

**Reviewer's opinion
on Ph.D. dissertation authored by**

Lukasz Kułacz

entitled:

*Utilization of Context Information for Spectral-Efficiency Enhancement
in Future Radio Communication Systems*

Upon accepting to act as a reviewer for this thesis, early June 2022, I have read the thesis, consulted some of the referenced scientific papers, and formed myself an opinion about the work. This opinion refers solely to the work presented in the thesis and is outlined below. In principle I follow the template that was sent to me and the questions phrased in this template, but occasionally I choose to divert and address aspects beyond those mentioned in the template, which I feel are necessary mentioning as an important basis for my conclusions.

There are no conflicts of interest for me to carry out this review.

1. Problem and its impact

This thesis addresses the problem of spectrum scarcity, spectrum under-use and, in general, the *spectrum efficiency* of radio networks. Kułacz chooses to approach this problem through explicit exploitation of prior information about a broad variety of physical and radio characteristics about the network infrastructure, its devices, and its users, information that oftentimes is not exploited by today's systems. Kułacz refers to this broad class of prior information as *Context Information*.

This general problem is very timely. The sixth generation of radio networks is in the process of being developed and the integration of intrinsically heterogeneous systems is a key topic. This development again highlights the problem of spectrum efficiency on an inter-network level. While this problem has been studied in the research community essentially since 1999, An upswing of the work on TV white spaces and Radio Environmental Maps took place around 2010. Kułacz nicely presents this background and the relevant work in European projects carried out during these years.

While the problem of secondary use of TV spectrum appears a bit outdated (TV spectrum has been compressed with the re-assignment of the 800- and 700-MHz bands, essentially reducing the available white spaces in many countries, compared with the situation in the early 2000s), but in the context of the overall thesis, lessons can be learned from these concepts for the abovementioned work on 6G. Upon careful reading of the chapter 3 and 4, many novelties and experimental case studies are useful for further conceptual understanding.

Impact of the work is very broad and found in many domains. In the scientific domain, the work in Chapter 5, on ultra-dense networks, provides most originality. This work is conceptual in nature and has the longest horizon to eventual use and application. In the engineering domain, the work in Chapters 3, 4 and 6 is relevant. Engineers will find algorithms and ideas in Chapter 3 and inspiration and insights from the experimental studies in Chapter 4. In the regulation and 6G-standardization domain results in Chapters 3 and 6 will have impact (spectrum management and the O-RAN developments).

2. Contribution

Kułaacz presents in this thesis new insights, concepts, algorithms, and performance analyses related to radio networks. In particular, he presents a broad range of novelties about how *spectral efficiency* (and other performance indicators such as energy efficiency, complexity, cost, etc) can be improved by exploiting *Context Information*.

Contributions to science and engineering are mainly found in Chapters 3-6 of the thesis. In general, it has been somewhat difficult for me to distinguish between the state-of-the-art of and the novelty and contribution of this thesis beyond this state – the text does not always clearly provide a self-assessment as to what are the novel and innovative steps. Often though, it is clear from the context, and the Summary Tables at the end of each Section in Chapter 3-6 have been of help, through the brief final comment line in each table.

Kułaacz has an impressive list of scientific publications listed separate in Appendix A of the thesis. My counting amounted to at least 14 journal articles and 15 conference contributions (I could not assess the value of the Polish publications). Related to my assessment of the novelty of the work in the thesis I rely to some extent on the mere fact that this work has been presented in so many high-end and peer-reviewed publications where novelty is a strict requirement for acceptance and publication.

In many of the *early* contributions (2017-2018, work on Chapters 3-4) Kułaacz has been a co-author among often many other authors and it therefore is not straightforward to assess the work of Kułaacz within the team and among other researchers that produce these publications (despite the short 'author's contribution' comments in Appendix A). However, Kułaacz is listed as the first author on at least 19 of his publications which I assume reflects the significance of his contribution to the work. Moreover, *later* work of Kułaacz (2019-2021, work on Chapter 5 and 6) appears in many cases to be the result of his direct work with Kliks, his advisor. Overall, at least 13 of his publications have been authored by them without any further contributors.

In general, I am confident that the Kułaacz accounts for the scientific contributions in the thesis, to an extent and that fully justifies a doctoral degree. Besides, I like to stress that his demonstrated ability and experience to co-author with a broad range of other scientists and engineers is a merit in and of itself and a true strength and asset in a further career as a researcher.

The main contributions in the various chapters are topically well-structured and clear. Chapter 3 presents (1) a new REM-based algorithm for DSA systems (with indoor-outdoor transitions) along with an experimental validation, (2) a new algorithmic approaches to efficient power/spectrum use in CBRS systems, and (3) a novel concept to increase spectrum efficiency by adaptive waveform

selection. Chapter 4 applies the generic results of Chapter 3 to a number of practical systems and standards, to WiMax, LTE, and M-MIMO LTE-A. Also in these applications, novel aspects are found. Chapter 5 presents the novel application of *Microglial* and *Astrocytal* network nodes to an ultra-dense network with characteristics borrowed from the biological nervous system. The application of these network nodes and their evaluation based on percolation theory and account for self-interference is novel. Finally, Chapter 6 presents new ways of spectrum management that implement policies and regulation, and new application of freemium licensing to dynamic spectrum sharing and pricing.

In parts of the thesis, sections appear somewhat as an excerpt or brief overview of longer versions that appear in the associated published journal or conference articles, perhaps for reasons of brevity and mere volume of the thesis. This necessarily compresses relevant background to a minimum and in several places, the reader is explicitly referred to references of the author for further details on a subject or on simulation or experiment set-up. This causes the thesis to lack full autonomy (a reader more or less needs the authors publications at the side to fully grasp the content). Despite this, at no point was this prohibitive for the conceptually understanding of the ideas and results.

3. Correctness

The methodologies that are applied in the thesis span mostly from simulations to experiments. The simulations results are in general convincing and so are the results obtained by experimental validation. Kułacz describes the simulations setups with care although I doubt that all of the results in the thesis are fully repeatable by a reader based on the mere descriptions in the thesis (potentially, the associated papers by the author fill these gaps).

I would have preferred a more thorough and extensive assessment of the performance criteria used in the thesis. In several instances, results have been evaluated with a single graph, a single Table of results, or a single experiment, while there would have been plenty more ways to assess and evaluate the algorithm or system under investigation. This limits to a certain extent the depth of the analyses. In other words, the evaluation could have been more extensive and rich, thus revealing more aspects, virtues and shortcomings of the respective radio systems. Despite this, the conclusions that Kułacz draws based on the presented results are fully justified and arguments are broadly correct.

I particularly enjoyed reading in Chapter 2-4 how simulations results and experimental results go hand in hand to jointly demonstrate the feasibility and improvement of spectral efficiency in the TV bands. I also want to highlight the innovative approaches of Chapter 5 with the introduction of the Astrocyte- and Microglia-type network nodes. These truly are new ideas worth to be researched in depth.

4. Knowledge of the candidate

The thesis is in many ways *broad* in scope. A range of different problems are treated, a large number of contemporary standards and systems have been used for application studies, and performance assessment has been done in a number of experimental and simulation set-ups. Kułacz demonstrates a broad knowledge of the topic, a good understanding of the problems and challenges

(from an academic as well as industrial standpoint), and a broad ability to apply scientific methods and instruments.

Depth of the work is found, in my opinion, in parts of Chapters 3 and 5. In Chapter 3, Kułacz demonstrates a deep understanding of the challenges and opportunities in systems with dynamic spectrum management. In Chapter 5, he is among those pioneering an interesting topic in depth that well may become a broadly researched topic within years.

Chapters 1 and to some extent Chapter 2 describe the background of the work and are more tutorial in nature. These chapters confirm a general knowledge of Kułacz in the discipline of **Information and Communication Technology**. The sub-disciplines of Wireless Radio Networks, Dynamic Spectrum Access, Radio Environmental Information, and TV White Space Access are covered by those chapters. The list of references is rich and seems to be accurate. At some instances in these chapters Kułacz refrains from full scientific more rigor, in places where it would have been desirable: for instance, a more firm and concrete definition of 'Context Information' would have been valuable. Also other key concepts are characterized a bit vague and seemingly deliberately kept open to various interpretations.

Beyond the tutorial part of the thesis, the remaining chapters demonstrate clearly the broad knowledge of Kułacz. Details about many contemporary standards, about the regulatory state-of-the-art, and about the behaviour of radio networks illustrates this throughout the remainder of the thesis.

5. Conclusion

Taking into account what I have presented above and the requirements imposed by Article 13 of the *Act of 14 March 2003 of the Polish Parliament on the Academic Degrees and the Academic Title (with amendments)*¹, my evaluation of the dissertation according to the three basic criteria is the following:

A. Does the dissertation present an original solution to a scientific problem? (the selected option is marked with **X**)

Definitely YES *Rather yes* *Hard to say* *Rather no* *Definitely NO*

B. After reading the dissertation, would you agree that the candidate has general theoretical knowledge and understanding of the discipline of **Information and Communication Technology**, and particularly the area of **Radio Communication Networks**?

Definitely YES *Rather yes* *Hard to say* *Rather no* *Definitely NO*

C. Does the dissertation support the claim that the candidate is able to conduct scientific work?

Definitely YES *Rather yes* *Hard to say* *Rather no* *Definitely NO*

¹ http://www.nauka.gov.pl/g2/oryginal/2013_05/b26ba540a5785d48bee41aec63403b2c.pdf

With this thesis Łukasz Kułacz demonstrates not only a broad mastering of the general topics of **Information and Communication Technology** and the area of **Radio Communication Networks**, their context and relevance, but his thesis also shows a strong engineering and scientific ability to develop and analyze new solutions that target their important weaknesses – solutions with a clear potential to improve and impact the performance and development of future radio systems.



Jaap van de Beek