Czech Technical University in Prague
PhD Thesis: *Optimized TDMA Scheduling Algorithms for Cluster-Tree WSNs*
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Report

With respect to the PhD thesis referred above, I herein state my assessment considering the following aspects:

Relevancy of the subject of the thesis to the current needs of the scientific community

The Wireless Sensor Networks (WSN) paradigm was proposed already a few decades ago but only recently it saw widespread application in practice. Similarly, the Internet of Things (IoT) saw practical applications in the last decade, only, and it is becoming now a mainstream paradigm for interaction with the environment that surrounds us. In this sense, WSN can constitute the lower layer of the IoT for sensing and actuation. However, this combination pushes WSN to their limit in scalability and Quality of Service (QoS) guarantees, particularly given that the communication medium bandwidth and the nodes computing power and energy are scarce. This thesis addresses this challenge, i.e., improving the effectiveness and efficiency of large scale WSN (for IoT) deployments, particularly using Time Division Multiple Access (TDMA) techniques at the medium access level. In particular, the thesis tackles the specially challenging case of a global cluster-tree topology with generic communication requirements between any nodes in the system, together with energy and reliability constraints. This is a scenario with strong demand in practice whenever QoS guarantees are needed, e.g., in industrial IoT settings (Industry 4.0). Overall, designing optimal communication schedules for such cases, meeting the referred constraints, is a complex and still open issue, needing further research towards the development and deployment of a practical real-time IoT.

Fulfilment of the main objectives

The work in the thesis aimed essentially at studying and improving the efficient use of TDMA techniques in the medium access control for WSNs organized in a cluster-tree topology, so that desired QoS requirements are met. Several service dimensions were considered, most of which conflicting, namely timeliness, energy, reliability, self-organization and scalability. This global aim was broken in 5 concrete objectives as follows:

1. Literature survey on TDMA scheduling in WSNs
2. Design and implementation of optimal TDMA scheduling methods for relevant cases
3. Provision of desired QoS guarantees
4. Verification on benchmark instances with relevant comparisons
5. Implementation of a simulation study to verify scalability

These concrete objectives are adequate and consistent with the global aim, setting a natural sequence of milestones that facilitates the management of the workplan. Overall, all objectives were met up to a reasonable level, as can be seen by the results achieved and the generated contributions.

One criticism that could be made, particularly in objective 4, is that existing widespread industrial Wireless Sensor Actuator Networks (WSANs) such as WirelessHART and ISA100, are not referred. Despite sharing the same data link layer, namely IEEE 802.15.4, these protocols set specific constraints to the traffic scheduling. Thus, it would have been interesting to see how the methods proposed in this thesis could, or not, consider those constraints and thus be applied in those contexts, beyond ZigBee, or even how ZigBee with the proposed methods compares with those protocols.

Appropriateness of the methods used in the thesis

The methodology is generally adequate. The work starts by setting the context and identifying a general problem in the real-time IoT domain. A potential solution is identified, based on WSN using ZigBee in a cluster-tree topology, using guaranteed time slots. This option is duly justified based on the need to provide timeliness guarantees. Once this definition is done, the problem is broken in three sub-problems of growing complexity, namely i) the design of a global communications schedule considering a single collision domain, ii) the design of a global communications schedule considering multiple collision domains, and iii) the design of distributed configuration and scheduling methods that allow nodes to join dynamically an existing operating network with single and multiple collision domains. These sub-problems are handled in a natural sequence, each one starting with a survey of related work, then a discussion of the proposed approaches and finally a validation with experiments concerning the schedule construction time and simulations to obtain operational parameters, comparing with competitive existing schedulers. The metrics are adequate, essentially the schedule construction time and the quality of the schedule concerning energy consumption, successful transmissions and timely delivery.

Main results and contributions of the work

The work in this thesis generated several results in the area of real-time traffic scheduling for WSNs that support the IoT in industrial settings, such as the Industry 4.0 paradigm. The results are, essentially, the traffic scheduling algorithms for multiple network configurations and their behavior when balancing reliability, energy and timeliness. The author claims four main contributions as follows:

1. Realistic system model for cluster-tree WSNs with multi-hop time-bounded data streams
2. Exact and heuristic, centralized and distributed TDMA scheduling methods meeting QoS requirements
3. Verification of the proposed algorithms on benchmarks comparing against existing works
4. Verification with simulation studies using Opnet Modeler 17.5

Among these, contributions 1, 3 and 4 do not seem to be scientific contributions on their own but necessary steps to establish the contributions that are, in fact, all within contribution 2. This contribution could have been demultiplexed and presented separately for all the developed scheduling methods, namely $TDMA^{scd}$, E_TDMA^{mcd}, H_TDMA^{mcd}, D_TDMA^{scd} and D_TDMA^{mcd}, or possibly grouped in 3 categories, as they were presented in the thesis, namely global schedule with single collision domain, global schedule with multiple collision domains and distributed schedule for single and multiple collision domains.

Another contribution that could have been claimed is the study on the configuration of the schedules regarding the conflicting requirements of energy efficiency, timeliness and reliability. Although it is known for a long time that these requirements are fundamental conflicts, showing how the traffic schedules can be trimmed to optimize a particular situation is a very valuable piece of knowledge.

Nevertheless, these criticisms do not reduce the merit of the results and value of the contributions for the scientific community working in this area.

Importance of the work for the further development of science

As referred already, the author chose a scientifically relevant and challenging problem, namely the construction of multi-hop traffic schedules in WSNs that provide QoS guarantees. Within the context of this problem, the author further focused on a relevant technology, namely cluster-tree ZigBee networks. Then, the thesis provided new scheduling methods that allow achieving better compromises between energy efficiency, reliability and timeliness than other existing scheduling

approaches. Moreover, the distributed scheduling approaches allow setting up a global network in a natural way, adding new nodes on the fly, with each node learning the right schedule and configuration parameters. These are non-trivial contributions that broaden the state-of-the-art in TDMA schedules for WSNs with QoS requirements, not only in the quality of the schedules but also in the way of generating and deploying them in practice, in a scalable way.

Nevertheless, a minor criticism could also be made here in the sense that the author does not point to future research. Identifying spin-off research lines that could be explored in the future is also a sign of research maturity that, unfortunately, is absent in this case.

Overall satisfaction of the conditions of a creative scientific work

Altogether, the thesis contains a valuable set of non-trivial scientific contributions to the state of the art in real-time traffic schedules for WSNs. These contributions were also published in relevant international venues, namely in one Q1 journal (IEEE TII), another one submitted to a Q2 journal (ACM TOSN) and in the proceedings of three international conferences (IEEE ETFA, IEEE WFCS and IFAC World Congress). This constitutes a pre-validation of the thesis at large and shows already some integration of the author in the related international research community.

Therefore, the author of the thesis proved to have an ability to perform research and to achieve scientific results. I do recommend the thesis for presentation with the aim of receiving a Ph.D. degree.

Luis Almeida,
Porto, 4th of September of 2019

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