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Reviewer's opinion
on Ph.D. dissertation authored by
Małgorzata Wasilewska
entitled:
New Machine Learning Methods for Spectrum Sensing in Wireless Communication Systems

1. Problem and its impact

In my opinion, the most important research problem discussed in the doctoral dissertation of Małgorzata Wasilewska is spectrum sensing in wireless communication systems. The main novelty and contribution of the dissertation is development of new machine learning methods for spectrum sensing with a detailed analysis of performance of these methods including comparison against existing baseline methods. The considered research problem as well as proposed methods are scientific ones and belong to the discipline of Information and Communication Technology. In more detail, the addressed research problem belongs to the subdiscipline of telecommunication, while the applied research methods belong to the subdiscipline of artificial intelligence.

Wireless networks, including 5G mobile networks and WiFi networks, play a fundamental role in modern society, impacting numerous aspects of daily life, industry, and technological advancement. With the development of 5G, mobile connectivity has reached new levels, offering low latency, high-speed internet, and support for massive device connections. Wireless networks boost economic growth by enabling smart industries, automation, and the Internet of Things. Spectrum sensing in wireless networks is crucial because it enables efficient and dynamic spectrum utilization, especially in cognitive radio networks. It should be underlined that the radio frequency spectrum is a limited and very expensive resource. However, much of radio frequency spectrum is underutilized. Spectrum sensing allows to detect unused spectrum and use it without interfering with licensed (primary) users. Moreover, by sensing the environment, networks can avoid interference with primary users, ensuring that communication remains reliable and interference-free. In addition, spectrum sensing helps identify idle spectrum and optimize resource allocation, leading to higher data rates and improved Quality of Service (QoS) as well as reducing power consumption in

wireless devices. Therefore, in my opinion the doctoral dissertation addresses a very important and practical problem.

The doctoral dissertation contains both theoretical and practical results. In the field of theoretical elements, Małgorzata Wasilewska developed a set of machine learning methods for spectrum sensing in wireless communication systems. It should be stressed that the PhD candidate accounted for recent and important machine learning concepts such as deep learning, federated learning as well as addressed the challenges related to levels of security required by modern communication systems. In turn, the practical aspect of the doctoral dissertation includes performing broad numerical experiments, comparisons and analysis of the proposed machine learning methods architectures as well broad discussion of the obtained results accounting for the domain knowledge in the field of wireless networks.

2. Contribution

In my opinion, the most important and original achievements and contributions of the doctoral dissertation are as follows:

- Development of general machine learning methods for spectrum sensing.
- Development of deep learning methods for spectrum sensing.
- Development of federated learning methods for cooperative spectrum sensing.
- Development of secure federated learning methods for cooperative spectrum sensing.
- Implementation of the proposed methods and broad numerical experiments for realistic simulation scenarios.
- Analysis of the proposed methods and comparisons against other baseline methods.

I want to underline that the concepts and results reported in the dissertation have large practical significance. In more detail, the author defined and then solved a real and up-to-date research problem related to spectrum sensing using advanced machine learning methods. In my opinion, we can trust what is claimed in the dissertation, presented arguments and discussions are correct.

The publication record, as well as the citation record, is very good considering that Małgorzata Wasilewska is an early-stage researcher. I would like to emphasize that Małgorzata Wasilewska is a co-author of an article published in IEEE Communications Magazine, one of the most prestigious journals in the field of telecommunications. Moreover, she has a publication at the ICC conference, which is one of the top conferences in the telecommunications field.

3. Correctness

The thesis of the dissertation is formulated as follows:

- *There exist new methods for spectrum sensing in wireless communication systems that are based on machine learning and that are more reliable than the existing ones.*

In my opinion, the thesis of the dissertation is formulated in an appropriate way. Małgorzata Wasilewska correctly determined the scope of her work based on a literature review and her knowledge, focusing on spectrum sensing and novel machine learning methods. The author solved the formulated research problem using correctly selected research methods and approaches including various machine learning methods and performing numerical experiments showing performance of the proposed approaches followed by a thorough discussion. In consequence, the goals of the dissertation have been achieved.

Below, I discuss the drawbacks of the doctoral dissertation and present my critical remarks.

General remarks

- The thesis of the dissertation ("*There exist new methods for spectrum sensing in wireless communication systems that are based on machine learning and that are more reliable than the existing ones.*") appears relatively easy to confirm. Moreover, the term "reliable" is not clearly defined within the thesis. The author could specify a more detailed performance metric used to compare the proposed against existing methods.
- The dissertation does not provide information on the complexity of the proposed machine learning methods, as the author does not report the training time or inference time of the examined methods. This information is important for a more comprehensive performance analysis of the proposed methods and analysis of the scalability of proposed approaches.
- In machine learning, the datasets used in experiments are of crucial importance. The ML community typically provides open access to these datasets to enable other researchers to replicate experiments or make further improvements. The dissertation does not provide link to datasets used in the experiments, though in In Section 1.5.4 the PhD candidate underlines that "*Moreover, the absence of public mobile network datasets leads to another problem: many investigations are performed on private data. Without comparing the performance of various models on the same data, it is hard to design and select the approach that works best and decide in what aspect it could be improved.*"
- Feature selection is vital in machine learning for many reasons, e.g., selecting relevant features helps reduce noise leading to better model accuracy and generalization; with fewer features ML models require less computational power reducing training time and making predictions more efficient; eliminating irrelevant or redundant features. The dissertation presents some basic information on the

selected features (e.g. Section 2.2). However, in my opinion the author should provide more deep analysis including motivation behind selecting particular features.

- A key aspect of developing machine learning methods is tuning the parameters (e.g., the number of nearest neighbors in kNN or the number of trees in RF) and hyperparameters (e.g., the number of layers in neural networks). Tuning involves analyzing different values of parameters and hyperparameters to find the best configurations. Another approach is to adopt settings proposed in the literature for similar types of ML problems. In my opinion, the dissertation should provide more detailed information on the tuning of ML methods and the rationale behind selecting the values of parameters and hyperparameters.

Polemical remarks

- The dissertation offers a very detailed and comprehensive state-of-the-art analysis of related works. However, it would be even more robust if the author concluded the literature review by identifying research gaps as a motivation for the PhD student's research.
- In Section 1.5.4, the author discusses the problems with access to datasets in the area of mobile networks, including real data. This an explanation of the decision to use synthetic data (artificially generated). However, to make the experiments more realistic and more reliable for potential users, semi-synthetic data could be generated, i.e. data containing some real trends. In the context of dissertation of Malgorzata Wasilewska real trends could be used for periodicity (*"Some random periodicity has been introduced in the generated signal to reflect communication traffic variations."* page 45). For instance, there is some real data on network traffic showing periodicity available in the Seattle Internet Exchange (SIX) (https://www.seattleix.net/statistics/) and other internet exchange points. Did the author consider generating semi-synthetic datasets?
- The dissertation presents many interesting machine learning approaches. However, in my opinion the presented research would be more interesting if Explainable AI (XAI) methods would be applied to verify and analyze performance of the proposed methods and provide potential information for feature selection engineering leading to better performance or lower inference time.
- The most important metrics for evaluating machine learning algorithms in terms of classification problems are: accuracy, precision, recall, F1-score or ROC-AUC. The PhD candidate does not use these metrics for showing performance of the developed machine learning methods in the context of spectrum sensing. Instead, she focuses on domain-specific metrics such as probability of achieving accurate positive results on signal's presence and probability of achieving false positive results on signal's presence. In my opinion, alongside these domain-specific metrics, the author should

also report basic ML metrics to enable a clearer comparison of the proposed methods and provide better understanding for the ML community.

Detailed remarks

- Table of contents does not include full name of section "Appendix A".
- Table 1.1 provides interesting information on the metrics and parameters used to define the instantaneous radio communication context. However, it would be more informative if it included references to publications or standards that provide further details on the presented metrics and parameters.
- In Section 2.3.2. the author writes "*With the second feature set used in the proposed detection algorithm, energy values calculated for separate RBs and all other features calculated based on them have been used directly in ML*". It is not clear for me what is the "*second feature set*".
- Figure 5.5. Both graphics (A) and (B) present two different scenarios, i.e., "(A) Coordinated attack (encapsulation) aimed at the false increase in RBs occupancy" and "(B) Coordinated attack (encapsulation) aimed at the false decrease in RBs occupancy". It is confusing that in both graphics the same red color denotes two different cases (occupied RB in (A) and free RB in (B)).

4. Knowledge of the candidate

In my opinion the doctoral dissertation confirms a general knowledge of the candidate in the discipline of Information and Communication Technology. The dissertation consists of seven sections: introduction and six chapters. The introduction includes an motivation, goals and thesis of the dissertation, outline of the dissertation and published contributions. The first chapter presents a discussion on the related works and state-of-the-art in the area of application of machine learning methods for spectrum sensing in wireless communication systems. The next four chapters describe original results of the PhD candidate including new methods, results of broad numerical results and deep discussion of the obtained results. In particular, Chapter 2 focuses on development of machine learning-based spectrum sensing methods. In Chapter 3, Małgorzata Wasilewska presents deep learning methods proposed for spectrum sensing. Chapter 4 includes federated learning approach for cooperative spectrum sensing. Finally, Chapter 5 is focused on secure federated learning for spectrum sensing. The last Chapter 6 concludes the research presented in the dissertation.

The doctoral dissertation is well structured. The PhD candidate starts her research with relatively basic machine learning methods for spectrum sensing and then she goes more deep and proposes more advanced machine learning approaches. The dissertation is written in fluent English and includes numerous illustrative examples that clarify the main issues. The figures are well-presented, and the graphs are easy to read.

The doctoral dissertation of Małgorzata Wasilewska centers on up-to-date topics related to wireless communication systems. The author performed a systematic bibliographic review, the list of references in the dissertation contains 208 items. Among them are the most important works related to:

- context awareness in wireless communications,
- machine learning methods for context awareness,
- machine learning for spectrum sensing,
- resource occupation pattern recognition,
- federated learning,
- secure federated Llearning.

I can confidently state that Małgorzata Wasilewska has general knowledge and understanding of the Information and Communication Technology discipline. In particular, the PhD candidate possesses knowledge of contemporary literature on various aspects of wireless communication systems, with a particular focus on switching application of machine learning methods for context awareness in wireless communications.

5. Other remarks

I would like to emphasize once again that the doctoral dissertation addresses a practical and up-to-date research problem. Moreover, I would like to highlight excellent publications of Małgorzata Wasilewska (especially IEEE Communications Magazine and ICC conference) which confirm that the obtained results are highly interesting.

6. 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
[X]	[ ]	[ ]	[ ]	[ ]

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 wireless communication systems?

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

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

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

Moreover, taking into account very high quality of the research reported in the dissertation as well as very good publication record of Małgorzata Wasilewska **I recommend to distinguish the dissertation** for its quality.

Signature