Formal Methods for Modelling Wireless Sensor Networks

Theses of Ph.D. Dissertation

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Research Background

In today's Internet of Things (*IoT*) applications, Wireless Sensor Networks (*WSNs*) provide a rapid and flexible solution for accessing information in many real-world applications [19, 24]. A *WSN* deploys a large number of small, inexpensive, self-powered devices that can sense their environment and gather local information used to make global decisions. The WSNs main purpose is to collect environmental data and transmit those measurements. Due to the rapid development of low-cost, small-sized, low-powered micro-electronic and electro-mechanic devices *(Micro-Electric-Mechanical-Systems – MEMS)* nowadays we can build cost-efficiently and easily wireless sensor networks consisting of thousands of sensors even on hard to reach terrains. The uses of such networks can even include among others the detection of seismic activity, or monitoring audible or radar sound waves. The sensors – that can be considered the nodes of the network - are capable of processing a limited amount of information and furthermore wireless communication. Nowadays sensor networks are an integral part of any `C4ISRT` system *(Command, Control, Communication, Computing, Intelligence, Surveillance, Reconnaissance, Targeting)* [1, 6]. The placement of the sensors can be either deterministic or random, but the final location depends largely on the attributes of the area or building, or simply on accessibility. While deterministic deployment takes into consideration the environmental parameters and the field of application to place the sensors strategically, the random method of deployment *(e.g. spreading from an air plane)* makes the sensors final position unpredictable. Another important trait of such networks is about the type of nodes it contains. We can differentiate homogeneous and heterogeneous nodes that made up a network [6]. The most critical aspect of a wireless sensor network is its fault tolerance. Many challenges are to be faced to ensure the appropriate level of fault tolerance, like problems with the power supply, hardware failures, communication errors/ disruptions, malicious attacks. Nowadays the most intensively researched field deals with the optimization of the sensor deployment locations to ensure more effective power-consumption and communication, and an acceptable level of fault tolerance [10].

The modelling and analysis of complex networks is an important interdisciplinary field of science. The networks belong to the field of graph theory. It is known that topology represents the properties of the whole network structure. A topology describes a real network *(with constraints)* and it can be converted to an undirected or directed graph. The common property of topological models is that they are usually calculated based on probabilities [3, 2, 5, 27]. There are many graph-based metrics for modelling complex networks [18]. Topological metrics commonly used on networks: number of nodes and edges, average degree, degree distribution, connectedness, diameter, number of independent paths. The objects of the model can be matched by the vertices of the graph. Edges can be used to describe the relations between the objects. Graph-based modelling can be one of two types: *ad-hoc*- or *measurement*-based. On large wireless networks the traditional measurements based procedures [7, 8, 14, 15, 16, 28, 31, 32, 30] can not be applied efficiently, but k-hop based approaches can be computed effectively also for large networks. In addition to graph theory, there are other tools for modelling and analyzing networks. The increasing complexity of networks requires other formalism [11] *(Propositional Logic, First-Order Logic, Higher-Order Logic, Temporal Logic, Intuitionist Logic, Hoare Logic, etc.)* with more advanced techniques *(Proof Assistants* [13, 17, 25], *Automated Theorem Provers* [12, 23, 29], *Model Checking tools*[4, 9], *etc.)* for analysis. These formalism and techniques are an important part of formal methods [20, 21, 22, 26].

Objectives

During the research we examined the theoretical and technological solutions to the current problems and challenges of the area. Our objectives have been formulated in the light of all of this.

1. We used zeroth-order logic which gives a limited set of tools to examine this field of application:

    - We have examined whether we can create a SAT-based representation to describe a randomly deployed wireless sensor network consisting of heterogeneous nodes.
    - We have also examined whether SAT solvers can effectively

solve this representation and if so what kind of solver should be used including sequential and also parallel solving methods.

2. We used first-order logic which gives a richer set of tools to examine this field of application:

   - We have examined whether we can create a *SMT* based representation of a randomly deployed wireless sensor network consisting of heterogeneous nodes that takes into account physical parameters of a real-world sensor enabling network lifetime investigation.
   - We also have examined whether *OMT* solvers can optimize the lifetime of networks represented this way and if so what kind of *OMT* solver should be used.

3. We used graph theory and their tools to examine this field of application:

   - We have examined whether we can create local density and redundancy based metrics for the k-hop environment of nodes other than the known ones.
   - We have also examined whether we can apply these metrics to be used for more sophisticated ranking and classification of nodes than metrics known so far.

Theses

1. We defined a new 2-*SAT* class, the *Black-and-White 2-SAT* problem. We proved that all strongly connected graphs can be represented as a *Black-and-White 2-SAT* problem. This representation can be used generally to represent any *WSNs*. We have created a problem-specific *SAT* solver, called `BaW 1.0`, that solves these problems in linear time.

   Related publications to thesis I:

   - **Cs. Biró** and G. Kusper and T. Tajti, *How to generate weakly nondecisive SAT instances* 2013 IEEE 11th International

Symposium on Intelligent Systems and Informatics (SISY), pp. 265–269. 2013.

- **Cs. Biró**, G. Kovásznai, A. Biere, G. Kusper, G. Geda, *Cube-and-Conquer approach for SAT solving on grids*, Annales Mathematicae et Informaticae 42 pp. 9-21, 2013.
- **Cs. Biró**, G. Kusper, T. Radványi, S. Király, P. Szigetváry, P. Takács, *SAT Representation of Randomly Deployed Wireless Sensor Networks*, Proceedings of the 9th International Conference on Applied Informatics, 2014, pp. 101–111.
- G. Kusper, **Cs. Biró**, Solving SAT by an Iterative Version of the Inclusion-Exclusion Principle, *SYNASC 2015*, IEEE Computer Society Press, 189–190, 2015.
- G. Kusper, **Cs. Biró**, Gy. B. Iszály, *SAT solving by CS-FLOC, the next generation of full-length clause counting algorithms*, Future IoT Technologies (Future IoT), 2018 IEEE International Conference, 2018, pp.1–9.
- **Cs. Biró**, G. Kusper, *Equivalence of Strongly Connected Graphs and Black-and-White 2-SAT Problems*, Miskolc Mathematical Notes, Vol. 19, No. 2, pp. 755-768, 2018.
- **Cs. Biró**, G. Kusper, *BaW 1.0 - A Problem Specific SAT Solver for Effective Strong Connectivity Testing in Sparse Directed Graphs*, IEEE 18th International Symposium on Computational Intelligence and Informatics (CINTI 2018), pp. 160-165, 2018.

2. We have created an *SMT* based representation of a randomly deployed wireless sensor network consisting of heterogeneous nodes that relies on *RF* energy model and which can be optimized in the lifetime of the network. We have defined a novel model-based incremental optimization process which is based on the results of an *SMT* solver. We have developed a problem-specific *OMT* solver that is order of magnitude more efficient than state-of-the-art solvers in case of monotonous *OMT* problems.

   Related publications to thesis II:

   - **Cs. Biró** *Botond - a Simulation and Optimization Framework for Wireless Sensor Networks*, 1st International Conference on

Future RFID Technologies and host the Workshop on Smart Applications for Smart Cities Eger, Hungary 6-7 November, 2014.

- G. Kovásznai, **Cs. Biró**, B. Erdélyi *Generating Optimal Scheduling for Wireless Sensor Networks by Using Optimization Modulo Theories Solvers*, CEUR Workshop Proceedings Vol-1889, 15th International Workshop on Satisfiability Modulo The- ories-SMT 2017, pp. 15-27, 2017.
- G. Kovásznai, **Cs. Biró**, B. Erdélyi , *Puli - A Problem-Specific OMT Solver*, 16th International Workshop on Satisfiability Modulo Theories - SMT 2018, paper: 362, 10 p., 2018.
- G. Kovásznai, B. Erdélyi, **Cs. Biró** *Investigations of graph properties in terms of wireless sensor network optimization*, 2018 IEEE International Conference on Future IoT Technologies, Future IoT 2018, IEEE, pp. 1-8. 2018.

3. We have defined three novel density- and three novel redundancy-based local metrics. We have compared these new metrics to known ones and we have shown how they can be used for ranking and classifying nodes.

   Related publications to thesis III:

   - **Cs. Biró** *Botond - a Simulation and Optimization Framework for Wireless Sensor Networks*, 1st International Conference on Future RFID Technologies and host the Workshop on Smart Applications for Smart Cities Eger, Hungary 6-7 November, 2014.
   - **Cs. Biró**, G. Kusper *Some k-hop Based Graph Metrics and Node Ranking in Wireless Sensor Networks*, Annales Mathematicae et Informaticae, Accepted manuscript, 2019.

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