# STAND-ALONE PROJECT - FINAL REPORT

**Project number** P20529

**Project title** Partially Synchronous Distributed Real Time Systems (PSRTS)

**Project leader** Ulrich Schmid (Embedded Computing Systems Group, TU Wien)

**Project website** http://ti.tuwien.ac.at/ecs/research/projects/psrts

# 1. Summary for public relations work

The ultimate goal of PSRTS (Partially Synchronous Distributed Real-Time Systems) has been to add a proper real-time systems perspective to fault-tolerant distributed algorithms, by establishing a sound scientific basis for fault-tolerant distributed real-time systems with a high degree of concurrency and, hence, relaxed synchrony-by-design.

By contrast, state-of-the-art distributed hard real-time systems adhere to the synchronous distributed computing paradigm, which is based on a fine-grained common notion of time that can be used to closely synchronize all distributed computations. For example, the popular Time-Triggered Protocol TTP is based on distributed processes that communicate over shared buses via time-slotted communication. Although strict synchrony-by-design greatly simplifies the handling of both real-time and fault-tolerance requirements, it does not allow the application to fully exploit the computing power available in the system: Due to the inevitable overhead of synchronous computation and communication, it is essentially the slowest part of the system that determines the overall computing speed. Besides sub-optimal utilization, i.e., wasting resources, this also creates the danger of running the system outside its specification sometimes.

Given the often severe power & space constraints and the criticality of aerospace/automotive applications, for example, increasing the concurrency in the system in order to better utilize scarce computing resources and to reduce the system's vulnerability is important. PSRTS has been devoted to the development of the scientific basis for such systems, and provided the following major results:

(i) A comprehensive Real-Time Model, which is the first distributed computing model that reconciles fault-tolerant distributed algorithms with real-time analysis. Essentially, it replaces zero-time state transitions by non-zero non-preemptable time computing steps and thus allows queueing effects and scheduling issues to enter the picture.

(ii) Several instances of partially synchronous system models, like the time-free Asynchronous Bounded Cycle model, which provide different relaxations of synchrony conditions, as well as related algorithms for fault-tolerant distributed agreement and proof techniques.

(iii) Advanced (real-time) analysis techniques, primarily based on non-standard algebras, and their application to some network algorithms. Essentially, these methods allow to treat distributed systems as linear dynamic systems.

Besides its primary research results, PSRTS also stimulated several follow-up projects, including transdisciplinary research in formal verification and digital integrated circuits.

Das Projekt PSRTS (Partially Synchronous Distributed Real-Time Systems) war der Schaffung einer soliden wissenschaftlichen Basis für verteilte fehlertolerante Systeme mit harten Echtzeitanforderungen gewidmet, die im Gegensatz zu existierenden Architekturen einen hohen Grad an Parallelität zulassen und daher nicht „synchron per Konstruktion" sind.

Im Gegensatz dazu basieren existierende synchrone Lösungen auf einem feingranularen globalen Zeitbegriff, der es möglich macht, verteilt ablaufende Berechnungen eng miteinander zu synchronisieren: So kommunizieren z.B. im Falle des populären Time-Triggered Protocols TTP global zeitsynchronisierte Prozesse mittels Zeitschlitzverfahren über einen (redundanten) Bus. Nun erleichtert dieser Ansatz zwar die Realisierung von Fehlertoleranz und Echtzeitfähigkeit sehr stark, macht es aber auf der anderen Seite unmöglich, die gesamte Rechenleistung des verteilten Systems der Anwendung zur Verfügung zu stellen: Wegen des unvermeidlichen Overheads synchroner Berechnung und Kommunikation sind es im wesentlichen die langsamsten Teile des Systems, die die Gesamtgeschwindigkeit bestimmen. Abgesehen von der daraus resultierenden schlechten Auslastung, d.h., der Verschwendung von Ressourcen, besteht dadurch aber auch die Gefahr, das System gelegentlich außerhalb der Spezifikation zu betreiben.

Angesichts der oftmals gravierenden Einschränkungen bezüglich des Energie- und Platzbedarfs z.B. in Automotive- und Aerospace-Anwendungen ist es wichtig, zu versuchen, den Grad der Parallelität im System zu erhöhen und somit sowohl die Verschwendung von Ressourcen als auch die Gefahr der Fehlspezifikation von kritischen Zeitparametern zu verkleinern. PSRTS war der Entwicklung der wissenschaftlichen Grundlagen für derartige Systeme gewidmet und hat folgende primären Ergebnisse erzielt:

(i) Ein umfassendes Real-Time Model, dem ersten verteilte Berechnungsmodell, das fehlertolerante verteilte Algorithmen mit einer realistischen Echtzeit-Analyse verträglich macht. Im Wesentlichen ersetzt es in Nullzeit ablaufende Zustandsübergänge durch zeitbehaftete, nichtunterbrechbare Operationen, wodurch Wartezeiten und Ablaufplanung relevant werden.

(ii) Mehrere Instanzen von partiell synchronen Systemmodellen, wie dem zeitfreien Asynchronous Bounded Cycle Modell, die verschiedene Relaxationen von Synchronitätsbedingungen bieten, sowie passende Algorithmen für fehlertolerante verteilte Agreement-Probleme und entsprechende Beweistechniken.

(iii) Komplexe (Echtzeit-)Analysetechniken, primäry basierend auf nicht-standard Algebren, und ihre Anwendung auf Netzwerk-Algorithmen. Diese Methoden erlauben es, verteilte Systeme als lineare dynamische Systeme zu behandeln.

Zusätzlich zu diesen primären Forschungsergebnissen hat PSRTS auch mehrere Folgeprojekte stimuliert, inklusive transdisziplinärer Forschung in Formaler Verifikation und in digitalen Integrierten Schaltungen.

# 2. Brief project report

## 2.1 Report on the scientific work

### 2.1.1 information on the development of the research work

The ultimate goal of PSRTS (Partially Synchronous Distributed Real-Time Systems[1]) has been to add a proper real-time systems perspective to fault-tolerant distributed algorithms. More specifically, its purpose was to establish a sound scientific basis for fault-tolerant distributed real-time systems with a high degree of concurrency and, hence, relaxed synchrony-by-design. The actual project work involved three sub-topics:

(1) Distributed real-time computing models that are compatible with classic distributed computing models, but also allow to properly incorporate the analysis of real-time properties, including scheduling and queueing effects.

(2) Partially synchronous system models that are synchronous enough to allow a solution of important distributed computing problems (like consensus), but asynchronous enough to allow a significant degree of concurrency.

(3) A reasonably simple but realistic worst case schedulability analysis of distributed algorithms running atop of (1) & (2), which allows to break the inevitable cyclic dependency of the timing performances of a distributed algorithm and the underlying distributed computing system.

The actual work in PSRTS essentially followed the original project plan, except that we had to severely reduce the real-time analysis-related part (3) of the project due to the substantial shortening (-50%) of the budget eventually granted for this project part.

### 2.1.2 most important results and brief description of their significance (main points) with regard to

As far as the envisioned accomplishments are concerned, we are happy to say that the work in PSRTS developed excellently. The scientific results obtained in and/or stimulated by PSRTS are documented in 7 journal papers, 26 papers in international conference proceedings, 4 PhD theses and 1 Master thesis. 4 additional journal papers will appear 2013 resp. are still under review, and several follow-up projects have already been/will (hopefully) be lauched.

**Key accomplishments:**

(i) Development of a comprehensive Real-Time Model [1, 2, 44], which is the first distributed computing model that reconciles fault-tolerant distributed algorithms with real-time analysis. In a nutshell, it replaces zero-time state transitions by non-zero time non-preemptable computing steps and thus allows queueing effects and scheduling issues to enter the picture. Interestingly, many correctness proofs and impossibility results obtained in decades of classic distributed algorithms research can be carried over to the Real-Time Model automatically. The work on (automated) real-time analysis initiated in PSRTS is currently continued in a follow-up project (FWF NFN Rigorous Systems Engineering S11405).

[1] Project web page: *http://ti.tuwien.ac.at/ecs/research/projects/psrts*

(ii) Development of the Asynchronous Bounded Cycle (ABC) model [3, 4] (best paper award at SSS'08 [5]). The ABC model essentially allows to replace end-to-end timing constraints between pairs of processes by a simple combinatorial property, namely, a bounded ratio of the length of the longest and shortest causal path between pairs of processes. It is, to the best of our knowledge, the first time-free distributed computing model that allows to implement lock-step rounds. Interestingly, the model also turned out to be useful for expressing bounded delay conditions in asynchronous digital circuits [6]. Note that this finding fuelled our interest in the "cross-community topic" *fault-tolerant distributed algorithms in systems-on-chip* [7], which has now become a major research area in our group, as witnessed by our very successful follow-up FWF project FATAL (P21694) [8, 9], for example.

(iii) Several weak partially synchronous system models for message-passing k-set agreement [10, 11, 12, 13, 42], along with novel correctness proof techniques and impossibility results. Our research has contributed quite substantially to this "hot topic" in distributed algorithms research, which has the aim to explore the solvability/unsolvability border of distributed agreement problems. Particular highlights are

a. the development of the first partially synchronous system models [termed Manti(k) and MSink(k)], where k-set agreement but not $k-1$-set agreement is solvable [10,42], and
b. the, to the best of our knowledge, currently weakest system model that allows to solve consensus in dynamic networks with unidirectional links [13, 43].

Note that we are planning a follow-up project to further explore this promising line of research, which will also try to contribute to the chase for the still unknown weakest failure detector for message-passing k-set agreement.

(iv) Advanced (real-time) analysis techniques, primarily based on min/+ and max/+ algebra, and their application to network algorithms [14, 15, 16, 17, 41, 45]. Essentially, these methods allow to consider networked distributed systems as *linear* dynamic systems, with topology-dependent adjacency matrices. Thanks to the power of solution techniques based on linear algebra, the performance analysis (work complexity, time complexity) of network algorithms boils down to determining certain characteristic parameters of the underlying communication graphs. We have already submitted a joint ANR/FWF follow-up project (COMMA) devoted to further exploring this particularly promising and challenging research direction.

### 2.1.3 information on the running of the project, use of the available funding and where appropriate any changes to the original project plan relating to

The project ran from March 2008 until March 2012, which is considerably longer than the originally projected 36 months. This (cost-neutral) extension was possible, since (a) both TU-funded staff (Martin Biely and Matthias Függer) was involved in the project, and (b) FWF-funded project members (Peter Robinson) moved to other places while continuing the work on PSRTS-related topics.

The project work in PSRTS followed the work plan in the proposal, except for the sub-topic (3) devoted to real-time analysis, cf. Section 2.1.1: Since only one of the two requested PhD positions foreseen for this part of the project was actually granted, we decided to shift the focus of the project more towards (2). As a consequence, we also launched research on very weak partially synchronous system models (item (iii) in Section 2.1.2) for k-set agreement, which was not explicitly written in the proposal.

Needless to say, real-time analysis was of course considered both in item (i) and (iv) in PSRTS, however.

### 2.2. Personnel development – importance of the project for the scientific careers of those involved (including the project leader)

Nonwithstanding the general difficulty of assessing scientific recognition, we can safely say that the work on PSRTS was very important for increasing the international reputation of our group as a whole, and for the project members in particular. This claim is confirmed by various collaborations, invited talks and keynotes, research visits of project members, PC memberships at related conferences etc.

- For the project leader *Ulrich Schmid*, PSRTS was particularly important for increasing the reputation in the area synchrony and time in distributed algorithms (witnessed e.g. by the FORMATS'10 invited tutorial [18]), and for stimulating interest in fault-tolerant distributed algorithms in systems-on-chip (witnessed e.g. by the SSS'08 keynote [19] and the co-organization of a related Dagstuhl seminar [7]).

- PSRTS has also been a very important step in the scientific career of *Peter Robinson*: He won a best paper award at SSS'08 [5] for the ABC model and wrote a PhD thesis [4] co-supervised by Michel Raynal (IRISA Rennes). After completing his PhD, he moved to Gopal Pandurangan's group at Nanjang University in Singapore, where he (besides very successful work on randomized algorithms, as e.g. witnessed by the best paper award at ICDCN'13[2]) still contributed substantially to the goals of PSRTS.

- Thanks to the work on the Real-Time Model conducted in PSRTS, *Heinrich Moser* not only gained considerable recognition in the scientific community, but also managed to finish his PhD with *summa cum laude* ("sub auspiciis praesidentis"); his co-supervisor was Jennifer Welch (Texas A&M University). He is now running his own company.

- PSRTS was also an important step for *Martin Biely*, who wrote a PhD thesis [20] on consensus in dynamic systems co-supervised by Bernadette Charron-Bost (Ecole Polytechnique Paris). He subsequently joined her group for a PostDoc, and then moved to Andre Schiper's group at EPFL Lausanne as an assistant professor, where he still contributed substantially to the goals of PSRTS.

- PSRTS was also an important driver for the work conducted by *Matthias Függer*, who not only wrote a PhD thesis on distributed computing in digital circuits [21] (in the context of the follow-up FWF project FATAL P21694), co-supervised by Jennifer Welch (Texas A&M University), but also took the lead of the dynamic systems analysis part (cf. item (iv) in Section 2.1.2) in PSRTS. He is currently assistant professor at our Embedded Computing Systems Group at TU Wien.

- Last but not least, PSRTS also paved the way for *Thomas Nowak* to join Bernadette Charron-Bosts group at Ecole Polytechnique Paris for a PhD thesis, thanks to his Master thesis [22] on topology in distributed computing. The very active collaboration between our groups owes much to his involvement.

[2] http://icdcn.tcs.tifr.res.in/sites/default/files/bestpaper_award_dc_trac.pdf

As detailed in List 3 in the appendix, the work in PSRTS stimulated several very successful collaborations with prominent researchers, in particular, Bernadette Charron-Bost and Jennifer Welch, which will certainly be intensified in the future (hopefully in the joint ANR/FWF project COMMA). This is also true for the very successful transdisciplinary research on distributed algorithms in systems-on-chip already pursued in the follow-up FWF project FATAL, which has been stimulated by PSRTS.

### 2.3 effects of the project outside the scientific field

As already mentioned, PSRTS was instrumental for our ability to provide transdisciplinary input into two different areas:

- Providing fault-tolerant distributed algorithms and real-time systems expertise to the formal verification community [18], primarily in the context of the follow-up NFN RiSE (S11405).
- Significant contributions to stimulating research on distributed algorithms in integrated circuits [19], which also includes the co-organization of the Dagstuhl seminar 08371 on "Distributed Algorithms in VLSI Chips" [7].

With respect to teaching, some of the results of PSRTS are used in advanced courses (like 182.703 Problems in Distributed Computing[3]) in our computer engineering Master program. Experience tells that this is a very effective means for educating students for current and future research projects.

Given the quite specialized and theoretical nature of PSRTS, we cannot report any public relation-related activities within the project.

[3] Course web page: *http://ti.tuwien.ac.at/ecs/teaching/courses/prdc/*

# 3. Information on project participants

| **not funded by the FWF** | | | **funded by the FWF (project)** | | |
|---|---|---|---|---|---|
| **co-workers** | **number** | **Person-months** | **co-workers** | **number** | **Person - months** |
| non-scientific co-workers | | | non-scientific co-workers | | |
| diploma students | | | diploma students | 1 | 6 |
| PhD students | 3 | 8 | PhD students | 3 | 67 |
| post-doctoral co-workers | 1 | 4 | post-doctoral co-workers | 2 | 13.5 |
| co-workers with “Habilitation” (professorial qualifications) | | | co-workers with “Habilitation” (professorial qualifications) | | |
| professors | 1 | 14 | professors | | |

# 4. Attachments

**List 1**

**1.a. scientific publications**
with an indication of the status (published, in press, submitted, in preparation)

PSRTS followed the FWF open access rules, by providing draft versions of all publications as technical reports. Moreover, since 2010, we negotiated open access with publishers of journal publications whenever possible, cp. [3, 23].

**1.a.1. Peer-reviewed publications (journals, contribution to anthologies, working papers, proceedings etc.)**

All listed publications have already appeared, unless otherwise noted.

**[1] Heinrich Moser and Ulrich Schmid. Reconciling fault-tolerant distributed algorithms and real-time computing. In 18th International Colloquium on Structural Information and Communication Complexity (SIROCCO), LNCS, pages 42–53, Berlin, Heidelberg, 2011. Springer-Verlag.**

**[3] Peter Robinson and Ulrich Schmid. The Asynchronous Bounded-Cycle Model. Theoretical Computer Science, 412(40):5580–5601, 2011. http://dx.doi.org/10.1016/j.tcs.2010.08.001.**

[5] Peter Robinson and Ulrich Schmid. The Asynchronous Bounded-Cycle Model. In Proceedings of the 10th International Symposium on Stabilization, Safety, and Security of Distributed Systems (SSS'08), volume 5340 of Lecture Notes in Computer Science, pages 246–262, Detroit, USA, November 2008. Springer Verlag. (Best Paper Award).

[6] Matthias Függer and Ulrich Schmid. Reconciling fault-tolerant distributed computing and systems-on-chip. Distributed Computing, 24(6):323–355, 2012.

[8] Varadan Savulimedu Veeravalli, Thomas Polzer, Andreas Steininger, and Ulrich Schmid. Architecture and design analysis of a digital single-event transient/upset measurement chip. In Proceedings 15th Euromicro Symposium on Digital System Design: Architectures, Methods and Tools (DSD'12), pages 8–17, sep 2012. (Best paper award).

[9] Varadan Savulimedu Veeravalli and Andreas Steininger. Radiation-tolerant combinational gates: An implementation based comparison. In Proceedings 15th IEEE International Symposium on Design and Diagnostics of Electronic Circuits and Systems (DDECS'12), pages 115–120, Apr. 2012.

[10] Martin Biely, Peter Robinson, and Ulrich Schmid. Weak synchrony models and failure detectors for message passing k-set agreement. In Proceedings of the International Conference on Principles of Distributed Systems (OPODIS'09), LNCS, pages 285–299, Nimes, France, Dec 2009. Springer Verlag.

[11] Martin Biely, Peter Robinson, and Ulrich Schmid. Easy impossibility proofs for k-set agreement in message passing systems. In Proceedings 15th International Conference on Principles of Distributed Systems (OPODIS'11), Springer LNCS 7109, pages 299–312, 2011.

[12] Martin Biely, Peter Robinson, and Ulrich Schmid. Solving k-set agreement with stable skeleton graphs. In T. Kikuno and T. Tsuchiya, editors: Proceedings 25th IEEE International Symposium on Parallel and Distributed Processing (IPDPS'11) Workshops, pages 1488–1495, Anchorage, Alaska, 2011. http://doi.ieeecomputersociety.org/10.1109/IPDPS.2011.301

[13] Martin Biely, Peter Robinson, and Ulrich Schmid. Agreement in directed dynamic networks. In Proceedings 19th International Colloquium on Structural Information and Communication Complexity (SIROCCO'12), pages 73–84, 2012.

[14] Bernadette Charron-Bost, Jennifer L. Welch, and Josef Widder. Link reversal: How to play better to work less. In Proceedings of the 5th International Workshop on Algorithmic Aspects of Wireless Sensor Networks (Algosensors'09), volume 5304 of LNCS, pages 88–101, 2009.

[15] Bernadette Charron-Bost, Matthias Függer, Jennifer L. Welch, and Josef Widder. Brief announcement: Full reversal routing as a linear dynamical system. In Proceedings 23rd ACM Symposium on Parallelism in Algorithms and Architectures (SPAA'11), 2011.

**[16] Bernadette Charron-Bost, Matthias Függer, Jennifer L. Welch, and Josef Widder. Full reversal routing as a linear dynamical system. In 18th International Colloquium on Structural Information and Communication Complexity (SIROCCO), LNCS, pages 101–112, Berlin, Heidelberg, 2011. Springer-Verlag.**

[17] Hyun Chul Chung, Peter Robinson, and Jennifer L. Welch. Optimal regional consecutive leader election in mobile ad-hoc networks. In Proceedings of the 7th ACM SIGACT/SIGMOBILE International Workshop on Foundations of Mobile Computing, FOMC'11, pages 52–61, New York, NY, USA, 2011. ACM.

[23] Martin Biely, Ulrich Schmid, and Bettina Weiss. Synchronous consensus under hybrid process and link failures. Theoretical Computer Science, 412(40):5602 – 5630, 2011. http://dx.doi.org/10.1016/j.tcs.2010.09.032.

[24] Heinrich Moser and Ulrich Schmid. Optimal deterministic remote clock estimation in real-time systems. In Proceedings of the International Conference on Principles of Distributed Systems (OPODIS), pages 363–387, Luxor, Egypt, December 2008.

[25] Peter Robinson and Ulrich Schmid. Brief announcement: The asynchronous bounded-cycle model. In Proceedings of the 27th ACM Symposium on Principles of Distributed Computing (PODC'08), page 423. ACM Press, August 2008.

[26] Martin Hutle, Dahlia Malkhi, Ulrich Schmid, and Lidong Zhou. Chasing the weakest system model for implementing Omega and consensus. IEEE Transactions on Dependable and Secure Computing, 6(4):269–281, 2009.

[27] Heinrich Moser. Towards a real-time distributed computing model. Theoretical Computer Science, 410(6–7):629–659, Feb 2009.

[28] Martin Biely and Josef Widder. Optimal message-driven implementations of Omega with mute processes. ACM Transactions on Autonomous and Adaptive Systems, 4(1):Article 4, 22 pages, 2009.

[29] Josef Widder and Ulrich Schmid. The Theta-Model: Achieving synchrony without clocks. Distributed Computing, 22(1):29–47, April 2009.

[30] Andreas Dielacher, Matthias Függer, and Ulrich Schmid. Brief announcement: How to speed-up fault-tolerant clock generation in VLSI systems-on-chip via pipelining. In Proceedings of the 28th ACM Symposium on Principles of Distributed Computing (PODC'09), page 423. ACM Press, August 2009.

[31] Bernadette Charron-Bost, Antoine Gaillard, Jennifer L. Welch, and Josef Widder. Routing without ordering. In Proceedings 21st ACM Symposium on Parallelism in Algorithms and Architectures (SPAA'09), pages 145–153, 2009.

[32] Martin Biely, Peter Robinson, and Ulrich Schmid. Weak synchrony models and failure detectors for message passing k-set agreement. In Proceedings of the 23rd International Symposium on Distributed Computing (DISC'09), pages 260–261, 2009.

[33] Matthias Függer, Gottfried Fuchs, Ulrich Schmid, and Andreas Steininger. On the stability and robustness of non-synchronous circuits with timing loops. 3rd Workshop on Dependable and Secure Nanocomputing, Jun. 2009.

[34] Matthias Függer, Andreas Dielacher, and Ulrich Schmid. How to speed-up fault-tolerant clock generation in vlsi systems-on-chip via pipelining. In Proceedings Eighth European Dependable Computing Conference (EDCC'10), pages 230–239, 2010.

[35] Alexander Kössler, Heinrich Moser, and Ulrich Schmid. Real-time analysis of round-based distributed algorithms. In Proceedings of the 1st International Real-Time Scheduling Open Problems Seminar (RTSOPS'10), in conjunction with 22nd Euromicro Conference on Real-Time Systems (ECRTS'10), pages 9–11, Jul. 2010. Published as a Technical Report under https://www.cs.york.ac.uk/ftpdir/reports/2010/YCS/455/YCS-2010-455.pdf.

[36] Hyun Chul Chung, Peter Robinson, and Jennifer L. Welch. Regional consecutive leader election in mobile ad-hoc networks. In Proceedings of the DIALM-POMC Joint Workshop on Foundations of Mobile Computing, pages 81–90, 2010.

[37] Hyun Chul Chung, Peter Robinson, and Jennifer L. Welch. Brief announcement: Regional consecutive leader election in mobile ad-hoc networks. In Proceedings 6th International Workshop on Algorithms for Sensor Systems, Wireless Ad Hoc Networks, and Autonomous Mobile Entities (ALGOSENSORS'10), Springer LNCS 6451, pages 89–91. Springer Verlag, 2010.

[38] Martin Biely, Peter Robinson, and Ulrich Schmid. Easy impossibility proofs for k-set agreement in message passing systems. In Proceedings of the 30th Annual ACM Symposium on Principles of Distributed Computing (PODC'11), pages 227–228. ACM, 2011.

[39] Bernadette Charron-Bost, Matthias Függer, Jennifer L. Welch, and Josef Widder. Partial is full. In 18th International Colloquium on Structural Information and Communication Complexity (SIROCCO), LNCS, 2011.

[40] Matthias Függer and Josef Widder. Efficient checking of link-reversal-based concurrent systems. In Maciej Koutny and Irek Ulidowski, editors, Proceedings CONCUR 2012 Concurrency Theory, volume 7454 of Lecture Notes in Computer Science, pages 486–499. Springer Berlin Heidelberg, 2012.

[41] Matthias Függer, Gottfried Fuchs, Ulrich Schmid and Andreas Steininger. On the Stability and Robustness of Non-Synchronous Circuits with Timing Loops, 3rd Workshop on Dependable and Secure Nanocomputing, Estoril, Portugal, 2009.

[42] Martin Biely, Peter Robinson and Ulrich Schmid. Weak Synchrony Models and Failure Detectors for Message Passing k-Set Agreement. To appear in IEEE Transactions on Parallel and Distributed Systems, 2013.

[43] Martin Biely, Peter Robinson and Ulrich Schmid. Agreement in Directed Dynamic Networks. http://arxiv.org/abs/1204.0641 (Submitted to Distributed Computing).

**[44] Heinrich Moser and Ulrich Schmid. Reconciling Fault-Tolerant Distributed Algorithms and Real-Time Computing. (Submitted to Distributed Computing).**

[45] Bernadette Charron-Bost, Antoine Gaillard, Jennifer L. Welch, Josef Widder. Link Reversal Routing with Binary Link Labels: Work Complexity. To appear in SIAM Journal on Computing, 2013.

**1.a.2. Non peer-reviewed publications (journals, contribution to anthologies research reports, working papers, proceedings, etc.)**

None.

**1.a.3. Stand-alone publications (monographies, anthologies)**

None.

## 1.b. publications for the general public and other publications

None.

## List 2 project-related participation in international scientific conferences

**2.1. Conference participations - invited lectures**

[7] Bernadette Charron-Bost, Shlomi Dolev, Jo Ebergen, and Ulrich Schmid, editors. Fault-Tolerant Distributed Algorithms on VLSI Chips, Schloss Dagstuhl, Germany, September 2008, 2009. http://drops.dagstuhl.de/opus/frontdoor.php?source opus=1927.

[18] Ulrich Schmid. Synchrony and time in fault-tolerant distributed algorithms - (invited tutorial). In Proceedings Formal Modeling and Analysis of Timed Systems Conference (FORMATS 2010), volume 6246 of Lecture Notes in Computer Science, page 46. Springer, 2010.

[19] Ulrich Schmid. Keynote: Distributed algorithms and VLSI. In Proceedings of the 10th International Symposium on Stabilization, Safety, and Security of Distributed Systems (SSS'08), volume 5340 of Lecture Notes in Computer Science, page 3, Detroit, USA, November 2008. Springer Verlag. (http://www.vmars.tuwien.ac.at/documents/extern/2467/sss08.pdf).

**2.2. Conference participations - lectures**

[24, 25, 5, 30, 14, 31, 10, 32, 33, 34, 35, 36, 37, 38, 11, 12, 15, 16, 39, 17, 1, 13, 40, 41, 8, 9]

**2.3. Conference participations - posters**

None.

**2.4. Conference participations - other**

None.

**List 3 Development of collaborations**

Indication of the most important collaborations (maximum 5), that took place (initiated or continued) in collaboration please give the name of the collaboration partner (name, title, institution) and a few words about the scientific content. Please also assign one of the following **categories** to each collaboration:

| | | | | | |
|---|---|---|---|---|---|
| N | | | Nature | **N**<br>**E**<br>**I** | (national);<br>(European);<br>(other international cooperation) |
| | E | | Extent | **E1**<br>**E2**<br><br>**E3** | **low** (e.g. no joint publications but mention in acknowledgements or similar);<br>**medium** (collaboration e.g. with occasional joint publications, exchange of materials or similar but no longer-term exchange of personnel);<br>**high** (extensive collaboration with mutual hosting of group members for research stays, regular joint publications etc.) |
| | | D | Discipline | **D**<br>**T** | within the discipline<br>transdisciplinary |

| N | E | D | Collaboration partner / content of the collaboration |
|---|---|---|---|
| E | E3 | D | 1) Name: Martin Biely Title: Dr.<br>Institution: EPF Lausanne<br>Content: Weak models for k-set agreement |
| E | E3 | D | 2) Name: Bernadette Charron-Bost Title: Dr.<br>Institution: Ecole Polytechnique Paris<br>Content: Distributed computing models |
| I | E2 | D | 3) Name: Halia Malkhi Title: Dr.<br>Institution: Microsoft Research<br>Content: Consensus in weak models |
| I | E3 | D | 4) Name: Jennifer Welch Title: Prof.<br>Institution: Texas A&M University<br>Content: Time and work complexity analysis of network algorithms |
| E | E3 | D | 5) Name: Josef Widder Title: Dr.<br>Institution: Ecole Polytechnique Paris<br>Content: Weak timing models |

**Note:** general scientific contacts and occasional meetings should not be considered as collaborations in the above sense.

## List 4 "Habilitations" (professorial qualifications) / PhD theses / diploma theses

### 4.1. Professorial Qualifications

None.

### 4.2. PhD Theses

[2] Heinrich Moser. A Model for Distributed Computing in Real-Time Systems. PhD thesis, Technische Universität Wien, Fakultät für Informatik, May 2009. (Promotion sub auspiciis).

[4] Peter Robinson. Weak System Models for Fault-Tolerant Distributed Agreement Problems. PhD thesis, Technische Universität Wien, Institut für Technische Informatik, Treitlstr. 3/3/182-1, 1040 Vienna, Austria, 2011.

[20] Martin Biely. Dynamic Aspects of Modeling Distributed Computations. PhD thesis, Technische Universität Wien, Institut für Technische Informatik, Treitlstr. 3/3/182-1, 1040 Vienna, Austria, 2009.

[21] Matthias Függer. Analysis of On-Chip Fault-Tolerant Distributed Algorithms. PhD thesis, Technische Universität Wien, Institut für Technische Informatik, Treitlstr. 3/3/182-2, 1040 Vienna, Austria, 2010.

### 4.3. Diploma Theses

[22] Thomas Nowak. Topology in distributed computing. Master thesis, Embedded Computing Systems Group, Technische Universität Wien, March 2010.

**List 5 Effects of the project outside the scientific field** (where appropriate)

**Sections of the list:**

### 5.1. Organization of scientific events

- Co-organization of Dagstuhl seminar 08371 on "Distributed Algorithms in VLSI Chips" [7]
- Many mutual visits with external collaborators devoted to PSRTS, including
  - PhD defenses of project members at TU Wien [2, 4, 20, 21]
  - Research visits of external collaborators at TU Wien
  - Research visits of project members at the collaborators' institutions

### 5.2. Particular honours, prizes etc.

- Best paper award at SSS'08 [5]
- Promotion "sub auspiciis praesidentis" Heinrich Moser [2], June 2010

### 5.3. Information on results relevant to commercial applications

None.

### 5.4. Other effects beyond the scientific field

None.

### 5.5. Relevance of the project in the organization of the relevant scientific discipline

- Transdisciplinary input of fault-tolerant distributed algorithms and real-time systems expertise to formal verification community [18], primarily in the context of the follow-up project RiSE (S11405).
- Significant contributions to stimulating research on distributed algorithms in integrated circuits [7, 19, 41].

## List 6. Applications for follow-up projects

**6.1 Applications for follow-up projects** (FWF projects)

- Approved: NFN Rigorous Systems Engineering (RiSE, S114052)[4]
- Approved: Fault-tolerant Asynchronous Logic (FATAL, P216943)[5]

**6.2 Applications for follow-up projects** (Other national projects)

None.

**6.3 Applications for follow-up projects** (International projects)

- Submitted: Convergence with Multiple Mobile Agents (COMMA, joint ANR/FWF proposal)

[4] See *http://arise.or.at/?id=nfn_org* for an overview of the project.
[5] Project web page: *http://ti.tuwien.ac.at/ecs/research/projects/fatal*

# 5. Zusammenarbeit mit dem FWF

Sie werden gebeten folgende Aspekte der Zusammenarbeit
mit dem FWF zu bewerten. **Anmerkungen (Ausführungen)**
unter Verweis auf den entsprechenden Referenzpunkt bitte auf Beiblatt.

**Skala**
**-2** sehr unzufriedenstellend,
**-1** unzufriedenstellend;
**0** angemessen;
**+1** zufriedenstellend;
**+2** sehr zufriedenstellend.
**X** nicht beansprucht

**Regelwerk**
(Richtlinien für Programm, Antrag, Verwendung, Bericht) **Wertung**

| | | |
|---|---|---|
| **Antragsrichtlinien** | Umfang | **+1** |
| | Übersichtlichkeit | **+1** |
| | Verständlichkeit | **+2** |

**Verfahren** (Einreichung, Begutachtung, Entscheidung)

| | | |
|---|---|---|
| | Beratung | **X** |
| | Dauer des Verfahrens | **0** |
| | Transparenz | **+1** |

**Projektbegleitung**

| | | |
|---|---|---|
| **Beratung** | Verfügbarkeit | **+2** |
| | Ausführlichkeit | **+1** |
| | Verständlichkeit | **+2** |

| | |
|---|---|
| **Durchführung Finanzverkehr** (Überweisungen, Gerätebeschaffungen, Personalwesen) | **+2** |

**Berichtswesen/ Prüfung/ Verwertung**

| | | |
|---|---|---|
| | Aufwand | **+1** |
| | Transparenz | **+2** |
| | Unterstützung bei Öffentlichkeitsarbeit/ Verwertung | **X** |

**Anmerkungen zur Zusammenarbeit mit dem FWF:**

| |
|---|
| Zusammenarbeit funktioniert seit vielen Jahren ausgezeichnet. |