Abstract

Cognitive radio (CR) was coined to address evolving user needs two decades ago. Since then, it also has been considered a way to mitigate perceived spectrum scarcity in various application areas. In this article, the status of military CR research is assessed through a systematic literature review of 193 articles, from 2013 to 2020, using IEEE thematic topics, technology readiness levels, as well as comprehensive capability meta-model as analytical frameworks. The annual distribution of military CR research indicates continuing interest. The military CR research seems to be prolific on topics like waveform design and security, not forgetting a steady interest in CR networking topics. Significantly low numbers of papers address applications, services, and standardization. In general, military CR research seemed sporadic and scattered. Our data suggest that a transition from individual techniques, component-level subsystem research in the direction of systems engineering approach, and system-level studies has not yet happened, and the overall TRLs remain low. The absence of publicly articulated comprehensive treatment of the notion of military cognitive radio system is graphic and has led to disjointed, scattered research at the subsystem level.

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Feature Article:
DOI. No. 10.1109/MAES.2021.3052310

A Systematic Literature Review: Is Military Cognitive Radio System on the Brink of the “Valley of Death”?

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INTRODUCTION

Cognitive radio (CR) is a notion or a concept initially coined in 1999 to address evolving user needs [1]. Since its inception, the concept of CR has also been considered a way to mitigate perceived spectrum scarcity [2]. The interest in CR has continued with the evolution of mobile telephony toward fifth generation wireless systems (5G), but the potential for military applications is yet to be explored for comprehensive coverage. Contemporary concepts in general mobile telephony and networking such as self-organizing networks (SON) and software-defined networking (SDN) [3] have adopted and paved the way ahead to some characteristics of cognitive radio systems.

For this document, cognitive radio is considered an evolution from a software defined radio (SDR) to support spectrum management and optimization, interfacing to a variety of networks, and to aid the human in his activities. Cognitive radio system (CRS) is defined as a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies, and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained. [4]. Thereby notions like spectrum sensing, modulation classification, policy engine, cognitive radio (as a node), and cognitive radio networking are considered functions, algorithms, components, or subsystems of a CRS as will be elaborated later when presenting the use of comprehensive capability metamodel (CCMM).

Greitemann *et al.* [5] posited that the implementation of emerging technologies into existing production environments is often time-consuming and expensive. To better understand the early phases and timescales of the system lifecycle, Gross *et al.* [6] divided the lifecycle into a) invention, development, and demonstration, and b) deployment and commercialization phases. Their main finding across several technology areas is that both the innovation and development as well as deployment phases each take 18 years (median) and altogether 32 years. The “Valley of Death” has been described as a stage or a phase between discovery and commercialization [7], and more specifically, as a phase between technology readiness levels (TRLs) five and seven [8].

Within the civilian domain, the cognitive radio system has been the object of study in some research reports just before the time range of our enquiry. In the military domain, cognitive radio at the system level has been associated with the Joint Tactical Radio System (JTRS) or other U.S. Defense Advanced Research Projects Agency’s (DARPA) programs. During the second decade of the research for cognitive radio technologies, the interest in cognitive radio networks (CRN) became evident. This interest was also recorded in our collection of military cognitive radio research. However, the use of the terms CR, CRN, and CRS are not consistent and sometimes misleading. Therefore, for the data collection for this article, the minimum common denominator CR has been used as a search term. Even though International Telecommunication Union (ITU) has a definition for a CRS, the absence of research on CRSs is noticeable. To the best of the authors’ knowledge, there is no survey of military CRS research available to the public. The closest match to such a study would be [9], [10], and [11].

Thereby, this article provides a comprehensive overview of MCRS research for the second decade since the term CR was coined. The research question for this article

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Manuscript received June 25, 2020; accepted November 14, 2020, and ready for publication January 14, 2021.
Review handled by Stefan Brueggenwirth.
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is: Does publicly available technical research data provide evidence that research and development on military cognitive radio systems progress toward an actual system proven in an operational environment. We observe that this formulation already identifies potential data sources as well as alludes to the use of Technology Readiness Levels (TRL) as a part of the analysis [12].

METHOD

This research has been inspired by the findings of [8] as to where do we stand in MCRS research today. Is there going to be a "Valley of Death" hindering the evolution of research into products? Or are we already standing on the brink of that valley? The research method of this survey is a systematic literature review (SLR), following the steps outlined in [13]. The research question for this survey is: Does publicly available technical research data provide evidence that R&D on military cognitive radio systems progresses toward an actual system proven in an operational environment. We observe that this formulation already identifies potential data sources as well as alludes to the use of TRLs as a part of the analysis [12].

The primary sources selected were the *IEEE Xplore Digital Library, Elsevier ScienceDirect, SpringerLink*, as well as the *Association of Computing Machinery Digital Library*. We collected explicitly "military" AND "cognitive radio" related articles. As the first 14 years since the inception of the notion of CR have already been covered in [14], we collected a dataset of military cognitive radio research covering the years 2013 to 2020. The collected papers were then coded in four dimensions: document type, thematic topic, the technology readiness level, as well as the CCMM level.

First, the collected papers were manually categorized into conference papers, journal articles, doctoral dissertations, and survey-type articles. The original intention was to use this grading as an indication of the maturity and quality of the article; however, it proved to be far from a useful indicator.

Second, the dataset was coded into thematic categories, topics, already used in [15]. Spectrum mobility, although listed as a topic in the original reference, was not addressed by any of the collected papers. However, spectrum mobility, as a phenomenon, has been touched upon in the margins of several papers. The number of articles by topics is shown below in Table 1.

Third, the papers were coded according to the TRL they portrayed. TRLs have been used since the 1980s in the U.S. National Aeronautics and Space Administration. The use expanded to the U.S. Department of Defense in the 1990s as well as globally. TRLs are used to describe the maturity of technology, especially within procurement processes [16].

As most of the articles address a single functionality, algorithm, or solution, the TRLs are valid and relatively easy to apply. For example, TRL 3 was initially described by NASA as "analytical and experimental critical function and characteristic proof-of-concept" and by the European Union as "Experimental proof-of-concept" [12]. Within wireless communications research, simulation is often used to provide

Table 1.

Number of Articles by Thematic Categories According to IEEE Topics [15]

Applications and services category	14 articles
New economics	1
Machine learning techniques	4
Spectrum sharing and multiple access	21
Analysis of dynamic spectrum access	2
Routing	23
Security and electronic warfare	41
Modeling of spectrum use	21
Simulation tools and testbeds	11
Waveform design	55

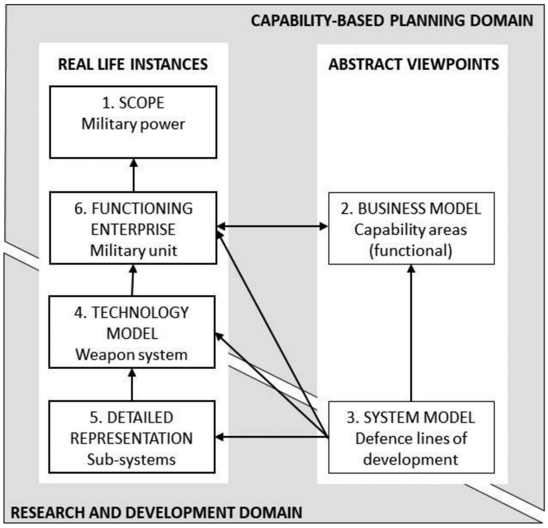

Figure 1.
CCMM viewpoints within respective communities of interest. Adopted from [19].

proof-of-concept [17], [18]. Therefore, articles describing the use of simulation have been coded to TRL 3. In this category, a significantly high number (63) of papers have been included. If the paper shows specific traits being a very narrow or early research paper or if the paper is part of a broader research effort, the coding to TRL 3 may have been adjusted by a level +-1.

As the fourth coding stage, the CCMM, depicted in Figure 1, was applied. The model has been developed from the Zachman framework for enterprise architecture to support the military capability-based planning domain. Sagduyu *et al.* [19] is an initial attempt to apply CCMM to military wireless communications R&D. For this survey, we shall apply capability viewpoints with emphasis on left-hand side viewpoints in Figure 1. The idea is to map our source data to the structure of the design artifacts of military capability viewpoints.

RESULTS

Within military CR research, EARTO [14] should already be considered as seminal. In this article, Dr. B. Fette, at that time with DARPA, outlines the first 14 years of the cognitive radio research and development since the inception of the notion of CR. The paper argues that, for the military, the essential feature of CR is not necessarily the enhanced user experience, nor spectrum access alone, but the full range adaptivity and flexibility in support of warfighter communications. Another important, yet easily overlooked, observation is that, although cognition has been widely researched from the spectrum access perspective, the military communication system needs to implement cognition at several layers of the communication protocol stack to provide the expected performance improvement.

Out of the total of 193 articles[1] collected for this review, seven are doctoral dissertations, 14 surveys, 33 journal articles, and 139 conference papers. However, the distribution of articles by publication type turned out not to be a useful metric. The minimal number of doctoral dissertations is in dire contrast to generic civilian CR research, whereby a large number of dissertations were excluded because they did not have any recognizable bearing or relation to military CRSs. The few military CRS oriented dissertations included, focus on security-related topics mostly involving electronic warfare measures. Of the 14 surveys included in our data, we point to Fette [10]. This report summarizes military cognitive radio research by the end of 2014. The report covers different national and organizational research roadmaps on military CRs and considers the significance of cognitive radio networks for future tactical wireless communications. According to the report, CRNs are expected to provide benefits such as dynamic spectrum access (DSA), increased communications resilience in dynamic, heterogeneous environments, and may provide the basis for tactical electronic warfare.

Many multinational research task groups of North Atlantic Treaty Organization's (NATO) Science and Technology Organization (STO) present publicly available conference papers in addition to formal research reports. Some of the reports are also available in the public domain, e.g., [11]. NATO STO reports used for this article have been tagged as surveys due to their contents and the way they address the topic. All of the included NATO papers address dynamic spectrum access one way or another and point toward the need to adjust current rigid administrative and bureaucratic mechanisms.

RESULTS BY TOPICS

As can be seen in Table 1, topics of waveforms, security, modeling spectrum use, and spectrum sharing have received the most attention (71%) in our dataset. In contrast, the topic of economics has a single reference.

Within the topic of machine learning, we observe that most years yield a steady two to three papers on the topic, whereas the sudden late increase in 2019 to 8 papers is noteworthy. As an example, the research team of the Royal Military Academy of Belgium suggests the use of machine learning techniques at the cognitive radio to avoid intentional, hostile jamming or to support channel selection.

The category of theoretical analysis of dynamic spectrum access contains two papers. Potentially the most exciting category of papers is related to security and electronic warfare. This is the second most populous category within the dataset with altogether 41 papers. Within this category,

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[1] Full listing of the reviewed articles is available from the corresponding author: topi.tuukkanen@mil.fi

Table 2.

Number of articles by Technology Readiness Levels [16]

TRL 1 basic principles	**27 articles**
TRL 2 technology concept formulated	73
TRL 3 experimental proof of concept	63
TRL 4 technology validated in the lab	25
TRL 5 technology is validated in a relevant environment	2
TRL 6 technology demonstrated in a relevant environment	1
TRL 7 system prototype demonstration in an operational environment	1
TRL 8 system complete and qualified	0
TRL 9 actual systems proven in the operational environment	0

Table 3.

Number of Articles by the CCMM Levels

CCMM level 1: Scope - Military power	**5 articles**
CCMM level 2: Business model – Military capability areas	0
CCMM level 3: System model - Defence lines of development	1
CCMM level 4: Technology model – System	20
CCMM level 5: Detailed representation - Sub-system	156
CCMM level 6: Functioning Enterprise - Military unit	11

e.g., Koivisto and Tuukkanen [20] considered in-band full-duplex (FD) capability as one of the great discoveries in wireless communications. By exploiting simultaneous transmission and reception capability through self-interference cancellation techniques, the FD capability is seen to double the spectral efficiency of wireless data transmission. Furthermore, the paper outlines and analyzes some potential defensive and offensive applications becoming available by the application of these capabilities. Full-duplex capacity is also addressed in [21], suggesting an integrated tri-band, dynamic spectrum shaping full-duplex cognitive radio for tactical communications.

Although not yet there, the topic of simulation tools and testbeds alludes in the direction of gradually (in the future) increasing TRLs through several papers on development, testing, and evaluation environments.

RESULTS BY TRLS

Table 2 portrays that the distribution of articles by TRLs is concentrated between TRL 2 and TRL 4, indicating that the CR related technologies are still under research and experimentation. At level TRL 5, the dissertation [22] considers airborne multiple input multiple output (MIMO) communications, physical layer authentication, and radio design through a holistic design approach. Similarly, at TRL 5, Mourougayane and Srikanth [23] details the field testing of multitransceiver DSA radios operating in the presence of a legacy system, providing a detailed, quantitative assessment of the spectral and network behavior of tactical systems across a diverse range of operational scenarios. Higher up, at level TRL 6, the survey [24] discusses the current status of work to define transmission security functions and how to implement them in radios. Finally, at level TRL 7, the report [25] analyses one implementation of a waveform through complementary methodologies. These include operational tests, assessment of the fundamental limitations of the technology, and modeling and simulation. Some of the identified challenges relate to shortcomings of the waveform design, while others reflect a disparity between the original concept and its actual implementation.

When the distribution of articles is mapped across publishing years (cf. e.g., Table 5 below), we observe that the distribution indicates a relatively steady and continuing interest in the CR paradigm and associated technologies. In general, the number of publicly available papers in the military domain remains significantly lower than those addressing civilian technologies.

Although one might have expected some evidence of logical evolution from early years-low TRLs toward later years-high TRLs, such progress is not apparent in our data. Individual papers coded to high TRLs are almost outliers, not yet providing sufficient foundations to articulate a general trend (cf. also Tables 4 and 5).

RESULTS BY CCMM LEVELS

As seen in Table 3, the category of CCMM 6 functioning enterprise—military unit level contains 11 articles, where the authors have either a background or professional affiliation with respective national military establishments.

Within the category CCMM, 3 defense lines of development, there is one article that applies defense lines of development doctrine, organization, training, materiel, personnel, leadership, facilities, information/interoperability (DOTMPLFI) framework to assess potential military capability implications the cognitive radio technology could introduce.

Category CCMM 1 scope contains five articles—these address a range of topics, for example, from military R&D to general spectrum administration. Nevertheless, the scope or viewpoint of these articles is above the military, i.e., national, technology wide, or even broader.

When the distribution of articles is mapped by CCMM levels and publishing years, it is evident that general interest is ongoing at the subsystem level of CCMM level 5, which with 156 articles, is the most populous category. However, mapping CCMM viewpoints by TRLs in Table 4 again portrays heavy concentration to CCMM level 5 and to low TRLs 1-3.

ADDITIONAL OBSERVATIONS

As we have already observed, the most populous categories across the topics are waveforms, security, modeling spectrum use, and spectrum sharing. Therefore, it should come as no surprise that these articles concentrate on the category of CCMM 5 Subsystems (156 articles).

Considering paper types across TRLs, we observe that a large number of conference papers have been published within the TRL1-4 domain (141 articles). Moreover, many journal articles, dissertations, and surveys are assigned to low TRL 1. This indicates that significant research effort remains to clarify military cognitive radios' functions, requirements as well as security aspects.

By far, most of the conference papers have been published through IEEE, where IEEE/AFCEA Military Communications Conference (MILCOM) and International Conference on Military Communications and Information Systems (ICMCIS) stand out as most productive venues. From the data, less than a dozen prolific authors emerge. However, these authors collaborate with established research groups we should recognize; Fraunhofer FKIE, Intelligent Automation Inc., NATO Science and Technology Organization, Royal Military Academy of Belgium, Rockwell Collins Advanced Technology Center, Thales Communications, University of Nevada, University of Oulu, and Wojskowa Akademia Techniczna of Poland.

In the process of searching, selecting, and coding papers, some enticing papers stand out in addition to those already mentioned. Matyszkiel *et al.* [26] provided a comprehensive survey of network coding techniques in CRNs. Our data includes some other conference papers addressing the same topic but from a narrower perspective.

Generally, spectrum sensing can be seen as a component or subsystem technology within a cognitive radio (as a node or device) or within a waveform (as a service or a component thereof). Marwick *et al.* [27] is an example CCMM 4 "system level," well developed TRL 4, survey. In this article, spectrum sensing is brought to a broader context of cognitive radio networking. The article reviews the spectrum sensing technologies and offers future research directions for cognitive radio networks.

Spectrum sharing, spectrum access, and spectrum regulation have been addressed in several papers. The journal article of [28] is an example of CCMM 1 "above military" way of addressing spectrum regulation for cognitive radios. At the same time, it stands out also as an example of conceptual work at a low TRL 1. A comparison can be made with [29] at TRL 2, where the authors challenge the current wireless coexistence paradigm. This article argues for a more generic solution in terms of frequency reuse and coexistence. A new generic medium sharing model that solves coexistence problems in a simple, efficient, and technology-agnostic way is presented. The suggested approach is compatible with all existing wireless communication technologies and incorporates capabilities for future modifications and additions to support emerging new technologies.

As an example of the U.S. Department of Defense funded military-oriented R&D, Saint and Brown [30] argues that spectrum agility should be complemented with network agility to achieve mission success. The authors suggest the use of a proactive and adaptive cross-layer reconfiguration framework for autonomous network adaptation. As an individual potential solution to a broader problem, the suggested approach is well in line with [11].

DISCUSSION

The military CR research seems to be prolific on topics like waveform design and security, not forgetting a steady interest in CR networking topics. Our data indicate that the vast majority of papers and topics have been categorized to CCMM 5 "subsystem" level, indicating that the TRLs are still valid tools for assessing maturity, as can be inferred from Table 4.

Significantly low numbers of papers address applications, services, and standardization. If continued, this may harm the scale and harmonization of the technology, as well as on interoperability, which is critical for the practical deployment decisions across different communities of interest.

The annual distribution of military CR research by TRLs in Table 5 indicates continuing interest. This finding is contradictory to general statistics from, e.g., IEEE Xplore Digital Library, whereby the numbers of general (civilian) CR research articles has been on the decline since 2014. This may indicate general technology

Table 4.

Number of articles by CCMM levels and by TRLs

CCMM levels by TRL	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9	SUM
CCMM 1	3	2								5
CCMM 2										0
CCMM 3		1								1
CCMM 4	3	5	5	5	1		1			20
CCMM 5	16	60	58	20	1	1				156
CCMM 6	5	5		1						11
SUM	27	73	63	26	2	1	1	0	0	193

Table 5.

Annual Distribution of Articles by TRLs

Numbers by years to TRL	2013	2014	2015	2016	2017	2018	2019	2020	SUM
TRL 1	5	3	4	2	8	1	4		27
TRL 2	13	9	12	9	8	13	9		73
TRL 3	11	10	9	7	7	3	14	2	63
TRL 4	7	1	8		7		3		26
TRL 5		1	1						2
TRL 6							1		1
TRL 7			1						1
TRL 8									0
TRL 9									0
SUM	36	24	35	18	30	17	31	2	193

maturing from singular techniques to address broader system-level issues. However, this is not yet evident in military CR research data.

Machine learning and artificial intelligence seem natural techniques to implement CR, and the interest is on the rise toward the end of our study epoch. In general, military CR research seemed sporadic and scattered. Our data suggest that a transition from individual techniques, node-level subsystem research in the direction of the CRS systems engineering approach, and system-level studies has not yet happened, and the overall TRLs remain low.

The authors recognize that coding, as described, may not be clear-cut and may, at times, be arbitrary. Papers may address topics that overlap more than one category. Although every attempt has been made to ensure that our dataset is comprehensive and representative, we cannot claim that all papers applicable made their way into our dataset.

CONCLUDING REMARKS

We collected 193 articles on military CR research from well-known publishers covering the period of 2013–2020. Our selection of data sources led our dataset to be dominated by subsystem level, low TRL-types of articles. Therefore, our data indicate that research on military cognitive radio systems remains at the subsystem (component) level and at low TRLs. Besides one outlier, there is no indication that anyone has been able to bridge the gap from TRL 5 to TRL 7. Toward the end of our study epoch, the increasing interest in machine learning techniques may eventually lead to a shift in this technology's TRLs in the coming years. Higher system level or high TRL related research questions should be addressed by selecting different kinds of data sources and remains a potential future research topic. Nevertheless, research on military

CRSs is nowhere near reaching the “testing validity in a relevant environment.” The brink of the “Valley of Death” has not been reached yet.

The absence of publicly articulated comprehensive treatment of the notion of military cognitive radio system (i.e., CCMM levels 1-3) is graphic and has lead to noninterconnected scattered research at the subsystem level (i.e., CCMM levels 4-5). The lack of such treatment also manifests in the absence of understanding, which components or subsystems constitute a MCRS. Therefore, the authors suggest that military operational, acquisition, as well as academic research and manufacturing communities, should all come together to frame a generic, publicly available vision for a MCRS.

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