Report on the doctoral thesis, the details of which can be found below:

University/Department: Czech Technical University in Prague, Czech Republic
Doctorate: Petr Jurcik
Title: Real-time Communication over Cluster-tree Wireless Sensor Networks
Director: Zdenek Hanzalek (CTU), Anis Koubaa (PIP – Portugal)

Rapporteur: Luís Almeida, University of Porto, Portugal

REPORT

1- Existence of concrete objectives and interest in the theme of the thesis.

The thesis addresses the temporal behavior of communication within wireless sensor networks (WSN). This is a very important and up to date topic as the technology for WSN is at the border of making them practical and there is a vast application domain for them. However, the target dimension of these networks, the unreliable communication medium as well as the unreliability and strong resource constraints of the typical nodes have hindered the development of timing analysis that are useful in practice. This is the context in which this thesis develops, bringing several contributions to the state of the art, particularly in what concerns the actual use of IEEE 802.15.4 and ZigBee protocols in contention-free beacon-enabled mode, with cluster-tree routing.

In order to achieve this goal, several concrete objectives have been settled, which are clearly and adequately stated in the beginning of the document. Namely, a) the provision of an accurate simulation model for the contention-free beacon-enabled mode within each cluster, b) the development of an optimization framework that provides a schedule for a cluster-tree that minimizes energy while meeting the communication time constraints and tolerating a bounded number of errors, c) a sensitivity analysis of energy and delay in cluster-trees with respect to the level of tolerance to errors (number of allowed retransmissions), and finally d) the development of a practical analytical framework that integrates a tool that allows evaluating worst-case delays under different conditions, which helps designing such networks.

2- Existence of a strategic methodology appropriate to the objectives.

The sequence of objectives itself, which is very well articulated in a step by step fashion, makes it clear that there is a precise methodology for reaching them. In fact, each objective is, in a certain way, a milestone to achieve the final goal of providing a tool to support designers deploying and configuring cluster-tree WSN with timing constraints, based on the IEEE 802.15.4 / ZigBee beacon-enabled technology.

Moreover, the methodology was based on using existing tools in order to reach the desired goals avoiding developing everything from scratch. Particularly, the simulator was developed within the Opnet simulation framework, the cluster-tree schedule optimization was expressed as an RCPS/TC problem (Resource Constrained Project Scheduling with Temporal Constraints) and solved with an ILP tool, and the communication model was expressed as service/demand affine curves at each routing level using, then, the Network Calculus framework to compute maximum delays and buffer requirements.

In this context, one remark could be made with respect to the initial part for studying the temporal behavior of the contention-free communication mode of IEEE 802.15.4. In fact, the use of GTS (Guaranteed Time Slots) within each beacon interval is an instance of the hierarchical scheduling problem that is relatively well studied and for which there are appropriate analytical tools. However, such tools were not used and the generated results miss some more or less relevant aspects. For example, what is shown is not a GTS throughput analysis, as claimed, but an evaluation of the GTS utilization. These become particularly different from each other when the GTS capacity is overloaded since the utilization curves omit the packets dropped due to insufficient capacity. A true throughput analysis would indeed be more adequate. Moreover, the dependence with the packet size should have been analyzed in a wider range, not just with two values, given the different relationships between packet size and slot duration which are likely to affect the GTS utilization and throughput.

3- Interest of the results obtained.

As referred above, the interest in WSN is growing at a steady pace given the emergence of technological solutions that are just at the border of making WSN practical, enabling a wide range of applications, such as environment and infrastructures monitoring.

In such applications, the received data is naturally time dependent and its quality degrades with delays induced by the communication infrastructure beyond a certain tolerance. It is also a fact that such delays are dependent on the setup of the network to a great extent. Factors such as the clustering, routing, scheduling and error recovery mechanisms have a decisive influence in the network induced delays.

Therefore, it is of paramount importance to have a good understanding of this relationship and to have tools to help designers in the task of designing, configuring and deploying WSN that meet given Quality of Service requirements, particularly in terms of induced latencies, using the least resources possible, such as network bandwidth and nodes energy and memory. The results achieved in this thesis are clear steps towards this general goal in the particular scope of the IEEE 802.15.4 / ZigBee protocols that are currently the most promising standards for WSN.

In this sense, it is important to note that the contributions of this work are not so much theoretical but practical, on one hand providing a better understanding of the temporal behavior of specific aspects of the involved protocols and on the other hand providing tools to support the design of WSN that meet given requirements with minimal resources. These tools

integrate complex analytical frameworks that had to be non-trivially adapted to fit the particular case of WSN based on the referred technologies.

Given the generalized lack of this kind of tools for WSN, the contributions of this thesis are particularly relevant. Nevertheless, they must be understood as initial steps in a direction that still requires substantial evolution. In fact, as it was clear from the results of the practical experiments relating the derived latencies upper bounds and the actual maximum latencies measured, it is clear that the current tools still entail substantial levels of pessimism, and still miss adequate error models to support an effective balance between reliability and timeliness.

4- Formal characteristics of the doctoral document

In what concerns the structure of the document, it seems very much adequate to the respective purposes. The objectives are clearly stated in the beginning, as a preamble. In this aspect, maybe it would have been better for the sake of the completeness of the text itself if they were inside the Introduction. The Introduction is adequate, with a good context and summary of main contributions. There is then a chapter explaining the basics of the IEEE 802.15.4 / ZigBee technologies on top of which the thesis is developed.

Then, there are three chapters (3 to 5) that present the three main contributions of the work, respectively addressing: a) the temporal behavior of the contention-free communication within IEEE 802.15.4 and the constructions of a simulator using the Opnet tool, b) the scheduling of traffic within ZigBee cluster-trees under temporal and resource constraints using an ILP optimization framework, c) and the analysis of delays and buffer requirements in a given cluster-tree WSN using Network Calculus that lead to a WSN design tool.

Each of these core chapters starts by setting the specific context of the respective problem and addressing the related work. In all these chapters, the set of references used is generally adequate, including substantial pointers to the state of the art in the respective topic. In this aspect, one could possibly reiterate the comment that chapter 3 would have benefited from references to hierarchical scheduling and in chapter 6 the references on worst-case topology determination are short. For example, the following one seems particularly adequate as it deals with coping with mobility by determining the worst-case topology in terms of propagating membership change requests and keep a team of mobile robots synchronized. The text includes a reference to a subpart of this work ([62]) that, however, does not address topology tracking:

T Facchinetti, G. Buttazzo, L. Almeida. Dynamic Resource Reservation and Connectivity Tracking to Support Real-Time Communication among Mobile Units, EURASIP Journal on Wireless Communications and Networking, 2005(5):712-730, December 2005.

Finally, the document ends with a global conclusion that wraps up the initial objectives and the main contributions.

One aspect that seems to be missing is a section on future work that could build upon the limitations of the contributions. This would have been a good complement to the global

conclusion. Chapters 3 and 5 do refer to some future work but in a rather condensed way. These references should have been presented consistently together and with somewhat more discussion, making it clear that the author is aware of current limitations and has established clear lines of future research.

Just to give a few examples of current limitations, note the current absence of error models, the resource inefficiency of deterministic error handling mechanisms such as those included in the GTS-based IEEE 802.15.4 communication, the level of pessimism of the current Network Calculus based analysis, the questionable scalability of requiring global adjency and collision matrices for building the communications schedule, the approach to deal with mobility, which is still at a very preliminary stage, etc.

5- Global evaluation

Globally, the thesis is very relevant to the state of the art in WSN that operate under timing constraints, with several contributions of practical interest that are valuable tools for WSN designers. The work includes substantial non-trivial adaptations of complex analytical tools, such as the RCPS/TC optimization and Networks Calculus, to come up with a new tool for the specific case of designing contention-free mode beacon-enabled IEEE 802.15.4 / ZigBee cluster-tree WSN that supports achieving timely communication with minimal bandwidth, energy and memory usage. This work also contributes to a better understanding of the relationship between timeliness, energy consumption and communication reliability in the context of those WSN. Moreover, the work also resulted in the development of a simulation model in a widely available network simulation framework, namely Opnet, as well as an experimental validation with a WSN based on TelosB motes.

The objectives were clearly established in the beginning and a clear and adequate methodology was followed, in close relationship with the state of the art, which allowed to meet the objectives to a good extent with innovative solutions. Therefore, the candidate proved to have the scientific competence and the ability to autonomously pursue further research work. Consequently, I do recommend the thesis for presentation with the aim of granting a Ph.D. Degree.

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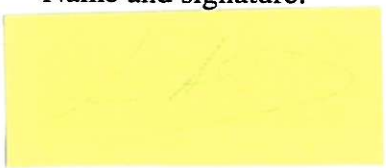

Luis Almeida

Associate Professor, University of Porto, Portugal