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REVIEW OF THE DOCTORAL DISSERTATION

Title: Optimization of Energy Efficiency in Fog Computing with Latency Constraints

Author: Bartosz Korpas, MSc

1. **What scientific problem is considered in the dissertation? Has the author formulated it enough? What is the nature of the dissertation (theoretical, experimental, other)?**

The thesis focuses on designing practical orchestration algorithms that optimize the offloading of computing tasks in the fog computing system to minimize energy consumption and satisfy latency constraints. The author considers three task allocation scenarios and proposes specific models for each. They cover: 1) allocating computing tasks between many fog and cloud nodes exploiting the CPU frequency tuning. The problem belongs to a class of non-convex Mixed-Integer Non-Linear Programming (MINLP) problems, so the Successive Convex Approximation (SCA) method transforms it into a series of convex MINLP problems solved by decomposition techniques. 2) The second scenario extends the previous one by considering the energy consumption of wireless transmission between mobile devices and fog nodes. 3) The third model considers the allocation of sequences of tasks using graph embedding techniques. The author proposed Clustered Network Embedding (CNE) algorithm and compared its effectiveness to Particle Swarm Optimization (PSO) methods.

The aim of the dissertation and the formulated thesis, i.e., "There exist optimal solutions to computational task offloading problems in fog networks minimizing energy consumption while maintaining required levels of latency," are reasonable and clearly defined. The orchestration problem is essential, and, in my opinion, its importance will increase in the future with the broad deployment of fog, 6G, and future generation systems deployed over the edge-cloud continuum infrastructures. Service providers will be interested in using the proposed optimization models and algorithms to orchestrate cloud-native appliances.

The dissertation is theoretical, with an inclination toward practical applications. The author verified the proposed algorithms in comprehensive simulation experiments considering different scenarios. The obtained results can be applied in practice.

2. Was the state-of-the-art analysis presented in the dissertation properly proving the author's sufficient knowledge? Are the conclusions from state-of-the-art analysis formulated clearly and convincingly?

The state-of-the-art analysis of the fog systems, including the energy-saving models, is presented in Chapter 2. The analysis provides a comprehensive survey of different approaches recently proposed in the research publications. In particular, the survey focuses on i) modeling the fog systems, including similar edge computing systems, Mobile/Multi-access Edge Computing (MEC), and IoT systems, ii) modeling the fog applications and analyzing related use case scenarios, where applications are deployed over the distributed fog system, and iii) fog optimization methods, including energy consumption as one of the optimization objectives.

In my opinion, this analysis is adequate, comprehensive, and well-structured. It contains 146 references to recent publications, conference papers, standardization documents, and specifications, including 10 references to the author's publications in IEEE ComMag, TCOM, or MDPI journals. It is worth mentioning that the analysis is performed systematically following the taxonomy proposed by the author. This taxonomy is especially important because of the wide scope of fog computing research and many publications.

The only minor issue is a lack of analysis of the currently investigated edge-cloud continuum systems and analysis of the current fog systems deployment and their perspective in the 5G/6G evaluation.

In conclusion, I do not doubt the author has a deep knowledge of fog systems. The state-of-the-art analysis is well done and summarized with clear conclusions presented after each section.

3. Did the author solve the considered scientific problem?, Did he use the adequate approach and justified assumptions?

The author considered three optimization problems related to computing task allocation in different use cases of fog systems. He used different optimization techniques, e.g., MINLP, SCA, Hungarian, and PSO to solve specific problems and evaluated proposed solutions by simulations.

The first problem focuses on task allocation in the fog system to minimize network energy consumption while meeting delay constraints specific to each offloaded task. The energy consumption model considers data processing (computing) and data transmission (communication) over wired links, assuming as much as possible some realistic models of devices. The objective is to find such task allocation to fog nodes and tune the clock's frequencies to minimize the overall energy consumption while satisfying delay constraints. The optimization problem is defined as a non-convex Mixed-Integer Non-Linear Programming (MINLP) problem, so the Successive Convex Approximation (SCA) method is applied, which transforms it into a series of convex MINLP problems and provides the optimal solution by using the primal and dual decomposition techniques as well as the Hungarian algorithm. The author also proposed a sub-optimal, lower-complexity solution. The performed comprehensive simulations confirmed the correctness and effectiveness of the proposed solutions.

The second problem extended the previous model by considering the energy consumption of wireless transmission between mobile devices and fog nodes. The optimization model and its decision space are extended to include the energy consumption on wireless links to transmit computational requests. The energy consumption of wireless transmission is expressed by the

energy-per-bit cost, following assumptions from [117]. The optimization is performed sequentially. The exact and heuristic solutions taking the closest wireless access point are proposed.

The third optimization model focuses on allocating a set of tasks composed into a service functions chain. The author proposed the Clustered Network Embedding (CNE) algorithm that allocates Virtual Network Requests (VNRs) to a fog-cloud substrate network. The algorithm's effectiveness is compared with the discrete Particle Swarm Optimization (PSO) approach and an exhaustive search.

While the applied optimization approaches are correct and no specific issues arise, some assumptions are taken arbitrarily, so they may need better explanations, e.g., the assumption about the sequential processing of tasks at all fog nodes, the M/M/n model of computing delay in the fog tire, the batch arrival of computing task assumed in simulations, which contradicts with the M/M/n model, or assumption of energy-per-bit for WLAN network. Of course, I understand that some assumptions must be taken, but there should be discussion about their consequences. In particular, how far is a given assumption from a real fog system, and how does it impact its performance?

Moreover, while optimization and simulation are adequate tools, performing at least some experiments in a real fog system seems reasonable. Such an experiment would allow us to verify assumptions and finally test the proposed solution.

4. What is the novelty of the dissertation? What constitutes the author's contribution? What is the position of the dissertation in relation to the state of knowledge?

The author's original achievements are the following:

1. Comprehensive state-of-the-art analysis based on proposed taxonomy that allows for a systematic review of a wide scope of fog computing research and effectively summarizes so many publications.
2. The proposed orchestration approach for the fog system optimizing task allocation to minimize energy consumption and satisfy delay constraints specific to each offloaded task. The proposed model with non-linear optimization techniques goes far beyond the currently investigated approaches.
3. The approach for embedding service function chains into the fog substrate. Most research focuses on allocating independent tasks, while applications deployed in fogs usually comprise correlated microservices following the SOA paradigm.
4. It is also important to emphasize that all proposed models and results are published in prestigious journals, like ComMag and TCOM.

5. Are the author’s achievements correctly and convincingly presented? Is distortion conciseness, clarity, editorial correctness of the dissertation?

In general, the solutions proposed in the dissertation and the results of performed experiments are presented concisely, carefully, and precisely. The editing of the dissertation does not raise any objections, the structure of the dissertation is clear and understandable.

There are some minor editing issues, e.g., on page 49, "For estimating computational delays in fog tier of the network the author let us assume that there is a queueing system," but they do not influence the dissertation quality..

6. What are the dissertation's weaknesses and main drawbacks?

The dissertation is at a very high level. Anyway, I have identified some of the dissertation's weaknesses that are:

1. As mentioned earlier, some model assumptions are taken arbitrarily and left without discussion. I would like to raise the following examples:

   a) there is an assumption about the sequential processing of tasks at all fog nodes. As some fog nodes may be equipped with powerful servers, the processor-sharing models seem more adequate.

   b) computing delay in the fog tire is modeled as the M/M/n system. The exponential service time of computing tasks seems far from reality. Maybe it is worth considering a more general M/G/n model?

   c) The simulations assume the batch arrival of computing tasks. This assumption contradicts the M/M/n model.

   d) The energy consumption of wireless transmission is modeled using a simple energy-per-bit parameter. Is it enough to model a complex wireless environment?

   Of course, I understand that some assumptions must be taken, but there should be discussion about their consequences. In particular, how far is a given assumption from a real fog system, and how does it impact its performance?

2. The proposed solutions are evaluated by simulations. However, some experiments could be conducted in real fog systems to verify the assumptions and confirm the proposed approaches.

7. What is the usefulness of a dissertation for technical sciences?

Undoubtedly, the dissertation focuses on important issues related to designing and developing effective orchestration algorithms for fog computing systems. This topic is of great interest to the scientific community because energy savings is one of the key requirements in future systems evolving toward edge-computing systems.

The proposed solutions are novel and have a strong theoretical background. The designed algorithms may be directly used in edge computing systems. Moreover, the results obtained may inspire other researchers. The impact of the results is confirmed by numerous publications at conferences and journals, including prestigious journals such as ComMAG and TOMC.

8. **Final conclusion: to which of the following categories the reviewer recommend the dissertation:**
   1. **which does not meet the requirements for hearings under the applicable regulations**
   2. **requiring corrections and re-reviewing**
   3. **that meets the requirements**
   4. **meeting the requirements with a clear excess of**
   5. **<u>Extremely good, deserving of distinction</u>**

I assess the dissertation as "Extremely good, deserving of distinction" and recommend its distinction by "Summa Cum Laude" award.

Justification

The developed orchestration algorithms and optimization models focused on energy-saving allocation of tasks in fog systems are novel, important, and based on a strong theoretical background. The results have been presented at international conferences and published in journals from the Ministry of Science and Higher Education list. The total number of publications by the author of the dissertation is 10, including prestigious journals such as ComMAG and TOMC.

Taking the above into account, I assess that the achievements of the author of the dissertation meet the conditions set for candidates applying for a doctoral degree in the relevant acts, and after meeting other formal conditions, I recommend the dissertation be admitted to public defense.

Andrzej Bęben

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