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Reviewer's opinion
on Ph.D. dissertation authored by
Bartosz Kopras
entitled:
Optimization of Energy Efficiency in Fog Computing with Latency Constraints

1. Problem and its impact

The ICT sector currently accounts for an estimated 4-6% of all electricity generated globally [UK Parliament POSTNOTE Number 677, September 2022], with projections of continued growth due to the expansion of data centres, mobile networks, and connected devices. To address the issue of rising costs of energy and the need to reduce the carbon footprint, manufacturers and operators of mobile systems are implementing diverse energy-saving techniques, including sleep modes for base stations, integration of renewable energy sources like solar and wind, smart cooling systems, energy-efficient reconfigurable reflecting surfaces (anticipated in 6G networks) - to decrease the number of necessary base stations or access points (particularly at THz frequencies), and AI-driven network management. Energy-efficient architectures, such as edge and fog computing, are expected to further decrease the energy consumption of data transmission and reduce reliance on big data centres, while energy-aware task scheduling optimizes resource utilisation in fog/cloud environments. Additionally, dynamic resource allocation and adaptive protocols in 5G/6G networks should optimize bandwidth and processing power based on real-time demand. Advanced hardware solutions, such as low-power chipsets and metamaterials can further reduce energy losses in RF subsystems, contributing to overall energy efficiency. Addressing the growing energy consumption and environmental impact of IoT systems, fog computing networks are one of key areas for energy optimisation, particularly under latency constraints. Developing advanced algorithms and models for task allocation and energy-efficient computation within edge/fog networks can significantly reduce energy usage without compromising performance KPI (e.g. latency). This important scientific problem was addressed by Mr Bartosz Kopras, which involved:

1. Formulating mathematical models for energy consumption and latency in fog networks.
2. Developing optimisation algorithms (energy consumption minimisation) to cope with non-convex objective functions, which are inherently challenging in computational sciences.
3. Conducting simulations and comparisons to validate the proposed optimisation solutions against selected benchmarks.

The PhD candidate's research extends the scientific understanding of distributed computing systems, optimisation under constraints, and sustainable computing, which are all significant areas of research in computer science and telecommunications. The problem has practical implications in the following aspects:

1. The research can contribute to reducing the environmental impact of fog and cloud computing systems, aligning with global goals for sustainable technology development.

2. By ensuring low-latency task execution, the solutions proposed are applicable to real-time and critical use cases, such as autonomous/connected vehicles, smart grids, and holographic vision (envisaged in 6G era after 2030).
3. The findings are relevant for managing the energy and performance demands of general IoT applications, which are rapidly proliferating in various industries/services.

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 major contributions from the PhD candidate are (For easier traceability, for each contribution I provide corresponding chapter and page numbers in the thesis.):

1. Comprehensive survey of the state of the art on energy optimisation in fog networks. This included a detailed review of existing models and solutions for energy-efficient fog networks, identification of research gaps and sometimes also explanation of how the dissertation addresses them. (Chapter 2: pp. 7–42)
2. Development of a comprehensive fog and cloud tier computing energy consumption and latency model. Importantly, the model is parameterised with values of energy consumption and latency for real-world communication and computing equipment. The model output shows the influence of network parameters on energy consumption and latency. (Chapter 3: pp. 45–53)
3. Formulation of task allocation optimisation problems. Optimisation problems were formulated to allocate offloaded tasks to fog and cloud nodes, considering energy minimisation objective with latency constraints. (Chapter 4: pp. 57–75)
4. Development of two original algorithms for non-convex optimisation: **E**nergy-**Eff**icient **R**esource **A**llocation (EEFFRA) and Low Complexity EEFFRA (LC-EEFFRA) algorithms to solve non-convex optimisation problems – both employing Successive Convex Approximation (SCA) and problem decomposition. (Chapter 4: pp. 62–66)
5. Inclusion of wireless communication specific links, extending the optimisation model to include wireless transmission between devices and fog nodes, modifying the objective function and constraints to account for energy costs and delays from wireless communication. (Chapter 5: pp. 77–95)
6. Development of optimisation scheme for sequential task offloading. This paradigm models sequential task offloading using directed acyclic graphs (DAGs), leading to proper subtask execution order, while optimizing energy consumption and delay. (Chapter 6: pp. 97–108)
7. Development of Clustered Network Embedding (CNE) algorithm to reduce the search space in large-scale fog networks by clustering nodes with similar parameters. (Chapter 6: pp. 101–108)
8. Analytical and simulation-based validation: Analytical solutions and extensive computer simulations were provided to validate proposed models and algorithms, with results compared against baseline solutions. (Chapter 4 (67–75), Chapter 5 (86–95), and Chapter 6 (104–108))
9. Insights on key parameters influencing offloading efficiency: Identified critical parameters, such as arithmetic intensity and cloud efficiency, influencing energy consumption and delay in fog computing networks. (Chapter 3: pp. 50–54)

10. Development of low-complexity solutions with performance comparable to computationally intensive solutions, demonstrating scalability and practicality for real-time applications. (Chapter 4 (66), Chapter 5 (83–86), Chapter 6 (101–104)

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.).

1. In my opinion, the author uses appropriate research methods and techniques (mathematical models, simulation methods, etc.) for the research topic under consideration. I would like to emphasize a comprehensive investigation of the topic and the ability to interpret results and formulate conclusions. The dissertation excels in the discussion of the literature and the state-of-the-art analysis, which is well prepared. The number of references is notable (146), and their selection is suitable both for the background/introductory knowledge and for the state-of-the-art analysis in the discussed field of fog/cloud computing energy efficiency.
2. The dissertation is well structured and comprehensible. The text is written in clear American English, with a style that is appropriate for technical writing, and the overall linguistic quality is very high. All the figures are well prepared and annotated. I found it straightforward to follow the logical flow of the study, verify the accuracy of the simulation models, and evaluate whether the conclusions are well-supported by the presented evidence. I have no critical remarks regarding these aspects of the thesis.
3. The most important research results are substantiated by the following peer-reviewed journal publications co-authored by Mr. Kopras (with reference numbering retained as in the thesis):

[6] B. Kopras, F. Idzikowski, and H. Bogucka, "A survey on reduction of energy consumption in fog networks - communications and computations," *Sensors*, vol. 24, no. 18, 2024.

[7] H. Bogucka, B. Kopras, F. Idzikowski, B. Bossy, and P. Kryszkiewicz, "Green time-critical fog communication and computing," *IEEE Communications Magazine*, vol. 61, no. 12, pp. 40–45, Dec. 2023.

[8] H. Bogucka and B. Kopras, "Uberization of telecom networks for cost-efficient communication and computing," *IEEE Communications Magazine*, vol. 61, no. 7, pp. 74–80, Jul. 2023.

[9] B. Kopras, F. Idzikowski, B. Bossy, P. Kryszkiewicz, and H. Bogucka, "Communication and computing task allocation for energy-efficient fog networks," *Sensors*, vol. 23, no. 2, 2023.

[10] B. Kopras, B. Bossy, F. Idzikowski, P. Kryszkiewicz, and H. Bogucka, "Task allocation for energy optimization in fog computing networks with latency constraints," *IEEE Transactions on Communications*, vol. 70, no. 12, pp. 8229–8243, Dec. 2022.

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.

A comprehensive state-of-the-art analysis demonstrates not only the PhD candidate's general knowledge but also his ability to critically review and synthesize existing research, highlighting his understanding of theory, methodologies, and current research gaps (however not always formulated directly). The thesis includes a comprehensive survey of the state of the art in energy-aware fog computing - covering

models, optimisation methods, and energy-saving strategies. In particular, the thesis demonstrates the candidate's expertise in several key areas of the Information and Communication Technology scientific discipline, such as fog and cloud computing concepts, energy efficiency in distributed systems, optimisation techniques such as successive convex approximation and low-complexity algorithms indicating strong proficiency in optimisation methods, wireless and wired communication modelling, directed acyclic graph task modelling. These aspects covered in the thesis jointly demonstrate the PhD candidate's thorough understanding of ICT research state of the art and challenges, particularly in energy-efficient computing, distributed-system optimisation, and real-world system modelling. Mr Kopras used various software tools to simulate and evaluate the performance of the proposed algorithms and methods in the research. He successfully used GNU Octave/Matlab, and C++ programming environments/languages.
The selection of literature references is suitable for both general knowledge of fog/cloud computing, specific problems of energy efficiency and optimisation methods in this regard..

5. Other remarks

Considering the high standard of the dissertation in all its aspects, I have only the following minor critical remarks and open questions:

1. The research claim (thesis) of the dissertation is not formulated with sufficient precision. I believe it could be refined and articulated more accurately, for instance, as follows:

   There exist optimization approaches to computational task offloading problems in fog networks, minimizing energy consumption by optimizing the allocation of tasks to fog nodes and cloud nodes, selection of CPU frequencies for processing these tasks, and the management of energy spent on both wireless and wired transmissions, while maintaining required latency constraints.

   Such a formulation would capture the main idea of the research while also specifying the variables and constraints involved in the optimisation process as described in the dissertation, focusing on task allocation, CPU frequency adjustments, and transmission energy management.

2. Has the impact of user mobility on task offloading decisions and energy consumption been addressed in the thesis? If not, how this could be done in the future research?
3. In the context of delay model it is stated (p. 48) that "The wireless communication channel between end devices and FNs/RRHs is not considered." It should be explained what the consequences of this assumption are.
4. "The FNs are capable of sharing the computational load between themselves. To simplify the model and calculations that follow, they do so by inducing neither additional delays nor power consumption. These costs have also been left out by other researchers [49, 50, 52]." (p. 45). Apart from the fact that other researchers made this assumption, how can it be justified?
5. "Many authors assume that rx << lx and ignore the costs related to the transmission of results altogether." (p. 14) What is the author's justification of this supposition?
6. The author selected a single-objective optimisation approach, referencing just one study ([30]) that adopts a multi-objective approach. Would a multi-objective optimisation approach – combining energy, latency, and monetary cost – be appropriate and feasible? Could a Pareto-based approach be applied, and if so, how might it be used?
7. Are the terms 'delay' and 'latency' used interchangeably in the thesis or do they have a different meaning?

8. Could the author specify how edge and fog computing are defined and how they differ within the context of the thesis?

I would like Mr. Kopras to thoroughly discuss and elucidate the above-mentioned issues during the public defence of his thesis.

The text is written in concise, clear English, with predominantly precise use of appropriate ICT terminology. I would, however, like to highlight the frequent misuse of hyphens in the term "state of the art" when it is used as a noun (e.g., on page 7), as opposed to its correct hyphenated form when employed as a compound adjective "state-of-the-art".

9. 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*

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 **wired and wireless communication systems**?

[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*

Moreover, taking into account that Mr Bartosz Kopras has:

- co-authored five peer-revied publications in high-profile journals,
- presented original solutions to the relevant scientific problems that have application potential in new and emerging technologies, such as 5G/6G wireless communication systems,

I **recommend to distinguish** the dissertation for its quality.

Sławomir Hausman

Signature

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