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Reviewer's opinion

on Ph.D. dissertation authored by

Saif Sabeeh

entitled:

Radio Resource Management for C-V2X Communication 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 subject of the reviewed doctoral dissertation focuses on the problem of resource allocation and planning in cellular networks for the purposes of reliable and error-free data transmission between vehicles and all elements of the C-V2X (*Cellular Vehicle-to-Everything*) telecommunication infrastructure. Therefore, the subject matter discussed in the doctoral dissertation is important, up-to-date and is part of the practical aspects related to vehicle traffic safety, reducing the number of road accidents and supporting drivers in driving these vehicles.

In his doctoral thesis, the author proposed a number of new algorithms supporting two transmission modes (centralised and decentralised for radio resource allocation) in C-V2X for two types of LTE (*Long Term Evolution*) and NR (*New Radio*) cellular networks.

In the dissertation, the Ph.D. student undertook to prove the following thesis using scientific methods: *Thanks to the methods proposed in this dissertation such as specific autonomous resource allocation, tracking radio resources, planning the accessible resources, adaptive modulation and coding scheme and balancing the physical parameters according to the channel load level, the performance of C-V2X communication systems may be substantially improved, e.g. in terms of packet reception ratio and collision ratio.*

To prove the adopted thesis, which is formulated unambiguously, the author primarily used the experimental method, consisting in conducting simulation tests in the MATLAB (*MATrix LABoratory* – programming and numeric computing platform) and SUMO (*Simulation of Urban MObility* – an open source, highly portable, microscopic and continuous multi-modal traffic simulation package designed to handle large networks) software environments, taking into account representative phenomena that may occur in real-world conditions.

The developed new algorithms have strong application potential, which has been confirmed by comprehensive simulation studies in conditions close to real.

At the end of this point, it should be clearly stated that the title, purpose and thesis of the dissertation were formulated correctly and clearly enough by the Ph.D. student.

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 the 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.).

The dissertation author's original contributions in the C-V2X area are described in chapters three to seven. In the Chapter Three, the Ph.D. student dealt with a detailed analysis of the sensing-based semi-persistent scheduling (S-SPS) algorithm, which is recommended for use in so-called Mode 4 for the allocation of radio resources between communicating vehicles without the participation of the mobile network telecommunications infrastructure (sidelink). Based on this analysis, he proposed two original algorithms for radio resource allocation in the aforementioned Mode 4 in the LTE-V2X system: estimation and reservation resource allocation (ERRA) and extension estimation and reservation resource allocation (E-ERRA). First, the Ph.D. student defined two quality parameters for the comparison of the developed algorithms: packet reception ratio (PRR) and collision ratio (CR). The simulation studies carried out for the three proposed scenarios in the combined MATLAB and SUMO environments clearly show the advantage of the ERRA and E-ERRA algorithms proposed by the author over the S-SPS algorithm standardised in the 3rd generation partnership project (3GPP) documents. The improvement in the value of the PRR parameter for the proposed algorithms reaches from a dozen to even 25% with the same adopted simulation parameters. The value of the CR parameter for the proposed algorithms also decreased significantly compared to S-SPS.

In Chapter Four, the author focused on improving the performance of the S-SPS algorithm in Mode 4 in the LTE-V2X system by using the adaptive modulation (AM) and adaptive modulation and collision detection (AMCD) mechanisms. As a result of the analysis, the Ph.D. student proposed two new algorithms: AM re-selection of resources and AMCD re-selection of resources, which largely eliminated the inconveniences of the S-SPS algorithm in its original version. As is well known, they were mainly related to collisions of transmitted packets when multiple users re-selected the same radio resource at the same time or when the radio channel load increased for the given transmission range. The correctness of the proposed algorithms was confirmed by simulation of the highway scenario with different vehicle density zones. For the adopted input parameters (for two modulation and coding schemes) when comparing these algorithms with each other, the AMCD algorithm possesses more favourable values of the defined PRR and CR indicators.

In Chapter Five, the Ph.D. student proposed a decentralised congestion control and transmission power control mechanism TPC-DCC (*Transmit Power Control – Decentralised Congestion Control*) with an adaptive threshold mechanism for receiving radio signals. The simulation studies carried out for four developed scenarios (two scenarios for each proposed type of network: standard and hybrid) clearly show that linking the proposed solution with the previously described S-SPS and E-ERRA algorithms will increase the efficiency of the system from several to several dozen percent.

In the next chapter, the author addressed the analysis of centralised resource allocation mechanisms in Mode 3 LTE-V2X. In order to reduce the number of packet collisions in the broadcast transmission, the Ph.D. student proposed that the road side unit (RSU) sends resource allocation commands without receiving requests from vehicles, resulting in a reduction in the total signalling traffic. In addition, the author proposed two new spectrum-sharing techniques: FFR (*Full Frequency Reuse*) and PFR (*Partial Frequency Reuse*). The proposed solutions were subjected to simulation studies for different values of vehicle traffic. To evaluate the performance of these solutions, the Ph.D. student used the previously

defined quality parameters or defined new ones: packet reception ratio (PRR), difference of the packet reception ratio (D-PRR), minimum frequency reuse distance (MFRD), average frequency reuse distance (AFRD), the percentage of vehicles located within the BCZ (*Broadcast Collision Zone*) areas to the total number of vehicles in the network ($Coll_{perc}$) and interference ratio (IR). The study found that both the FFR and PFR techniques used resulted in higher system performance than in the absence of bandwidth sharing. It was also found that the division of the frequency band into two sub-bands for individual users (PFR technique) works better than permanently splitting the available band into two non-overlapping sub-bands for adjacent RSUs (FFR technique).
In the final substantive chapter, centralised resource allocation techniques in Mode 1 in the NR-V2X system for vehicles travelling on highways were analysed. The Ph.D. student developed a new centralised-estimation and reservation resource allocation (C-ERRA) algorithm and compared it through simulation tests with the configured grant (CG) resource allocation algorithm proposed by the 3GPP organisation. The study clearly shows that the C-ERRA algorithm reduces the delay in the reallocation of resources.
The most interesting results, according to the reviewer, are contained in chapters four, five and seven, in which the Ph.D. student independently developed four new algorithms. Transcript of them in the form of so-called pseudo-codes are included in the dissertation. As a reminder, the first three algorithms are related to Mode 4 in the LTE-V2X system, with the first two based on the use of adaptive modulation and adaptive modulation and collision detection mechanisms, respectively. In turn, the proposed algorithm 3 is used to generate a multi-level channel busy ratio in accordance with the concept of decentralised congestion control. The fourth algorithm, dedicated to Mode 1 in the NR-V2X system, reduces the delay in resource reallocation in centralised solutions.
In conclusion, the author has solved the tasks set using the correct methods (analytical and simulation), using reasonable assumptions.

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 dissertation of M.Sc. Saif Sabeeh is written in English in a good style. The whole is an interesting scientific reading, accessible to the reader. The conclusions drawn by the Ph.D. student on the basis of the collected research material are correct and clear.
I leave two main issues for discussion during the public defence of the doctoral dissertation of M.Sc. Saif Sabeeh:

1. No explanation is given for the adopted value of noise power during simulation tests at -95 dBm on a channel with a width of 10 MHz (it is known that at room temperature, the power of thermal noise on a radio channel of this width is -104 dBm). It is also no explained from what the values of the adopted SINR parameter in Table 5.2 to two decimal places are derived.
2. What was the reason for choosing these two modulation and coding schemes, i.e. 8 and 14, for the simulation studies of the algorithms from the Chapter 4? Similarly, during the simulation studies of the modified algorithm from Chapter 5, but this time these were schemes 8 and 15?

During the analysis of the dissertation received for review, some editorial errors were noticed, including:

- There is no list of symbols, which would make it easier to follow the author's thinking.
- It is good practice to list the bibliography alphabetically, and to enter the date of access for links to websites.

- All references should be cited at least once in the main text of the dissertation; the following bibliography items are missing [34], [55], [60], [65], [73], [75], [81], [82], [83], [84], [88], [89], [90] and [137], which is more than 10% of the items not cited, and moreover items [11] and [34] overlap.
- It is a good idea to enter the digital object identifier (DOI, if any) next to each bibliography item – the DOI identifier is only part of the item in the list of references.
- Spelling errors were noted, especially in the summary in Polish.
- A chapter should not start with a drawing (point 3.5.3, Fig. 3.3), a comment would be useful first.
- In the dissertation, sequences of signs inadequate to the content were found: p. 83 – [??????????????????]; p. 22 – Fig. ?? and p. 32 – [?]
- It is also useful to refer to the content of the figures in the main text of the dissertation, e.g. Figure 2.3 is not cited in the text of the dissertation.
- The description of the symbols used in Equation (3.12) does not match.
- In the dissertation, it would also be worth unifying the nomenclature: method – algorithm, methods are mentioned in the thesis, and then in the main text methods – algorithms are mentioned alternately; according to the reviewer, it is mostly about the algorithms.
- It is unfortunate to give the power of the transmitted signal in [dB], when it is known that this is a relative unit, see page 48, Equation (3.3).

In the light of the above, the editorial form of the dissertation is at an average level, however, due to the value of the substantive results obtained, the above comments do not affect the positive, final assessment of the whole work.

4. Knowledge of the candidate

What are the chapters of the dissertation (or sections in chapters) that resemble a tutorial and thus confirm the 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 the 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 of or against the claim that the candidate has general knowledge and understanding of the* ***Information and Communication Technology*** *discipline.*

The doctoral dissertation of M.Sc. Saif Sabeeh has been edited into 191 pages, in the form of eight chapters, including an introduction and summary, and a bibliography containing 138 items, as well as one appendix containing a list of publications of the Ph.D. student. The dissertation also includes a summary of the thesis in Polish and English, a list of figures and tables, and a list of the most important abbreviations used in the work. The bibliography includes 7 items co-authored by the Ph.D. student, including 2 items that are under review, and current items by other authors from recognised foreign journals and international conferences, links to standardisation documents of the 3GPP organisation, as well as 4 links to websites.

In the introduction, the author defined the purpose of the dissertation and its contents. In the first few pages of the dissertation, he presented a historical outline of the evolution of cellular systems and an outline of the technical requirements for 5G cellular systems, which are the subject of this dissertation with a special focus on C-V2X transmission. The Ph.D. student also defined 6 research areas in this chapter, which are the author's original contribution to the development of C-V2X.

The second chapter is a review of the bibliography regarding the theoretical basis of the issues included in the reviewed dissertation. The author focuses on reviewing information from two fundamental areas of vehicle-to-vehicle communication: the IEEE 802.11p standard and solutions dedicated to LTE (LTE-V2X) and 5G (NR-V2X) cellular networks. The chapter also includes a

comparative analysis of the IEEE 802.11p standard and LTE-V2X, as well as radio resource allocation issues in NR-V2X. There is also a description of the physical layer of the NR-V2X standard along with the possible transmission modes.
The next five chapters, a detailed analysis of which can be found in Section 2 of this review, are the Ph.D. student's own contribution to research in the C-V2X area.
The material presented in the theoretical part proves the author's good understanding of the subject under consideration, and the conclusions resulting from the analysis of the bibliography on the subject are clear and factually correct. The collected material therefore confirms the general knowledge of the Ph.D. student in the discipline of Information and Communication Technology.

5. Other remarks

In justification of the final conclusions in Section 6, it can be clearly stated that M.Sc. Saif Sabeeh:

- submitted a doctoral dissertation for evaluation entitled *Radio Resource Management for C-V2X Communication Systems*, which meets the requirements of this type of work;
- undertook important, interesting and up-to-date research topics of strong utility, related to the issues of data transmission for C-V2X;
- developed several new, more efficient radio resource allocation algorithms for LTE-V2X and NR-V2X systems compared to the solutions reported in the bibliography;
- is a co-author of three papers published in the proceedings of an internationally recognised scientific conference on radio communications and one paper in a well-known international journal.

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), 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 **radio communication**?

[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*

Signature