Generalized strictly periodic scheduling analysis, resource optimization, and implementation of adaptive streaming applications

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Bibliography

[1] Embedded System Market. https://www.gminsights.com/industry-analysis/embedded-system-market. [Cited December 17, 2019].

[2] SDFˆ 3. http://www.es.ele.tue.nl/sdf3/download/examples.php. [Cited December 30, 2019].

[3] H. I. Ali, B. Akesson, and L. M. Pinho. Generalized extraction of real-time parameters for homogeneous synchronous dataflow graphs. In *2015 23rd Euromicro International Conference on Parallel, Distributed, and Network-Based Processing*, pages 701–710. IEEE, 2015.

[4] J. H. Anderson, V. Bud, and U. C. Devi. An EDF-based scheduling algorithm for multiprocessor soft real-time systems. In *17th Euromicro Conference on Real-Time Systems (ECRTS'05)*, pages 199–208. IEEE, 2005.

[5] H. Aydin and Q. Yang. Energy-aware partitioning for multiprocessor real-time systems. In *Proceedings International Parallel and Distributed Processing Symposium*, pages 9–pp. IEEE, 2003.

[6] T. P. Baker and S. K. Baruah. Schedulability analysis of multiprocessor sporadic task systems. In *Handbook of Real-Time and Embedded Systems*, pages 49–66. Chapman and Hall/CRC, 2007.

[7] M. Bamakhrama. *On hard real-time scheduling of cyclo-static dataflow and its application in system-level design*. Leiden Institute of Advanced Computer Science (LIACS), Leiden University, 2014.

[8] M. Bamakhrama and T. Stefanov. Hard-real-time scheduling of data-dependent tasks in embedded streaming applications. In *Proceedings of the ninth ACM international conference on Embedded software*, pages 195–204. ACM, 2011.

[9] M. Bamakhrama and T. Stefanov. Managing latency in embedded streaming applications under hard-real-time scheduling. In *Proceedings of the eighth IEEE/ACM/IFIP international conference on Hardware/software codesign and system synthesis*, pages 83–92. ACM, 2012.

[10] M. Bamakhrama and T. Stefanov. On the hard-real-time scheduling of embedded streaming applications. *Design Automation for Embedded Systems*, 17(2):221–249, 2013.

[11] M. Bambagini, M. Marinoni, H. Aydin, and G. Buttazzo. Energy-aware scheduling for real-time systems: A survey. *ACM Transactions on Embedded Computing Systems (TECS)*, 15(1):7, 2016.

[12] S. K. Baruah, N. K. Cohen, C. G. Plaxton, and D. A. Varvel. Proportionate progress: A notion of fairness in resource allocation. *Algorithmica*, 15(6):600–625, 1996.

[13] S. K. Baruah, L. E. Rosier, and R. R. Howell. Algorithms and complexity concerning the preemptive scheduling of periodic, real-time tasks on one processor. *Real-time systems*, 2(4):301–324, 1990.

[14] A. Bastoni, B. B. Brandenburg, and J. H. Anderson. An empirical comparison of global, partitioned, and clustered multiprocessor EDF schedulers. In *2010 31st IEEE Real-Time Systems Symposium*, pages 14–24. IEEE, 2010.

[15] S. S. Bhattacharyya and E. A. Lee. Memory management for dataflow programming of multirate signal processing algorithms. *IEEE Transactions on Signal Processing*, 42(5):1190–1201, 1994.

[16] G. Bilsen, M. Engels, R. Lauwereins, and J. Peperstraete. Cycle-static dataflow. *IEEE Transactions on signal processing*, 44(2):397–408, 1996.

[17] B. Bodin, A. Munier-Kordon, and B. D. de Dinechin. K-periodic schedules for evaluating the maximum throughput of a synchronous dataflow graph. In *2012 International Conference on Embedded Computer Systems (SAMOS)*, pages 152–159. IEEE, 2012.

[18] B. Bodin, A. Munier-Kordon, and B. D. de Dinechin. Periodic schedules for cyclo-static dataflow. In *The 11th IEEE Symposium on Embedded Systems for Real-time Multimedia*, pages 105–114. IEEE, 2013.

[19] B. Bodin, A. Munier-Kordon, and B. D. de Dinechin. Optimal and fast throughput evaluation of CSDF. In *Proceedings of the 53rd Annual Design Automation Conference*, page 160. ACM, 2016.

[20] A. Burns, R. I. Davis, P. Wang, and F. Zhang. Partitioned EDF scheduling for multiprocessors using a C= D task splitting scheme. *Real-Time Systems*, 48(1):3–33, 2012.

[21] G. C. Buttazzo. *Hard real-time computing systems: predictable scheduling algorithms and applications*, volume 24. Springer Science & Business Media, 2011.

[22] J. M. Calandrino, H. Leontyev, A. Block, U. C. Devi, and J. H. Anderson. Litmusˆ rt: A testbed for empirically comparing real-time multiprocessor schedulers. In *2006 27th IEEE International Real-Time Systems Symposium (RTSS'06)*, pages 111–126. IEEE, 2006.

[23] E. Cannella, M. A. Bamakhrama, and T. Stefanov. System-level scheduling of real-time streaming applications using a semi-partitioned approach. In *2014 Design, Automation & Test in Europe Conference & Exhibition (DATE)*, pages 1–6. IEEE, 2014.

[24] E. Cannella, O. Derin, P. Meloni, G. Tuveri, and T. Stefanov. Adaptivity support for MPSoCs based on process migration in polyhedral process networks. *VLSI Design*, 2012, 2012.

[25] E. Cannella and T. Stefanov. Energy efficient semi-partitioned scheduling for embedded multiprocessor streaming systems. *Design Automation for Embedded Systems*, 20(3):239–266, 2016.

[26] G. Chen, K. Huang, and A. Knoll. Energy optimization for real-time multiprocessor system-on-chip with optimal DVFS and DPM combination. *ACM Transactions on Embedded Computing Systems (TECS)*, 13(3s):111, 2014.

[27] H. Cho, B. Ravindran, and E. D. Jensen. An optimal real-time scheduling algorithm for multiprocessors. In *2006 27th IEEE International Real-Time Systems Symposium (RTSS'06)*, pages 101–110. IEEE, 2006.

[28] E. G. Coffman, J. M. R. Garey, and D. Johnson. Approximation algorithms for bin packing: A survey. *Approximation algorithms for NP-hard problems*, pages 46–93, 1996.

[29] R. I. Davis and A. Burns. A survey of hard real-time scheduling for multiprocessor systems. *ACM computing surveys (CSUR)*, 43(4):35, 2011.

[30] R. H. Dennard, F. H. Gaensslen, V. L. Rideout, E. Bassous, and A. R. LeBlanc. Design of ion-implanted MOSFET's with very small physical dimensions. *IEEE Journal of Solid-State Circuits*, 9(5):256–268, 1974.

[31] N. W. Fisher. *The multiprocessor real-time scheduling of general task systems*. PhD thesis, The University of North Carolina at Chapel Hill, 2007.

[32] M. Geilen and S. Stuijk. Worst-case performance analysis of synchronous dataflow scenarios. In *CODES+ISSS*, 2010.

[33] M. Geilen and S. Stuijk. Worst-case performance analysis of synchronous dataflow scenarios. In *Proceedings of the eighth IEEE/ACM/IFIP international conference on Hardware/software codesign and system synthesis*, pages 125–134. ACM, 2010.

[34] A. H. Ghamarian, M. Geilen, T. Basten, B. D. Theelen, M. R. Mousavi, and S. Stuijk. Liveness and boundedness of synchronous data flow graphs. In *2006 Formal Methods in Computer Aided Design*, pages 68–75. IEEE, 2006.

[35] A. H. Ghamarian, M. Geilen, S. Stuijk, T. Basten, B. D. Theelen, M. R. Mousavi, A. Moonen, and M. Bekooij. Throughput analysis of synchronous data flow graphs. In *Sixth International Conference on Application of Concurrency to System Design (ACSD'06)*, pages 25–36. IEEE, 2006.

[36] L. Gide. Embedded/cyber-physical systems ARTEMIS major challenges: 2014-2020. *Draft Addendum to the ARTEMIS-SRA 2011*, 2013.

[37] M. I. Gordon, W. Thies, and S. Amarasinghe. Exploiting coarse-grained task, data, and pipeline parallelism in stream programs. *ACM SIGOPS Operating Systems Review*, 2006.

[38] M. Grant and S. Boyd. Graph implementations for nonsmooth convex programs. In V. Blondel, S. Boyd, and H. Kimura, editors, *Recent Advances in Learning and Control*, Lecture Notes in Control and Information Sciences, pages 95–110. Springer-Verlag Limited, 2008. `http://stanford.edu/~boyd/graph_dcp.html`.

[39] M. Grant and S. Boyd. CVX: Matlab Software for Disciplined Convex Programming, version 2.1. `http://cvxr.com/cvx`, Mar. 2014.

[40] P. Greenhalgh. Big. little processing with arm cortex-a15 & cortex-a7. *ARM White paper*, 17, 2011.

[41] J. L. Hennessy and D. A. Patterson. *Computer architecture: a quantitative approach*. Elsevier, 2011.

[42] P. Huang, O. Moreira, K. Goossens, and A. Molnos. Throughput-constrained voltage and frequency scaling for real-time heterogeneous multiprocessors. In *Proceedings of the 28th Annual ACM Symposium on Applied Computing*, pages 1517–1524. ACM, 2013.

[43] A. Jantsch and I. Sander. Models of computation and languages for embedded system design. *IEE Proceedings-Computers and Digital Techniques*, 152(2):114–129, 2005.

[44] A. Jerraya, H. Tenhunen, and W. Wolf. Multiprocessor systems-on-chips. *IEEE Computer*, 38(7):36–40, July 2005.

[45] D. S. Johnson. *Near-optimal bin packing algorithms*. PhD thesis, Massachusetts Institute of Technology, 1973.

[46] D. S. Johnson and M. R. Garey. *Computers and intractability: A guide to the theory of NP-completeness*. WH Freeman, 1979.

[47] H. Jung, H. Oh, and S. Ha. Multiprocessor scheduling of a multi-mode dataflow graph considering mode transition delay. *ACM Transactions on Design Automation of Electronic Systems (TODAES)*, 22(2):37, 2017.

[48] A. H. Khan, Z. H. Khan, and Z. Weiguo. Model-based verification and validation of safety-critical embedded real-time systems: formation and tools. In *Embedded and Real Time System Development: A Software Engineering Perspective*, pages 153–183. Springer, 2014.

[49] P. S. Kurtin, J. P. Hausmans, and M. J. Bekooij. Combining offsets with precedence constraints to improve temporal analysis of cyclic real-time streaming applications. In *2016 IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS)*, pages 1–12. IEEE, 2016.

[50] E. Le Sueur and G. Heiser. Dynamic voltage and frequency scaling: The laws of diminishing returns. In *Proceedings of the 2010 international conference on Power aware computing and systems*, pages 1–8, 2010.

[51] E. A. Lee and S. Ha. Scheduling strategies for multiprocessor real-time DSP. In *1989 IEEE Global Telecommunications Conference and Exhibition'Communications Technology for the 1990s and Beyond'*, pages 1279–1283. IEEE, 1989.

[52] E. A. Lee and D. G. Messerschmitt. Synchronous data flow. *Proceedings of the IEEE*, 75(9):1235–1245, 1987.

[53] E. A. Lee and A. Sangiovanni-Vincentelli. Comparing models of computation. In *Proceedings of International Conference on Computer Aided Design*, pages 234–241. IEEE, 1996.

[54] C. L. Liu and J. W. Layland. Scheduling algorithms for multiprogramming in a hard-real-time environment. *Journal of the ACM (JACM)*, 20(1):46–61, 1973.

[55] D. Liu, J. Spasic, G. Chen, and T. Stefanov. Energy-efficient mapping of real-time streaming applications on cluster heterogeneous mpsocs. In *2015 13th IEEE Symposium on Embedded Systems For Real-time Multimedia (ESTIMedia)*, pages 1–10. IEEE, 2015.

[56] D. Liu, J. Spasic, J. T. Zhai, T. Stefanov, and G. Chen. Resource optimization for CSDF-modeled streaming applications with latency constraints. In *2014 Design, Automation & Test in Europe Conference & Exhibition (DATE)*, pages 1–6. IEEE, 2014.

[57] P. Marwedel. *Embedded System Design: Embedded Systems, Foundations of Cyber-Physical Systems, and the Internet of Things*. Springer International Publishing: Imprint: Springer, 2018.

[58] P. Marwedel, J. Teich, G. Kouveli, I. Bacivarov, L. Thiele, S. Ha, C. Lee, Q. Xu, and L. Huang. Mapping of applications to MPSoCs. In *Proceedings of the seventh IEEE/ACM/IFIP international conference on Hardware/software codesign and system synthesis*, pages 109–118. ACM, 2011.

[59] T. Mitra. Heterogeneous multi-core architectures. *Information and Media Technologies*, 10(3):383–394, 2015.

[60] O. Moreira. Temporal analysis and scheduling of hard real-time radios running on a multi-processor. *ser. PHD Thesis, Technische Universiteit Eindhoven*, 2012.

[61] A. Nelson, O. Moreira, A. Molnos, S. Stuijk, B. T. Nguyen, and K. Goossens. Power minimisation for real-time dataflow applications. In *2011 14th Euromicro Conference on Digital System Design*, pages 117–124. IEEE, 2011.

[62] S. Niknam and T. Stefanov. Energy-efficient scheduling of throughput-constrained streaming applications by periodic mode switching. In *2017 International Conference on Embedded Computer Systems: Architectures, Modeling, and Simulation (SAMOS)*, pages 203–212. IEEE, 2017.

[63] S. Niknam, P. Wang, and T. Stefanov. Resource Optimization for Real-Time Streaming Applications Using Task Replication. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 37(11):2755–2767, 2018.

[64] S. Niknam, P. Wang, and T. Stefanov. Hard Real-Time Scheduling of Streaming Applications Modeled as Cyclic CSDF Graphs. In *2019 Design, Automation & Test in Europe Conference & Exhibition (DATE)*, pages 1549–1554. IEEE, 2019.

[65] S. Niknam, P. Wang, and T. Stefanov. On the Implementation and Execution of Adaptive Streaming Applications Modeled as MADF. In *Proceedings of the International Workshop on Software and Compilers for Embedded Systems (SCOPES)*. ACM, 2020.

[66] ODROID. `http://www.hardkernel.com/`. [Cited December 17, 2019].

[67] S. Park, J. Park, D. Shin, Y. Wang, Q. Xie, M. Pedram, and N. Chang. Accurate modeling of the delay and energy overhead of dynamic voltage and frequency scaling in modern microprocessors. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 32(5):695–708, 2013.

[68] J. Parkhurst, J. Darringer, and B. Grundmann. From single core to multi-core: preparing for a new exponential. In *Proceedings of the 2006 IEEE/ACM international conference on Computer-aided design*, pages 67–72. ACM, 2006.

[69] R. Pellizzoni, P. Meredith, M.-Y. Nam, M. Sun, M. Caccamo, and L. Sha. Handling mixed-criticality in SoC-based real-time embedded systems. In *Proceedings of the seventh ACM international conference on Embedded software*, pages 235–244. ACM, 2009.

[70] M. Processor. Exynos 5 Octa (5422). https://www.samsung.com/semiconductor/minisite/exynos/products/mobileprocessor/exynos-5-octa-5422/. [Cited December 17, 2019].

[71] G. Qu. What is the limit of energy saving by dynamic voltage scaling? In *Proceedings of the 2001 IEEE/ACM international conference on Computer-aided design*, pages 560–563. IEEE Press, 2001.

[72] Real Time Engineers Ltd. The FreeRTOS Project. http://www.freertos.org/. [Cited December 17, 2019].

[73] M. Shafique and S. Garg. Computing in the dark silicon era: Current trends and research challenges. *IEEE Design & Test*, 34(2):8–23, 2016.

[74] A. K. Singh, A. Das, and A. Kumar. Energy optimization by exploiting execution slacks in streaming applications on multiprocessor systems. In *2013 50th ACM/EDAC/IEEE Design Automation Conference (DAC)*, pages 1–7, 2013.

[75] A. K. Singh, M. Shafique, A. Kumar, and J. Henkel. Mapping on multi/many-core systems: survey of current and emerging trends. In *2013 50th ACM/EDAC/IEEE Design Automation Conference (DAC)*, pages 1–10. IEEE, 2013.

[76] F. Siyoum, M. Geilen, O. Moreira, R. Nas, and H. Corporaal. Analyzing synchronous dataflow scenarios for dynamic software-defined radio applications. In *2011 International Symposium on System on Chip (SoC)*, pages 14–21. IEEE, 2011.

[77] D. Sopic, A. Aminifar, and D. Atienza. e-glass: A wearable system for real-time detection of epileptic seizures. In *2018 IEEE International Symposium on Circuits and Systems (ISCAS)*, pages 1–5. IEEE, 2018.

[78] J. Spasic, D. Liu, E. Cannella, and T. Stefanov. Improved hard real-time scheduling of CSDF-modeled streaming applications. In *Proceedings of the 10th International Conference on Hardware/Software Codesign and System Synthesis*, pages 65–74. IEEE Press, 2015.

[79] J. Spasic, D. Liu, E. Cannella, and T. Stefanov. On the improved hard real-time scheduling of cyclo-static dataflow. *ACM Transactions on Embedded Computing Systems (TECS)*, 15(4):68, 2016.

[80] J. Spasic, D. Liu, and T. Stefanov. Energy-efficient mapping of real-time applications on heterogeneous MPSoCs using task replication. In *2016 International Conference on Hardware/Software Codesign and System Synthesis (CODES+ ISSS)*, pages 1–10. IEEE, 2016.

[81] J. Spasic, D. Liu, and T. Stefanov. Exploiting resource-constrained parallelism in hard real-time streaming applications. In *Proceedings of the 2016 Conference on Design, Automation & Test in Europe*, pages 954–959. EDA Consortium, 2016.

[82] S. Sriram and S. S. Bhattacharyya. Embedded multiprocessors: scheduling and synchronization. 2009.

[83] S. Stuijk, T. Basten, M. Geilen, and H. Corporaal. Multiprocessor resource allocation for throughput-constrained synchronous dataflow graphs. In *2007 44th ACM/IEEE Design Automation Conference*, pages 777–782. IEEE, 2007.

[84] S. Stuijk, M. Geilen, and T. Basten. SDFˆ 3: SDF for free. In *Sixth International Conference on Application of Concurrency to System Design (ACSD'06)*, pages 276–278. IEEE, 2006.

[85] S. Stuijk, M. Geilen, and T. Basten. Throughput-buffering trade-off exploration for cyclo-static and synchronous dataflow graphs. *IEEE Transactions on Computers*, 57(10):1331–1345, 2008.

[86] S. Stuijk, M. Geilen, B. Theelen, and T. Basten. Scenario-aware dataflow: Modeling, analysis and implementation of dynamic applications. In *2011 International Conference on Embedded Computer Systems: Architectures, Modeling and Simulation*, pages 404–411. IEEE, 2011.

[87] B. D. Theelen, M. C. Geilen, S. Stuijk, S. V. Gheorghita, T. Basten, J. P. Voeten, and A. H. Ghamarian. Scenario-aware dataflow. *Technical Report ESR-2008-08*, 2008.

[88] W. Thies and S. Amarasinghe. An empirical characterization of stream programs and its implications for language and compiler design. In *2010 19th International Conference on Parallel Architectures and Compilation Techniques (PACT)*, pages 365–376. IEEE, 2010.

[89] R. Van Kampenhout, S. Stuijk, and K. Goossens. A scenario-aware dataflow programming model. In *2015 Euromicro Conference on Digital System Design*, pages 25–32. IEEE, 2015.

[90] R. Van Kampenhout, S. Stuijk, and K. Goossens. Programming and analysing scenario-aware dataflow on a multi-processor platform. In *Proceedings of the Conference on Design, Automation & Test in Europe*, pages 876–881. European Design and Automation Association, 2017.

[91] M. H. Wiggers, M. J. Bekooij, and G. J. Smit. Efficient computation of buffer capacities for cyclo-static dataflow graphs. In *2007 44th ACM/IEEE Design Automation Conference*, pages 658–663. IEEE, 2007.

[92] K. Yang and J. H. Anderson. Soft real-time semi-partitioned scheduling with restricted migrations on uniform heterogeneous multiprocessors. In *Proceedings of the 22nd International Conference on Real-Time Networks and Systems*, page 215. ACM, 2014.

[93] J. T. Zhai. *Adaptive streaming applications: analysis and implementation models*. PhD thesis, Leiden Embedded Research Center, Faculty of Science (LERC), Leiden Institute of Advanced Computer Science (LIACS), Leiden University, 2015.

[94] J. T. Zhai, S. Niknam, and T. Stefanov. Modeling, analysis, and hard real-time scheduling of adaptive streaming applications. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 37(11):2636–2648, 2018.

[95] F. Zhang and A. Burns. Schedulability analysis for real-time systems with EDF scheduling. *IEEE Transactions on Computers*, 58(9):1250–1258, 2009.

[96] J. Zhu, I. Sander, and A. Jantsch. Energy efficient streaming applications with guaranteed throughput on MPSoCs. In *Proceedings of the 8th ACM international conference on Embedded software*, pages 119–128. ACM, 2008.