Reliable Wireless Channel Access for Large-Scale Cyber-Physical Systems

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***Abstract*—Cyber-physical systems, such as industrial plants, call for a complex setup and make high demands in terms of reliability on all involved components. Though, using wireless technologies promise high cost savings and high flexibility by waiving extensive cabling. This is especially relevant for systems with a very high number of devices, such as a solar tower power plant. The proposed research analyzes the usage of wireless technologies in such applications. The research is conducted by means of analytical and formal methods to allow for the investigation of very large networks, as well as simulations and testbeds to test the proposed techniques under more realistic conditions. Particular emphasis is placed on the channel access since it was shown that the popular CSMA/CA is especially prone to packet collisions.**

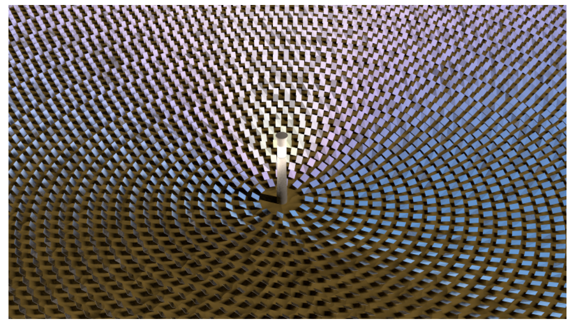

Fig. 1. A solar tower power plant.

I. Motivation

The usage of wireless networks in industrial applications is very promising due to high flexibility and low investment costs. One example is a solar tower power plants as depicted in Fig. 1 where the movement of a huge number of mirrors is to be controlled. Using a wireless field bus promises very high cost savings in the order of several hundred dollars per mirror [1] and the deployment is considerably simplified. However, the requirements of industrial applications call for special attention on the design and implementation of the wireless network. During the course of the AutoR research project [2], several challenges of the application were identified as presented in [3]. In particular packet loss that is common for such large scale wireless networks can have severe impacts on the operation of the plant.

II. Research Questions

The research is guided by the following questions:

- Are such large-scale networks realizable and which technologies are suitable?
- Can the access to the wireless channel be enhanced to avoid packet collisions in this application?
- How does traffic in cyber-physical systems differ from other scenarios and how can it be taken into account?

III. Wireless Technologies

A huge number of wireless technologies are available that could potentially be used in industrial applications. However, technologies with a large geographical coverage as required for the presented application, such as LoRa, can only be realized with a very low data rate and therefore do not scale to a large number of devices [4]. Using multiple base stations would increase the overall costs, so it is assumed that only wireless mesh networks where data is forwarded in a multi-hop fashion are suitable in this scenario. It is still questionable if wireless mesh networks are inherently better than single-hop networks for such large-scale applications or if an equally good or better performance can be achieved with a carefully designed single-hop network, considering the legal restrictions in terms of frequency utilization.

IV. Analytical Model of CSMA/CA

A prominent technology for implementing mesh networks in such a cyber-physical system is the IEEE 802.15.4 standard. Since the method of accessing the wireless channel has a huge impact on the reliability of the message transmission, an analytical model was developed and presented in [5] and [6]. It analyzes the performance of the conventionally used CSMA/CA by modeling the mesh as a network of Markov models to allow for fast calculation and for finding optimal system parameters. In Fig. 2, an exemplary result shows that for a network of 1185 nodes the packet rate shall not exceed one packet every two minutes if a packet reception probability of 98% is anticipated. The work concludes that due to the high amount of collisions, CSMA/CA is not suitable for reliable data transfer in large scale networks.

V. IEEE 802.15.4 DSME

Since collisions were identified as the main cause of packet loss in this scenario, a time division multiple access to the channel (TDMA) and the parallel usage of several frequencies is promising. The recent version of the IEEE 802.15.4 [7], published in 2016, adds the support of TDMA for multi-hop

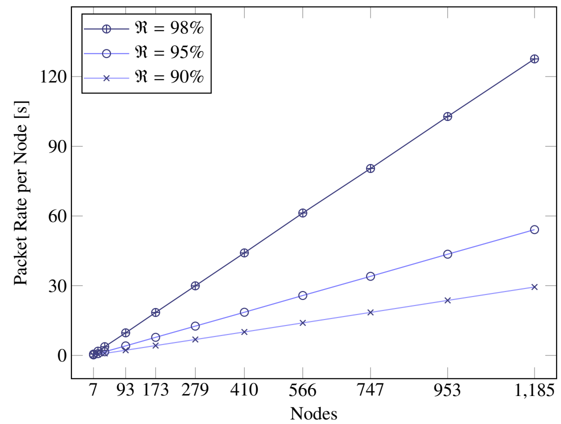

Fig. 2. The minimum packet sending interval to reach a given reliability in a concentric topology with Poisson distributed data collection traffic.

networks, namely TSCH and DSME. While TSCH depends on upper layers, such as 6TiSCH [8], to maintain the time slots, DSME already provides a mechanism for distributed slot management.

Since DSME promises a high scalability, but no implementation is available yet, openDSME was developed [9]. The portability of openDSME allows the integration in multiple existing operating systems and hardware platforms. Currently the OMNeT++ simulator is supported as well as the M3 open nodes deployed in the IoT-LAB [10]. Integrations into other platforms such as the Contiki operating system are currently in progress. First results as depicted in Fig. 3 in fact show that DSME outperforms CSMA/CA in terms of reliability, given the network is not saturated.

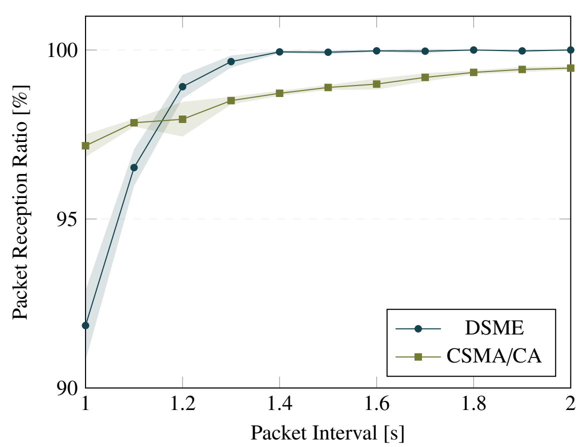

Fig. 3. Comparison of DSME and CSMA/CA for a network of 62 nodes in a concentric topology with Poisson distributed data collection traffic.

VI. Formal Verification of DSME

These results are in fact only possible if the distributed slot management was successful. However, several weaknesses of the standard were identified, for example the possibility of lost messages during the slot allocation handshake. Therefore, the slot management was verified by means of model checking using the UPPAAL environment [11]. The results as presented in [12] show that in fact inconsistencies in the slot schedule are not avoidable and the resolution can take up to one hour. Therefore, an enhancement of the IEEE 802.15.4 standard was proposed that reduces the time until the inconsistency is recognized to under one second.

VII. Future Work

In the work presented above, Poisson distributed data collection traffic is assumed. While it allows to demonstrate the general behavior of the channel access approaches, it is uncommon for cyber-physical systems, especially if the wireless network is part of a control loop. Future work shall therefore include the analysis of the proposed technologies under more realistic traffic scenarios and the generalization to other cyber-physical systems that share similar requirements with the presented application.

References

[1] G. J. Kolb, S. A. Jones, M. W. Donnelly, D. Gorman, R. Thomas, R. Davenport, and R. Lumia, "Heliostat cost reduction study," Sandia National Laboratories, Tech. Rep. SAND2007-3293, Jun. 2007.

[2] Institute of Telematics, TUHH, Autonomous, Light-Weight Heliostat with Rim Drives. [Online]. Available: http://www.ti5.tu-harburg.de/research/projects/autor

[3] A. Pfahl, M. Randt, F. Meier, M. Zaschke, C. P. W. Geurts, and M. Buselmeier, "A Holistic Approach for Low Cost Heliostat Fields," in *20th International Conference on Concentrated Solar Power and Chemical Energy Technologies (SolarPACES)*, Peking, China, Sep. 2014.

[4] M. C. Bor, U. Roedig, T. Voigt, and J. M. Alonso, "Do LoRa Low-Power Wide-Area Networks Scale?" in *Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, Nov. 2016.

[5] F. Meier and V. Turau, "An Analytical Model for Fast and Verifiable Assessment of Large Scale Wireless Mesh Networks," in *Proceedings of the 11th International Conference on the Design of Reliable Communication Networks (DRCN)*. Kansas City, MO, USA: IEEE, Mar. 2015.

[6] F. Meier and V. Turau. (2015) Analytical Model for IEEE 802.15.4 Multi-Hop Networks with Improved Handling of Acknowledgements and Retransmissions. arXiv:1501.07594 [cs.NI]. [Online]. Available: http://arxiv.org/abs/1501.07594

[7] *IEEE 802.15.4™-2015 - IEEE Standard for Local and metropolitan area networks–Part 15.4: Low-Rate Wireless Personal Area Networks (WPANs)*, IEEE Std., 2016.

[8] T. Watteyne, M. R. Palattella, and L. A. Grieco, "Using IEEE 802.15.4e Time-Slotted Channel Hopping (TSCH) in the Internet of Things (IoT): Problem Statement," RFC 7554, May 2015. [Online]. Available: https://www.rfc-editor.org/rfc/pdfrfc/rfc7554.txt.pdf

[9] M. Köstler, F. Kauer, T. Lübkert, and V. Turau, "Towards an Open Source Implementation of the IEEE 802.15.4 DSME Link Layer," in *Proceedings of the 15. GI/ITG KuVS Fachgespräch Sensornetze*, J. Scholz and A. von Bodisco, Eds. University of Applied Sciences Augsburg, Dept. of Computer Science, Sep. 2016.

[10] C. Adjih, E. Baccelli, E. Fleury, G. Harter, N. Mitton, T. Noel, R. Pissard-Gibollet, F. Saint-Marcel, G. Schreiner, J. Vandaele, and T. Watteyne, "Fit iot-lab: A large scale open experimental iot testbed," in *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*, Dec 2015.

[11] K. G. Larsen, P. Pettersson, and W. Yi, "Uppaal in a Nutshell," *Int. Journal on Software Tools for Technology Transfer*, vol. 1, no. 1–2, Oct. 1997.

[12] F. Kauer, M. Köstler, T. Lübkert, and V. Turau, "Formal Analysis and Verification of the IEEE 802.15.4 DSME Slot Allocation," in *Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM)*, Nov. 2016.