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# Reviewer's opinion

## on Ph.D. dissertation authored by

*mgr inż. Marcin Hoffmann*

## entitled:

*Radio Environment Maps, and Machine Learning Techniques for Spectral and Energy Efficiency Improvement of Wireless Communications, with Emphasis on Massive MIMO Systems*

## 1. Problem and its impact

*What is, in your opinion, the most important problem discussed in the dissertation? Is it a scientific one? Does it have a practical meaning?*

The central problem addressed in the dissertation is the efficient utilization of radio resources in 5G and prospective 6G wireless networks, with particular emphasis on improving spectral efficiency and energy efficiency under increasing system complexity. This problem is approached by Mr Hoffmann through the integration of Radio Environment Maps (REMs) and machine learning (ML) techniques to enable data-driven optimization of network functions such as interference management, beam management, cell on/off switching, and resource allocation, especially in massive MIMO and Open RAN architectures. This dissertation (which has the form of "PhD by publication", supported by the abstract and introductory chapters) identifies spectral and energy efficiency optimization as the primary research objective.

The studied problems are scientific in nature. They are grounded in well established theories of wireless communications and optimization, and the candidate develops them through the application of machine learning methods, including reinforcement learning and federated learning. The dissertation formulates a research claim (hypothesis), proposes novel models and algorithms, and validates them through simulations and partly also experimental evaluations, which are characteristic features of scientific research in ICT.

The investigated problems are important and the proposed solutions have practical relevance. The proposed methods address real-world challenges encountered by mobile network operators, such as reducing energy consumption, improving network performance, and enabling intelligent network management in increasingly dense and heterogeneous deployments. It is worth noting that mobile network operators aim to counterweight the rapidly increasing energy demands resulting from network densification, massive MIMO deployments, and heterogeneous service requirements by improving energy efficiency. The focus on Open RAN, massive MIMO, V2X, and IoT scenarios, as well as validation using realistic simulations and testbeds, suggest that the results might offer a potential for practical application in 5G and future 6G network deployments.

## 2. Contribution

*What is the main, original contribution of the dissertation? If appropriate, you can make a distinction between what the Ph.D. candidate claims to be the main contribution and what you consider as the main contribution. If this is the case, indicate the reason for which you do not agree (e.g. it could be that somebody else has already proposed a given idea or it can be original but not correct due to some flaws described in Sec. 3 of the reviewer's opinion). You can also comment on practicality of the proposed solutions (it could be that the problem is highly practical, but the proposed solution is not). If applicable, you can refer to other quality indicators you know about (e.g. quality of publications by the candidate, patents authored by the candidate, citations, existing applications of the proposed solutions etc.).*

In my opinion, the main original contribution of the candidate lies in novel methods of integration of Radio Environment Maps (REMs) with machine learning – based on control and optimization mechanisms to improve both spectral efficiency and energy efficiency in advanced wireless networks, with particular emphasis on massive MIMO systems and Open RAN architectures.

From the perspective of the PhD candidate, the primary contribution is the proposal of a data-driven framework in which REMs are used as a key factor for smart network management. Within this framework, several machine learning techniques – particularly reinforcement learning and federated learning – are developed and applied to concrete network functions such as beam management, interference mitigation, cell on/off switching, and resource allocation. The originality claimed by the candidate stems from (i) the joint consideration of REMs and learning-based optimization, (ii) the adaptation of these methods to massive MIMO and Open RAN scenarios, and (iii) the evaluation of the proposed solutions in realistic, application-oriented use cases, including V2X and IoT.

While merging REMs and machine learning techniques has been previously studied in the literature and is not a conceptual novelty, their joint combination into a practical network control framework, targeting both energy and spectral efficiency and aligned with Open RAN principles, creates an original contribution (algorithms, evaluation framework, Open RAN implementations). This novelty does not involve entirely new learning algorithms, but rather ways in which existing methods are adapted and combined into a wireless network context by Mr Hoffmann. This system-level integration, supported by detailed simulations and performance evaluations, represents a convincing contribution of the dissertation.

Regarding practicality, the addressed problems are clearly of high real-world relevance, as they correspond to current challenges faced by mobile network operators. Probably, the proposed solutions could be implemented, particularly in the context of Open RAN, where data availability and software-based control are fundamental features. At the same time, some solutions rely on assumptions such as sufficiently accurate REMs, reliable data exchange, or centralized learning components, which may limit immediate deployment at large scale. Nevertheless, the candidate's assumptions are reasonable within a research context and show directions for further development and real-world testing.

Overall, the dissertation demonstrates significant originality with a link between theory and practice, and contributions that are consistent with the state of the art in modern wireless communications research.

Being first author in 15 out of 16 peer-reviewed publications provides strong evidence that Mr Hoffmann was the principal contributor to problem formulation, methodology design, experimental evaluation, and manuscript preparation. The dominance of two- and three-author papers indicates substantial independent research activity, while the presence of a few larger collaborations [1], [2] demonstrates the ability to contribute to and lead work within broader research teams.

To sum up, the publication record provides strong evidence that:

- Mr Hoffmann is the main scientific contributor to the body of work underlying the dissertation;
- The dissertation is not a compilation of unrelated publications, but rather a consistent research program led by the candidate;
- The candidate demonstrates maturity, independence, and continuity in research activity.

This analysis strongly supports the claim that the dissertation reflects the candidate's own substantial and original scientific contribution.

The dissertation in the form of "PhD by publication" is based on the following contributions:

**[1]** M. Hoffmann, S. Janjić, A. Samorzewski, Ł. Kułacz, C. Adamczyk, M. Dryjański, P. Kryszkiewicz, A. Kliks, and H. Bogucka, "Open RAN xApps design and evaluation: Lessons learnt and identified challenges," *IEEE Journal on Selected Areas in Communications*, vol. 42, no. 2, pp. 473–486, Feb. 2024, doi: 10.1109/JSAC.2023.3336190.
**[2]** H. Bogucka, M. Hoffmann, P. Kryszkiewicz, and Ł. Kułacz, "An Open-RAN testbed for detecting and mitigating radio-access anomalies," *IEEE Communications Magazine*, early access 2025.
**[3]** M. Hoffmann and P. Kryszkiewicz, "Signaling storm detection in IoT networks based on the Open RAN architecture," in *Proc. IEEE INFOCOM 2023 Workshops*, 2023, pp. 1–2.
**[4]** M. Hoffmann and P. Kryszkiewicz, "O-RAN for energy-efficient serving cluster formulation in user-centric cell-free mMIMO," in *Proc. IEEE INFOCOM 2024 Workshops*, 2024, pp. 1–2.
**[5]** M. Hoffmann, P. Kryszkiewicz, and A. Kliks, "Frequency selection for platoon communications in secondary spectrum using radio environment maps," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 3, pp. 2637–2650, Mar. 2022.
**[6]** M. Hoffmann, P. Kryszkiewicz, and A. Kliks, "Increasing energy efficiency of massive-MIMO network via base stations switching using reinforcement learning and radio environment maps," *Computer Communications*, vol. 169, pp. 232–242, 2021.
**[7]** M. Hoffmann, A. Kliks, P. Kryszkiewicz, and G. P. Koudouridis, "A reinforcement learning approach for base station on/off switching in heterogeneous mMIMO networks," in *Proc. IEEE WoWMoM*, 2020, pp. 170–172.
**[8]** M. Hoffmann and P. Kryszkiewicz, "Similarity measures for location-dependent mMIMO 5G base station on/off switching using radio environment maps," in *Proc. IEEE WoWMoM*, 2021, pp. 286–291.
**[9]** M. Hoffmann and P. Kryszkiewicz, "Reinforcement learning for energy-efficient 5G massive MIMO: Intelligent antenna switching," *IEEE Access*, vol. 9, pp. 130329–130339, 2021.
**[10]** M. Hoffmann and P. Kryszkiewicz, "Contextual bandit-based amplifier IBO optimization in massive MIMO networks," *IEEE Access*, vol. 11, pp. 127035–127042, 2023.
**[11]** M. Hoffmann and M. Dryjański, "Energy efficiency in Open RAN: RF channel reconfiguration use case," *IEEE Access*, vol. 12, pp. 118493–118501, 2024.
**[12]** M. Hoffmann and P. Kryszkiewicz, "Evaluation of user-centric cell-free massive multiple-input multiple-output networks considering realistic channels and frontend nonlinear distortion," *Applied Sciences*, vol. 14, no. 5, Art. no. 1684, Mar. 2024.
**[13]** M. Hoffmann and P. Kryszkiewicz, "Beam management driven by radio environment maps in O-RAN architecture," in *Proc. IEEE ICC Workshops*, 2023, pp. 54–59.
**[14]** M. Hoffmann, P. Kryszkiewicz, and G. P. Koudouridis, "Modeling of real-time kinematics localization error for use in 5G networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 2020, no. 1, Art. no. 31, 2020.
**[15]** M. Hoffmann, P. Kryszkiewicz, and A. Kliks, "Federated learning-based interference modeling for vehicular dynamic spectrum access," in *Proc. Int. Conf. Mobile and Ubiquitous Systems: Computing, Networking and Services (MobiQuitous)*, Springer, 2022, pp. 431–454.

**[16]** M. Hoffmann and P. Kryszkiewicz, "Radio environment map and deep Q-learning for 5G dynamic point blanking," in *Proc. Int. Conf. Software, Telecommunications and Computer Networks (SoftCOM)*, 2022, pp. 1–3.

It is worth noting that the candidate's percentage share (confirmed in the co-authors' statements) is predominant in most publications, and in subsequent publications [1-16] it amounts to 20%, 30%, 85%, 85%, 70%, 70%, 70%, 80%, 80%, 80%, 60%, 75%, 70%, 65%, 60%, and 90%, correspondingly. The authorship distribution fully satisfies expectations for a doctoral dissertation: leadership by the candidate, strong collaboration with the supervisor, and occasional participation in larger consortiums.

The sixteen publications [1–16] jointly develop a consistent research program focused on improving spectral and energy efficiency in modern and future wireless networks through the combined use of radio environment maps, machine learning techniques, and Open RAN architectures. The works address a wide range of relevant problems, including energy-efficient base-station and antenna management in massive MIMO systems [6–9], beam management driven by REMs in Open RAN [13], and serving-cluster formulation in user-centric cell-free mMIMO networks [4], as well as interference coordination mechanisms such as dynamic point blanking [16]. Interference-aware spectrum access and frequency selection for vehicular scenarios are investigated in [5], [14], and [15], while adaptive power-amplifier and RF-chain configuration is addressed in [10] and [11]. Anomaly and signaling-storm detection in operational Open RAN–based networks are covered in [1]–[3]. Across these studies, the candidate proposes data-driven and learning-based solutions [6–10], [13], [15], validates them using realistic channel models and system-level simulations – most notably including 3D ray-tracing-based propagation and nonlinear hardware modeling [12] –and, for selected Open RAN security-related contributions, experimental verification in a real 5G testbed [2]. Taken together, the publications show a clear progression from fundamental modeling and algorithm design [14], [16] to practical, architecture-aware solutions aligned with Open RAN principles [1], [2], [4], [11], highlighting the applicability of the proposed methods to real-world 5G and emerging 6G deployments.

In my opinion, the above mentioned results are the major scientific achievements of the dissertation presented in the candidate's cycle of scientific publications.

## 3. Correctness

*Can we trust what is claimed in the dissertation? Are the arguments correct? Indicate the flaws you have noticed, if any. Also point out those aspects concerning correctness that you value most (elegance of proofs, design of experiments, analysis of empirical data, quality of prototype software/hardware etc.).*

The research results presented in the cycle of scientific publications are validated primarily through comprehensive simulation studies and, for a selected subset of contributions, through real-world testbed experiments. Simulation-based confirmation is employed across the majority of the candidate's works (e.g. [5]–[10], [12], [16]), while experimental validation in an operational 5G Open RAN testbed is provided for the jamming/signalling-storm detection ([2], [3]).

It is important to note that the key research results have been already independently verified through peer-reviewed journal (IEEE Journal on Selected Areas in Communications, IEEE Transactions on Intelligent Transportation Systems, IEEE Communications Magazine, IEEE Access, Computer Communications – Elsevier, EURASIP Journal on Wireless Communications and Networking, MDPI Applied Sciences) and conference (IEEE INFOCOM Workshops, IEEE International Conference on Communications Workshops, IEEE World of Wireless, Mobile and Multimedia Networks, International Conference on Software, Telecommunications and Computer Networks, and International Conference

on Mobile and Ubiquitous Systems) publications co-authored by Mr. Hoffmann. Acceptance of these contributions in high-quality journals and conferences shows an external validation of their scientific relevance.

Also, part of the dissertation – specifically the Open RAN security and signalling-storm detection – goes beyond simulation-only validation and includes experimental verification in an operational 5G environment. This increases validity for this subset of contributions when compared to purely simulation-based studies.

The critical remarks presented below identify issues and questions that would benefit from clarification or discussion by the candidate during the public defence:

1. The stated research claim "The usage of information stored in Radio Environment Maps can improve spectral and energy efficiency of wireless networks, especially those using massive MIMO, by utilizing machine learning" is consistent with the dissertation's content but remains broad and somewhat self-evident, as Radio Environment Maps are inherently designed to provide contextual information for network optimization. The claim would benefit from a more precise formulation specifying the concrete REM-derived features, the employed machine-learning methods, and the conditions under which spectral or energy efficiency gains are obtained. Only as an example, the research claim could be reformulated as follows: "The Radio Environment Maps combined with machine-learning techniques, can be used to improve spectral and energy efficiency of 5G/6G wireless networks through selected mechanisms such as beam management, interference modelling, and resource allocation."
2. The candidate claims that the massive-MIMO solutions are evaluated under an "accurate 3D ray-tracing–based radio channel model" ("Wireless InSite™ 3D Ray-Tracer. It is configured to consider 15 reflections and 1 diffraction between the MMIMO BS's antennas and each of the single-antenna users.") [10]. The use of a 3D ray-tracing channel modelling enhances realism, however, the study would benefit from a clearer justification of specific modelling parameter values (e.g., number of reflections and diffractions) and a brief discussion of their impact on accuracy-complexity trade-offs
3. Claimed performance gains (e.g., 'up to 70% improvement in energy efficiency') should be interpreted (within individual publications) as scenario-dependent and relative to some defined baselines. While these results demonstrate the potential of the proposed methods, the dissertation-level summary would benefit from a clarification of the adopted energy-efficiency definitions, scenarios, and baselines.
4. Statements such as 'Unlike many state-of-the-art works…' appear in the thesis and would benefit from being supported by explicit references to earlier studies and a clearly defined comparison scope, especially at the dissertation-level summary.
5. The paragraph explaining the limitations of the 5.9 GHz band would benefit from more in-depth justification. It is true that spectrum in the 5.850–5.925 GHz range is allocated for V2X, however the statement that this band will be insufficient to ensure low latency and high reliability as vehicle density increases should be supported by concrete evidence (not only two references), since the claim is quite strong. The motivation for exploring complementary spectrum options – whether in unlicensed bands such as 2.4 GHz or via Dynamic Spectrum Access in licensed bands like TV White Spaces – is reasonable, but it requires a more quantitative explanation of why inter-platoon communication in particular necessitates additional spectrum.

The above remarks are intended as minor points for discussion and do not diminish the overall very positive assessment of the dissertation.

## 4. Knowledge of the candidate

*What are the chapters of the dissertation (or sections in chapters) that resemble a tutorial and thus confirm a general knowledge of the candidate in the discipline of Information and Communication Technology. What areas of that discipline are covered by those chapters/sections? What do you think about quality of those chapters/sections? What is your opinion on the list of references? What is the degree of its completeness? Provide any other arguments in favour or against the claim that the candidate has general knowledge and understanding of the Information and Communication Technology discipline.*

Several chapters of the thesis have a tutorial or survey-like character, thereby demonstrating the candidate's general knowledge and understanding of the Information and Communication Technology (ICT) discipline. In particular:

1. Chapter 1 – Introduction serves a tutorial function. It introduces the evolution from 5G to future 6G networks and discusses fundamental challenges such as network densification, massive MIMO deployment, spectral efficiency, and energy efficiency. It also provides conceptual explanations of Radio Environment Maps, Open RAN architecture, and the role of machine learning in modern wireless systems.
2. Chapter 2 – V2X Communications Use Case (Background and Related Work section) The background and related-work sections in this chapter have a survey-like nature. They explain V2X communication requirements, localization mechanisms (e.g., GNSS/RTK), interference characteristics, and spectrum usage before introducing original contributions.
3. Chapter 3 – mMIMO Communications Use Case (Background and Related Work section) includes explanatory sections describing massive MIMO principles, user-centric cell-free architectures, beamforming concepts, and interference coordination. These sections are mostly general and position the candidate's work within the broader research landscape.
4. Chapter 4 – IoT Use Case (Background and Related Work section) explains signalling storms, denial-of-service phenomena, and KPI-based monitoring in cellular networks, thus extending the tutorial coverage beyond the physical layer into network operation and security aspects.

The quality of these sections can be assessed as very good. They demonstrate breadth of the candidate's knowledge in ICT.

The references provided within [1–16] are extensive and relevant, covering aspect such as: foundations works in wireless communications and massive MIMO, key standards and architectural concepts (e.g., 3GPP, Open RAN), recent research on machine learning, reinforcement learning, and federated learning applied to wireless networks.

Overall, the tutorial-style chapters of the thesis and introductory sections of the published papers, together with the selection of referenced literature and application scenarios, provide evidence that the candidate has a solid understanding of the ICT discipline, extending beyond narrow specialization.

## Other remarks[1]

None.

[1] Optional

## 5. Conclusion

Taking into account what I have presented above and the requirements imposed by Article 187 of *the Act on Higher Education and Science of the Polish Parliament* (Dz. U. 2018 poz. 1668 with amendments)[2], 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**)

| [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 ....?

| [X] | [ ] | [ ] | [ ] | [ ] |
|---|---|---|---|---|
| *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?

| [X] | [ ] | [ ] | [ ] | [ ] |
|---|---|---|---|---|
| *Definitely YES* | *Rather yes* | *Hard to say* | *Rather no* | *Definitely NO* |

I would like to stress that Mr. Hoffmann has satisfied all formal and customary requirements for a doctoral dissertation in ICT with a quality that goes beyond the usual academic standards.

Moreover, taking into account the extensive range of research problems addressed, the originality and clarity of the proposed solutions, the methodological correctness, and the combination of practical relevance with a very good level of international visibility of the associated peer-reviewed publications, **I recommend that the dissertation be distinguished for its high quality.**

*Signature*

[2] http://www.nauka.gov.pl/g2/oryginal/2013_05/b26ba540a5785d48bee41aec63403b2c.pdf