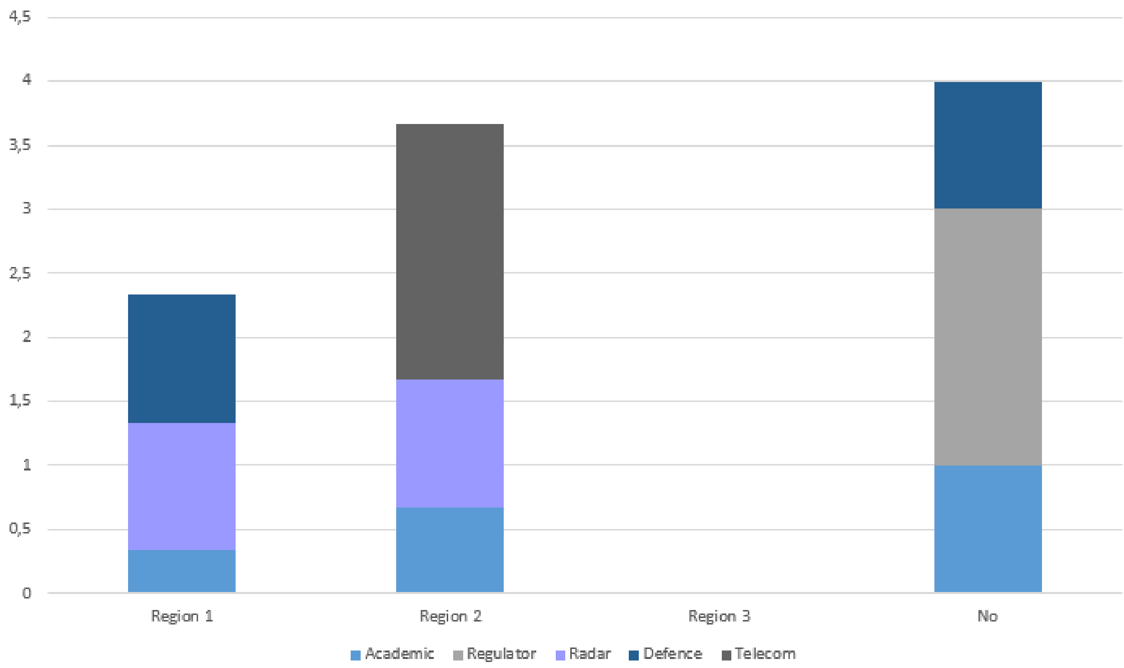

Figure 4.6: If any ITU region will implement coexistence solutions faster

The visualization shows that some experts believe that ITU's regions 1 and 2 will be relatively early in their implementation of new coexistence solutions. Reasons for that region 1 would be in the front mainly concerned the high demand on spectrum while motivations for a rapid region 2 includes the history of being first with DFS and the current CBRS advancement. Once a successful method is implemented in some part of the world, experts predict that it will quickly spread to the rest of the world based on ITU recommendations. Especially region 3 is expected to follow the lead from successful attempts in either region 1 or 2. Potential for different coexistence methods might exist between region 1 and 2, although the regions are also likely to in the long term incorporate the globally proven most successful method. Timeframe for a regional successful implementation to spread globally is difficult to estimate but can require 2-3 world radio conferences, corresponding to 6-12 years.

Finally, a scenario was given to the experts where some countries' military radar equipment enable more effective and efficient spectrum sharing capabilities with radio access networks than other countries. An opportunity will then occur for these countries to allow further coexistence to benefit the countries' economy and digitization while still fulfilling the radar's functionality. The experts were then asked how likely it is that these countries with such capabilities will allow coexistence beyond what is recommended in the ITU radio regulations, Figure 4.7 presents the findings.

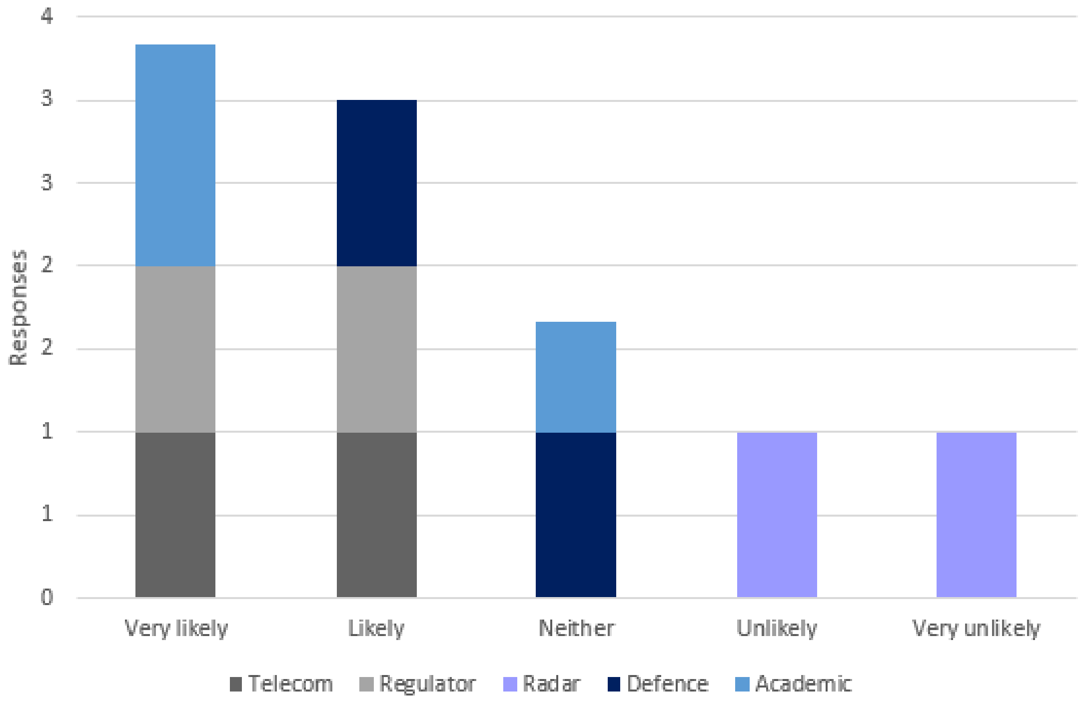

Figure 4.7: Likelihood of countries going beyond ITU's radio regulations if superior coexistence capabilities exist

Comments from the experts regarding the scenario were that every country has the decision power to perform such advancements, but that military users might still try to defend own interest to protect spectrum instead of cooperating. A country implementing such superior coexistence methods must also ensure not to interfere with neighboring countries following the ITU's radio regulations and if the method works successfully, the whole world will likely attempt to implement it. Also, since the spectrum coexistence between military radars and radio access networks is a very complex challenge with many stakeholders, it would require much from an individual country to drive the development on its own.

4.3 Findings from expert interviews at Saab

In parallel to the delphi study, six expert interviews were conducted at Saab to discover technologies that would be feasible for their military radars' coexistence with radio access networks. All six technologies have been summarized in the following sections, based on the interview data.

4.3.1 Continuous arbitrary waveforms

Continuous arbitrary waveforms is a method to create deep notches with sharp edges to allow other systems to use the frequencies within the resulting empty spaces. The technology is based on the radar's knowledge about its own transmitted signal and is able to subtract the transmission signal from the received signal. The subtraction which replaces filtering must be very effective and a major challenge is therefore to detect and quantify potential leakage created by the equipment. Continuous arbitrary waveforms is a development based on Frequency Modulation Continuous Wave (FMCW). FMCW has been used in automotive radar but since the vehicle companies are not transparent with their used technology, specific similarities and differences are difficult to compare. However, a fundamental difference is that FMCW always transmits a continuous sweep, while continuous arbitrary waveforms is free to continuously transmit also in other ways.

Continuous arbitrary waveforms could be used in both automotive radar and military radar purposes. For military usage, the need for an alternative to the pulse radar has been realized since low frequency radars must be able to leave free frequencies in between the total bandwidth to allow radio access networks to exist without interfering. With a traditional pulse radar, such free spaces are not possible to generate because of the side lobes which result in time alternation as the only coexistence technique for pulse radar, i.e. that a system sends and then waits to let other systems perform their tasks before transmitting again. Beyond allowing for holes in the transmitted frequencies, continuous arbitrary waveforms also implies an approximately 20 times lower transmission peak power compared to a pulse radar for obtaining the same radar result. However, the continuous arbitrary waveforms technique require a continuous transmission and will therefore not pause to completely avoid using the frequencies for a period of time as in pulse radar.

4.3.2 Orthogonal waveforms

Orthogonal waveforms is a waveform-design method, which creates mutually independent signals. By implementing an orthogonal waveforms technology, the total combined spectrum is used by all users where individual codes in the signal transmission enables the users to separate their own signals among others. At Saab, the technology is developed specifically for automotive application where an example of 5GHz spectrum range is estimated to enable approximately 2000 unique codes with continuous transmission, which implies more efficient use of the spectrum. The codes are created by changing phase settings with a certain pattern over a suggested one millisecond cycle time before the signal is repeated. Currently, GPS is using similar technology to distinguish which satellite the receiver reads signals from.

Saab's development of the technology is primarily intended for automotive use to allow multiple cars' radars to coexist without interference. The project is developed together with universities and other companies and the adoption of the technology in military radar is yet uncertain. A foreseen challenge is the significantly smaller allocated spectrum for military radar, which limits the number of possible unique codes. The possibility to render unique codes is also decreased by approximately ten times for a certain bandwidth if the radar use pulse transmission instead of continuous, which might be desired to detect objects far away. The potential to leverage the orthogonal waveforms technology for radar coexistence with radio access system is uncertain and is complicated by that communication require the signal to vary for creating the sent message and can not only iterate a predetermined code.

4.3.3 Digital radar

The use of the concept digital radar systems may be considered to have started from the time when radar designers began to use analogue-to-digital and digital-to-analogue converters to process the received and transmitted signal digitally, by using software. Since the analogue-to-digital and digital-to-analogue converters have become faster, the interface between the analogue and digital parts within the radar have moved further into the analogue radar front-end part and are now converting data on an radio frequency level.

This, in turn, has reduced the radar sensitivity to temperature variations and non-linearities, most often attributable to analogue components, since the number of analogue components will decrease when digitization is done on the radio frequency level. However, it is not possible to achieve 100 percent digitization. A digital radar will always be depending on an antenna, analogue amplifiers and filters which interfaces the analogue space. What is often meant today when discussing the concept digital radar can be attributed to that the digitization is done on an radio frequency level, which provides great opportunities to in an early stage create and process radar signals in both time and space. An advantage of today's digital radar concept is that the system can be designed in a technically simpler manner and become more general in its design, which also makes the radar system easier to handle and to reconfigure by only switching the software.

With today's computer technology, a digital radar system can develop far more advanced radar functions compared to a traditional radar system and thereby gain higher degree of operation freedom. Instead of only one radar function at a time, a digital radar system will be able to simultaneously perform several radar functions by using MIMO.

Saab Surveillance has currently no digital radar system on the market but will soon launch the Giraffe 1X system to the market.

4.3.4 Front-end technology

Front-end technology is an area which focus on the analogue components in any radio frequency system. In a radar system context, a front end includes an antenna system, a transmitting channel and a receiver channel which are built up on analogue components. It is a vital technology for any radar system and the development is continuously ongoing to increase the performance of the technology. For coexistence purpose, the front-end area can be leveraged by increasing the filtering capability. The idea is to install filters within the antenna apparatus and to further potentially leverage controllable filters where the target frequency can change.

Historically, filters have typically been analogue and placed in various places within the radar flow. In modern usage, filtering is often made after the signal is converted from analogue to digital. However, there is a risk that the incoming power level of the desired radar signal combined with other noise is too high for the digital filtering to handle. In such cases, the signal analysis process becomes saturated and the information from the signal is lost. By integrating an initial analogue filter within the antenna apparatus, the risk of becoming saturated for further signal amplification and digital filtering decreases. Furthermore, an analogue filter within the antenna is space efficient and the early filter placement in the signal process decreases losses in signal quality. However, increased filter characteristics such as sharp edges and the possibility to implement controllable filtering that change target frequency corresponds to bigger filters, which complicates the fitting within the antenna apparatus.

4.3.5 Multifunction system

Military multifunction systems consisting of radar, Electronic Warfare (EW) and communications can enhance coexistence capabilities for radar systems by leveraging the combined possibilities from its systems. By reading and estimating the risk of interference between the multifunction system and external wireless communication systems, the multifunction system's performance can be optimized for mutual interference minimization. For example, if there are many active external communication transmissions, the multifunction system could use the EW system to detect targets from reading these transmissions instead of using the radar to send own transmission. Only when the EW performance to read from other's signals is insufficient, the radar's transmission will be activated which will then initiate the risk of mutual interference with external wireless communications. Using the EW for detection also implies that the multifunction system's location will not be revealed, which can be an advantage for security.

Furthermore, the integrated communications capability in a multifunction system can be used to share information with external communication systems for coordinating the systems' performances to utilize spectrum as efficiently as possible. Examples of such shareable information can be locations of various transmitters and targets as well as requirements and requests for future use of spectrum to fulfill the various systems' tasks.

The possibility to efficiently utilize spectrum based on mutual communication can be directly related to cognitive radio, where a system's actions should be based on readings from its environment. Hence, military multifunction systems can be viewed as an enabler for cognitive radio where radar and external radio access system such as 5G cooperate to ensure efficient use of spectrum while minimizing mutual interference

4.3.6 Adaptive interference cancellation

Adaptive interference cancellation is a technology to make a radar listen selectively. By using multiple channels, the radar can avoid listening in certain directions. The choice of direction, in which the radar becomes blind, can then be used for the purpose to avoid known interference transmitters, such as radio access networks. The drawback of being blind in a direction to avoid interference is that the radar system will also be blind to potential threats in that direction.

The technology behind adaptive interference cancellation is the physical antenna interface, which is divided into multiple channels, both horizontally and vertically. A channel can be defined as a physical area on the antenna where it receives and converts transmissions to a signal. More channels correspond to an increased ability to be narrow in the selective listening. That means that the radar's blind spots can be minimized. The technology is currently implemented on few-channel antennas, with an additional few channels for suppression purposes. This restricts the ability of a jamming suppression scheme to cope with so-called dense interference environments, characteristic for populated areas with wireless transmission infrastructures. Saab´s G4A antenna, on the other hand, has a very good potential for adaptive interference cancellation due to its architecture.

5
Analysis

In this chapter, the results from the previous chapter are analyzed together and based on concepts presented in the theoretical framework. First, the trend towards coexistence environment is discussed based on findings from the documentary research together with the outcome from the delphi study. Based on that, theories are used to derive implications for military radar providers, followed by analyzes of possible resources and capabilities for Saab to develop for promoting the company's ability to take advantage of the trend.

5.1 Trend towards coexistence environment

The demand for effective and efficient spectrum sharing between military radars and radio access networks is without doubt increasing as digitization impacts our society. Because of military radars many unused frequencies of its allocated spectrum at a given time, multiple sources estimate great potential for coexistence between military radar and radio access networks. However, there are high uncertainties in which coexistence methods that will be most beneficial and how implementation of the methods will occur across the world. The current DFS method that is recommended by the ITU is not considered to be sufficient because it does not ensure avoidance of interference for advanced military radars and also results in very inefficient use of spectrum where some providers of radio access networks do not even try operating in the bands with DFS requirement because of the low benefit.

The studied coexistence methods between military radars and radio access networks are still in early development stages and the feasibility and implications are therefore difficult to estimate. Historical developments of coexistence agreements have tried to center the uncompromised performance of military radars, but have failed primarily because of challenging radar transmission characteristics for detection, including rapid frequency hopping and low transparency in specific radar operations that originates from national safety and security reasons. However, the delphi experts ranked the following four methods to be most feasible for future coexistence: 1) location-based; 2) resource allocation; 3) cognitive radio; and 4) interference cancellation. After closer inspection of the methods, it can be noted that they are not necessarily alternatives to each other, enabling future scenarios where two or more of the methods are implemented, to commonly constitute the basis for efficient coexistence without harmful interference. In such scenarios, data-base approaches could also be an important dimension.

Recent attempts to achieve coexistence beyond the DFS are found in the US, where presidential memorandums have driven the development towards more efficient use of spectrum. Specifically interesting is the 3.55-3.7 GHz CBRS band, where radio access networks are expected to start entering the band in late 2018 or early 2019, to coexist with e.g. military radars under the tier-system presented in Section 4.1.7. Furthermore, close insight into the EDA-projects might foretell the near future of coexistence, since the initiatives focus on how one of the most promising methods for coexistence, cognitive radio, can aid efficient spectrum sharing, with military radars' functionality in focus.

Because the command & control model has been the basis for spectrum allocation since 1927, in combination with the continued need to protect services from interference, the model is assumed to persist. However, DFS is an example of how ideas from the commons model have been integrated in the command & control model. As demand of spectrum increases, more shared frequencies in the regulations supported by rules instead of licenses seem likely due to the potential efficiency increase.

The study of sample countries' frequency allocation plans compared to ITU's radio regulations, showed that national deviations from ITU's general recommendations exist but are often mentioned in the footnotes in the radio regulations. This finding indicates that countries can develop in different directions when it comes to implementation of coexistence between military radars and radio access networks but that the development can be presumed to be discussed during ITU's creation of new radio regulations, especially during coming world radio conferences. Interesting aspects to consider for estimating specific countries' likelihood to drive own creation of new, more advanced coexistence between military radars and radio access networks are: 1) the nation's economic incentives for making spectrum usage more efficient; 2) coexistence capabilities from current military radar equipment; and 3) coexistence capabilities from current radio access networks. If a country has high economic benefit from making spectrum usage more efficient, in combination with advanced capabilities from both military radars and radio access networks to coexist, the country is more likely to develop own solutions to promote coexistence than a country that lacks one or more of the three criteria. US is an example of a country with very high economic incentives to make spectrum usage more efficient, which might explain why they are in the front of developing and testing new solutions such as the shared CBRS band.

If a country succeeds in implementing better coexistence methods between military radar and radio access networks, the solution is expected to be shared to other countries through new recommendations from ITU, decided on world radio conferences. However, the three criteria for a countries likelihood for implementing new coexistence methods should also be considered in this case, since new coexistence might presume advanced coexistence capabilities from both military radars and radio access networks, resulting in significant investments for some countries. Naturally, the economic benefit from using spectrum more efficient should then be larger than the investments, to motivate a country to adapt the new coexistence solutions.

To understand capabilities for coexistence from countries' radar equipment, the individual nations' equipment should be studied since it can vary based on provider and year. The coexistence capabilities for radio access networks can of course also vary between countries but have historically been driven by IEEE standards like the ones described in Section 4.1.6. Furthermore, the importance of extensive collaboration between stakeholders should not be discarded for achieving efficient national and international spectrum sharing without harmful interference. By cooperation, the mutual requirements to avoid harmful interference could be defined and the overall societal benefit could be maximized. However, since military radars' functionality is a consideration for national safety and security, regulators must ensure the prioritized radar functionality and clearly enable sufficient consequences for any actor not complying with the agreements.

5.2 Implications for military radar providers

As previously mentioned, spectrum sharing between military radars and radio access networks has already started with ITU's DFS recommendation in the 5 GHz band and US' recent CBRS implementation in the 3.55-3.7 GHz band. Stakeholders emphasize the need for better coexistence methods that ensure avoidance of harmful interference while also enabling efficient spectrum usage. It is in the countries best interest to maximize the access to desirable frequencies for radio access networks to promote digitization and realize the great economic potential from it, presumed that the military radar performance is not compromised.

Since many of the suggested coexistence models require advanced functionality from both military radars and radio access networks, the equipment's capabilities of coexistence can definitely be a source of future competitive advantage. For example, if a radar provider can show that the purchase of certain military radar equipment promotes the nations digitization by allowing overall more efficient use of spectrum through coexistence, it might influence purchase decisions. The 42 billion dollars in net profit, recently generated in the US by making spectrum usage more efficient gives a reference for what the national benefit can be. However, the current uncertainties in which coexistence methods that will be most beneficial and probable timeframes for implementations, makes it difficult for any radar provider to know what development to prioritize.

When planning for the development of new military radar characteristics, in this case to promote effective and efficient spectrum sharing with radio access networks, the theoretical model describing shifts in customer preferences, shown in Figure 2.3 can be valuable to consider. The ability to enable advanced coexistence beyond ITU's general recommendations is probably only a delight for customers of military radar today and that ability will likely not be necessary for a purchase decision. However, as demand for efficient spectrum usage grows from the corresponding potential economic benefit from allocating more frequencies to radio access networks,

the delight can rapidly become both an order-winner and later a qualifier for purchase. If time would have this impact on the competitive benefit from coexistence ability, then it would be vital for radar providers to be in the front of such performance. It would not necessarily be enough for a radar provider to be in the front of some type of coexistence technology since the coexistence development is also driven by providers radio access networks and regulators.
It is important for a military radar provider to formulate specific performance objectives for enhancing the probability of being in the front or at least not behind when it comes to the ability to coexist with radio access networks, in accordance with the operation strategy matrix, presented in Section 2.1. Examples of possible performance objectives are to be prepared to perform the military radars' part in the four most feasible coexistence methods: 1) location-based; 2) resource allocation; 3) cognitive radio; and 4) interference cancellation. Also, any combinations of the methods and support from data base approaches should then be included in the preparation for scenarios and performance objectives.

In the operations strategy matrix, performance objectives are then used to align operational goals with different internal capabilities which are called decision areas. Clearly set performance objectives can be derived from the four different coexistence methods respective requirements. Examples of characteristics that would fulfill many of the radar's requirements are: 1) transmission flexibility; 2) interference robustness; and 3) cognitivity with respect radio access networks.

Flexibility refers to the ability to change geographical directions of transmission and generate flexible waveforms. Robustness is the level of resistance to interference and ability to filter the desired signal. Cognitivity is the level of adaption to its environment to let other users operate in conjunction with radars. Different levels of fulfillment of each of the three characteristics is useful for some of the four most feasible coexistence methods. Hence, these more specific performance objectives can aid a military radar providers' effective adaption. In addition, for a military radar provider's coexistence solution to be valuable for potential customers, it must comply with current regulations. A coexistence solution will need to be accepted by both providers radio access networks and regulators.

Market requirements originate from changing surrounding conditions and represents the overall market trends. To recognize market requirements, several aspects need to be considered since there are many stakeholders in the coexistence advancement. One type of stakeholders is the potential customers, which represent the demand of military radar products and need to be carefully communicated with to understand their needs. Another stakeholder category is the regulators that create basic compliance requirements. Such requirements may change the radio spectrum environment in favor for certain users and thereby result in changed market characteristics.

Many experts from the delphi study believed that military radars and radio access networks will fully share radio spectrum without harmful interference within the coming 20 years. Hence, new regulatory breakthroughs that enable a shared radio environment with other users are a possible scenario. The importance of identifying market requirements is embedded in the operations strategy concept for competitive advantage. It is a way of being proactive in market changes rather than being reactive.

However, to leverage the combination of right performance objectives for the market requirements, the organization must create resources and capabilities to achieve long-term effective development of feasible coexistence solutions. Decisions should reflect a pattern that is aligned with market requirements for obtaining long-term competitive advantage.

5.3 Resources and capabilities for Saab to develop

According to the resource based view, presented in Section 2.2, competitive advantage is obtained through superior resources that can perform an activity better than competitors are able to. The resource based view concept can be applied to Saab's context as a military radar provider, facing an uncertain coexistence trend with radio access networks. To analyze Saab's potential to create competitive advantage from the trend, the company's existing resources and how they can be turned into competitive advantage should be considered in combination with desirable additional resources and capabilities to develop.

Saab should create and leverage resources and capabilities to fulfill the performance objectives of being prepared for executing the military radar equipment's part of the derived likely methods for spectrum sharing between military radar and radio access networks. Proposed resources to develop that can aid the achievement of the performance objectives are listed below.

- Competitive technologies, in regards to the previously defined performance objectives to fulfill the military radars part in the most feasible coexistence methods and more specifically enable high transmission flexibility, interference robustness and cognitivity.
- Close collaboration with providers of radio access networks, to develop common solutions that enable efficient use of spectrum without harmful interference.
- Extensive insight and involvement in national and international policy development to enable reactive efforts to adapt the company's offers to coming regulations, but also to be proactive by influencing decision in favorable directions based on own performance.

Corresponding to the first of the three bullets above, the following section presents VRIO analyzes of the six technologies at Saab which were studied through interviews with the company's technology experts. The VRIO framework is presented in Section 2.2.1 and is applied to determine potential competitive advantage from the technologies, in regards of being used for coexistence with radio access networks. Both the second and especially the third bullet above implies that Saab should adapt to a changing external environment, preferably faster and with less investments than its competitors. Within the resource based view, the ability to change and thereby achieving long-term success is called dynamic capabilities, which is also discussed in Saab's context in a following section. Finally, potential drivers behind Saab's decision to develop internally or collaborate are presented.

5.3.1 VRIO analysis of technologies

The VRIO framework, based on the resource based view, has been used to analyze the coexistence potential for each studied technology at Saab and its potential to constitute competitive advantage. Note that the analysis regarding the technologies is solely based on the interviews, with some additional information to what was used in the summaries in Section 4.3

Table 5.1: VRIO analysis of continuous arbitrary waveforms technology

VRIO dimension	Analysis of continuous arbitrary waveforms
Value	+ Can create sharp notches/holes in transmission to allow other equipment to operate in these spaces, e.g. wireless communications, which increases the capability to be cognitive. + Decreases the peak transmission power with approximately 20 times compared to pulse radar, making the system easier to coexist with among sensitive equipment + Can increase spectrum efficiency to perform a certain radar task compared to traditional pulse radar + Enhances the performance of the technology named orthogonal waveform by increasing the transmission flexibility to create more possible codes and coexisting systems on the same frequencies - Challenging subtraction to identify difficult targets that would otherwise be detected with filtering - Occupies frequencies all the time, in comparison to pulsed radar
Rarity	+ Saab has no known direct competition for this technology applied in military radars and is a leader of the development in Europe - Uncertain how far the automotive industry are in the similar FMCW technology due to low transparency
Imitability	+ Patents on continuous arbitrary waveforms at Saab which protect the technology but is primarily intended for showing Saab's contribution in joint development projects + No known patents held by other military radar providers + Very difficult to imitate since the technology requires extensive knowledge on radar technology and physics to develop
Organization	Company confidential, not included

Table 5.2: VRIO analysis of orthogonal waveforms technology

VRIO dimension	Analysis of orthogonal waveforms
Value	+ Enables multiple radar systems operating on the same frequencies, i.e. more efficient use of spectrum - Uncertain potential for military radar use together with wireless communication services
Rarity	+ Saab is probably relatively far in the technology development - Presumes that other companies possess similar knowledge although it is not public
Imitability	+ There are patents at Saab which protect a method to create more possible unique codes by using continuous transmission, closely linked to continuous arbitrary waveforms + No other known patents for Saab's competitors on this technology - Cannot patent the general technology
Organization	Company confidential, not included

Table 5.3: VRIO analysis of digital radar technology

VRIO dimension	**Analysis of digital radar**
Value	+ Enhanced possibility to cognitivity since the degrees of freedom in transmissions are increased, e.g. create waveforms and spatial lobes + Because of a generic hardware and high digital processing capacity, it enables multifunctional systems - Exposed to more interference, which stress the importance of effective filtering
Rarity	+ Saab is believed to be relatively far in the technology compared to its competitors - Many competitors are developing the technology
Imitability	+ The development require advanced competence with focus on digital electronics, radar-system technology and various function calculations + The process to start developing the technology for a company is estimated to be long, including an extensive study followed by building a test system + Saab has more detailed patents for solutions that are enabled by digital radar, e.g. a technique to combine short and long distance detection simultaneously - The digital radar concept is too general to patent
Organization	Company confidential, not included

Table 5.4: VRIO analysis of front-end technology

VRIO dimension	**Analysis of front-end technology**
Value	+ Ability to filter within antenna apparatus helps to avoid saturation when noise signals have high power and to effectively detect only the desired signal, which increases robustness to interference. + Controllable filter may increase cognitivity in new bandwidths since the radar can leverage an effective filtering process for multiple frequencies
Rarity	+ By reading research literature on the topic, no indication of implementation of this type of filtering has been found for military radar - Saab is still early in the development although the need for the technology is clear - Competitors are likely at similar development stages
Imitability	+ Controllable filtering is expected to be challenging for a military radar provider to develop - Integrated filters within the antenna apparatus has a relatively short path for an established military radar provider to develop - No patents at Saab
Organization	Company confidential, not included

Table 5.5: VRIO analysis of mulifunction system technology

VRIO dimension	**Analysis of multifunction system**
Value	+ Increased cognitive ability by utilizing the multifunction system's broad functionality to decide optimal strategy in different circumstances + Increased spectrum efficiency by "pooling", i.e. by sharing information that can be used for different purposes + The integrated communication enables real-time cooperation with external systems to efficiently use spectrum while minimizing interference + By using EW system in crowded spectrum to leverage other systems' transmission, the multifunction system can perform target determination without occupying any spectrum
Rarity	+ The broad required competence for a multifunction system exists within Saab and only few competitors - No unique idea, other companies are presumed to combined possess similar knowledge to Saab
Imitability	+ Competitors to Saab that do not have the broad competence required for developing a multifunction system have a disadvantage - No patents at Saab to protect and limited possibility to patent the general idea of multifunction systems
Organization	Company confidential, not included

Table 5.6: VRIO analysis of adaptive interference cancellation technology

VRIO dimension	**Analysis of adaptive interference cancellation**
Value	+ Can use interfered frequencies in other directions than the interfering transmitters, resulting in increased frequency efficiency and robustness. + An adaptive suppression scheme is likely to work efficiently for interference that enters surface-based antennas through reflections from masts, walls, random enclosures etc. - The radar also becomes blind to detect in the direction that is blocked due to interfering transmission - Requires many channels to enable flexible blocking of the direction of an interfering transmission
Rarity	+ No advanced implementation from any radar provider for coexistence purpose - The technology itself is not new, Saab and its competitors are likely to have a similar, relatively short path to implement the functionality
Imitability	+ To develop effective adaptive interference cancellation, a company needs extensive knowledge within multiple digital channels and digital waveform generation + Saab already has a multiple year advantage over potential competitors that has not yet tried the technology, maybe as much as 10 years - No patents at Saab
Organization	Company confidential, not included

5.3.2 Assessment and combinations of technologies

From the VRIO analysis of the six technologies, it can be concluded that five of them have sufficient value to aid coexistence between military radars and radio access networks. The technology that did not show sufficient potential was the orthogonal waveform technology, since it is in a very early development phase and require certain transmission patterns that are not currently possible for radio access networks to combine with sending standard transmission information. A key insight when analyzing the results from the remaining five technologies was they they all offer various relevant benefits for coexistence without necessarily being substitutes to each other. Hence, the technologies can theoretically exist in the same system and thereby achieve a combination of their individual benefits. However, the practical feasibility of that combination should be done by Saab experts.

Still, the digital radar showed potential to facilitate a multifunction system by leveraging generic hardware which can change activities only from software differences. Furthermore, the high digital processing capacity in digital radar systems aid potential multifunction Systems, implementation of continuous arbitrary waveforms and also adaptive interference cancellation. However, as digital radar was also found to be exposed to more interference, it requires effective filtering. For the filtering purpose, advanced front-end technology is desired, e.g. with filters within the antenna apparatus or controllable filters. In this example, all studied technologies except orthogonal waveform was combined to demonstrate an example that seem to have potential to generate competitive advantage in its ability to coexist with radio access networks.

To create competitive advantage from the technologies, Saab should beyond value consider the rarity, imitability and organization dimensions. The VRIO analyzes above, which are solely based on the technology expert interviews give an indication of the current situation, but come with high uncertainties because of the very limited insight in competitors' knowledge. Furthermore, the organization dimension is not included in this report, due to company confidentiality.

Based on a patent search which is fully presented in Appendix E, an indication was derived that there are few relevant patents for the studied technologies. The patent search contained all six technologies, except for multifunction system, which was replaced by a search for cognitive radar patents. The replacement was performed since no patents were found for the studied type of multifunctions systems and cognitive radar was of interest since it is a part of cognitive radio, which was one of the most feasible methods for spectrum coexistence according to the delphi study. The patent searches only used the specific keywords that are presented in the appendix and might have missed relevant patents which did not contain those specific words. However, the patent search is considered to give an indication of the current patent situation for the technologies and can be used as a basis for Saab to develop the company's patent strategies for the technology areas.

The motivation for Saab to patent its technologies which enables enhanced coexistence abilities, can vary according to the patent strategy theory presented in Section 2.3. Firstly, Saab can use patents to protect and ensure superior product performance, in regards to the coexistence ability with radio access networks, based on the proposed methods for spectrum sharing. This would complicate the imitability for Saab's competitors to achieve similar functionality. However, companies have historically been very creative to invent around patents, which imply that Saab should only patent if they believe that the competitors will experience significant difficulties to perform the functionality in another way. If Saab decides to patent, then the company should consider to drive the legal work in-house to foster a long-term positive effect on its patent strategy performance. Further drivers behind why the technologies should potentially be patented are discussed in Section 5.3.4.

5.3.3 Promote Saab's ability to adapt

As discussed in Section 2.2.2, dynamic capabilities are shown in a company's ability to integrate, build and reconfigure external and internal competencies to address a changing environment. In Saab's context for the trend towards coexistence with radio access networks, successful dynamic capabilities would have the effect promoting that new readings from other stakeholders regarding future coexistence actually result in suitable corrections in Saab's development.

Managers at Saab can create strategic and organizational routines to promote that the company derives correct readings from new coexistence trends and ensure that product development projects adapt to their implications. Examples of such organizational routines can be clearly assigned responsibilities to monitor and participate in national and international policy creation and how to process that knowledge into input for future product development and potential cooperation with other stakeholders. It is the managers that create the processes that have the responsibility to ensure that the company is structured for delivering demanded and competitive offers, but also that the company is observant to changes and flexible enough to change accordingly.

5.3.4 Collaboration or internal development

An important consideration for Saab is what to develop internally and when to collaborate with competitors and other stakeholders. As described in Section 2.1.1, there are general guidelines for the characteristics of the activities that should be performed internally or potentially in cooperation with others. Generally, an activity should be considered to be performed internally if the activity is of strategic importance, specialized knowledge exists within the company, superior operation performance is shown by the company or if significant operations performance improvement is likely.

Applying the guidelines to Saab's activity to develop military radars for the purpose of coexisting with radio access networks, the activity can definitely be argued to have strategic importance based on reasoning from Section 5.2. Furthermore, specialized knowledge does exist within the company, referring to the six technologies, where company internal experts were interviewed. Because of limited insight into Saab's competitors, the interviews could not with certainty determine Saab's technologies' performance relatively the company's competitors. Such comparisons should however be possible to execute during future customer negotiations where coexistence ability is discussed.

Furthermore, Saab's patent position can be a basis for decisions whether to collaborate. As presented in Section 2.3, patents can not only be used to make imitation for competitors more difficult, but also to create a strong basis for collaboration. For example, Saab can consider using the strong patent position with continuous arbitrary waveforms for common creation of cooperative standards, where subsequent innovation builds on them. In this way, continuous arbitrary waveforms' potential to become an industry dominant design will increase. As the company with a strong patent position in such collaborations, Saab is likely to obtain a favorable network position and higher market power. Also, since such strategic cooperation generally enhances performance and market deployment, Saab would have the potential to generate significant license money. The same reasoning would be applicable for any other technology where Saab has or will develop a strong patent position for. However, the benefits from collaboration should always be compared to the alternative benefits from keeping the patent internally, which is why companies with clearly superior patents than its competitors tend to avoid collaborations where patent rights are shared.

If Saab would enter strategic alliances or joint ventures to acquire and develop technologies to enable effective and efficient coexistence with radio access networks, the company should be very rigorous in efforts to build secure defences to protect own interests. Since innovation of coexistence likely requires something from both providers of military radar and radio access networks, a strategic alliance between both sides can constitute a protected environment for common innovation. Potential collaboration with other military radar providers would mainly be motivated by knowledge transfer and enhance possibility to influence policy making processes. Finally, Saab can consider joining ITU-R to participate in their preparation work and thereby ensure close insight into international policy making, which was mentioned as a key resource to establish for a successful adaption to the coexistence trend.

6
Discussion

This chapter contains discussion subjects regarding the trade-off between societal welfare benefits and national security, interesting topics from the delphi study and further studies that can be of interest for Saab and other researchers.

6.1 Societal welfare vs national security

The aim of harmonizing the frequency spectrum is according to the Swedish spectrum management authority PTS that social benefit should be maximized. A governmental organization is assumed to represent the total need from society to represent its interest. If an increasing amount of allocations for radio access networks are made to share spectrum with military radars, the reasoning is that the total social benefit is increased. Hence, to motivate an allocation in radio access networks favor, the incremental benefit from services originated from radio access networks need to make up for any decrease in social benefit loss due to a more congested spectrum, and thus increasing risk of interference for military radars. It is perhaps a delusional perception but the welfare effect is very clear to motivate an increase allocation for radio access networks. It is no doubt based on the massive support for all possible applications areas derived from digitization such as internet of things and industry 4.0, supported by 5G networks.

Since 5G is expected to evolve many basic characteristics in social and industrial situations where human intelligence and attention were the main control variables of global economy, it is easy to understand why there is a strong push for harmonizing the radio spectrum in its favor. But the importance of military radars should not be forgotten in the discussion. It is perhaps more difficult to motivate why military radars should keep specific allocations reserved in the spectrum with limited use for other systems that can pose interference threats, when there exist unused frequencies that can be utilized better. The importance of military radars are perhaps arguably less in peace time, but societies are always relying on effective counter terrorism operations and radiolocation support during natural disasters, although not as frequently visible to people's everyday lives as the effects from radio access networks. Hence, the debate on social welfare versus social security is a topic that needs to be addressed with great caution and deep analysis to what really constitutes maximized social benefit.

The trade-off between businesses' own economic incentives and societal benefits are also important to consider. If actors have own interests that only benefits its own business, what are the incentives to work for the maximized benefit for the society? Since the allocation of frequencies are a long political process involving many regulatory requirements on users of spectrum, there is naturally a strong incentive to gain leverage over the political processes to benefit for own profits. Hence, a lot of responsibility is put on the national frequency authorities to remain neutral and not act based on influence from stakeholders.

6.2 The possibility of new coexistence standards for military radar

Delphi experts believed that a better coexistence method can be developed and implemented in a specific country with high incentives for efficient spectrum usage, to later spread to other countries and ITU's regions. That coexistence methods can vary between nations is an assumption that was used to motivate why a military radar provider can achieve competitive advantage from the radar's ability to coexist with radio access networks. However, if the future will show that countries do not allow further coexistence that could result in overall more efficient use of spectrum, the potential for competitive advantage from superior coexistence performance would be limited.

A scenario like this would possibly result in an international coexistence standard for military radar equipment where providers such as Saab can only comply without benefit from over-achievement. This development towards an international standard, implying that all United Nation's members would develop towards coexistence in the same way seems unlikely, given findings from documentary research and stakeholder responses from the delphi study.

6.3 Combined military radar and radio access network

An interesting coexistence method that was found during the documentary research was a joint resource allocation, where the radio access network and military radar coexist within the same system. Ideally, the solution is a system product which can function as both a military radar and a fixed- or mobile network provider. In this case, the coexistence has to be done within its own system, switching between what service to deploy. The idea of an integrated radar and radio access network is a effective application for efficient use of the radio spectrum, since it maximizes the time it transmits. For instance, when radar operations are not necessary, the radio access network is allowed to transmit as much as possible similar to the primary-secondary paradigm today. As a joint resource system, the communication and coexistence flexibility between the services should be much more effective than the

DFS solution.

Although the idea is good, the feasibility of such a joint system is unclear to say the least. This method was not ranked high as a feasible coexistence method by the delphi experts but could be a future method for long-term coexistence since it is a efficient method of frequencies usage. The reason to its low ranking could possibly be explained by the complexity of both the technical and compliance aspects of implementing the method. If the radar is integrated in a radio access network, the issue of information-sharing between the systems is paramount. It is unlikely that military radars will share information about its system to this extent with any other system due to security reasons. A primary objective for the military radar is its stealth ability, and keeping information for itself is the key to remain hidden to enemies. To make the joint resource method a reality, a radar product with secondary communication abilities similar to a radio access network (e.g. wifi) seems as a necessary option to secure the radar operations on primary basis. The joint resource system needs to be developed by a single provider which demands entering a new industry. To enter the telecommunication service industry as a military radar provider seems daunting due to the high competition, and providers of radio access networks will have to compete with established military providers - two industries with high barriers to entry due to technical difficulty and extensive regulation.

6.4 Further studies

Saab has not had a similar master thesis project dealing with the coexistence dilemma at a strategic level. Hence, the scope of the problem was found to be very broad including all kinds of radio access networks that can potentially cause interference and military radars at Saab's product range. The wide scope of the project opened up for various subareas in where separate master thesis or bigger projects sizes are applicable:

- **Concept of radar system for coexistence purpose:** There were several techniques that showed potential to be effective in coexistence with radio access providers. In addition, there could be combinations of techniques that could utilize an overall enhanced radar product. Since there were many promising technologies, functional concept developments can be done to investigate the coexistence with radio access networks, as an example. Previous developments have not directly focused on pure military radar coexistence with radio access networks but sometimes other coexistence applications. Based on the findings from this study, the top methods that were feasible as coexistence solutions could be ideal concepts to develop. Hence, location-based, resource allocation, cognitive radar and interference cancellation can be the focus for future concept development.

- **Rigorous patent study:** Another area that could be more investigated is the importance of patent strategy and an assessment of current patents. This project has included a basic patent search to list what patents that could possible be of interest for the studied coexistence solutions. However, an analysis of the patents have not been performed due to the technical complexity of the documents. This is an area for professional patent experts to evaluate if Saab recognize the need for it.

- **Study on compliance issues:** An interesting aspect that was raised by delphi experts was the unclear definition of harmful interference and consequences when the problem occurs. The radio regulations definition do not specifically tell how severe an interference can be, but it is a relative measure, which opens up for interpretations. There is also a growing problem with systems that do not comply with the DFS requirements.

  A subgroup of radio access networks are wifi applications, which are the most used access medium for internet connection and a major enabler to current and future socioeconomic benefits. It is also a topic of future challenges in a coexistence environment. Delphi experts commented that there is an increasing number of wifi systems which are not complying with the DFS requirements, called illegal wifi. If illegal wifi is reported, where the DFS function is turned off deliberate or accidental, one has to wonder why this is happening. The DFS requirement does in fact undermine the wifi transmission due to primary-secondary spectrum order, and when a primary user is present, the wifi is not allowed to transmit. However, the requirements are applied for a reason and that is to secure the primary user operations to mitigate for interference. Still, the problem with illegal wifi was mentioned in the delphi study as a rapidly growing problem. This situation is part of the regulatory control of spectrum usage. As demand for radio frequencies increases and examples of such illegal wifi increases, more pressure needs to be put on legal consequences if actors do not comply with the laws of spectrum usage. This is an important issue for regulators to address, since it affects actors that use radio spectrum and how each service should be developed. If the spectrum becomes an unguarded environment, common solutions and gentle coexistence techniques may no longer be as attractive if some actor ignore other users' needs. A harsh environment where each player puts its own interest on top is then a more likely scenario, since each player competes for the same limited resource.

  Future research could investigate how severe the problem with harmful interference is, what kind of services that are the biggest abusers and the main reasons behind it. It would be interesting to map the development of the issue and to investigate if there is a trend behind it. In addition, studies could target the compliance situation of the problem to find what requirements exists and how regulation bodies are monitoring and maintaining control of illegal users.

7
Conclusion

Currently, there is an international recommendation for coexistence between military radars and radio access networks in the 5 GHz band called DFS, under the conditions that radio access networks identify radar transmission and actively change frequencies to avoid interference. However, the DFS method has performed poorly, both for providing radio access networks with additional capacity and for avoiding mutual interference. The poor performance stresses the need for alternative approaches to achieve effective and efficient coexistence between military radars and radio access networks. Research propose multiple possible methods for radio spectrum coexistence, where experts believe that the most feasible methods are: 1) location-based; 2) resource allocation; 3) cognitive radio; and 4) interference cancellation. The timeframe for reaching full coexistence without harmful interference is very uncertain and may vary between countries, since the decision power for spectrum allocation is a national right. Different countries' current military radar equipment and radio access networks can in combination with varying economic incentives for increasing radio access networks' capacity, result in very different willingness to promote and invest in further coexistence. If a country implements new successful coexistence, the method is likely to spread to other with enough high incentives within 6-12 years. An example of a current development of new coexistence is the US' CBRS band between 3.55-3.7 GHz. Major challenges for the worldwide development towards coexistence between military radars and radio access systems are: 1) the lack of sufficient cross-industry coordination, with involvement from technology, policy and economy; 2) the absence of a clear and operationalizable definition of harmful interference; and 3) regulators must ensure that radio spectrum users comply with the coexistence agreements, with clear consequences.

There are three main resources that Saab can pursue to effectively adapt to the coexistence trends between military radars and radio access networks: 1) competitive technologies for the 4 most feasible coexistence methods; 2) close collaborations with providers of radio access networks to develop common solutions; and 3) extensive insight and involvement in national and international policy development for radio spectrum allocation. Analyzes of six internal technologies at Saab for coexistence purpose have been executed, in regards to their ability to generate competitive advantage for the company. Furthermore, Saab can create dynamic capabilities in the form of routines that ensure that future trends will be identified and translated into company implications and actions. Finally, Saab can consider entering strategic alliances where potential knowledge transfer, patent position and regulator influence should be used as basis for decision.

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Appendicies

A

Questionnaire from delphi study

A.1 Round 1

A.1.1 Introduction

Hi!

Thank you for participating as an expert in our Master Thesis at Chalmers University of Technology in collaboration with Saab Group, a Swedish provider of military radar. Please read the brief introduction to the survey below before answering the questions.

Demand on radio spectrum is increasing as more industries and organizations want to deploy new and better services. The increasing demand on radio spectrum, driven by 5G requirements, stresses the importance of more efficient use of spectrum, e.g. by allowing different services to coexist.

This survey aims to forecast a likely future spectrum sharing environment between military Surveillance Radars and telecom's Radio Access Networks. The survey has been sent to 12 experts with considerable knowledge within frequency spectrum allocation/usage. After collecting all answers, a result summary will be sent to all experts, possibly together with a few additional questions.

Once again, thank you for your participation!

Please contact us if you have any questions,
Johannes Berghult, berghult@student.chalmers.se
Alexander Lesser, lesser@student.chalmers.se

A.1.2 Questions

1. Please state your name.
2. When will Surveillance Radars and Radio Access Networks fully coexist in the same frequency band without any harmful interference?
    - Within 5 years
    - 5-10 years
    - 10-15 years
    - 15-20 years

    - 20+ years
    - Never
3. Future development of frequency spectrum coexistence between Surveillance Radars and Radio Access Networks will primarily be driven by international regulations and not voluntary by providers of the services.
    - Strongly Disagree
    - Disagree
    - Neither agree nor disagree
    - 15-20 years
    - 20+ years
    - Never
4. Which actor is most responsible for developing coexistence solutions to avoid harmful interference between Surveillance Radar and Radio Access Networks? (Please drag the slider below to answer)
    - Surveillance Radar providers
    - Joint responsibility
    - Radio Access Network providers
5. Based on the following seven methods of coexistence, please pick your top three methods that you believe are the most feasible as coexistence solutions between Surveillance Radars and Radio Access Networks.
    - Cognitive radio, automatically detects available channels in wireless spectrum, then accordingly changes its transmission or reception parameters to allow more concurrent wireless communication in a given spectrum band at one location.
    - Resource allocation, enables the radar–communication coexistence via resource allocation within the communication system, e.g., maximizing spectrum eciency subject to interference constraint on the radar system.
    - Null space projection, project the radar signals to the null space of the communication system. Such methods are also termed "spatial spectrum sharing".
    - Waveform design-based methods, a collection name for other waveform methods apart from Null-space projection which can support coexistence, e.g. radar waveform design algorithms.
    - Location-based methods, where location information is exchanged between radar and communication systems, to achieve better utilization of the spectrum.
    - Interference cancellation methods, which permits radars to demodulate interference from communication systems and thereby enable radars to subtract these signals from the received signals.
    - Joint resource allocation, presupposes radar imaging and communications integrated into the same hardware where joint resource allocation schemes can leverage the integration such that the spectrum usage efficiency is maximized.
6. Do you recognize any other coexistence technology that can enable a more efficient use of radio spectrum between Surveillance Radar and Radio Access Networks?

7. Will any of the three ITU world regions implement coexistence solutions between Surveillance Radar and Radio Access Networks more quickly than others?
    - Yes, Region 1
    - Yes, Region 2
    - Yes, Region 3
    - No
8. In brief, please motivate your answer for the previous question (7).
9. What key actions or problems will be important for stakeholders to address for future allocation and use of the frequency spectrum without causing harmful interference between different services?

A.2 Round 2

A.2.1 Introduction

Hi,

Thank you again for participating as an expert in the follow-up survey for our master thesis at Chalmers University of Technology, in collaboration with Saab Group. As mentioned previously, our goal with these questions is to forecast a future likely coexistence environment between military surveillance radar and telecommunication's Radio Access Networks (RAN). Please read the result report that was attached in your invitation email before you answer the questions.

Please contact us for any questions you may have,
Johannes Berghult: berghult@student.chalmers.se
Alexander Lesser: lesser@student.chalmers.se

A.2.2 Questions

1. Please state your name.
2. Do you allow that we write your name in our master thesis report?
    - Yes, you can use my name in your thesis report
    - No, I want to be anonymous in your thesis report
3. As presented in result report from the first survey, there was high variation in when full coexistence between surveillance radars and RANs is expected to occur. Why do you think the variation was high and how did you interpret "fully coexist without harmful interference"?
4. Cognitive radio has recently been a hot topic, including both cognitive radar and cognitive communications. Currently, a type of cognitive communication, namely Dynamic Frequency Selection (DFS) has been implemented in the 5 GHz band with conditions for telecom equipment to detect and avoid radar emissions. How well have radio access network providers been able to exploit the frequencies with DFS requirement?
    - Very good

  - Good
  - Poor
  - Very poor
  - No perception/Unable to answer
  - Other (please specify)
5. What is your perception of the DFS performance to ensure that harmful mutual interference between surveillance radars and Radio access Networks is avoided?
  - Very good
  - Good
  - Poor
  - Very poor
  - No perception/Unable to answer
  - Other (please specify)
6. How likely do you think that it is that the requirements for cognitivity will also demand certain performance characteristics from surveillance radar equipment in terms of making it easier to avoid mutual interference?
  - Very likely
  - Likely
  - Neither likely nor unlikely
  - Unlikely
  - Very unlikely
  - Other (please specify)
7. Based on the previous question (6), please describe the type of requirements that could be created for surveillance radar equipment.
8. In the previous survey, some experts believed that ITU's region 2 (America) or region 1 (Europe) will most quickly adapt coexistence solutions since the US are currently executing attempts to use frequencies more efficient and because of Europe's high frequency demand. Assume that further regional implementations of further coexistence between surveillance radar and Radio Access Networks are successful. Please describe how you think that these regional solutions will spread to other parts of the world and a likely timeframe for that?
9. Please assume a scenario where some countries' radar equipment enable more effective and efficient spectrum sharing capabilities with Radio Access Networks than other countries. An opportunity will then occur for these countries to allow further coexistence to benefit the countries' economy and digitization while still fulfilling the defence radar functionality. How likely is it that countries with such possibilities will allow coexistence beyond the ITU Radio Regulations?
  - Very likely
  - Likely
  - Neither likely nor unlikely
  - Unlikely
  - Very unlikely
  - Other (please specify)

10. There were variations in the responses on which coexistence techniques that are likely to be implemented. Why do you think that the responses varied that much and what does that imply? Also, please include any thoughts you may have on our first result report here.

B

Full result from delphi study

B.1 Round 1

Question:
When will Surveillance Radars and Radio Access Networks fully coexist in the same frequency band without any harmful interference?
Answer:

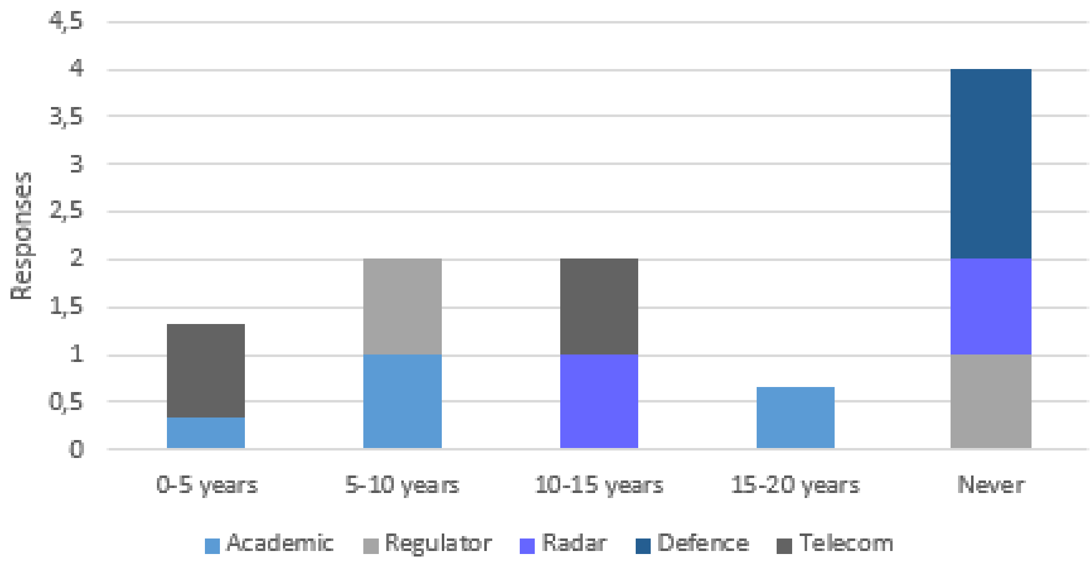

Figure B.1: Timeframes of when radio access networks and military radar will be able to fully coexis

Question:
Future development of frequency spectrum coexistence will primarily be driven by international regulations and not voluntary by providers of the services
Answer:

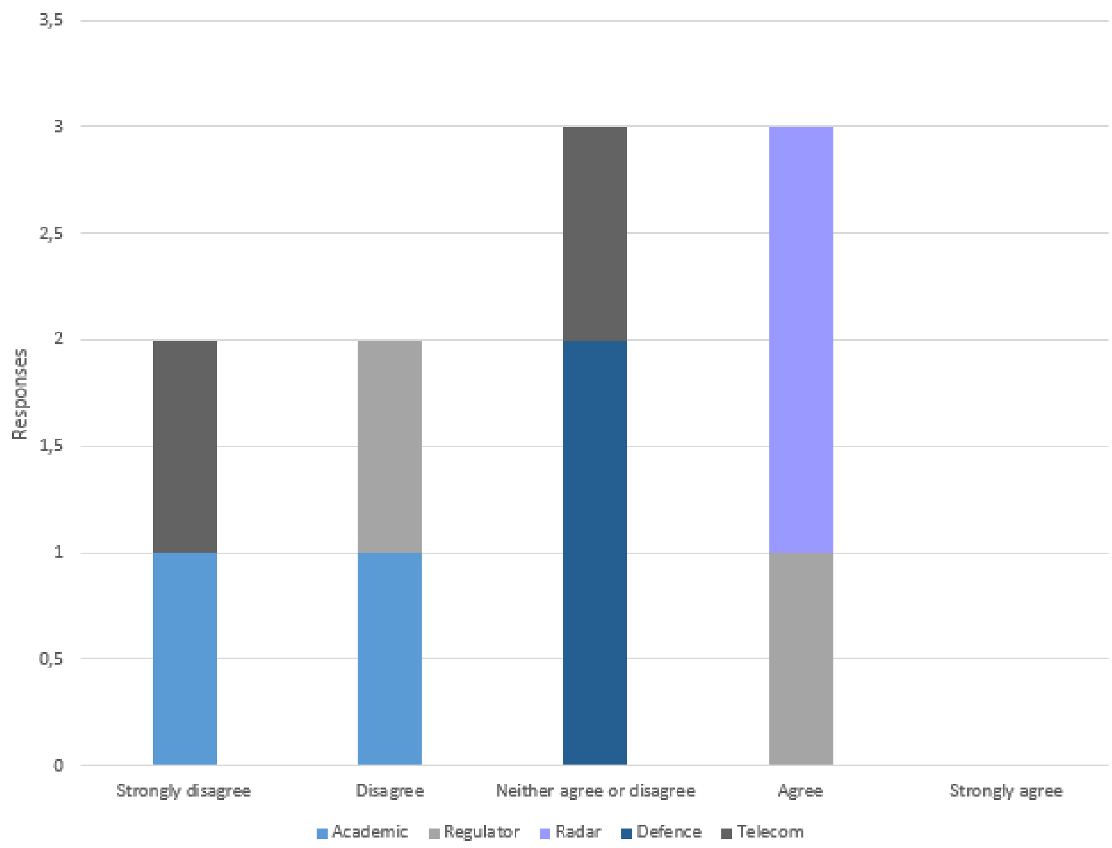

Figure B.2: If development will be driven by international regulations

Question:
Which actor is most responsible for developing coexistence solutions to avoid harmful interference between Surveillance Radar and Radio Access Networks? (-50 is all responsibility on radio access network, +50 is all responsibility on surveillance radar)
Answer:

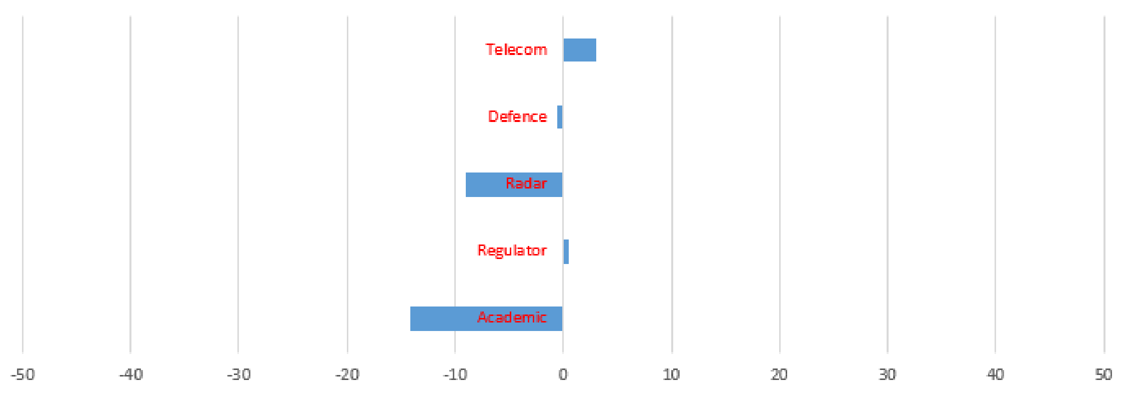

Figure B.3: Where the most responsibility lies

Question:
Based on the following seven methods of coexistence, please pick your top three

methods that you believe are the most feasible as coexistence solutions between Surveillance Radars and Radio Access Networks.

Answer:

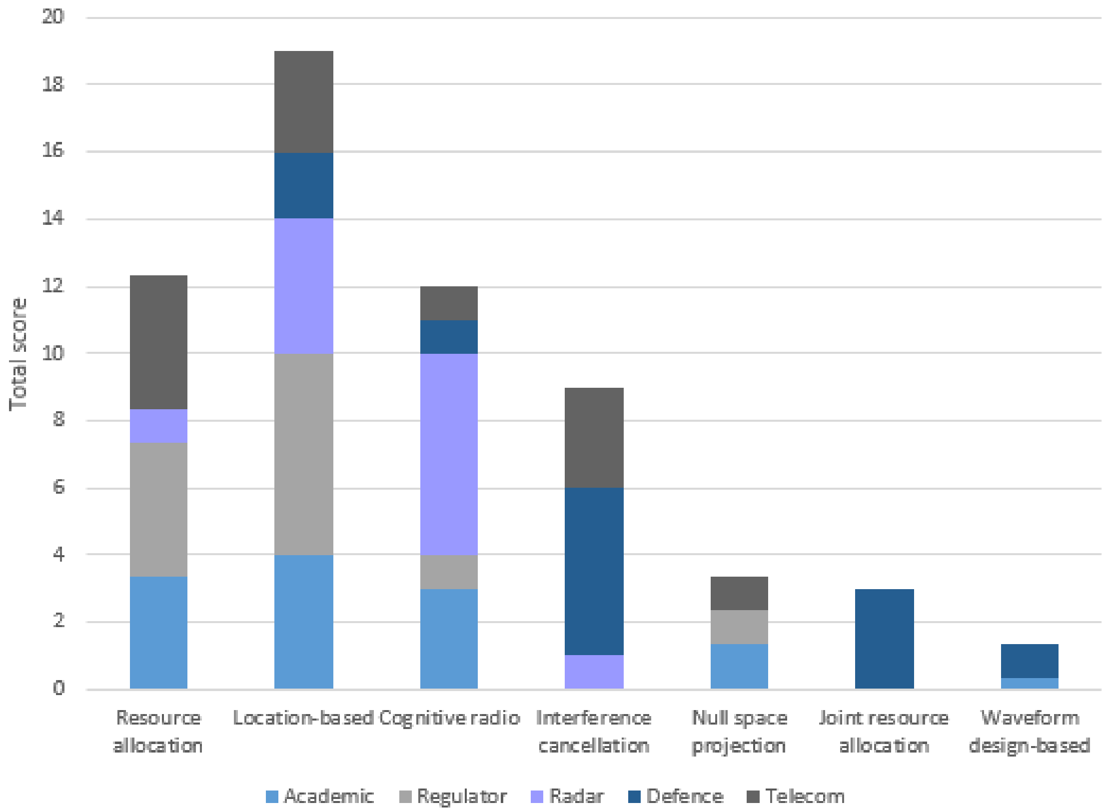

Figure B.4: Assessment of radio spectrum coexistence methods

Question:

Do you recognize any other coexistence technology that can enable a more efficient use of radio spectrum between Surveillance Radar and Radio Access Networks?

Answer:

The respondents mentioned the following possible coexistence methods:

- Spectrum access database, e.g. as planned for the 3.5 GHz in the US.
- Database approach where surveillance radar information is included and radio access networks can be designed to protect the radar in specific locations.
- Cognitive radar as an important part of cognitive radio.
- Time division with radar priority, i.e. radio access network can uses spectrum when radar does not require.
- CBRS style.
- Simultaneous multi-band operations and beam-forming capabilities of both surveillance radar and mobile systems for improved redundancy and reduced susceptibility .
- Using receive-only surveillance radars, using the energy from wireless communication. systems by e.g. a geographically distributed antenna system.

- Using the mobile network as an integrated surveillance radar system.

Question:
Will any of the three world regions shown in the figure above implement coexistence solutions between Surveillance Radar and Radio Access Networks more quickly than others?
Answer:

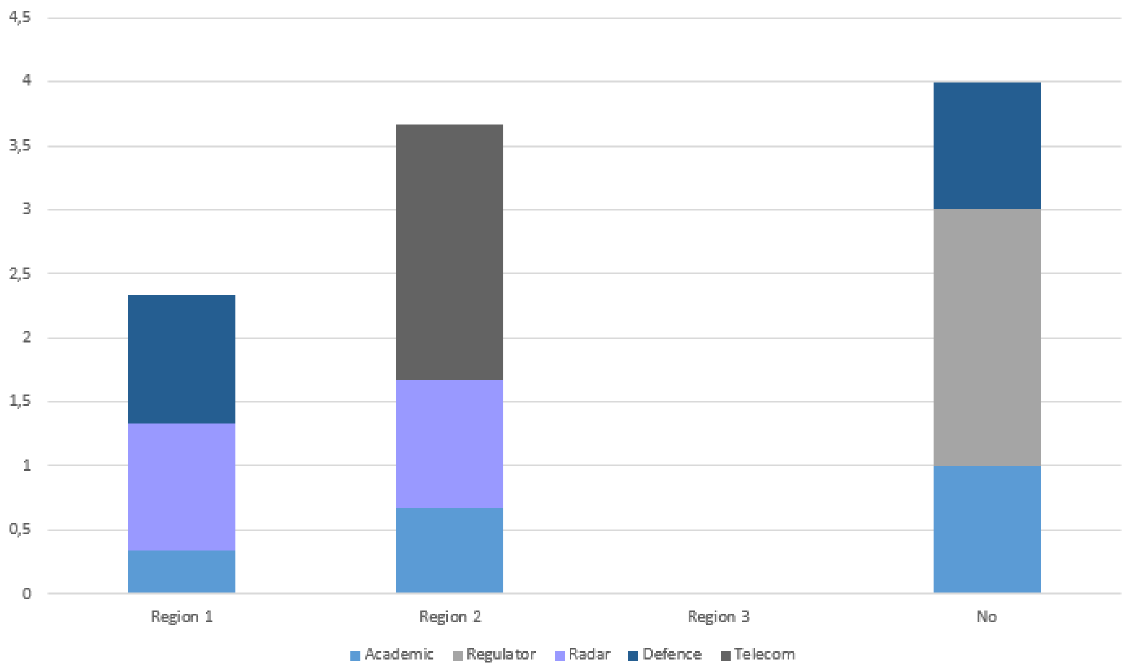

Figure B.5: If any ITU region would implement coexistence solutions faster

Question:
In brief, please motivate your answer for the previous question.
Answer:
Motivations for why region 1 would be faster:

- In Region 1 there is generally a higher density of systems using spectrum. Therefore the coexistence topic is more relevant.
- Highest density of concurrent services (much smaller issue in Region 3).
- The interests in Region 3 are More "Rogue" Economically. The Military Industrial Complex in Region 2 is More Protective and thrives for NoC in radio regulations.

Motivations for why region 2 would be faster:

- 3.5 GHz sharing rules are already in place, the database providers are being certified, and the on-shore detection systems are being designed (though how they're going to be paid for is an open question AFAIK).
- US ahead on CBRS at 3.5GHz.

- US has always been the leader in technical solutions. E.g. DFS was first defined in US before the function was stated in.
- The technical, market, demands and businesses developments for both surveillance radar and mobile systems are more favorable in Region 2. In Region 1 the circumstances for developments of new advanced mobile services are e.g. over-regulated which is limiting the willingness to invest in such technologies. In Region 3 the market circumstances are more fragmented and not as transparent as in the other Regions.
- US has been working on coexistence between radar and radio access networks for the past few years in the Citizens Broadband Radio Service (3.55-3.7GHz). The sharing regulations are defined by FCC with the help of NTIA. The WInnForum and CBRS Alliance are developing the technical standards to enable coexistence. The US Department of Defense which uses the radar systems and the radio networks stakeholders like Nokia are involved in the technical work, which is crucial for success. Nokia is an industry leader in that space. We can expect first deployments of radio networks in CBRS band where radars exist late 2018/early 2019.

The main motivations for that no region would be faster:

- Best practises are shared between regions.
- There are interested and motivated actors in each of these regions. All have significant cooperation with each other.
- There is no particular reason for one ITU-R Region to get ahead of the others and if good solutions are adopted first in one of them they will quickly be adopted globally.
- I would not think in terms of regions, but in terms of countries. The radio spectrum is used in very different ways in the various countries around the globe. Each country decides who to use the spectrum in its territory. It depends on national prerogatives and possibilities whether coexistence mechanisms will take place. The US is developing the Spectrum Access System (SAS) which I think will also apply to surveillance radar.

Question:
What key actions or problems will be important for stakeholders to address for future allocation and use of the frequency spectrum without causing harmful interference between different services?
Answer:
The responses contained the following:

- An operationalizable definition of harmful interference.
- Time-scales of the different systems are often miss-matching. Entrants can use the lates technology for interference management while existing legacy systems are typically expensive to modify and can have long life-cycles. Legacy systems have not been designed for sharing which is a key problem. Regulators should consider different stakeholders' views critically - the protection requirements of incumbents can be too conservative and should be investigated with trials.
- Tech, policy, econ need to co-evolve and multiple equilibria possible. Coor-

dinating selection of equilibria is the issue. The question is what constitutes harmful interference – need to move away from any other Tx in RF is interference to situations where harm is economic and demonstrable.
- Clearer definition of what is "harmful" and what is "interference", as well as clear ex post adjudication and enforcement.
- Emissions should be reduced to a minimum, in-band, out-of-band and in the spurious domain. This concerns emission power, bandwidth, duration and angular coverage.
- Accepting that allocation does not need to be exclusive for any service with good RF management and system intelligence.
- FIltering, signal processing, Waweforms.
- Move away from the "my band" paradigm. Sharing will be key. Look at the US CBRS solution.
- Awareness of the problems that may arise and good cooperation in finding solutions.
- Radiolocation Stakeholders Will First Meet Political, Economical and Legal Action. Is the Radar Stakeholder Community United ?
- To be able to talk to each other, understand each others needs and in the long run be able to interact around technical solutions.
- All users, meaning all users, including private users as well as Government users, should be paying a market price for spectrum allocations and usage with the aim of improving efficient spectrum use and stimulating the use of modern and efficient technologies. Some level of integration of surveillance radar and mobile networks. Sharing of operational information between stakeholders as to use spectrum more efficiently e.g. when surveillance radars are not in use the spectrum could be used by other stakeholders and requesting/forcing a take-back of the spectrum resource when needed.
- The different stakeholders should cooperate with one another and with the regulators.
- The US regulator and standards bodies like WInnForum have already done a ton of work. Getting all the stakeholders involved is crucial. It helps with better understanding of how the systems work and what problems need to be solved. E.g., how to detect and protect the radar is an important problem. Then how the detection information is transmitted to the radio networks needs to be sorted out just like what actions the radio networks need to take to mitigate interference. When it comes to interference to radio networks, typically the RF design of the products is crucial as well as distance from the radar systems. Again, a lot of work has been done.

B.2 Round 2

Question:
As presented in result report from the first survey, there was high variation in when full coexistence between surveillance radars and radio access networks is expected to occur. Why do you think the variation was high and how did you interpret “fully coexist without harmful interference”?

Answer:
Answers contained:

- I think the variation was that high because of different understandings of the terms "fully coexist" and "harmful interference". Both terms are not defined quantitatively. I interpreted it such way, that several systems would coexist without performance degradation. Coexistence will always lead to drawbacks in some dimensions, e.g. bandwidth restrictions, restricted time slots, spatial limitations, increased system complexity or reduced performance in general.
- In my understanding, fully coexistence without harmful interference would mean that services can access the same band without seriously degrading the performance of a service, causing safety issues, or else. The concept of interference and harmful interference are defined in the ITU regulations.
- It may depend on how familiar people are aware of work going on in this space. There needs to be measures in place to enable coexistence via database approach, more resilient systems, etc.
- The term "harmful interference" conflates a physical event (interference) with an economic consequence (harmful). It is also a term that has legal/regulatory significance (at least in the US). Interference need not be harmful; whether it is depends on the magnitude of the event and the design of the receiver. Pierre de Vries has developed the useful notion of "harm-claim threshold" to distinguish harmful from non-harmful interference. If you surveyed people invested in surveillance radars, they may believe/claim that any interference is harmful, whereas people connected with radio access networks might be more optimistic about their ability to avoid interference as well as not being convinced of claims of harm.
- I believe that all respondents made their own interpretation of "harmful interference". Avoiding interference requires modifying equipment/standards and if no one will modify standards or filter transmission/reception it will never happen. It is thus question of cost.
- In my opinion it was high because it is difficult to predict the future and I interpret fully coexist without harmful interference the feasibility of both systems to be able to operate in a satisfactory manner.
- The term "Harmful interference" can be interpreted in different ways. For me, as a "Radar user", I would consider any energy emitted in the radar frequency as "Harmful interference", since it will raise the noise level, thus reducing the performance of the radar.
- Predicting the future is always challenging and giving a clear time-line is difficult. My interpretation of full coexistence without harmful interference is that both the entrant cellular and incumbent radar stakeholders agree on sharing rules and conditions that are decided and enforced by the national regulatory authority and both stakeholders comply with these requirements in operating their wireless systems. The rules and conditions are defined such that the impact of interference to the victim network is in an acceptable level.
- The contributors are coming from very different communication communities and background, also the military and civilian domains have very different requirements, and there is no economic incentive for military users to use

spectrum efficient
- The answer is a judgment call. The difference between 5+ years and "never" is not that great. In effect, 5 years means "it's possible" and never means "it's unlikely". I took the "without harmful interference" to mean that the radio access network could operate effectively to at least a significant proportion of users. That is, coexistence may restrict the range of devices that can work in a particular location bearing in mind that the device is likely to be connected as a part of a hetnet
- Full coexistence is quite a strong statement.
- 1. In such a short question, shorthand like "fully coexist" and "harmful interference" is unavoidable. However, there is a wide range of possible meanings, and respondents would give different answers depending on their interpretation of the term. 2. Different parties will be more or less optimistic depending on their interests. radio access network operators are likely to be sanguine, radar operators likely to be conservative. For radio access network operators, coexistence is net upside, and for radar operators, all downside. Qualitative interviews are necessary to flush out the details.
- This may depend on how optimistic are when it comes to how you may technically solve the coexisting problem. New users are more confident in that their technology will solve the problem. New users also want to gain access to more frequency bands by convincing about the technology's possibilities. Former users are by experience more skeptical. My interpretation of "fully coexist without harmful interference" is simply to fully coexistence without harmful interference.
- That we would reach reasonable agreement in next 10 years that harmful interference does not mean NO interference. Expect that there will always be some level of harmful interference events but co-existence will be norm rather than non-existent exception of today.

Question:
Cognitive radio has recently been a hot topic, including both cognitive radar and cognitive communications. Currently, a type of cognitive communication, namely Dynamic Frequency Selection (DFS) has been implemented in the 5 GHz band with conditions for telecom equipment to detect and avoid radar emissions. How well have radio access network providers been able to exploit the frequencies with DFS requirement?
Answer:

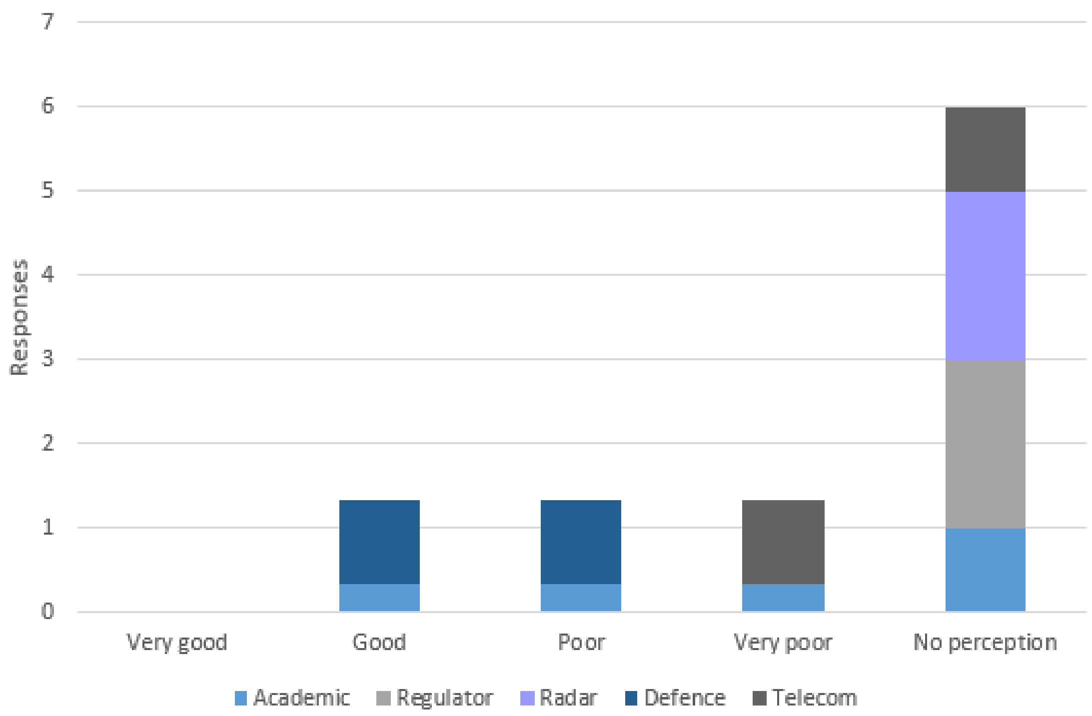

Figure B.6: DFS exploitation of frequencies

The following comments were also made:

- We get very different interpretations of that. Generally it seems to work well.
- DFS is more useful with certain types of emissions than others, I don't know about radar emissions: it would depend on the operating environment.
- It is widely used, As far as we know, however, DFS have a number of limitations, when it comes to protecting radars. for instance it is often easy to override the DFS function, by altering the settings in the WLAN device. the DFS also have limitations in detecting some lower power radars, or long range radars at a distance.
- It is widely used, As far as we know, however, DFS have a number of limitations, when it comes to protecting radars. for instance it is often easy to override the DFS function, by altering the settings in the WLAN device. the DFS also have limitations in detecting some lower power radars, or long range radars at a distance.
- The DFS use is extremely spectral inefficient as access time and search in databases is extremely slow in comparison the extremely efficient radio access network usage.
- The results have been mixed. Part of the issue is that radar emissions in the 5 GHz band may only occur on an infrequent basis (especially those associated with defence).
- The existence of ILLEGAL Wifi is definitely Increasing.
- In the US at least, the detailed operating rules (e.g. vacate for 30 minutes if signal detected) are so onerous that operators don't even bother to try operating.

- It was almost impossible to use the 5 GHz band for a telecom operator when attempting to operate in the area around Saab Surveillance which is used for radar testing 24/7.

Question:
What is your perception of the DFS performance to ensure that harmful mutual interference between surveillance radars and Radio access Networks is avoided?
Answer:

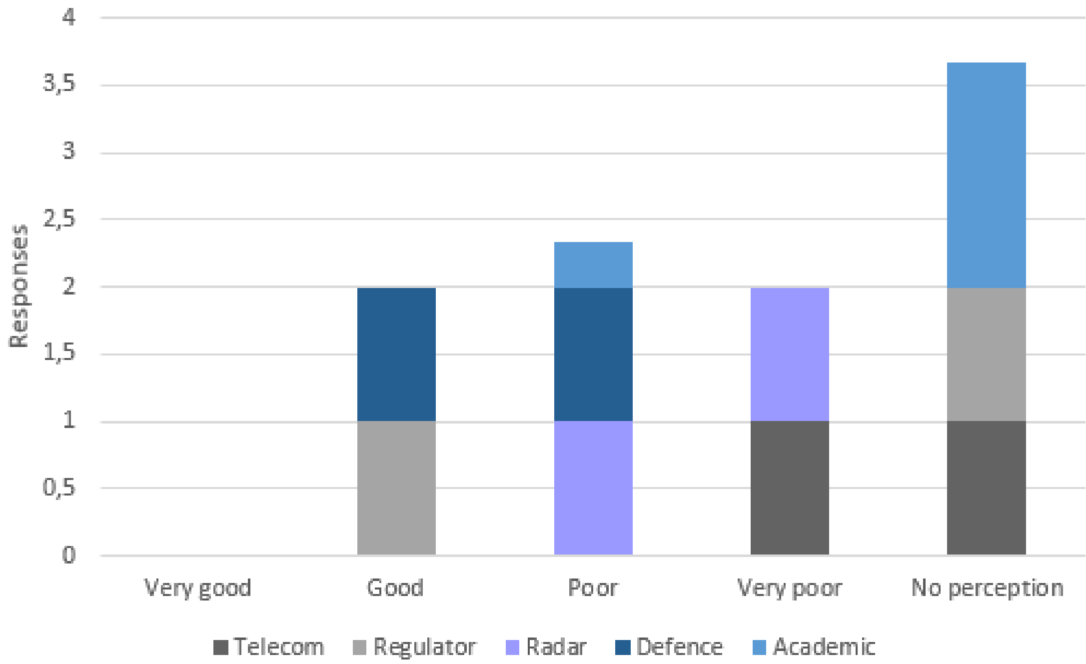

Figure B.7: DFS performance

The following comments were also made:

- Modern radars are hopping in frequency and not transmitting all the time. The listen-period in the DFS algorithm before radio access network transmission is insufficient.
- From technical viewpoint, the characteristics of the radar system and its deployment determine how well it can be detected and protected using DFS. I have not studies this so it is not possible to say whether DFS from all possible interference management techniques would work. Database based approach might be needed too.
- 1. Many radar signatures are confidential for national security reasons. Some of the proxies that were published turned out not to be good approximations 2.Signatures change as new radars are deployed, but device manufacturers have to ship something. Unless/until DFS devices can be guaranteed to be universally and rapidly upgraded over-the-air, these problems will persist.
- My opinion is that DFS works when radar systems transmit at a fixed frequency in conjunction with a high output power.

Question:
How likely do you think that it is that the requirements for cognitivity will also demand certain performance characteristics from surveillance radar equipment in terms of making it easier to avoid mutual interference?
Answer:

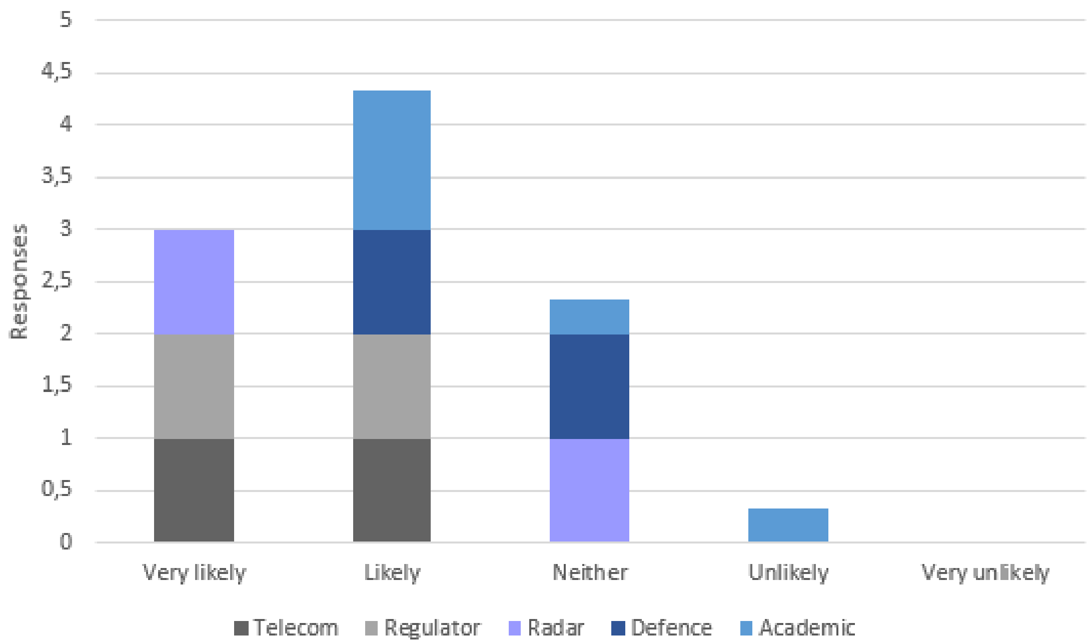

Figure B.8: Likelihood of radar requirements for future coexistence

The following comments were also made:

- Depends on which kind of characteristics: It is conceivable that status information of uncritical radar systems (e.g. current frequency and field of view) is made available for other frequency users, but a “control link” to the radar sensor seems very unlikely.
- No cognitive system will be able to avoid interference altogether. Interference avoidance can be improved by coordination between primary and secondary users.
- To coexist you need to collaborate at one level or another.
- Any such requirements on radars would severely limit the available performance envelope for radars, and furthermore drastically limit the development of radars and radar capabilities in the frequency bands affected.
- If cognitivity refers to cognitive radio system capabilities defined by the ITU-R, these techniques will be important in interference coordination between mobile communication networks and radar systems. It will be hard to request existing equipment to include new cognitive features if their life span is still ongoing and their licenses will be valid for a long time. If their licenses are being renewed, then it’s easier to impose new requirements on the radar equipment.

- Primary Allocations must Ensure Functionality concerning Secondary Allocations according to the ITU radio regulations.
- This would help, but it's a difficult ask particularly for military radar where stealth is a design requirement.

Question:
Based on the previous question (6), please describe the type of requirements that could be created for surveillance radar equipment.
Answer:
The responses contained:

- An algorithm similar to the DFS might be possible: The radar cycle starts with a listening period before transmitting and has to avoid the frequency channel or angular direction, where communication equipment is operating. This can reduce radar performance and is difficult to realize in an agile scenario.
- I just argue that for the creation of a sharing environment, there needs to be cooperation between the sharing parties and all equipment that is used needs to be adapted to a sharing environment. Whether it is just about building exclusion zones, creating databases, or adjusting receivers and transmitters, I cannot tell.
- Use same/similar technology as radio access network.
- Details of the antenna beam directionality should be made available to potential secondary users so that interference avoidance can be improved. As well, improvements in rejection filters and receiver design could increase the threshold at which harm can be claimed.
- To improve the detectability of radar signals, possibly in advance, that is, with predictability.
- I do not think the radar industry would accept such limitations on their products.
- They depend on the system characteristics and deployment. If there are static deployments, traditional protection areas can be feasible implemented with a database approach. Requirements can include interference threshold levels at certain distance from the radar equipment that the radio access network must obey. This can be accomplished with database + network management.
- Databases including spatial and temporal as well as other information, possibly also waveform information.
- Operate only when required. Beacon for an interval before operation.
- Mitigation, Filters, etc.
- I can imagine radar being required to disclose operation in some cases to reduce harmful interference both from and to radio access networks, and improve its interference resilience against radio access network signals.
- Since there are a number requirements in a military surveillance radar to be able handle electronic warfare, there should also be a number of requirements to be able to handle "civilian interference systems".
- Reference to mode of action/type of use.

Question:

In the previous survey, some experts believed that ITU's region 2 (America) or region 1 (Europe) will most quickly adapt coexistence solutions since the US are currently executing attempts to use frequencies more efficient and because of Europe's high frequency demand. Assume that further regional implementations of further coexistence between surveillance radar and Radio Access Networks are successful. Please describe how you think that these regional solutions will spread to other parts of the world and a likely timeframe for that?
Answer:
The responses contained:

- From a manufacturer's perspective, one product that can be sold worldwide would be most efficient. Therefore they will push for worldwide standardization as soon as possible. This is also in the interest of the end-users.
- Issue is more political than technical.
- To the extent that equipment manufacturers can develop "turn-key" (or nearly turn-key) hardware and software solutions, they will leverage their successes in regions 1 and 2 to increase sales in other parts of the world. They may well use their leverage at the ITU-R to gain the needed secondary use allocations if they don't already exist.
- Good solutions will spread but implementation will depend on costs and spectrum needs.
- It all starts from the demand side. If nobody is requesting sharing to happen, it won't happen. There should be the clear need to access the new band and proposals on mechanisms how the interference protection can be realized.
- The USA is early out on 5G, Europe is slow suggesting that currently there is no high demand. The first choice of (co-channel) sharing is not Radar and radio access network (5G) it rather sharing between Satellite and radio access network, and also Fixed (radiolink systems); at this point it is more of adjacent band sharing/coexistence considered between radar and radio access network. Possibly, sharing could at the earliest be considered beyond year 2023 based on possible ITU world radio conference-23 decisions. Possibly, the USA could consider sharing in the range 2900 - 4200 MHz prior to the world radio conference-23. However, sharing in the European context would come much later, perhaps in the timeframe between 2023 - 2028 also considering other frequency ranges.
- The solutions adopted in the first region to use them will be employed in Region 3 almost contemporaneously. In general, Region 3 adopts on Region 1 announcement. This means that Region 3 may actually deploy quicker than Europe.
- Region 3 is More Likeable to Spread their Regions solutions to the other parts of the World...Fast - let´s say two world radio conference-cycles - 6-8 Years
- 1. My impression is that 3rd party countries tend to align with either the US or Europe. If those regulators come up with different approaches, 3rd party countries may split in the approach they support. 2. Conversely, if this is taken up by 3GPP, a globally standardized approach may emerge that's adopted by all cellular radio access networks over time, leading to de facto global harmonization. I think we're probably looking at a 5-10 year timeframe,

given how slowly this happens. If this isn't a topic that's already part of world radio conference-19 prep, it won't be on the world radio conference-23 (or whenever) agenda. 3GPP has its hand full delivering on 5G, so I doubt it'll attend to this seriously for at least three years.

- I am not so sure that regions outside the US and Europe have sufficient capacity to develop and retain own technologies which could spread to other parts of the world.

Question:
Please assume a scenario where some countries' radar equipment enable more effective and efficient spectrum sharing capabilities with Radio Access Networks than other countries. An opportunity will then occur for these countries to allow further coexistence to benefit the countries' economy and digitization while still fulfilling the defence radar functionality. How likely is it that countries with such possibilities will allow coexistence beyond the ITU Radio Regulations?
Answer:

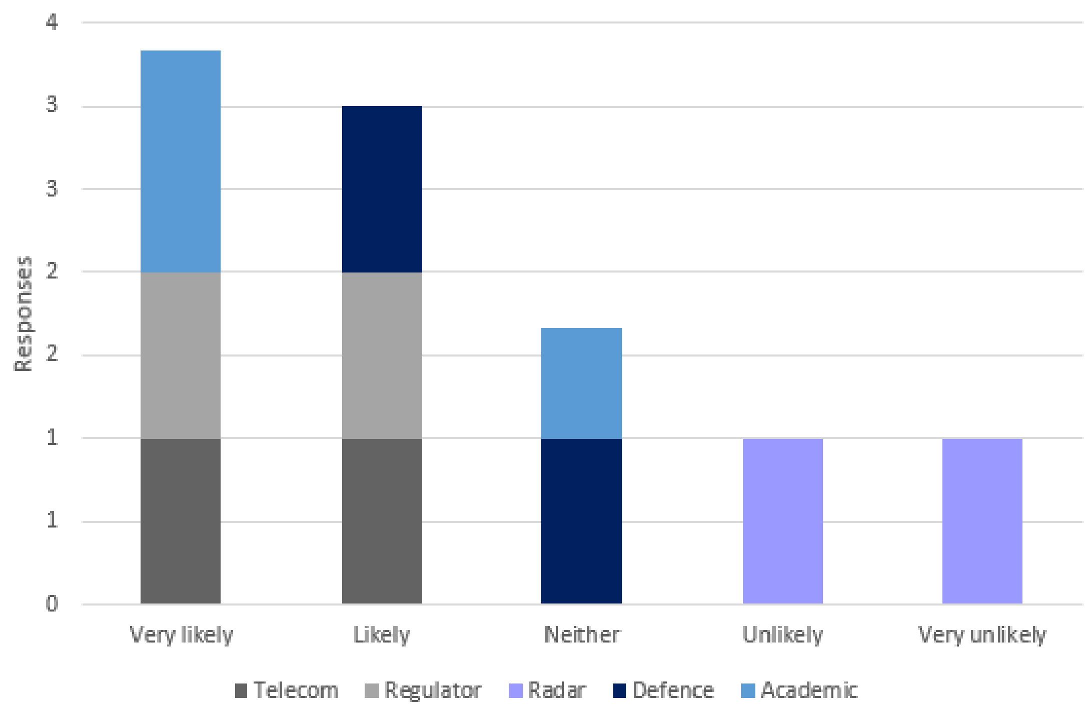

Figure B.9: Likelihood of countries going beyond ITU's radio regulations if superior coexistence capabilities exist

The following comments were also made:

- It is unlikely that there are such large differences in the coexistence capabilities of radars and communications between the nations. Furthermore, also in this case the military would still try to keep as much spectrum as possible to maximize radar performance.
- Every country decides what to do with their spectrum, regardless of the ITU

Radio Regulations, as long as they do not cause harmful interference; - In many countries, the military is not willing to share their spectrum for several reasons. Even if there is an opportunity to benefit for more sharing, it is not sure that that can be implemented.
- In the end, it is a national political decision.
- The radio regulations are treaty-binding and individual country solutions can be implemented under No. 4.4. Also the radio regulations can be updated in the future to accommodate enhanced solutions.
- Since the Member states can deviate from ITU regulations as long as no interference is caused to radio services in other states, that scenario is at least theoretically possible.
- If regulators are very forward looking, they could go well beyond. Often they spend their efforts on protecting the existing status quo and following the old approach. However, it is highly dependent on the national situation.
- Depending on the situation for the Country's Neighbors. Coordination is affecting the possibility for coexistence.
- All sovereign nations does not need to comply with ITU-R's radio regulations. Each nation decides over its own use of frequency spectrum within the nation borders, so the possibility of acting outside the ITU-R's radio regulations is always possible.However, I am very doubtful that this will happen.I think that if someone finds a well-functioning coexistence solution, this will have impact throughout the world. However, I do not think that any single nation will come up with such a solution because the entire frequency issue is in principle owned by ITU-R. It's hard to imagine that any nation by itself would work with such a complex problem.

Question:
There were variations in the responses on which coexistence techniques that are likely to be implemented. Why do you think that the responses varied that much and what does that imply? Also, please include any thoughts you may have on our first result report here.
Answer:
The responses contained:
- Each expert has a different background and own experiences with the techniques.
- There are many technologies available and probably no one excels compared to the others. There are still tests conducted to verify whether and to what extent these technologies can be used; although these technologies are good they might be very expensive; manufactures may not want to produce the equipment if they cannot benefit from economies of scale (having a big market); there is a lot of uncertainties and maybe companies do not what to make large investments.
- Likely linked to the fact that people are not aware of what's going on.
- It is not surprising to find large variations given the newness of the technology. As well, spectrum sharing is not yet a normal state of affairs for most license holders, so their perceptions of harm might be exaggerated, just as radio access

network providers might be over optimistic in their ability to avoid interference.

- The topic itself is very complex with economic, political, strategic and technical dimensions.
- If you would benefit from these "techniques", you would probably speak in favour of that technique, and vice versa. Furthermore, different people may have different levels och technical expertise, and may have different levels of understanding what these techniques actually will do, in practice.
- the Radar community need to think outside the box for new approaches.
- There are a variety of ways of addressing coexistence. They will partly be driven by radio access network manufacturers and partly at a state level. Ultimately, the diversity of answers suggests a healthy and broad approach to the problems.
- The technology is immature, and still in prototype stage. We don't yet know what will work. It's not surprising that there was a range of opinions over what will be implemented.
- I think there exists a great believe in that the technology is able to solve all problems. My believe is that nations, governments, researchers, manufacturers and users must talk and negotiate with each other and that the technology then will be developed with the help of agreed rules. It will certainly take a long time, but I think this way is the only way to reach success. The technological development in information technology has gone much faster than the worldly harmonization of the use of the frequency spectrum. Very soon you will reach the maximum limit for using the frequency spectrum, and when you will reach this limit all kind of users will be forced to use each frequency as efficiently as possible without causing any mutual harmful interference and this must be solved by mutual talks and negotiations.
- Future is uncertain and there are lots of possible equilibria so reasonable to have scatter of forecasts. Also, folks may have hand in the game.

C

Questions for technology interviews

C.1 Introduction

A. Your profession.
a. What is your definition of the technology area related to your profession expertise?
b. Where is the technology implemented, for example, in a radar system? (briefly)
c. What is the technology essentially intended to solve and how does this work? (briefly)
d. Has the technology, you are dealing with, potential to be used for coexistence purposes in the frequency spectrum?

C.2 Value

B. If we start from Saab Surveillance radar products and ignore the jamming features built into the systems, there is currently no function implemented that enables collaboration with other RF systems in the radar frequency bands. Do you believe that your technology area or any other technology area would be able to develop and implement in Saab Surveillance products to better interact with, for example, wireless communication systems (radio access networks) in order to achieve:
a. A mutual non harmful interference situation?
b. Increased spectrum efficiency?
c. Increased radar robustness?
d. Enhanced cognitivity?
e. Other characteristics that benefit coexistence with radio access networks?

C.3 Rarity

C. Do you believe that the technology knowledge is possessed by none, few or the majority of Saab's competitors?

C.4 Imitability

D. Do companies without the technology face a cost disadvantage in developing or obtaining it?
a. Patents at Saab?
b. Patents at other companies?
c. Approximate cost to develop? – Estimate time, number of employees and other investments.

C.5 Organization

E. Do you currently have enough employees to develop this technology to the market? How long would this take?
F. Are additional investments needed to develop the technology to the market?
G. How have you experience the management support to develop this technology to the market?
H. Do you recognize anything else that is missing from an organizational perspective that complicates successful development of the technology to the market?

D

National frequency allocations

National differences to ITU's general recommendations marked with red. The allocations marked in orange are exceptions but are listed in the footnotes to the general recommendations and are additional allocations. In addition, the US has RF-devices as secondary users which remain unclear of its categorization. Hence, those services was also marked with orange.

D.1 ITU region 1

Table D.1: National differences for frequency allocation, ITU region 1 [16, 94, 95, 96]

Frequency [MHz]	ITU's Radio Regulations, region 1	Sweden, United Kingdom, United Arab Emirates
3300-3400	RADIOLOCATION 5.149 5.429 5.429A 5.429B 5.430	RADIOLOCATION Amateur (UK) Fixed (UAE) Mobile (UAE) Mobile (UK)
5250-5255	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A 5.447F RADIOLOCATION SPACE RESEARCH 5.447D 5.447E 5.448 5.448A	RADIOLOCATION SPACE RESEARCH MOBILE except aeronautical mobile EARTH EXPLORATION-SATELLITE (active)
5255-5350	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A 5.447F RADIOLOCATION SPACE RESEARCH (active) 5.447E 5.448 5.448A	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile SPACE RESEARCH (active) RADIOLOCATION
5350-5460	EARTH EXPLORATION-SATELLITE (active) 5.448B RADIOLOCATION 5.448D AERONAUTICAL RADIONAVIGATION 5.449 SPACE RESEARCH (active) 5.448C	RADIOLOCATION AERONAUTICAL RADIONAVIGATION EARTH EXPLORATION-SATELLITE (active) SPACE RESEARCH (active)
5460-5470	EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION 5.448D RADIONAVIGATION 5.449 SPACE RESEARCH (active) 5.448B	EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION RADIONAVIGATION SPACE RESEARCH (active)
5470-5570	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION 5.450B MARITIME RADIONAVIGATION SPACE RESEARCH (active) 5.448B 5.450 5.451	MARITIME RADIONAVIGATION EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile RADIOLOCATION SPACE RESEARCH (active)
5570-5650	MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION 5.450B MARITIME RADIONAVIGATION 5.450 5.451 5.452	MOBILE except aeronautical mobile RADIOLOCATION MARITIME RADIONAVIGATION

Frequency [MHz]	**ITU's Radio Regulations, region 1**	**Sweden, United Kingdom, United Arab Emirates**
5650-5725	MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION Amateur Space research (deep space) 5.282 5.451 5.453 5.454 5.455	MOBILE except aeronautical mobile RADIOLOCATION Amateur Space research (deep space) Fixed (UAE) Amateur-satellite (Earth to space) (UK)
5725-5830	FIXED SATELLITE (Earth-to-Space) RADIOLOCATION Amateur 5.150 5.451 5.453 5.455	FIXED-SATELLITE (Earth-to-space) RADIOLOCATION Amateur AERONAUTICAL RADIONAVIGATION (Swe) Land Mobile (UK) Fixed (UAE) Mobile (UAE)
5830-5850	FIXED SATELLITE (Earth-to-space) RADIOLOCATION Amateur Amateur-Satellite (space-to-Earth) 5.150 5.451 5.453 5.455	FIXED-SATELLITE (Earth-to-space) RADIOLOCATION Amateur Amateur-Satellite (space-to-Earth) Fixed (UAE) Mobile (UAE) AERONAUTICAL RADIONAVIGATION (Swe) Land Mobile (UK)

D.2 ITU region 2

Table D.2: National differences for frequency allocation, ITU region 2 [16, 97, 98]

Frequency [MHz]	**ITU's Radio Regulations, region 2**	**United States of America, Brazil**
3300-3400	RADIOLOCATION Amateur Fixed Mobile 5.149 5.429C 5.429D	RADIOLOCATION Fixed (Bra) Radiolocation (US non-Fed) Amateur (US non-Fed, Bra) Private Land Mobile (US FCC Rule Part(s)) Amateur Radio (US FCC Rule Part(s))
5250-5255	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A 5.447F RADIOLOCATION SPACE RESEARCH 5.447D 5.447E 5.448 5.448A	EARTH EXPLORATION-SATELLITE (active) MOBILE except except aeronautical mobile (Bra) RADIOLOCATION SPACE RESEARCH (active) Earth Exploration-Satellite (active) (US non-Fed) Radiolocation (US non-Fed) Space Research (US non-Fed) RF Devices (US FCC Rule Part(s)) Private Land Mobile (US FCC Rule Part(s))
5255-5350	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A 5.447F RADIOLOCATION SPACE RESEARCH (active) 5.447E 5.448 5.448A	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile (Bra) RADIOLOCATION SPACE RESEARCH (active) Earth Exploration-Satellite (active) (US non-Fed) Radiolocation (US non-Fed) Space Research (US non-Fed) RF Devices (US FCC Rule Part(s)) Private Land Mobile (US FCC Rule Part(s))
5350-5460	EARTH EXPLORATION-SATELLITE (active) 5.448B RADIOLOCATION 5.448D AERONAUTICAL RADIONAVIGATION 5.449 SPACE RESEARCH (active) 5.448C	EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION AERONAUTICAL RADIONAVIGATION SPACE RESEARCH (active) Earth Exploration-Satellite (active) (US non-Fed) Radiolocation (US non-Fed) Space Research (US non-Fed) Aviation (US FCC Rule Part(s)) Private Land Mobile (US FCC Rule Part(s))
5460-5470	EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION 5.448D RADIONAVIGATION 5.449 SPACE RESEARCH (active) 5.448B	EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION RADIONAVIGATION (US) SPACE RESEARCH (active) Earth exploration-satellite (active) (US non-Fed) Radiolocation (US non-Fed) Space research (active) (US non-Fed) Maritime (US FCC Rule Part(s)) Aviation (US FCC Rule Part(s)) Private Land Mobile (US FCC Rule Part(s))

Frequency [MHz]	**ITU's Radio Regulations, region 2**	**United States of America, Brazil**
5470-5570	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION 5.450B MARITIME RADIONAVIGATION SPACE RESEARCH (active) 5.448B 5.450 5.451	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile (Bra) RADIOLOCATION MARITIME RADIONAVIGATION (US) SPACE RESEARCH (active) Earth exploration-satellite (active) (US non-Fed) Space research (active) (US non-Fed) RF Devices (US FCC Rule Part(s)) Maritime (US FCC Rule Part(s)) Private Land Mobile (US FCC Rule Part(s))
5570-5650	MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION 5.450B MARITIME RADIONAVIGATION 5.450 5.451 5.452	MOBILE except aeronautical mobile (Bra) RADIOLOCATION MARITIME RADIONAVIGATION (US) METEOROLOGICAL AIDS (US 5600-5650 MHz) RF Devices (US FCC Rule Part(s)) Maritime (US FCC Rule Part(s)) Private Land Mobile (US FCC Rule Part(s))
5650-5725	MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION Amateur Space research (deep space) 5.282 5.451 5.453 5.454 5.455	MOBILE except aeronautical mobile (Bra) RADIOLOCATION (US Fed, Bra) Amateur (US non-Fed, Bra) RF Devices (US FCC Rule Part(s)) ISM Equipment (US FCC Rule Part(s)) Amateur Radio (US FCC Rule Part(s))
5725-5830	RADIOLOCATION Amateur 5.150 5.453 5.455	RADIOLOCATION (US Fed, Bra) Amateur (US non-Fed, Bra) RF Devices (US FCC Rule Part(s)) ISM Equipment (US FCC Rule Part(s)) Amateur Radio (US FCC Rule Part(s))
5830-5850	RADIOLOCATION Amateur Amateur-Satellite (space-to-Earth) 5.150 5.453 5.455	RADIOLOCATION (US Fed, Bra) Amateur (US non-Fed, Bra) Amateur-satellite (US non-Fed, Bra) RF Devices (US FCC Rule Part(s)) ISM Equipment (US FCC Rule Part(s)) Amateur Radio (US FCC Rule Part(s))

D.3 ITU region 3

Table D.3: National differences for frequency allocation, ITU region 3 [16, 99, 100, 101, 102]

Frequency [MHz]	**ITU's Radio Regulations, region 3**	**Indonesia, India, Japan, Australia**
3300-3400	RADIOLOCATION Amateur 5.149 5.429 5.429E 5.429F	RADIOLOCATION Amateur Fixed (Indo, Indi) Fixed (Aus) MOBILE (Indo, Indi) MOBILE (Aus)
5250-5255	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A 5.447F RADIOLOCATION SPACE RESEARCH 5.447D 5.447E 5.448 5.448A	EARTH EXPLORATION–SATELLITE (active) RADIOLOCATION SPACE RESEARCH MOBILE except aeronautical mobile MOBILE (Japan) Fixed (Indi) Note: Indonesian allocations are not listed
5255-5350	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A 5.447F RADIOLOCATION SPACE RESEARCH (active) 5.447E 5.448 5.448A	EARTH EXPLORATION–SATELLITE (active) RADIOLOCATION SPACE RESEARCH (active) MOBILE except aeronautical mobile MOBILE (Japan) Fixed (Indi) Note: Indonesian allocations are not listed
5350-5460	EARTH EXPLORATION-SATELLITE (active) 5.448B RADIOLOCATION 5.448D AERONAUTICAL RADIONAVIGATION 5.449 SPACE RESEARCH (active) 5.448C	EARTH EXPLORATION–SATELLITE (active) SPACE RESEARCH (active) AERONAUTICAL RADIONAVIGATION RADIOLOCATION Note: Indonesian allocations are not listed
5460-5470	EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION 5.448D RADIONAVIGATION 5.449 SPACE RESEARCH (active) 5.448B	RADIONAVIGATION EARTH EXPLORATION–SATELLITE (active) SPACE RESEARCH (active) RADIOLOCATION AERONAUTICAL RADIONAVIGATION (Jap) Note: Indonesian allocations are not listed
5470-5570	EARTH EXPLORATION-SATELLITE (active) MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION 5.450B MARITIME RADIONAVIGATION SPACE RESEARCH (active) 5.448B 5.450 5.451	MARITIME RADIONAVIGATION MOBILE except aeronautical mobile EARTH EXPLORATION–SATELLITE (active) SPACE RESEARCH (active) RADIOLOCATION MOBILE (Jap)
5570-5650	MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION 5.450B MARITIME RADIONAVIGATION 5.450 5.451 5.452	MARITIME RADIONAVIGATION MOBILE except aeronautical mobile RADIOLOCATION MOBILE (Jap)

Frequency [MHz]	ITU's Radio Regulations, region 3	Indonesia, India, Japan, Australia
5650-5725	MOBILE except aeronautical mobile 5.446A 5.450A RADIOLOCATION Amateur Space research (deep space) 5.282 5.451 5.453 5.454 5.455	RADIOLOCATION (Indi, Jap, Aus) MOBILE except aeronautical mobile (Indi, Aus) Amateur Space research (deep space) MOBILE (Indo, Indi, Jap) FIXED (Indo, Indi)
5725-5830	RADIOLOCATION Amateur 5.150 5.453 5.455	RADIOLOCATION (Indi, Jap, Aus) Amateur MOBILE (Indi, Jap) FIXED (Indo, Indi)
5830-5850	RADIOLOCATION Amateur Amateur-Satellite (space-to-Earth) 5.150 5.453 5.455	RADIOLOCATION (Indi, Jap, Aus) Amateur Amateur–satellite (space-to-Earth) (Indi, Jap, Aus) MOBILE (Indi, Jap) FIXED (Indo, Indi)

E

Patents for coexistence technologies

E.1 Continuous Arbitrary Waveform

Table E.1: Patents for continuous arbitrary waveform,
Search keywords: "Continuous arbitrary waveform", radar

Patent number	Applicants and inventors	Patent name and abstract
WO2018147786 (A1) [103]	**Applicant:** SAAB AB [SE] **Inventors:** HELLSTEN HANS [SE] DAMMERT PATRIK [SE]	**SHORT RANGE RADAR COHABITATION:** The present invention relates to a method for a continuous arbitrary waveform radar configured for transmitting and receiving signals over a selected communication band. The method comprises: generating the radar transmit signal with a waveform having a non-monotonic frequency change, modifying the waveform to obtain at least one spectral notchand isolating reception and transmission by cancellation. Each spectral notch at a selectable frequency with a selectable bandwidth, and the waveform is modified to maintain the spectral density of the transmit radar signal.
WO2017069664 (A1) [104]	**Applicant:** SAAB AB [SE] **Inventors:** HELLSTEN HANS [SE]	**METHOD FOR MULTIPLE TRANSMISSION NOTCHING OF A BROADBAND RADAR:** The present disclosure relates to a method for operating a broadband continuous arbitrary waveform radar system for achieving high performance notching of a predetermined number of frequencies of a first radar waveform model during transmission. The method comprises performing a first order correction of a transmit signal by iteratively obtaining an approximate solution to a minimization problem in finding the phase ripple coefficient for respective frequency to be notched by setting the remaining phase ripple coefficients to be 0 and subsequently inserting calculated phase ripple functions and phase ripple coefficients in a phase ripple radar waveform model. The present disclosure also relates to broadband continuous arbitrary waveform radar systems configured for executing said methods.

E.2 Orthogonal waveform

Table E.2: Patents for orthogonal waveform,
Search keywords: "Orthogonal waveform", radar

Patent number	Held by	Patent name and abstract
CN105116384 (A) [105]	**Applicant:** UNIV ELECTRONIC SCIENCE & TECH **Inventors:** LIN HOUHONG LU XIAXIA JIANG SIYUAN TAN PENGCHAO	**Radar orthogonal waveform design method based on frequency modulation and phase modulation of chaotic sequence:** The invention discloses a radar orthogonal waveform design method based on frequency modulation and phase modulation of a chaotic sequence, comprising the following steps: S1, using a chaotic system to generate a chaotic sequence of which the length is N*P, and cutting the chaotic sequence into P sequence sections (the length of each sequence section is N), selecting one sequence section, and letting the sequence section be x(0), x(1), x(2),...,x(N); S2, encoding a chaotic joint frequency modulation and phase modulation signal, dividing a pulse into a series of equal sub pulses, and carrying out frequency modulation differently on different sub pulses, and then, using the sequence section obtained in S1 to carry out phase encoding on each cycle of a waveform in each frequency encoding sub pulse, and obtaining a phase-frequency joint modulation chaotic radar signal through use of a randomly-generated initial phase; and S3, calculating a complex envelope signal of the phase-frequency joint modulation chaotic radar signal obtained in S2. The signal frequency and phase change as a chaotic signal changes, the orthogonality of signals is improved, and the interception probability is reduced.
US2015323650 (A1) [106] **Also published as:** US9207313 (B2)	**Applicant:** SRC INC [US] **Inventors:** SCHUMAN HARVEY K [US]	**MIMO ANGLE ESTIMATION WITH SIMULTANEOUS MAINLOBE JAMMER CANCELLATION:** A radar system includes a transmit antenna array having subarrays disposed at predetermined positions. An orthogonal waveform signal is directed to a corresponding one of the subarrays. On receive, an adaptive processor derives a plurality of adaptive weight factors from a plurality of receive signals and applies them to the receive signals to obtain a jammer cancelled signal. That signal is separated into its orthogonal waveform components by passing it through a bank of correlators. The correlator system provides a plurality of unique receive signals substantially corresponding one-to-one to the unique transmit subarrays. The receive beamformer derives an angular estimate of at least one target relative to boresight from the unique receive signals.

Patent number	Held by	Patent name and abstract
CN104849712 (A) [107] **Also published as:** CN104849712 (B)	**Applicant:** BEIJING INST TECHNOLOGY **Inventors:** ZENG TAO HU CHENG MAO CONG TIAN WEIMING MAO ERKE LONG TENG	**Three-dimensional deformation monitoring system based on multi-base multiple-input multiple-output synthetic aperture radar (MIMO-SAR):** The present invention provides a three-dimensional deformation monitoring system based on multi-base multiple-input multiple-output synthetic aperture radars (MIMO-SARs), which can adapt to characteristics of tiny surface displacement, deformation space hop and macroscopical unstability abruptness of high and steep rock slopes. Three MIMO-SAR radar systems are placed in a separated manner at three different positions in a space to acquire deformation information in different angle directions, is uniformly controlled by a control and data processing center, and transmit orthogonal waveform signals, thus to instantly complete scanning of the surface morphology of a scene; when receiving echoes, each radar receives single-base echoes from itself and also receives double-base echoes from the other two radar systems; after each-time scanning, each radar transmits echo data to the control and data processing center for real-time data processing so as to acquire multiple MIMO-SAR images at different view angles, thereby realizing high-precision and rapid measurement of a three-dimensional deformation field through difference interfering, image matching and three-dimensional deformation resolving treatment.
CN104836768 (A) [108]	**Applicant:** UNIV DALIAN TECH **Inventors:** WANG ZONGBO LIN ZHIBIN	**OFDM-based coherent MIMO radar orthogonal waveform design method:** The invention relates to a radar orthogonal waveform design method, and especially relates to an OFDM-based coherent MIMO radar orthogonal waveform design method. The OFDM-based coherent MIMO radar orthogonal waveform design method comprises the steps of establishing the OFDM signal mathematical module; generating random base band sequence; conducting polarity transformation on the random base band sequence; conducting QPSK modulation on the transformed random base band sequence; building random drawing function; arranging Ci from small to large by means of bubbling method; conducting zero filling on each sequence; conducting IFFT by means of new modulation sequence generated by the step 2-7. With the OFDM signal in the original communication being as the base and through constructing the random function, random drawing of the sub-carrier of the OFDM signal can be conducted, and thereby a plurality of groups of modulation code sequences can be obtained, and the final SI-OFDM signal can be obtained by means of rapid inverse Fourier transform in discrete time. The OFDM-based coherent MIMO radar orthogonal waveform design method is advantageous in that the method is simple and clear; with the IFFT, signal generation is easy, and engineering practice is more practical.
CN104635229 (A) [109] **Also published as:** CN104635229 (B)	**Applicant:** ELECTRONIC SCIENCE RES INST CHINA ELECTRONICS TECHNOLOGY GROUP CORP **Inventors:** ZHANG ZHAO LI XIANGRU	**Coherent MIMO (multiple-input multiple-output) radar waveform design method oriented to unambiguous zone area expansion:** The invention discloses a coherent MIMO (multiple-input multiple-output) radar waveform design method oriented to unambiguous zone area expansion. The method includes building a model of a frequency orthogonal waveform group, comprising multiple waveforms, of a coherent MIMO radar, wherein any two waveforms of the waveform group keep orthogonal within coherent processing time; adjusting a frequency interval of each two adjacent waveforms in the waveform group to enable unambiguous Doppler of the coherent MIMO radar to be 1/T and unambiguous time delay of the coherent MIMO radar to be T, wherein the T refers to pulse repetition period. The method has the advantages that by means of adjusting a value of the frequency interval of any two waveforms in the frequency orthogonal waveform group of the coherent MIMO radar, the unambiguous Doppler of ambiguity function slices of the coherent MIMO radar to be 1/T, so that the unambiguous zone area of the coherent MIMO radar keeping orthogonal is expanded.

Patent number	Held by	Patent name and abstract
CN104569924 (A) [110] **Also published as** CN104569924 (B)	**Applicant:** ELECTRONIC SCIENCE RES INST CHINA ELECTRONICS TECHNOLOGY GROUP CORP **Inventors:** ZHANG ZHAO JIANG BAIFENG	**Fuzzy-free region area expansion oriented incoherent MIMO radar waveform design method:** The invention discloses a fuzzy-free region area expansion oriented incoherent MIMO (Multi-Input Multi-output) radar waveform design method. The method comprises the following steps: creating a frequency orthogonal waveform model, comprising a plurality of waveforms, of incoherent MIMO radar, wherein any two waveforms in the waveform model can be kept orthogonal in the coherent processing time; adjusting frequency intervals between every two adjacent waveforms in the waveform group, so as to enable the incoherent MIMO radar fuzzy-free Doppler to be 1/T, meanwhile enabling the incoherent MIMO radar fuzzy-free time delay to be T which is a pulse repetition period. According to the fuzzy-free region area expansion oriented incoherent MIMO radar waveform design method disclosed by the invention, the frequency interval values of any two waveforms in the incoherent MIMO radar frequency orthogonal waveform group can be adjusted to fuzzy function section fuzzy-free Doppler of the incoherent MIMO radar to be 1/T, so that the incoherent MIMO radar fuzzy-free region area keeping orthogonal can be expanded.
CN104515975 (A) [111] **Also published as:** CN104515975 (B)	**Applicant:** ELECTRONIC SCIENCE RES INST CHINA ELECTRONICS TECHNOLOGY GROUP CORP **Inventors:** ZHANG ZHAO ZHEN JUNYI	**Coherent MIMO (multiple input multiple output) radar waveform design method facing clutter suppression:** The invention discloses a coherent MIMO (multiple input multiple output) radar waveform design method facing clutter suppression. The coherent MIMO radar waveform design method includes building up a model comprising a plurality of frequency orthogonal waveform groups of waveforms as coherent MIMO radar detection waveforms, and keeping any two of waveforms of the waveform groups orthogonal within the coherent processing time; adjusting frequency interval between two adjacent waves in the waveform groups, and suppressing grating lobes and minor lobes of the orthogonal coherent MIMO radar delay dimension and Doppler dimension. The coherent MIMO radar waveform design method effectively solves the problem that clutter suppression performance during filter matching cannot be effectively improved in the prior art of the coherent MIMO radar waveform design.
CN103592647 (A) [112] **Also published as:** CN103592647 (B)	**Applicant:** CHINESE ACAD INST ELECTRONICS **Inventors:** WANG YANPING HAN KUOYE TAN WEIXIAN HONG WEN WU YIRONG	**Array three-dimensional SAR data acquisition method:** The invention provides an array three-dimensional SAR data acquisition method. According to the array three-dimensional SAR data acquisition method, at every course-made-good slow moment when a radar platform moves along a track, echoes after sampling are decoded to achieve cross-course aperture synthesis imaging sampling by adopting a cross-course multi-transmitting multi-receiving thinned array and simultaneously transmitting/receiving OFDM-Chirp orthogonal waveform coding signals, so that signals sampled in the elevation direction, the track direction and the cross-course direction are acquired, and then three-dimensional imaging is performed to acquire a three-dimensional focusing image of a scene.; According to the method, the cross-course array aperture synthesis is performed by simultaneously transmitting the orthogonal waveform coding signals, and compared with a time-division transmitting/receiving method, the method has the advantages that the pulse repetition frequency of a system can be reduced, and the echo storage data size is small.

Patent number	Held by	Patent name and abstract
CN103076596 (A) [113] **Also published as:** CN103076596 (B)	**Applicant:** UNIV XIDIAN **Inventors:** LIU HONGWEI JIU BO WANG XU WANG YINGHUA ZHOU SHENGHUA	**Prior-information-based method for designing transmitting direction diagram of MIMO (Multiple Input Multiple Output) radar:** The invention discloses a prior-information based method for designing a transmitting direction diagram of MIMO (Multiple Input Multiple Output) radar, mainly solving the problem that the traditional method cannot be utilized to inhibit stronger nonuniform sidelobe clutters effectively. The method comprises the following steps of: transmitting a orthogonal waveform, and solving a correlation matrix of an orthogonal waveform echo according to received echo data of an interest distance unit; optimizing a correlation matrix of a transmitted waveform according to the correlation matrix of the orthogonal waveform echo and estimated direction and strength of a target; designing an initial waveform by adopting a CA (Cyclic Algorithm) according to the correlation matrix of the transmitted waveform;; and designing the transmitted waveform by adopting the maximized signal noise ratio criterion by using the correlation matrix of the orthogonal waveform echo and the initial waveform. According to the invention, the stronger sidelobe clutters are inhibited adaptively based on the perception of the orthogonal waveform to a clutter environment, and the method can be utilized to design the transmitting direction diagram of the MIMO radar under the non-uniform clutter environment.
CN102998659 (A) [114] **Also published as:** CN102998659 (B)	**Applicant:** UNIV TSINGHUA **Inventors:** MENG ZANGZHEN XU JIA PENG YINGNING PENG SHIBAO GUO RUI WANG LIBAO	**Doppler frequency spectrum shaping method and system based on interpulse modulation:** The invention provides a Doppler frequency spectrum shaping method and system based on interpulse modulation. The method comprises the following steps: generating a transmission pulse through a waveform generator and determining a Doppler frequency spectrum shaping function of the transmission pulse; performing interpulse modulation on the transmission pulse according to the Doppler frequency spectrum shaping function to generate a modulation pulse; receiving the modulation pulse (echo signals) and performing digital sampling; and performing interpulse fast Fourier transform on the modulation pulse obtained by sampling so as to obtain a shaping Doppler frequency spectrum.; According to the method of an embodiment, the radar anti-jamming performance can be improved by shaping the transmission pulse Doppler frequency spectrum, and a novel technical approach is provided for orthogonal waveform separation of a multi-transmitting and multi-receiving radar system.
CN102540187 (A) [115] **Also published as:** CN102540187 (B)	**Applicant:** UNIV ELECTRONIC SCIENCE & TECH **Inventors:** ZHULIN ZONG LEI ZHANG LIDONG ZHU JIANHAO HU KAI XIN	**Orthogonal waveform designing method for formation flying satellites SAR (synthetic aperture radar):** The invention relates to a waveform design for a formation flying satellites SAR (synthetic aperture radar), and provides an orthogonal waveform designing method which is used for carrying out phase encoding for linear frequency modulation (LFM) signals. The orthogonal waveform designing method includes generating a linear frequency modulation signal at first, dividing the linear frequency modulation signal into N parts according to equal time intervals to form N sub-pulses, carrying out random phase encoding for each sub-pulse by M times according to the number M of the formation flying satellites, establishing an ambiguity function expression, calculating cluster tolerance xi meeting formation flying satellite synthetic aperture radar Doppler mismatch, finding out a critical N value meeting requirements by the aid of a searching comparison method, finally selecting energy and functions which are in autocorrelation and cross-correlation as cost functions, namely fitness functions in genetic algorithm, searching code values of phase encoding of the various sub-pulses by the aid of the genetic algorithm, and finding out orthogonal waveforms after optimization at last. The waveforms have low autocorrelation side lobes, cross-correlation peak values, bandwidth occupation ratio and Doppler mismatch, and excellently suppress echo signal interferences among different space-borne SARs.

Patent number	Held by	Patent name and abstract
WO2007044051 (A2) [116] **Also published as:** WO2007044051 (A3) EP1880232 (A2) EP1880232 (B1) ES2542855 (T3) IL182942 (A) JP2008530535 (A) KR101240876 (B1) KR20070114149 (A) US7151478 (B1)	**Applicant:** RAYTHEON CO [US] **Inventors:** ADAMS VINH N [US] DWELLY WESLEY H [US]	**PSEUDO-ORTHOGONAL WAVEFORMS RADAR SYSTEM, QUADRATIC POLYPHASE WAVEFORMS RADAR, AND METHODS FOR LOCATING TARGETS:** In some pseudo-orthogonal waveform embodiments, a radar system (100) transmits pseudo-orthogonal waveforms and performs multiple correlations on a combined single receiver channel signal. In some quadratic polyphase waveform embodiments, a radar system (100) may simultaneously transmit frequency separated versions of a single quadratic polyphase waveform on a plurality of transmit antennas, combine the return signal from each antenna into a combined time-domain signal, and perform a Fourier transformation on the combined time- domain signal to locate a target. The radar system may identify a target, such as sniper's bullet, incoming projectile, rocket-propelled grenade (RPG) or a mortar shell. In some embodiments, the system may estimate the target's trajectory to intercept the target.; In some embodiments, the system may estimate the target's trajectory and may further extrapolate the target's trajectory to locate the target's source, such as the sniper.

E.3 Digital radar

Table E.3: Patents for digital radar,
Search keywords: "Digital radar", detection

Patent number	Held by	Patent name and abstract
CN108111221 (A) [117]	**Applicant:** SICHUAN JIUZHOU ATC TECH CO LTD **Inventors:** WANG JIANFENG LIU YONGGANG CHEN WEI WANG QIANG	**Optical fiber link auto detection method based on digital radar of certain shipborne platform:** The invention provides an optical fiber link auto detection method based on a digital radar of a certain shipborne platform. The shipborne platform comprises data emitting links and data receiving links and automatically detects an optical fiber link through the data emitting links and the data receiving links, wherein the data emitting links sequentially comprise a data emitting link of a controlcenter, a data emitting link of a programmable logic device, a data emitting link of a data exchange extension, a data emitting link of a synthesis extension and a data emitting link of a transceiverextension, and the data receiving links sequentially comprise a receiving link of the transceiver extension, a receiving link of the synthesis extension, a receiving link of the data exchange extension, and a receiving link of a processing extension. The method is realized through software programming by using intrinsic hardware resources of a digital phased array radar, special test instruments are not adopted and professional test persons do not interfere, so that manpower and material costs are saved, system test efficiency is improved, test time is shortened, and the device can be manufactured and maintained conveniently.

Patent number	Held by	Patent name and abstract
CN107667033 (A) [118] **Also published as:** EP3298425 (A1) US2016341821 (A1) WO2016191034 (A1)	**Applicant:** QUALCOMM INC **Inventors:** WANG QI	**METHODS AND APPARATUS UTILIZING DIGITAL SIGNAL PROCESSING OF ULTRA WIDE BAND RADAR SIGNALS FOR LIVING TARGET DETECTION:** An apparatus for detecting an object in a detection area of a wireless power transfer system is provided. The apparatus comprises a receiver configured to receive a plurality of radar signals from a radar transceiver. The apparatus comprises a processor configured to convert the plurality of radar signals to a plurality of digital radar signals. The processor is configured to bandpass filter the plurality of digital radar signals. The processor is configured to remove frequency content below a first threshold frequency common to at least two consecutive digital radar signals of the plurality of digital radar signals. The processor is configured to down-convert the plurality of digital radar signals into a plurality of complex digital baseband signals. The processor is configured to detecta range, a speed, and a direction of the object in the detection area based at least in part on the plurality of complex digital baseband signals.
CN106597398 (A) [119]	**Applicant:** LEIHUA ELECTRONIC TECH RES INST AVIATION IND CORP CHINA **Inventor:** GUO LI'AN	**Digital radar simulation system:** The present invention belongs to the digital radar simulator simulation technical field and relates to a digital radar simulation system. The digital radar simulation system includes a radar signal simulation module used for simulating radar echo baseband signals, and a radar processor module used for simulating the signal processing of a radar and the working environment of data processing; and the radar processor module is also used for receiving the echo baseband signals transmitted by the radar signal simulation module, processing the echo baseband signals so as to obtain radar detection information and transmitting the detection information to the radar signal simulation module. According to the digital radar simulation system of the invention, the existing hardware and software modules of an actually installed radar are fully utilized, so that quickness and convenience in construction can be realized, and a target or image information outputted by the radar can have high consistency with the actually installed radar, and the performance and fidelity of the simulator are largely improved, and high-fidelity radar detection information can be provided for test verification or the platforms of other radars.
RU2592076 (C1) [120]	**Applicant:** OTKRYTOE AKTSIONERNOE OBSHSHESTVO NP TS ELEKTRONNYE VYCHISLITELNO INF SISTEMY [RU] **Inventors:** PETRICHKOVICH YAROSLAV YAROSLAVOVICH [RU] PYATKIN ALEKSEJ KONSTANTINOVICH [RU] YANAKOVA ELENA SERGEEVNA [RU] SHAROV ALEKSANDR IGOREVICH [RU] RAKUTIN ALEKSANDR NIKOLAEVICH [RU]	**RADAR SYSTEM:** FIELD: radar.SUBSTANCE: invention relates to radar and can be used in security systems for detection and measurement in real time of trajectory parameters of moving objects during control over large areas of territories, water bodies and air space.EFFECT: technical result is creation of a digital radar system with a wider sector of observation (up to 360 degrees) due to presence of multiple radar modules with a set of transceiving antennae, located in different planes; with high degree of protection against external active interference due to that each of radar system modules is configured to encode initial phase of each probing pulse according to a random law to generate a unique phase key for coherent pulse sequence, which is used for subsequent matched filtering of "own" echo-signals with random phase compensation, wherein echo signals from neighbouring "foreign" radar systems, as well as external harmonic (quasi-harmonic) active interference are subjected to destruction in digital receiving channel of radar module as a result of their phase modulation; with increased range of detection owing to compensation for attenuation of echo signals in switch, which is part of radar module.

Patent number	Held by	Patent name and abstract
CN105416172 (A) [121]	**Applicant:** ATECH AUTOMOTIVE (WUHU) CO LTD **Inventor:** CHEN ZEJIAN	**Digital automobile backing radar:** The invention discloses digital automobile backing radar. The digital automobile backing radar is characterized in that digital radar probes installed on the periphery of an automobile are connected with slave nodes of a Lin network respectively to be connected to an automobile body controller which is a main node and a gateway; and the automobile body controller is connected to an automobile instrument through the Lin network. By the adoption of the structure, the digital automobile backing radar is high in anti-interference capacity, better in EMC performance, more accurate and more stable in obstacle detection performance, easy to install and capable of adopting non-shielded wires, assisting a driver in overcoming the defects of view dead angles and blurred vision and improving driving safety.
RU2553279 (C1) [122] **Also published as:** CN103718060 (A) CN103718060 (B) EP2734858 (A1) EP2734858 (B1) JP2014523535 (A) JP6026531 (B2) US2013021197 (A1) US8803730 (B2) WO2013012517 (A1)	**Applicant:** ZE BOING KOMPANI [US] **Inventor:** TSZJAN TSIN	**RADAR PULSE DETECTION USING DIGITAL RADAR RECEIVER:** FIELD: radio engineering, communication.SUBSTANCE: in electronic warfare, radar stations operate in an environment with highly dense electronic signals. As a result, the radar stations may receive thousands or millions of radar pulses every second. Detecting and sorting out radar pulses emitted from different radars stations is a challenging problem in electronic warfare. The present invention provides a radar pulse detection system that utilises digital channelisation and joint-channel detection techniques to detect and separate radar pulses that are emitted from different radar emitters. The main features of the present invention are: 1) a digital channelisation technique to separate radar pulses from their mixtures; 2) a multi-channel detection technique to detect radar pulses; and 3) a technique to separate overlapped radar pulses.EFFECT: improved method of detecting radar pulses intended for use with digital radar receivers.
CN203224623 (U) [123]	**Applicant:** UNIV WUHAN **Inventors:** WEN BIYANG TIAN YINGWEI TAN JIAN LI KE YANG XING WU SHICAI	**Multi-frequency compact-type array all-digital radar device:** The utility model discloses a multi-frequency compact-type array all-digital radar device including a monopole multi-frequency transmitting antenna, a transmitter, a DDS (Direct Digital Synthesis) chip, a PLL (Phase Locking Loop) clock synthesizer, a temperature-compensation crystal oscillator, a monopole/cross loop array receiving antenna, a receiving switch, a receiving filter, a receiving amplifier, an analog-to-digital converter, an FPGA (Field-Programmable Gate Array), a USB controller and a host. By adopting the monopole multi-frequency transmitting antenna, one or more frequency signals can be transmitted at the same time. By adopting the monopole/cross loop array receiving antenna, one or more frequency signals can be received at the same time. The multi-frequency compact-type array all-digital radar device provided by the utility model can monitor distribution of external noise in real time and selects appropriate working frequency. The multi-frequency compact-type array all-digital radar device is simple in structure, small in size, low in cost, good in performance and flexible to control and is quite suitable for ocean surface kinetic parameter observation and sea surface low-speed target detection and is easy to extend in use.

Patent number	**Held by**	**Patent name and abstract**
US3761922 (A) [124]	**Applicant:** HUGHES AIRCRAFT CO **Inventor:** WEVANS N	**DIGITAL MEAN LEVEL DETECTOR:** A digital mean level detector that processes the digital radar data so that the mean or RMS noise level is accurately determined and selected offset threshold levels can be varied to provide highly accurate and reliable signal detection. The system first provides mean level detection of the digital input signal which is applied to a threshold compare circuit having a plurality of thresholds such as two, for example. The output signals of the threshold compare circuit are encoded and sent both to a delay register and to an accumulator, with the outputs of both being applied to a subtractor for eliminating the oldest signal of a moving window sum held in the accumulator. The signal at the output of the subtractor is applied to the accumulator where it is added to the present signal at the output of the threshold compare circuit. At each range bin, the accumulated sum is then compared with an expected count representing the mean level of the noise for the selected number of range bins. The difference, representative of a predetermined error of the input noise level, is then adjusted and used to correct a signal detector having an offset threshold as determined by selected detection codes.
US3727218 (A) [125] **Also published as:** AU3680471 (A) AU459111 (B2) DE2202581 (A1) DE2202581 (B2) FR2123539 (A1) FR2123539 (B1) IT948345 (B) JPS5223719 (B1)	**Applicant:** HUGHES AIRCRAFT CO **Inventors:** CANTWELL T WILMOT R	**DIGITAL RADAR DETECTOR SYSTEM:** An automatic digital target detector and azimuth measuring system that includes a digital filter whose amplitude weighting function corresponds to the antenna beam pattern so as to provide a desirable target detection probability and azimuth measurement accuracy. The target detector utilizes a digital matched time delay filter concept for target detection and azimuth beam splitting with only two sweeps of series connected delay or data storage being required. The binary weighted data is processed with a feedback path provided from the detector output to the input of each delay means, and with each feedback path including a variable multiplying factor which may be set or controlled to match the detector to different antenna beam shapes and beam widths, or may be set or controlled to operate with different or variable scan rates or with different radar pulse repetition frequencies. The detector is adaptable to different beam widths, to different scan rates and to different pulse repetition frequencies by controlling the period of impulse response.
US7006034 (B1) [126]	**Applicant:** RAYTHEON CO [US] **Inventors:** KRIKORIAN KAPRIEL V [US] ROSEN ROBERT A [US] KRIKORIAN MARY [US]	**Fast and slow time scale clutter cancellation:** Target detection in the presence of non stationary clutter is improved by a radar receiver on a moving platform for detecting a target using a plurality of short coherent arrays and a plurality of long coherent arrays synthesized from the short coherent arrays overlapping the target. The target is obscured by slow scale clutter and fast scale clutter in the vicinity of the target. The radar receiver has a plurality of subapertures overlapping to acquire radar returns reflected from the target during the arrays, an analog to digital converter for each of the subapertures to convert the radar returns into digital radar returns for a plurality of range bins covering the target, the slow scale clutter and the fast scale clutter; and a digital computer for performing steps of SAR image creation, further enhanced by thresholding short array magnitude data, computing a time domain component of threshold filters using the thresholded short array magnitude data then coherently subtracting the time domain component of threshold filters from the short arrays, and using the result to synthesize long coherent arrays. A Space Time Adaptive Algorithm (STAP) is applied to the long coherent arrays thus obtained to suppress slow and stationary clutter. The short coherent arrays are between 10 and 400 milliseconds long. The long coherent arrays are between 400 and 4000 milliseconds long.

Patent number	Held by	Patent name and abstract
RU95101285 (A) [127] **Also published as:** RU2080618 (C1)	**Applicant:** VOENNAJA AKADEMIJA PVO IM ZHUKOVA G K **Inventors:** BOGDANOV A V VASIL EV O V SHCHEKOTILOV V G CHERNYKH M M	**DIGITAL RADAR-SIGNAL PROCESSING UNIT:** FIELD: radar engineering; doppler pulse radars. SUBSTANCE: digital radar-signal processing unit has two phase detectors whose combined first inputs function as unit input, two analog-to-digital converters, phase shifter, fast Fourier transform unit whose output function as radar-signal digital processing unit, meter, quasi-optimal filter, digital-to-analog converter, controlled local oscillator, and sampling-frequency oscillator. Meter has two delay lines, two adders, multiplier of sixteen complex signals, correlator, phase meter, scaling amplifier, and differentiating unit. Sampling- frequency oscillator has decoder, first, second, and third pulse generators, first, second, and third AND gates, and OR gate. EFFECT: provision for maximum possible range of airborne target detection under various flying conditions.
JPH03251781 (A) [128] **Also published as:** JP2546010 (B2)	**Applicant:** NEC CORP **Inventors:** MURAKAMI SUMINORI MUKOYAMA TORU	**RADAR VIDEO COMPRESSING APPARATUS:** PURPOSE:To enhance transmission efficiency to a large extent by sampling the max. value in the unequal interval cycle of a radar video signal at every unequal interval cycle to issue output at an equal interval. CONSTITUTION:A radar video signal 5 is sampled by an equal interval sampling signal 6 and the digital radar video signal 7 thereof is inputted to a max. value detection means 2 within the cycle of an unequal interval sampling signal 8 and the max. value of the radar video signal is detected. Only a max. value video signal 9 is stored in a memory means 3 and the max. value thereof is read by a reading signal 11 of a definite interval.; Herein, since the unequal interval sampling signal 8 is one gradually increased in its cycle as a distance becomes long, one max. value is detected from more radar video signals 7 in a long distance part and, therefore, the compression quantity of signals in the long distance part is enhanced and transmission capacity or a transmission band can be reduced.
WO2006072255 (A1) [129]	**Applicants:** SIMRAD STOEVRING AS [DK] BIEHL KARSTEN [DK] **Inventor:** BIEHL KARSTEN [DK]	**DIGITAL RADAR SYSTEM WITH CLUTTER REDUCTION:** The present invention relates to a digital radar system with clutter reduction. A first object of the invention is to provide a system for clutter reduction and target detection in a radar system enabling detection of small targets in signals with high amounts of clutter and simultaneously enabling detection of fast moving targets. A further object of the invention is to avoid latency when an operator changes manual adjustments of e.g. gain, clutter controls or changing display modes. This might be achieved by a radar system where the processor means store N independent scan-related images in a memory, which images are stored in a true-motion format. The processor means maintain a clutter map. The processor means generate M 2-dimentional sensitivity maps, the calculation of which may be based on the clutter map, the scan-related images and manual input from the operator. The processor means perform M scan-to-scan correlations, each using one of the sensitivity maps. The resulting M images from the scan- to-scan correlations are combined into a single image, which can be rotated and displaced to be presented to the operator, in his choice of display mode. Each scan-to- scan correlation can use data from 1 to N scan related images. By using individual sensitivity maps for each scan-to-scan correlation, the contribution of clutter from each scan-to-scan correlation can be controlled.

Patent number	Held by	Patent name and abstract
CN2653464 (Y) [130]	**Applicant:** CHEN RENFU [CN] **Inventor:** CHEN RENFU [CN]	**Electromechanical digital radar monitoring system:** An electromechanical digital radar monitoring system belongs to the field of electromechanical check and automatic radar monitoring, and an electromotor is used as the source of power. With the application of a mechanical transmission, a gravity detector moves up and down in a breeze container through a steel wire to detect the stock, temperature and humidity of breeze. The altitude detection of breeze is sent back by a camera device and showed on a display in a control room. The stock of breeze is printed out through digital display by a compound system of engine and photoelectricity. The temperature and humidity of the breeze container is conveyed by a transfer device of the temperature and humidity and showed on the specific instrument of the control room. The improved radar device automatically disposes that the breeze pile emits and receives the electromagnetic wave, and the dynamic stock of the breeze container is sent back by the device, showed and printed by the instrument of the control room. With safety and convenience, the utility model is suitable for the automatic control.

E.4 Front-end technology

Table E.4: Patents for front-end technology,
Search keywords: Radar, "controllable filter"

Patent number	Held by	Patent abstract
JPS5694282 (A) [131] **Also published as:** JPS6252830 (B2)	**Applicants:** BOEICHO GIJUTSU KENKYU HONBUCH FUJITSU LTD **Inventors:** SAWADA MICHIHIRO TAMURA MASARU OGAWA SHINPEI	**PULSE TRAIN SEPARATING AND DISCRIMINATING SYSTEM:** PURPOSE:To eliminate the need for using multiple filters and make constitution simple by performing searching and leading out of specific pulses by using a controllable filter. CONSTITUTION:An input signal enters a branching circuit 3 by passing through an electronic tuning filter 2 from an input terminal 1. The one of the outputs branched by the circuit 3 is demodulated by a demodulating circuit 4 and is made into a pulse train corresponding to the modulating signal of a radar signal. This pulse train is amplified with a video amplifier 5, and is collated with the data having beforehand been stored in a collating circuit 8. The data of the matched pulse width and repetitive period are inputted to a decision circuit 6.; The circuit 6 compares and decides the data from the circuit 8 and the video data and transmits the signal corresponding to the matched pulse width and repetitive period to filter control circuit 9 and a gate control circuit 11.
GB2349759 (A) [132]	**Applicant:** AUTOLIV CELSIUS AB [SE] **Inventor:** TULLSSON BERT ERIC [SE]	**Radar heartbeat monitor:** A device for monitoring the heartbeat of a living body comprises a radar (1) which directs a beam of microwave radiation (e.g. within the frequency band 1-25 GHz) towards a body whose heartbeat is to be monitored. A phase-shift signal is derived representative of the phase-shift between the transmitted signal and the reflected signal. A controllable filter (3) (which may be a digital filter) filters the phase-shift signal to pass a frequency spectrum anticipated to contain signals corresponding to the heartbeat monitored. The output of the filter is passed to a spectral analysis unit (5) which provides a signal to control circuit (4) which controls the filter. An output signal representative of a heartbeat being monitored may be passed to an alarm (7) which may be associated with additional sensor means (8). The device may incorporate an antenna located in a support for the body whose heartbeat is to be monitored.

E.5 Adaptive Interference Cancellation

Table E.5: Patents for adaptive interference cancellation,
Search keywords: Adaptive interference cancellation, radar

Patent number	Held by	Patent name and abstract
US2018231655 (A1) [133] **Also published as:** US2017293027 (A1) US9689967 (B1) US9945943 (B2) WO2017175190 (A1)	**Applicant:** UHNDER INC [US] **Inventors:** STARK WAYNE E [US] BORDES JEAN P [US] DAVIS CURTIS [US] RAO RAGHUNATH K [US] MAHER MONIER [US] HEGDE MANJU [US] SCHMID OTTO A [US]	**ADAPTIVE TRANSMISSION AND INTERFERENCE CANCELLATION FOR MIMO RADAR:** A radar sensing system for a vehicle includes a transmit pipeline, a receive pipeline, and a memory module. The transmit pipeline includes transmitters for transmitting radio signals. The receive pipeline includes receivers for receiving radio signals that include the transmitted radio signals transmitted by the transmitters and reflected from objects in an environment. The memory module is configured to store interference estimates for each receiver of the plurality of receivers that are estimates of interfering radio signals received by each of the receivers that are transmitted by each respective transmitter of the plurality of transmitters. Each receiver of the plurality of receivers is configured to mitigate interference that is due to interfering radio signals transmitted by the plurality of transmitters, as defined by the stored interference estimates of the plurality of transmitters for each particular receiver.
WO2017187339 (A1) [134] **Also published as:** US2017307728 (A1) US2018259619 (A1) US9945935 (B2) WO2017187304 (A2) WO2017187304 (A3)	**Applicant:** UHNDER INC [US] **Inventors:** ESHRAGHI ARIA [US] BORDES JEAN P [US] DAVIS CURTIS [US] RAO RAGHUNATH K [US] ALI MURTAZA [US] DENT PAUL W [US]	**VEHICULAR RADAR SYSTEM WITH SELF-INTERFERENCE CANCELLATION:** A digital FMCW radar is described that simultaneously transmits and receives digitally frequency modulated signals using multiple transmitters and multiple receivers and associated antennas. Several sources of nearby spillover from transmitters to receivers that would otherwise degrade receiver performance are subtracted by a cancellation system in the analog radio frequency domain that adaptively synthesizes an analog subtraction signal based on residual spillover measured by a correlator operating in the receivers' digital signal processing domains and based on knowledge of the transmitted waveforms. The first adaptive cancellation system achieves a sufficient reduction of transmit-receive spillover to avoid receiver saturation or other non-linear effects, but is then added back in to the signal path in the digital domain after analog-to-digital conversion so that spillover cancellation can also operate in the digital signal processing domain to remove deleterious spillover components.
CN106980110 (A) [135]	**Applicant:** WUHAN BINHU ELECTRONIC CO LTD **Inventors:** XU MINCHAO LI QING CHEN ZHONG HAN WENFENG	**Adaptive side-lobe cancellation method for resisting multipath active suppressing interference:** The invention relates to the ground-based radar active interference resistance field and particularly relates to an adaptive side-lobe cancellation method for resisting multipath active suppressing interference. According to the method, time-space joint of data in a side-lobe cancellation channel received by a radar is carried out, side-lobe cancellation is carried out through utilizing an ECA algorithm, and a stable side-lobe cancellation purpose is realized. The method is advantaged in that high sensitivity of performance of a radar side-lobe cancellation algorithm depends on the position environment is reduced, and stability of performance of the side-lobe cancellation algorithm is guaranteed.

Patent number	Held by	Patent name and abstract
CCN106772254 (A) [136]	**Applicant:** UNIV HOHAI **Inventors:** MA QINGHUA JIANG DEFU	**Improved digital adaptive interference cancellation-based transmitting-receiving isolation method:** The present invention discloses an improved digital adaptive interference cancellation-based transmitting-receiving isolation method. According to the method, reference jamming signals coupled from a jamming transmission channel are inputted into adaptive filters; a set of weight coefficients are changed, so that the error signal controlled adaptive filters render optimal estimation for relevant jamming in jammed received signals; and the influence of the jamming is eliminated, so that radar signals of enemies can be better detected. With the method of the invention adopted, difficulty in the transmitting-receiving isolation of a detection receiving antenna and a detection transmitting antenna which operate simultaneously can be eliminated, and detection in jamming and jamming in detection can be realized. The method is applicable to a condition where detection and jamming of a jammer on a small platform operate simultaneously.
CN106597443 (A) [137]	**Applicant:** NAT UNIV DEFENSE TECHNOLOGY PLA **Inventors:** LI YUELI LI XIANGYANG AN DAOXIANG HUANG XIAOTAO FAN CHONGYI LIU XIAOCONG	**Low-frequency synthetic aperture radar image comparison and cancellation radio frequency interference suppression method:** The invention discloses a low-frequency synthetic aperture radar image comparison and cancellation radio frequency interference suppression method. The method includes three steps: 1. conducting range spectrum and SAR imaging based on radar time-frequency domain echoes to obtain an image (I-bar <1>(t<m>,t<f>); 2. conducting intra-pulse RFI suppression and SAR imaging based on adaptive filtering to obtain an image (I-bar<2>(t<m>,t<f>); and 3. comparing the amplitude values of the pixel points of the image (I-bar <1>(t<m>,t<f>) and those of the image (I-bar<2>(t<m>,t<f>) point by point and removing residual RFI to obtain an image I<o> (t<m>, t<f>) which is the SAR image with the residual RFI suppressed by adopting the method of image comparison and cancellation. According to the invention, the method uses the spectrum balancing which can stabilize RFI suppression properties in combination with adaptive NLMS filtering, realizes complementary properties of the RFI suppression and obviates the need for registering the generated image. The method can conduct direct comparison on image domain point by point, removes the residual RFI, requires small operation, has strong real-timeness and is easy to be engineered.
KR20170021149 (A) [138] **Also published as:** KR101733009 (B1)	**Applicant:** AGENCY DEFENSE DEV [KR] **Inventor:** YANG EUN JUNG [KR]	**Apparatus and Method for adaptive side lobe cancelation applicable to interference environment:** The present invention relates to a radar system technology and, more specifically, to a method and an apparatus for blocking an adaptive side lobe by removing a clutter and a jammer in an interference environment without a separate auxiliary antenna and ensuring the performance of a side lobe signal breaker.
CN106483506 (A) [139]	**Applicant:** UNIV HOHAI **Inventors:** WANG FENG MA ZHENGYING ZHANG CHI JIANG DEFU CHEN JIAQI	**Cognitive self-adaptive interference inhibition method:** The invention discloses a cognitive self-adaptive interference inhibition method. The method is characterized in that signals received by an array are used to obtain needed wave beam output via digital wave beam formation, and part of auxiliary channels is extracted to determine the amount of interference; first interference characteristic analysis is completed after the digital wave beam formation; and according to different interference types, different interference cancellation methods are used. The cognitive self-adaptive interference inhibition method has the advantages that ideas of interference describers and self-adaptive strategy selection are established so that a radar can analyze interference characteristics rapidly; an intelligent cognition technology is combined with an anti-interference technology effectively, interference characteristics are determined, different interference types are identified after digital wave beam formation and pulse compression, and an intelligent self-adaptive strategy center module is constructed; and a matched interference cancellation method is scheduled in the self-adaptive strategy center module, and the cognitive anti-interference technology is realized.

Patent number	Held by	Patent name and abstract
KR20160144448 (A) [140] **Also published as:** BR112016023652 (A2) CN106165468 (A) EP3130079 (A1) JP2017516371 (A) US2015296413 (A1) US9503134 (B2) WO2015157190 (A1)	**Applicant:** QUALCOMM INC [US] **Inventors:** SADEK AHMED KAMEL GROB MATTHEW STUART	**METHODS AND APPARATUS FOR ADAPTING TRANSMITTER CONFIGURATION FOR EFFICIENT CONCURRENT TRANSMISSION AND RADAR DETECTION THROUGH ADAPTIVE SELF-INTERFERENCE CANCELLATION:** Certain aspects of the present disclosure relate to adapting transmitter configuration for efficient concurrent primary user detection through adaptive self-interference cancellation. A wireless transmitting device may schedule a transmission in a shared spectrum. The device may scan at least a portion of the shared spectrum during the transmission to receive a signal. Interference caused by the transmission may he cancelled from the received signal using self-interference cancellation circuitry. The device may determine whether the received signal indicates usage by a primary user of the shared spectrum. In an aspect, the transmission may be a SISO transmission. In another aspect, carrier aggregation may be used for the transmission and a potential carrier may be subject to primary user detection. The device may determine a self-interference cancellation complexity for a combination of carriers including the potential carrier, and may select one or more carriers for aggregation based on the self-interference cancellation complexity.
CN105093187 (A) [141] **Also published as:** CN105093187 (B)	**Applicant:** UNIV ELECTRONIC SCIENCE & TECH **Inventors:** CUI GUOLONG JI PENG LI QIAN LI YACHENG KONG LINGJIANG YANG XIAOBO YI WEI WANG MINGYANG	**Method for pre-processing images of through-the-wall radar extracted based on target trajectory:** The present invention provides a method for pre-processing images of a through-the-wall radar extracted based on a target trajectory, belonging to the technique field of through-the-wall radar. The method includes the steps as follows: firstly, confirming a wall position based on a range image of a target echo before cancellation, and dividing a detection region by utilizing the wall position; secondly, cancelling the range images of two continuous periods so as to highlight target information; thirdly, performing an adaptive threshold process period by period in the divided detection region of the range images after cancellation so as to distinguish a target and a background and then find the position of the target and define a width of the target trajectory; and finally, imaging the data in the region covered with the target trajectory so that the radar images only contain target information. The method includes the steps of the pre-processing of echo data of the through-the-wall radar based on a multiple-input multiple-output configuration, the wall position confirming, the detection region dividing, and the target trajectory extracting so that an image effect is dramatically enhanced, and an object expansion and a multipath interference of the radar images due to scene closing of the radar images can be restrained.
CN104678365 (A) [142]	**Applicant:** UNIV HOHAI **Inventors:** MA QINGHUA JIANG DEFU	**Adaptive interference cancellation method for radar jammer:** The invention relates to an adaptive interference cancellation method for a radar jammer. The adaptive interference cancellation method comprises the following steps: acquiring an external signal d received by a detection antenna on the radar jammer in real time, simultaneously acquiring an interference signal which is generated in the radar jammer and is not transmitted by a transmitting antenna of the radar jammer and using the interference signal as a reference interference signal J; then conveying the external signal d and the reference interface signal J to an adaptive filter to carry out adaptive interference cancellation. According to the adaptive interference cancellation method, an active digital adaptive cancellation technology is adopted; related cancellation principles are utilized; a convergence step size is regulated; compromise of a convergence rate and convergence stability in an adaptive interference cancellation algorithm is effectively realized; finally, the interference signal entering the detection antenna can be effectively eliminated and a useful detection signal is obtained.

Patent number	Held by	Patent name and abstract
CN103728594 (A) [143] **Also published as:** CN103728594 (B)	**Applicant:** BEIJING INST TECHNOLOGY **Inventors:** SHAN TAO MA YAHUI TAO RAN FENG YUAN ZHUO ZHIHAI YANG XUEHUI	**External radiation source radar sea clutter interference suppression method based on multi-channel NLMS:** The invention relates to an external radiation source radar sea clutter interference suppression method based on a multi-channel NLMS and belongs to the technical field of radar signal processing. According to the method, the frequencies of reference signals received by a direct wave antenna are modulated to the Doppler frequency of sea clutter to form a plurality of reference channels corresponding to sea clutter Doppler frequency components, then a multi-channel normalized least mean square (NLMS) adaptive interference canceling filter is obtained, a mathematic model of the multi-channel NLMS filter is established to enable the multiple reference signals to counteract interference of sea clutter of different frequencies, broadened sea clutter interference can be well inhibited, and cancellation gain and a target signal to noise ratio are improved.
CN101581782 (A) [144] **Also published as:** CN101581782 (B)	**Applicant:** UNIV WUHAN [CN] **Inventors:** HAO ZHOU [CN] BIYANG WEN [CN] SHICAI WU [CN] ZHENHUA SHI [CN]	**Method for inhibiting ionospheric clutter in portable high frequency groundwave radar:** The invention relates to the radar anti-interference technical field, in particular to a method for inhibiting ionospheric clutter in portable high frequency groundwave radar. In the invention, a plurality of sets of auxiliary crossed loops are arranged in the vertical direction of original crossed loop antennas of the portable high frequency groundwave radar, adaptive cancellation is carried out on the received signals of auxiliary crossed loop antennas, a main crossed loop and monopole antennas; the received signals of the main crossed loop and the monopole antenna are used as a basic input signal, the difference of the received signals between each auxiliary crossed loop antenna and the main crossed loop antenna are used as a reference signal to input three mutually independent self-adapting filters;; an error signal is output from the self-adapting filters to be echoed signals of the main crossed loop and the monopole for inhibiting ionospheric clutter. The invention has the following advantages: an ideal ionospheric clutter reference signal can be obtained and the working efficiency and detection performance of radars can be greatly increased.
AU2009200844 (A1) [145] **Also published as:** AU2009200844 (B2) AU2002340707 (B2) CA2446404 (A1) CA2446404 (C) DK1386176 (T3) EP1386176 (A2) EP1386176 (B1) HK1062332 (A1) IL158724 (A) JP2004526165 (A) JP4257122 (B2) KR100836521 (B1) KR20040012789 (A) US2002167440 (A1) US6703968 (B2) WO02091011 (A2) WO02091011 (A3)	**Applicant:** LOCKHEED CORP **Inventor:** BAUGH, KEVIN W	**System and method for mitigating co-channel interference in passive coherent location applications:** SYSTEM AND METHOD FOR MITIGATING CO-CHANNEL INTERFERENCE IN PASSIVE COHERENT LOCATION APPLICATIONS A system and method for mitigating co-channel interference is disclosed. A radar system detects targets from received signals at an antenna array. The received signals include direct signals and target signals transmitted from remote transmitters (310, 312). An antenna array (320) receives the signals (340, 342). A signal processing system (302) is coupled to the antenna array to perform processing operations on the received signals. The processing system (302) includes a primary cancellation component (304) and a secondary cancellation component (306). A primary illuminator signal is cancelled from the received signals by the primary cancellation component (304). An adaptive beamformer (322) obtains a secondary illuminator signal from the received signals.; A reference regenerator (324) regenerates the secondary illuminator signal. An adaptive cancellation filter (326) removes noise from the secondary illuminator signal. The secondary cancellation component (306) mitigates co-channel interference by cancelling the secondary illuminator signal from the received signals. a)0 (0 i N r7 -W Ou E m 00 cnl. 0 > cv) =m g t - C) (0 u) nO

Patent number	Held by	Patent name and abstract
US2003020646 (A1) [146] **Also published as:** DE60218244 (T2) EP1267444 (A2) EP1267444 (A3) EP1267444 (B1) US6661366 (B2)	**Applicants:** YU KAI-BOR LOCKHEED MARTIN CORPORATION **Inventor:** YU KAI-BOR [US]	**Adaptive digital sub-array beamforming and deterministic sum and difference beamforming, with jamming cancellation and monopulse ratio preservation:** A radar system and technique provide the capability to detect a target of interest and maintain the detection in the presence of multiple mainlobe and sidelobe jamming interference. The system and technique utilize the versatility of digital beamforming to form sub-arrays for canceling jamming interference. Jamming is adaptively suppressed in the sub-arrays prior to using conventional deterministic methods to form the sum, SIGMA, and difference, DELTA, beams for monopulse processing. The system and technique provide the ability to detect a target of interest, provide an undistorted monopulse ratio, m, and maintain target angle estimation, in the presence of multiple mainlobe and multiple sidelobe jammers. Further, this system and technique are not constrained by requiring a priori knowledge of the jamming interference.
US4439770 (A) [147]	**Applicant:** US NAVY [US] **Inventors:** LEWIS BERNARD L [US] KRETSCHMER JR FRANK F [US]	**Cascaded adaptive loops:** A sidelobe-canceller system for cancelling jamming interference signals from a radar signal includes serially cascaded cancellation channels utilizing preprocessing cancellers and main-channel cancellers. The last serially cascaded cancellation channel includes terminal preprocessing cancellers and terminal main-channel cancellers. The preprocessing is improved by the use of AGC circuits connected one each between the terminal preprocessing cancellers and terminal main-channel cancellers to stabilize the gain of the terminal main-channel cancellers, thus improving the cancellation ratio and transient response of the system.
US3995271 (A) [148]	**Applicant:** US AIR FORCE **Inventor:** GOGGINS JR WILLIAM B	**Adaptive clutter cancellation and interference rejection system for AMTI radar:** In an AMTI radar having digital doppler processing, adaptive clutter and interference rejection is achieved by automatically adjusting antenna phase and amplitude weights to trim for uncalibrated errors and to put nulls in the antenna receive patterns in the direction of the source of interference or jamming signals. Antenna weights are initially chosen to achieve an optimum signal to clutter ratio. The radar receive signals are averaged over many range cells, filtered and summed by adaptive processor circuits. Feedback loops adjust the antenna weights to minimize the summed output. The circuits effect this by mechanizing the steepest descent algorithm.
US2008040037 (A1) [149] **Also published as:** US7680266 (B2)	**Inventors:** DE LAMARE RODRIGO CAIADO [BR] SAMPAIO-NETO RAIMUNDO [BR]	**System and Method for Adaptive Reduced-Rank Parameter Estimation Using an Adaptive Decimation and Interpolation Scheme:** The present invention describes a system and method for general parameter estimation using adaptive processing that provides a performance that significantly exceeds existing reduced-rank schemes using reduced computational resources with greater flexibility. The adaptive processing is accomplished by calculating a reduced-rank approximation of an observation data vector using an adaptive decimation and interpolation scheme. The new scheme employs a time-varying interpolator finite impulse response (FIR) filter at the front-end followed by a decimation structure that processes the data according to the decimation pattern that minimizes the squared norm of the error signal and by a reduced-rank FIR filter.; According to the present invention, the number of elements for estimation is substantially reduced, resulting in considerable computational savings and very fast convergence performance for tracking dynamic signals. The current invention is aimed at communications and signal processing applications such as equalization, interference suppression of CDMA systems, echo cancellation and beamforming with antenna arrays. Amongst other promising areas for the deployment of the present technique, we also envisage biomedical engineering, control systems, radar and sonar, seismology, remote sensing and instrumentation.

Patent number	Held by	Patent name and abstract
US4549183 (A) [150]	**Applicant:** SELENIA SPA [IT] **Inventor:** FARINA ALFONSO [IT]	**Interference suppressor for an electronically or mechanically scanning monopulse radar generating sum and difference signals from received microwave energy:** An electronically or mechanically scanning monopulse radar has an antenna feeding incident microwave energy contaminated by jamming signal to a processor which has a sum channel and one or two difference channels generating a raw sum signal SIGMA along with a raw azimuthal difference signal DELTA theta and/or a raw elevational difference signal DELTA phi . Each channel includes an algebraic adder subtracting from its own raw output signal a contamination signal representing estimated disturbance which is derived with the aid of an adaptive cancellation loop from the raw output signal or signals of the other channel or channels, thereby producing a purged sum signal SIGMA ' as well as one or two purged difference signals DELTA ' theta , DELTA ' phi . The purged output signal of each channel is fed back to the corresponding cancellation loop for correlation with the raw output signal or signals from the other channel or channels.
US2007036202 (A1) [151]	**Inventors:** GE HONGYA [US] SCHARF LOUIS L [US]	**Code, signal and conjugate direction design for rapidly-adaptive communication receivers and electromagnetic, acoustic and nuclear array processors:** A system and method are disclosed that substantially reduce the complexity of receivers in digitally modulated wireless communication systems such as systems that use CDMA and similar multi-access coding. Transmitted signals are designed to use orthogonal or non-orthogonal codes with specific amplitudes that reduce the number of distinct eigenvalues in a code correlation matrix or in a code-plus-interference-plus-noise correlation matrix, so that a few steps of a conjugate direction calculation will compute a reduced rank Wiener filter that can be used to provide approximate de-correlation type receivers in a substantially reduced number of steps when compared to inverse correlation matrix calculations, or when compared to conjugate direction computations run on correlation matrices with un-shaped eigenvalues. These techniques can also be applied to active or passive imaging systems such as sonar, ultrasound and radar imaging systems and phased array systems that use beam forming. Cancellation of interference and noise can also be accomplished by exploiting eigenvalue shape or by designing the codes and amplitudes of the transmitted signal and using the reduced rank Wiener filter to filter interference and noise from the receive signal. The techniques enable the use of code design and power control for the control of system complexity and bandwidth.
US2003184473 (A1) [152]	**Applicant:** YU KAI BOR **Inventor:** YU KAI BOR [US]	**Adaptive digital sub-array beamforming and deterministic sum and difference beamforming, with jamming cancellation and monopulse ratio preservation:** A radar system and technique provide the capability to detect a target of interest and maintain the detection in the presence of multiple mainlobe and sidelobe jamming interference. The system and technique utilize the versatility of digital beamforming to form sub-arrays for canceling jamming interference. Jamming is adaptively suppressed in the sub-arrays prior to using conventional deterministic methods to form the sum, Sigma, and difference, Delta, beams for monopulse processing. The system and technique provide the ability to detect a target of interest, provide an undistorted monopulse ratio, m, and maintain target angle estimation, in the presence of multiple mainlobe and multiple sidelobe jammers. Further, this system and technique are not constrained by requiring a priori knowledge of the jamming interference.

Patent number	Held by	Patent name and abstract
JP2008116345 (A) [153] **Also published as:** JP5193455 (B2)	**Applicant:** TOSHIBA CORP **Inventor:** TAKEYA SHINICHI	**RADAR SIGNAL PROCESSOR:** PROBLEM TO BE SOLVED: To provide a radar device capable of suppressing clutters and an interference, holding a main lobe, and obtaining high suppressing performance. SOLUTION: This radar signal processor comprises a beam-combining circuit 2 for beam-combining signals from a main antenna 11, having a plurality of antenna elements or sub-arrays; a Fourier transform circuit 3 for Fourier-transforming the output from the beam-combining circuit and generating a main channel signal, an adaptive processing circuit 4 for performing adaptive processing by a tapped delay line by using a signal of PRI unit or range cell unit of an auxiliary channel signal from an auxiliary antenna 12 that shares a part of the plurality of antenna elements or sub-arrays; and a cancelation processing circuit 5 for suppressing unwanted waves, contained in the main channel signal by subtracting the signal adaptive-processed by the adaptive processing circuit from the main channel signal that is transmitted from the Fourier transform circuit.
JP2006258581 (A) [154] **Also published as:** JP4559884 (B2)	**Applicant:** TOSHIBA CORP **Inventor:** TAKEYA SHINICHI	**RADAR SIGNAL PROCESSING DEVICE:** PROBLEM TO BE SOLVED: To sufficiently suppress both a clutter and an interference even in an environment wherein the clutter or the interference exists. ;SOLUTION: Pre-processor circuits 1511-15MB provided in each frequency bank output acquired by FFT conversion of an auxiliary antenna signal detects an interference component by performing adaptive processing by the first systolic array circuit of a Gram-Schmidt type relative to each tap delay signal on the first tapped delay line TDL1 for inputting a frequency bank signal and dividing it into a range cell unit, and detects a clutter component by performing adaptive processing by the second systolic array circuit of the Gram-Schmidt type relative to each tap delay signal on the second tapped delay line TDL2 for inputting a main antenna signal and dividing it into a PRI unit. The interference/clutter detected components are inputted into cancellation circuits 161-16B in a corresponding filter bank, to thereby suppress interference/clutter components in the main channel signal.
EP0065499 (A1) [155] **Also published as:** EP0065499 (B1) IT1142442 (B) US4544926 (A)	**Applicant:** SELENIA IND ELETTRONICHE [IT] **Inventor:** GIULI DINO DOTT	**Adaptive polarization for the cancellation of intentional interference in a radar system:** This invention relates to an adaptive polarization receiver for the cancellation of intentional interference in a radar system having two receiving channels each of which processes one of the two signals taken from a double polarization antenna, each of the two receiving channels being formed by an adaptive cancellor which performs the cancellation of the intentional interference by using the signal received from the other channel as an auxiliary signal, and a switching device which switches the processed signal from the least disturbed receiving channel to the output of the receiver.

E.6 Cognitive radar

Table E.6: Patents for cognitive radar,
Search keywords: "Cognitive radar"

Patent number	Held by	Patent name and abstract
EP3339883 (A1) [156]	**Applicant:** AIRBUS DEFENCE & SPACE GMBH [DE] **Inventors:** SANTRA AVIK [IN] GANIS ALEXANDER RUDOLF [DE] PRECHTEL ULRICH [DE] ZIEGLER VOLKER [DE]	**A COGNITIVE RADAR SYSTEM:** A cognitive radar system (1) comprising an antenna array (2) having antennas and an antenna selection module (11) adapted to switch between horizontally polarized and vertically polarized transmit antennas of said antenna array (2) to transmit radar pulses based on a measured target Signal to Interference plus Noise Ratio, SINR, of radar pulses received by horizontally polarized and vertically polarized receive antennas of said antenna array (2).
CN107329124 (A) [157]	**Applicant:** NAT UNIV DEFENSE TECHNOLOGY PLA **Inventors:** LIU ZHEN CHEN RUI SUI JINPING WEI XIZHANG	**Intermittent sampling forwarding interference suppression method based on cognitive radar waveform:** The invention provides an intermittent sampling forwarding interference suppression method based on a cognitive radar waveform. The technical scheme comprises the following steps: the first step of intermittent sampling forwarding interference parameter estimation, a cognitive radar emits a linear frequency modulation pulse signal firstly, an echo signal is analyzed, and an estimation value of a sampling pulse width and an estimation value of a forwarding period are obtained; and the second step of intermittent sampling forwarding interference suppression, the cognitive radar emits a specific intra-pulse frequency modulation signal, interference interval signal zero setting is performed on a received radar echo signal, splicing is performed then, and matching filtering is performed on the signal to obtain a pulse pressure result of a jammer Real target detection performance can be effectively improved, and intermittent sampling forwarding interferences in direct forwarding, repeated forwarding and other forwarding modes are achieved.
CN107209993 (A) [158] **Also published as:** EP3164860 (A1) EP3164860 (A4) WO2016003474 (A1)	**Applicant:** GM GLOBAL TECH OPERATIONS INC **Inventors:** BILIK IGAL GAZIT RAN Y	**Vehicle cognitive radar methods and systems:** Methods and systems for a vehicle cognitive radar are provided. The system includes a transmitter is configured to transmit a first plurality of transmittal signals for a cognitive radar system of a vehicle, the cognitive radar system having at least a first modality. An interface is configured to receive sensor data from one or more sensors having a second modality that is different from the first modality. A processor is coupled to the interface, and is configured to select an adjusted waveform for a second plurality of transmittal signals for the cognitive radar system using the sensor data.

Patent number	Held by	Patent name and abstract
CN107102300 (A) [159]	**Applicant:** UNIV NANJING AERONAUTICS & ASTRONAUTICS **Inventors:** ZHANG JINGDONG WU YUE JIA YIQUN CHEN WANYINGG	**Cognitive radar waveform designing method based on interference and side-lobe equilibrium suppression:** The invention discloses a cognitive radar waveform designing method based on interference and side-lobe equilibrium suppression. The method comprises: on the basis of a self-adaptive framework, in a noise suppressing interference model, and through the MMSE criteria, introducing and structuring a cognitive radar waveform optimization model of interference and side-lobe equilibrium suppression; converting the model into a minimized multivariable and multi-constrained objective function model; then according to Lagrange multiplier method, developing the Lagrange function of the objective function, and according to the principle of duality, converting the model into the optimized dual function again, solved with the introduction of auxiliary variables and the KKT optimality; and finally, designing the alternating iterative method to combine with the optimized emission shape and the filter sequence; and estimating the evaluation of performance brought about by the comprehensive processing algorithm. The simulation results show that the proposed algorithm can realize the balance of the interfering signal suppression and the self-processing side-lobe, which improves the detection performance of the target.
CN107102305 (A) [160]	**Applicant:** UNIV OF ELECTRONIC SCIENCE AND TECHNOLOGY OF CHINA & ASTRONAUTICS **Inventors:** CUI GUOLONG FU YUE XIONG DINGDING YU XIANXIANG KONG LINGJIANG YI WEI ZHANG TIANXIAN YANG XIAOBO	**Robust cognitive radar transmitting-and-receiving combined designing method in clutter environment:** The invention discloses a robust cognitive radar transmitting-and-receiving combined designing method in a clutter environment, wherein the method belongs to the field of signal processing. The invention relates to the robust cognitive radar transmitting-and-receiving combined designing method in the clutter environment. Each iteration step in the method of the invention relates to a MVDR settlement problem and a plurality of one-directional fractional programming problems which can be efficiently settled by means of a Dinkelbach process. Simulation proves a fact that the algorithm can effectively improve an outputted SINR in short time, and realizes efficiency breakthrough and effect breakthrough relative to an SDR algorithm, thereby improving system testing performance.
CN106257302 (A) [161]	**Applicant:** UNIV ELECTRONIC SCIENCE & TECH CHINA **Inventors:** YU XUELIAN HAO YINGJIE QU XUECHAO CHANG JUNJIE ZHOU YUN	**Method for cognitive radar target tracking in clutter environment:** The invention discloses a method for cognitive radar target tracking in the clutter environment. The method includes the steps that all measurement values at the current moment are acquired, and measurement values falling into a correlation wave gate are calculated; the probabilities that the measurement values falling into the correlation wave gate come from a target are calculated; equivalent measurement values at the current moment are calculated; the equivalent measurement values serve as input of a perceptive memory, system equation parameters at the current moment are obtained after outputting; state and measurement prediction is carried out according to the system equation parameters and the equivalent measurement values, and state prediction covariance is obtained; the state prediction covariance serves as input of an executive memory, and a transmitted waveform parameter set is obtained after outputting; innovation covariance and state error covariance under each waveform parameter are calculated; optimal waveform parameters are selected; innovation covariance, state error covariance and the state estimation value at the current moment are calculated according to the optimal waveform parameters. The method solves the problems that an existing cognitive radar target tracking technology can not run normally in the clutter environment, and the tracking performance in the clutter environment can be improved.

Patent number	Held by	Patent name and abstract
CN105759271 (A) [162] **Also published as:** DE102016100130 (A1) US2016195614 (A1)	**Applicant:** GM GLOBAL TECH OPERATIONS LLC **Inventors:** TABRIKIAN JOSEPH BIALER ODED BILIK IGAL	**Spatial cognitive radar:** A spatial cognitive radar system, method of assembling the radar, and method of selecting antenna elements in the radar are described. The system includes a phased array of a plurality of antenna elements and a plurality of receiver channels, the plurality of receiver channels being a value greater than one and less than a number of the plurality of antenna elements. The system also includes a processor to determine a subset of the plurality of antenna elements, equal in number to the plurality of receiver channels, to be used in transmitting or receiving with the spatial cognitive radar system.
CN104991240 (A) [163]	**Applicant:** UNIV XIDIAN **Inventors:** LIU HONGWEI DAI FENGZHOU JI YUAN QIN TONG SU HONGTAO	**Target scattering cross section prediction method:** The invention discloses a target scattering cross section prediction method based on a hidden Markov model, and mainly solves the problem that scattering cross section of a target cannot be predicted precisely at some moment in the prior art. The method comprises the following realization steps: 1) setting hidden Markov model parameters; 2) deducing transition probability of a target state through a state transition model; 3) deducing posterior probability of the target scattering cross section at the t moment by utilizing the hidden Markov model; 4) deducing prior probability of the target scattering cross section at the t+1 moment according to the results of the step 2) and the step 3); and 5) predicating the predicted value of the scattering cross section of the target according to the results of the steps 1)-4). The method is low in complexity and simple to realize, can accurately predicate the scattering cross section of the target at the next moment, can be used for reasonable resource allocation for the transmitter end of a cognitive radar, and furthermore, optimizes the tracking performance and effect of the radar.
US2015201420 (A1) [164] **Also published as:** US9635508 (B2)	**Applicant:** US ARMY RES LAB ATTN RDRL LOC I [US] **Inventors:** MARTONE ANTHONY F [US] RANNEY KENNETH I [US]	**FAST METHOD FOR WIDEBAND SPECTRUM SENSING:** Embodiments of the present invention relate cognitive radar and RF technologies, and more particularly, to spectrum sensing processing for rapidly monitoring the RF spectrum for channel availability and activity. The goal is to find and use unoccupied RF channels to broadcast and receive information. According to one embodiment, a method for analyzing a received RF signal to determine unused channels, or frequencies, therein, comprises: analyzing a received RF signal to determine anchor points that represent high energy frequency locations; calculating distances between the determined anchor points; identifying and eliminating clusters or isolated anchor points defined as a high energy region of interference based on the calculated distances; and selecting at least one remaining unoccupied frequency for transmitting or receiving a RF signal. The method may further include performing an optional quality or risk assessment on remaining frequencies of the waveform, and eliminating high risk frequencies from consideration in some instances.

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CN104199001 (A) [165] **Also published as:** CN104199001 (B)	**Applicant:** UNIV ELECTRONIC SCIENCE & TECH **Inventors:** CUI GUOLONG; WU JIAN LI WENWEN YU LIYAN KONG LINGJIANG YI WEI YANG XIAOBO	**Velocity-deception-jamming-resistant phase encoding method for cognitive radar:** The invention discloses a velocity-deception-jamming-resistant phase encoding method for a cognitive radar, belongs to the technical field of radar jamming resistance, and particularly relates to a radar jamming-resistant waveform design technology. According to the method, relevant parameters of a target and jamming are extracted from prior information acquired by the cognitive radar, a stop band is arranged close to each real target Doppler according to a real target Doppler estimated value, a stop band is arranged at the same position as a constant-mode encoding sequence configured in advanced, and an optimal pulse-to-pulse phase encoding transmission waveform is designed according to the criterion that the spectrum energy of a coded signal in the stop band, thereby effectively inhibiting velocity deception jamming in a multi-target and multi-jamming scene, increasing the signal-to-jamming ratio of each real target, and realizing the effect of correct detection of a plurality of real targets.
CN104198993 (A) [166]	**Applicant:** BEIJING INST TECHNOLOGY **Inventors:** FU XIONGJUN LI TING GAO MEIGUO WANG CAI ZHAO HUIPENG LI WENJING	**Cognitive radar optimal waveform design method suitable for parameter estimation:** The invention discloses a cognitive radar optimal waveform design method suitable for parameter estimation. The cognitive radar optimal waveform design method suitable for parameter estimation comprises the steps of building a channel model by use of actual target impulse response more consistent with the actual situation, and obtaining the energy spectrum density of the desired waveform by use of a water injection method according to the channel model so that the maximum target information quantity can be obtained from echo, taking the energy spectrum density and time-domain complex waveform amplitude as constant constraint conditions and obtaining the time-domain complex waveform of constant amplitude by use of an iteratively weighted least square method without wasting the power of a transmitter, next, transmitting the designed time-domain complex waveform by use of a radar to obtain target echo and performing parameter estimation by use of the target echo, after the expiry of the accumulated time of estimation of one parameter, updating the target impulse response by use of the current target echo and carrying out waveform design and transmission again so that the waveform transmitted at present changes along with the change of the target and the environment, and guaranteeing that the target echo obtained at present always contains the maximum target information quantity so that target parameter estimation can be carried out favorably.
CN203911900 (U) [167]	**Applicant:** UNIV CHANGCHUN SCIENCE & TECH **Inventors:** WANG CHUNYANG YU YANXIN CHEN YU LIU XUELIAN	**Broadband frequency agility X wave band signal generating device for cognitive radar:** The utility model relates to a broadband frequency-agility X wave-band signal generating device for a cognitive radar, and belongs to the field of electronic technology. The signal generating device comprises a crystal oscillator, a phase discriminator, a loop filter, a voltage control oscillator, a band-pass filter, a low-noise amplifier, a frequency mixer and a power divider. The phase discriminator, the loop filter, the voltage control oscillator, the band-pass filter and the low-noise amplifier form a loop 1 and a loop 2. The signal generating device is advantaged by high frequency resolution, short switching time, wide frequency band and low phase noise; defects of large size, complex hardware and high cost of a module circuit of a traditional signal generating module are overcome; and requirements of fast switching speed, wide frequency band and high frequency precision required by the cognitive radar for emitting signals are satisfied.

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CA2884769 (A1) [168] **Also published as:** CA2884769 (C) EP2906964 (A1) EP2906964 (A4) US2014097979 (A1) US8860602 (B2) WO2014056102 (A1)	**Applicant:** ACCIPITER RADAR TECHNOLOGIES INC [CA] **Inventors:** NOHARA TIMOTHY J [CA] HAYKIN SIMON [CA]	**DEVICE & METHOD FOR COGNITIVE RADAR INFORMATION NETWORK:** In cognitive radar information networks (CRINs) human-like cognitive abilities of attention and intelligence are built into radar systems and radar information networks (RINS) to assist operators with information overload. A CRIN comprises a plurality of radar sensing nodes monitoring an environment, a repository or memory, and a cognitive radar controller. Each radar sensing node includes a radio frequency transmitter, a transmitting antenna, and a receiver and receiving antenna. The receiver includes a digital radar processor for generating receiver information from the received echoes about the environment. The repository is configured for receiving and storing the receiver information generated by the digital radar processor. The cognitive controller is configured to automatically focus the system's attention on a region of interest within the surveillance volume in response to an attention request, by selecting the transmitter's waveform, selecting the receiver's processing mode, and controlling the transmitter's antenna. The cognitive controller learns from the environment by exploiting the repository's historical receiver information and further learns from the consequences of its past decision.
CN103336276 (A) [169] **Also published as:** CN103336276 (B)	**Applicants:** UNIV TAIYUAN TECHNOLOGY SHANXI KAISHENG AUTOMATION EQUIPMENT CO LTD **Inventors:** ZHANG CHAOXIA ZHOU JUNJIE HAI ZHENHONG ZHANG DONGZE QIAO JIPING	**Cognitive radar detection device based on neural network:** The invention relates to a cognitive radar detection device based on a neural network, whose main structure comprises a chassis, a liquid crystal display, indicator lamps, a power supply switch, reset switches, signal transmitting adjustment and control devices, signal receiving adjustment and control devices, a transmitting antenna, a receiving antenna, a circuit board, a direct current power supply and a circuit board circuit. Aiming at limitation of the traditional radar, the cognitive radar detection device uses the advantages of the neural network, information processing is performed on signals of the transmitting antenna and the receiving antenna, the neural network consists of nerve cells with nonlinear mapping functions, and information of the neural network is stored in a continuous weight coefficient by weight coefficient connection, so that the network has very high fault tolerance; information loss is reduced; self-organizing and the adaptivity of the neural network are high; the recognition capability is improved; the neural network, digital signal processing, and digital information collection, receiving and processing are accomplished by a computer program, so that informatization, programming and automation of the device are achieved;; and as a very ideal cognitive radar detection device based on the neural network, the device is advanced in design, compact in structure and accurate in measurement data, and can be widely applied to various industrial detection fields.
CN103116154 (A) [170] **Also published as:** CN103116154 (B)	**Applicant:** UNIV XIDIAN **Inventors:** LIU ZHENG WU XUZI LIU YUNFU	**Clutter environment based transmitting and receiving jointly optimized adaptive filtering method:** The invention discloses a clutter environment based transmitting and receiving jointly optimized adaptive filtering method which mainly solves the problems that operation quantity is large while a receiver and a transmitter are not in jointly optimized utilization in the prior art. The method includes the implementation procedures: 1) transmitting a group of phase-coded signals; 2) calculating received echoes; 3) performing matched filtering for the received echoes; 4) feeding back a scattering center amplitude estimated value obtained by matched filtering to a transmitter, and setting a transmitted signal side lobe weight; 5) optimizing the phase-coded signals to enable weighted integral side lobe level to be the smallest; 6) transmitting the optimized phase-coded signals and calculating received echoes;; and 7) performing adaptive filtering for the received echoes to obtain an amplitude estimated value of a scattering center. The method is optimal to an existing filtering method in amplitude estimation performance of the scattering center, is small in operation quantity, preliminarily achieves closed loop feedback of cognitive radar from a receiver to the transmitter, and can be used for radar clutter suppression and target detection.

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CN102565762 (A) [171] **Also published as:** CN102565762 (B)	**Applicant:** UNIV XIDIAN **Inventors:** BO JIU HONGWEI LIU BIAO JIN SHENGHUA ZHOU TAO SU HUJUN YANG	**Waveform optimization method based on target cognition and transmitted power distribution:** The invention discloses a waveform optimization method based on target cognition and transmitted power distribution, which mainly solves the problem that the current waveform optimization algorithm is not suitable for a broadband radar. The method comprises the following steps of: (1) building a waveform-optimized signal model of a cognitive radar of a broadband; (2) utilizing a single echo to estimate the power spectral density of a target; (3) calculating the transmitted power of a transmit signal being a linear frequency modulation signal to be used as a constrained initial value of the transmitted power; (4) constructing a cost function; (5) solving the cost function; (6) optimally setting the power spectral density of transmitted waveform corresponding to the transmitted power; (7) calculating the related coefficient of the estimated value and the true value of the power spectral density of the target corresponding to the optimized waveform; (8) and judging and outputting the power spectral density of the transmitted power and the transmitted waveform according to whether the related coefficient meets the requirements. According to the method, the transmitted waveform optimization and power distribution of a cognitive radar system of the broadband can be realized, and the efficiency and overall performance of the system are increased.