Prof. Piotr Gajewski DSc, PhD, Eng.
Military University of Technology
piotr.gajewski@wat.edu.pl

22.12.2025

Reviewer's opinion

on Ph.D. dissertation authored by

Mgr eng. 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

The rapid development of wireless systems is associated with intensive research conducted in many areas, such as mastering increasingly higher frequency ranges for transmission, combining of computing and communication processes, integration of terrestrial and spatial systems, heterogeneous in terms of services and applications with various requirements for basic system evaluation indicators, including quantitative metrics such as throughput, latency, and qualitative parameters like the security and intelligence levels. The common denominator of these studies is the search for solutions aimed at optimal use of the natural resource that is the EM field from the point of view of both energy and spectral efficiency (EE and SE).

In this context, the presented dissertation is in line with contemporary research trends and is related to the achievements of the Poznań University of Technology team in the field of work on the concept of the O-RAN (Open – Radio Access Network's) standard.

The candidate's research area in this field covers three classes of services defined for 5G networks as eMBB – enhanced Mobile BroadBand, mMTC – massive Machine-Type Communications, and URLLC – Ultra-Reliable Low Latency Communications, (for 6G networks have been expanded as strengthening), which on the one hand has been limited by the adoption of MIMO transmission technology, and on the other hand has been significantly expanded by the use of location information.

The choice of MIMO technology is fully justified by the possibilities offered by beam control, especially in Massive MIMO (MMIMO), in terms of increasing transmission efficiency and its security. Location procedures enable increased wireless network efficiency through the use of electromagnetic environment information that is collected and provided in the form of a REM (Radio Environment Map). Rapid changes in environmental parameters, especially in conditions of high user equipment mobility, require real-time data entry, prediction of changes, and generalization of REM data from multiple sources, which is possible thanks to the use of ML machine learning algorithms.

For each of the above-mentioned services classes, the doctoral student considers selected use cases of V2X for URLLC, MMIMO for eMBB, and IoT for mMTC, respectively, defining the following research hypothesis:

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.

The hypothesis is justified by the solutions presented by the dissertation candidate in 16 original scientific publications, in which he is the leading author, with a significant contribution described in the dissertation, which will be evaluated in the next section of the review.

The work is scientific in nature, as emphasized by both the analyses of the state of knowledge in each of the cases solved and the descriptions of analytical and simulation models contained in the publications, together with the research results. It is of significant importance for the development of the O-RAN standard, as the proprietary algorithms are proposed as dedicated xApps and rApps applications for Radio Intelligent Controllers (NearReal-Time RIC and NonReal-Time RIC) in the O-RAN structure. .

2. Contribution

The original Author's contributions are strictly connected with his doctoral thesis and includes proposals for 10 original solutions demonstrating significant increases in the energy and spectral efficiency of next-generation wireless networks through the use of various ML techniques to build REM and use it effectively based on location awareness.

In particular, they address issues such as cell/antenna activation, beam management, system interference control, and power amplifier operating point control. As mentioned earlier, these contributions relate to three use cases:

- V2X communication as a URLLC application,
- MMIMO system oriented towards the implementation of eMBB services,
- IoT as a basic mMTC example.

These solutions are described in five chapters. The introduction describes the origins of the problem, including concise characteristics of 5G network classes, MMIMO technology for cellular and cell-free architectures, the REM concept extended with location-dependent data related to the aforementioned service classes, and an indication of the author's contributions in each of these classes. In the next three chapters, the author describes his own solutions more detailed against the background of state-of-the-art analysis and related work.

For the V2X Communication use case, the Candidate's considerations focus on two aspects, namely the problem of platoon-based driving, typical for car traffic, especially trucks along highways, and the handling of individual high-speed vehicles with beam switching in the MMIMO system. which requires accurate vehicle location and intelligent beam management. Here, four original solutions are proposed:

- The first one is Modelling of Real Time Kinematics (RTK) location error for REM based on satellite geometry and the results of measurements done in related work. A full description of the achievement can be found in publication P14, which presents analytical models for determining location errors, their use in the REM update process, and an assessment of their applicability in 5G systems.
- The second solution is dedicated to REM-Based frequency selection for platoon communication, where REM contains location-dependent interference model based on interference samples provided by the platoon along a route and using Gaussian Mixture

Model, Density Based Spatial Clustering of Applications with Noise (DBSCAN) to REM size reduction, and novel channel assignment mechanism based on the adaptation of Dijkstra algorithm to minimalization or channel reselection over the platoon route. It is mainly described in P5 (not P4 which is indicated in description).

- Since the above solution concerned a single platoon of vehicles, the author proposed new solution to use the Federated Learning to model multiple platoon interference with hierarchical REM architecture with local and global REM. The main approach proposed by the candidate in P15 aims to expand the possibilities of using in global REM the FedAvg algorithm with GMM models. To demonstrate the capabilities of the proposed method, the Candidate developed a simulation framework for generating interference, demonstrating the benefits of the proposed method in reducing RMSE.
- Fourth solution proposed by the author for seamless connection of high-speed URLLC users in a cellular network (C-V2X) using MMIMO is an intelligent beam management algorithm that enables switching sequence prediction using REM data and an ML algorithm, as described in P12 (not P13, as indicated in the description). For this, the PhD candidate proposed a novel REM architecture containing an EU mobility Pattern Map with information about the distribution of user speed and direction for each location. The beam selection along the route was defined as an MDP (Markov Decision Problem). Unique policy iteration algorithm allows balance between two optimization goals namely minimalization beam reselection and receive power maximalization. In complement simulation PhD candidate investigated the impact of location error, excluding the possibility of using standard GPS, which provides location accuracy of several meters.

For the MMIMO Communications use case, five original solutions are proposed by Author for Energy Efficiency improvement and for Spectrum Efficiency improvement, which are described in Section 3. Here, five original achievements were indicated by the PhD candidate, based on the conclusions from the analysis of the state of knowledge presented in subsection 3.1.

- First two solutions are dedicated for EE improvement in MMIMO networks. The first, described in P6, P7 and P8, concerns the use of REM and the development of an RL algorithm to solve the problem of base station activation (Cell On/Off Switching) in an MMIMO network based on the spatial distribution of UE. Its originality lies in the application of REM structure modification to map a set of EU locations, a dedicated set of active BSs, and the use of an RL algorithm for which EE reward is defined as the ratio of median user throughput to average power consumption. In order to reduce training time, the author proposed using REM entry knowledge to determine the set of active BSs based on the assumption of similarity between this set and the distribution of UE locations. To conduct simulation tests, the candidate developed an MMIMO network simulator. The results obtained during the simulation indicate a 70% improvement in EE compared to the SWES method described in the literature and a 44% improvement compared to the results obtained without optimization. In addition, the doctoral student compared several metrics of similarity between sets of points, demonstrating that the sum of minimum distances metric gives the highest EE value.

- In the second solution (P9 and P11), the candidate proposed a method of intelligent antenna selection to solve the problem of transceiver chains off. The essence of the solution, as in the first one, is to use REM to map the set of EU locations onto a set of active antennas to serve them using the RL algorithm. In order to avoid the problem associated with the huge number of combinations, the candidate proposed dividing it into two phases: determining the number of active antennas and selecting an antenna in two program blocks. As before, the author developed an algorithm that shortens training time by utilizing knowledge about the similarity of REM entries, which he called the REM-Empowered Action Selection Algorithm (REASA). To evaluate the proposed solutions, the author used his own extended simulator. To evaluate the proposed solutions, the author used his own extended simulator, demonstrating an approximately 18% improvement in EE compared to that determined using the analytical model presented in the literature.
- Another achievement of the Candidate is related to the use of REM and RL (in this case DRL) to optimize the PA operating point from the point of view of user throughput. The proprietary method (described in P10), called COBBIO (Contextual Bandit-Based Input back off Optimization), involves building a REM that remembers throughput values for different transmission conditions and using DRL, where the reward is the throughput value. To conduct the research, the author expanded the previously developed MMIMO simulator with a nonlinear distortion model and an analog Equal Gain Transmission precoder. During the research, the parameters of the neural network were determined, and then the obtained results were compared with the analytical results taken from the literature, showing approximately 10% throughput gain for the proposed method.
- The Candidate's next original achievement is related to increasing SE by coordinating interference between cells in MMIMO (P16), in which a DRL algorithm was proposed for intelligent DPB (Dynamic Point Blanking) extension based on the spatial distribution of users. The solution uses REM and DRL to coordinate interference, extending the idea of mapping (described in P6 as a method of improving EE) with a DRL agent defining the reward as a 10% increase in UE throughput. Due to the limitation of the fixed size of the DNN input layer, the author proposed preliminary clustering of EU locations using the K-means unsupervised learning method. Simulations have shown that the proposed solution increases cell-edge user throughput by approximately 21% compared to a solution without DPB and by over 50% compared to a classic DPB application.
- While solutions 1-4 can be linked to the development of O-RAN for MMIMO 5G NR networks, with the possibility of extension to 6G, the PhD candidate's next achievement goes beyond typical mobile network architectures and concerns cell-free architecture as one of the proposals for increasing transmission capabilities in next-generation networks, including 6G with spatially distributed AP (Access Points). For UCCF (User Centric Cell Free) MMIMO network O-RAN architecture can be exploited thank to adequate solutions of O-CU, O-DU and R-DU, in which each UE can be served by a set of BSs, selecting by using dedicated e.g. SCF (Serving Cluster Formulation) algorithm. Here, the main PhD Candidate's achievements are: development of scheduling and AP strategies to improve both EE and SE of UCCF MMIMO network, proposals of xApps

and rApps for network control, utilising O-RAN potential abilities for disaggregation and virtualization, validation of network performance using 3D ray tracing and nonlinear modeling In this solution, xApp manages the process of SCF, based on guidance from rApps. In last one REM and ML modules analyse network KPIs in order to optimize xApp performance.

- The candidate's achievement for the mMTC case is focused on the wireless IoT network and concerns the issue of protecting it against DDoS attacks in the RAN domain (P3). More specifically, it is a solution for a dedicated algorithm for SSD (Signaling Storm Detection) using REM and ML. This solution was validated in a real testbed (Amarisoft 5G BS), which shows both maintaining SE and preserving devices battery life (EE).

A significant PhD candidate achievement is demonstrating the path to integration of the proposed algorithms into the O-RAN architecture as standard xApps and rApps applications, e.g. RCR-rApp for intelligent antenna selection. The success of the adopted approach is demonstrated by the publications on which the dissertation is based. These include 16 original articles presented in international significant journals and proceedings of high reputation conferences.

While in most of the publications cited, the candidate's achievements can be clearly identified, nevertheless publications P1 and P2, the first presenting the idea of O-RAN, the creation and evaluation of the application, and the second containing a description of the testbed, should be attributed to the entire team of the Institute of Radio Communications at the Poznań University of Technology and RimedoLabs..

3. Knowledge of the candidate

It is quite difficult to evaluate a doctoral dissertation in which collective publications are a significant or even fundamental element. Even if the authors' statements indicate the Candidate's significant contribution to the works described in these publications, it is difficult to clearly determine which parts of the texts were written by him, who selected the literature for each publication, and usually the final conclusions are also jointly edited. However, the summary of the Candidate's achievements presented above indicates his broad knowledge in the field of Computer Science and Telecommunications, which is undoubtedly very deep in the area of wireless communications.

The presented, original solutions indicate that the Candidate has acquired the ability to carry out scientific and research work, as evidenced by:

- identification of gaps in knowledge and technological solutions in the studied area,
- ability to create analytical models and generalize them in simulation models,
- ability to use AI and ML achievements to create algorithms that improve the communication functions of current and future radio access network solutions for complex application scenarios,
- research methodology and ability to evaluate it, including indicating how it can be used as a standard for the O-RAN open radio access network model.

The Candidate's work as a member of the research team has very high scientific and application potential. Particularly noteworthy are articles published in international journals

with high impact, such as (Journal of Selected Areas in Communication, Communication Magazine, Wireless Communications Letters, Access). It testifies to the Author's deep knowledge, broad understanding of the subject, and excellent ability to extract and generalize knowledge contained in the publications listed in the references.

4. Other remarks

The reviewer did not evaluate individual publications listed by the candidate, and the basis for the assessment was the concise description of his achievements related to the O-RAN concept, mainly the use of REM and ML for applications that can be implemented in this environment, which, in my opinion, significantly exceed the requirements for doctoral dissertations, demonstrating both a high scientific level and research and application potential.

An unquestionable mistake made by the author of the dissertation is the incorrect references in several places to publications, which have been replaced in the appendix. This applies to publications [P4] and [P5] as well as [P12] and [P13].

Despite the diversity of solutions, the dissertation is a comprehensive study of the possibilities offered by the application of REM and ML techniques for SE and EE improvement and IoT security.

While editing the review, I had a few questions that require comments from the candidate:

1- REM solutions (originally intended for use in cognitive radio networks) are based on selected digital terrain models with a specified coordinate resolution in three dimensions. What maps were used in REM models where very high location accuracy was required?
2- In the context of processing large databases, has an assessment been made of the necessary memory and computing resources, and can the candidate evaluate them?
3- In integrated LSN (Land Space Network) networks, and especially in UAV-assisted land networks, three-dimensional REM is necessary. Can the candidate assess the usefulness of the developed methods in 3D networks?
4- What is the possibility of using IRS-based relay technology?

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**)

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

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

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 **ML REM based solutions for O-RAN standardization of next generation of wireless networks**

[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*

Taking into account general impression of the Author's contribution, the style of presenting the problems and the results obtained, the novelty of the proposed solutions, their quality and scientific value I **recommend to distinguish** the dissertation for its high quality.

Signature