Self-Organizing Synchronization in Networked Systems

Christian Bettstetter

University of Klagenfurt
and Lakeside Labs

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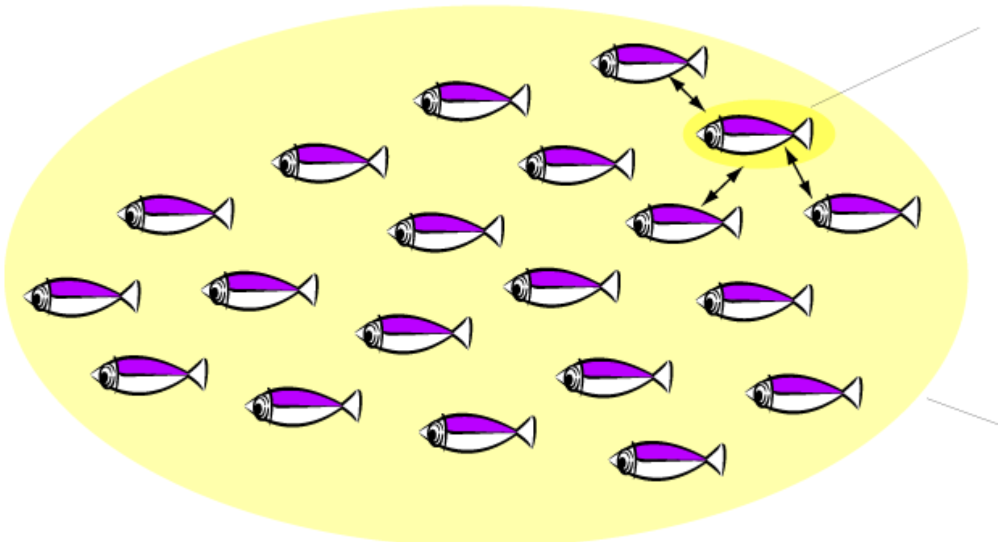
Self-Organization



Individual Entity (Fish)

- Has simple behavior rules
- Has local view only

⇩ Emergence

Entire System (Shoal)

- Solves a complex task
- Is adaptive to changes
- Is scalable and robust

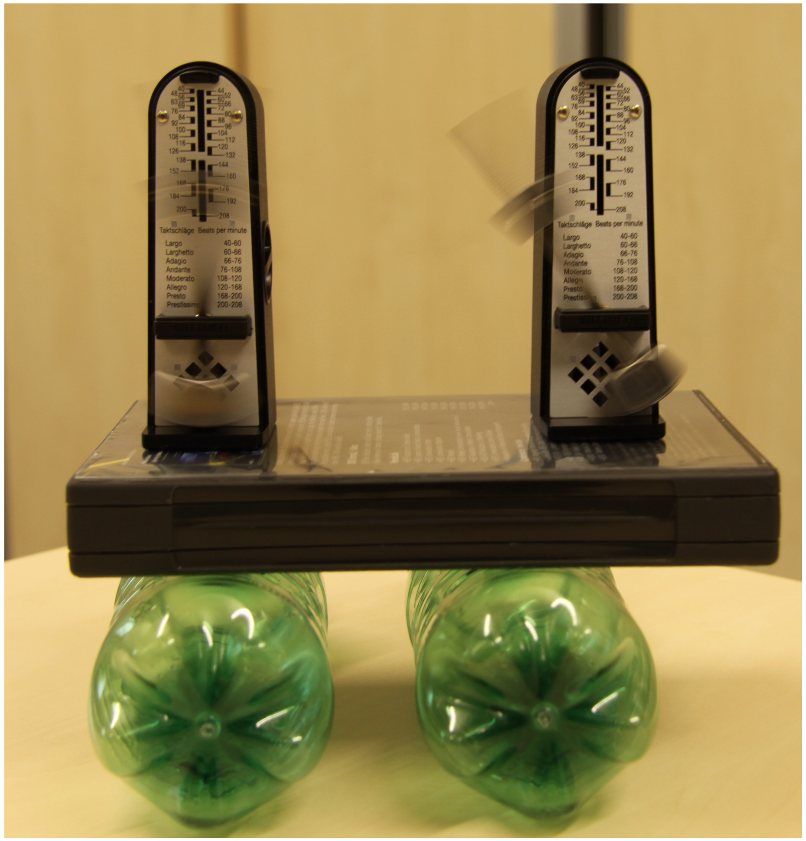
Camazine, Deneubourg, Franks, Sneyd, Theraulaz, Bonabeauet: *Self-Organization in Biological Systems*, 2001.

Prehofer, Bettstetter: Self-organization in communication networks: Principles and design paradigms. *IEEE Communications Magazine*, July 2005.

Synchronization

Definition and experiment with metronomes

- *sýn = together* + *chrónos = time*
- Synchronous events occur at the same time.
- Synchronization is an adjustment leading to synchronous events.
- Different types of synchronization
- Performance measures include convergence, time to synchrony, precision, scalability, robustness.



Synchronization
Experiment with metronomes

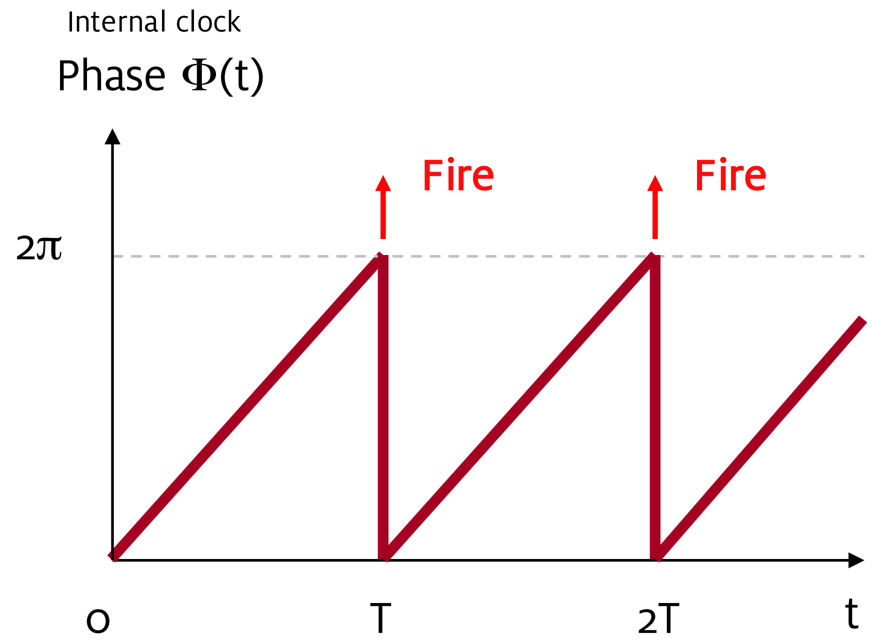
Hint: A high definition video is available at YouTube.

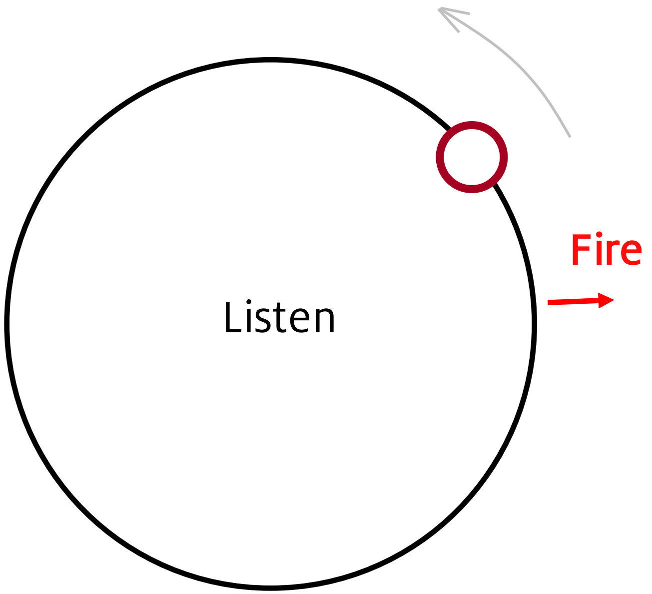
Outline of this talk

Self-organizing synchronization in networked systems

1. How can we model self-organizing synchronization phenomena?
2. Can it be used in wireless systems? Which precision is achieved?
3. For which assumptions can we prove convergence to synchrony?
4. What to consider when designing a synchronization algorithm?

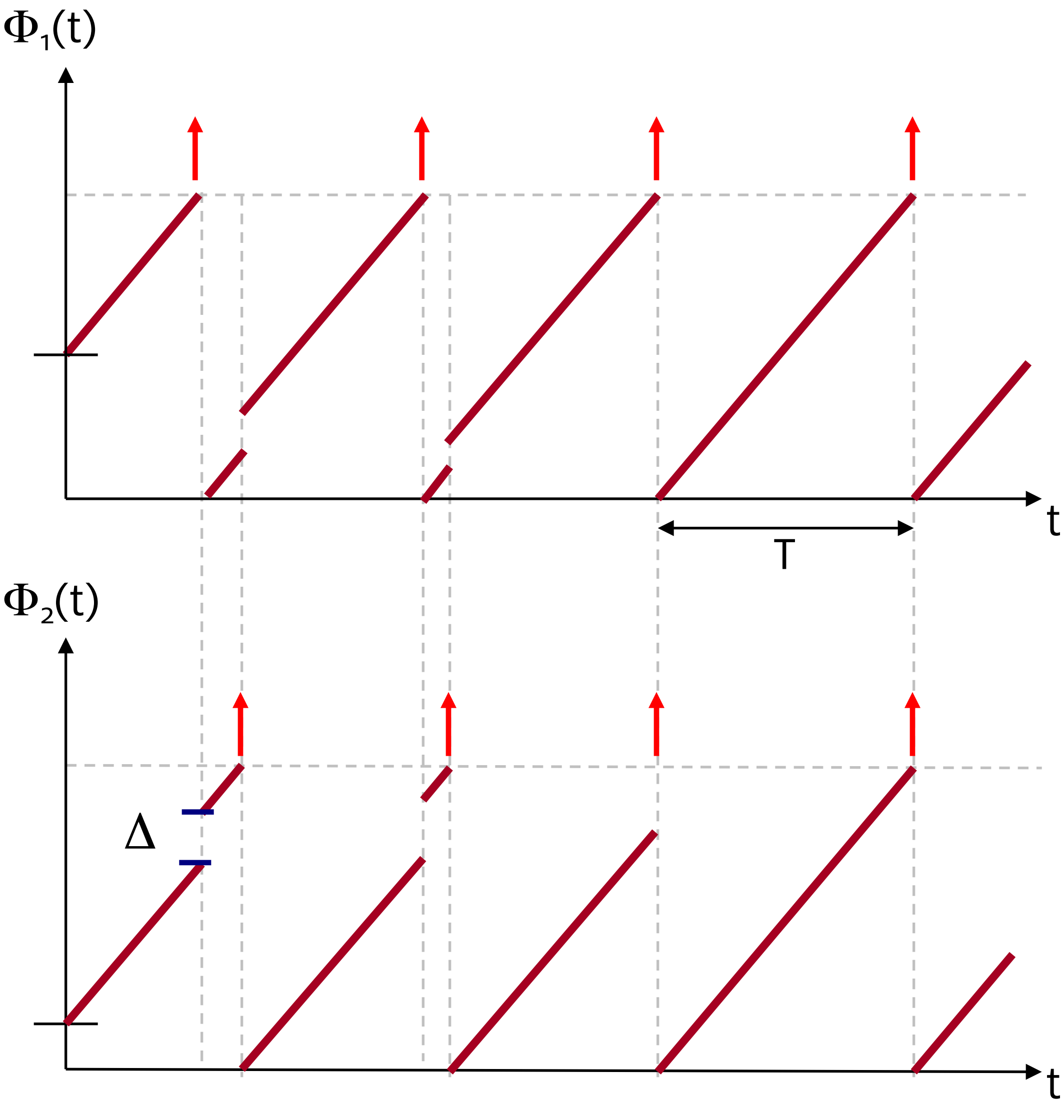
Modeling synchronization
Integrate-and-fire oscillator





Mirollo, Strogatz: Synchronization of pulse-coupled biological oscillators. *SIAM J. Applied Mathematics*, 1990.

Two coupled oscillators

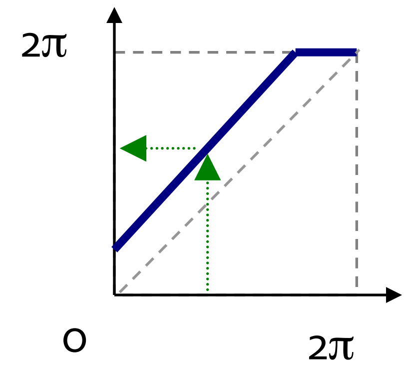


Phase jump upon reception of a pulse:

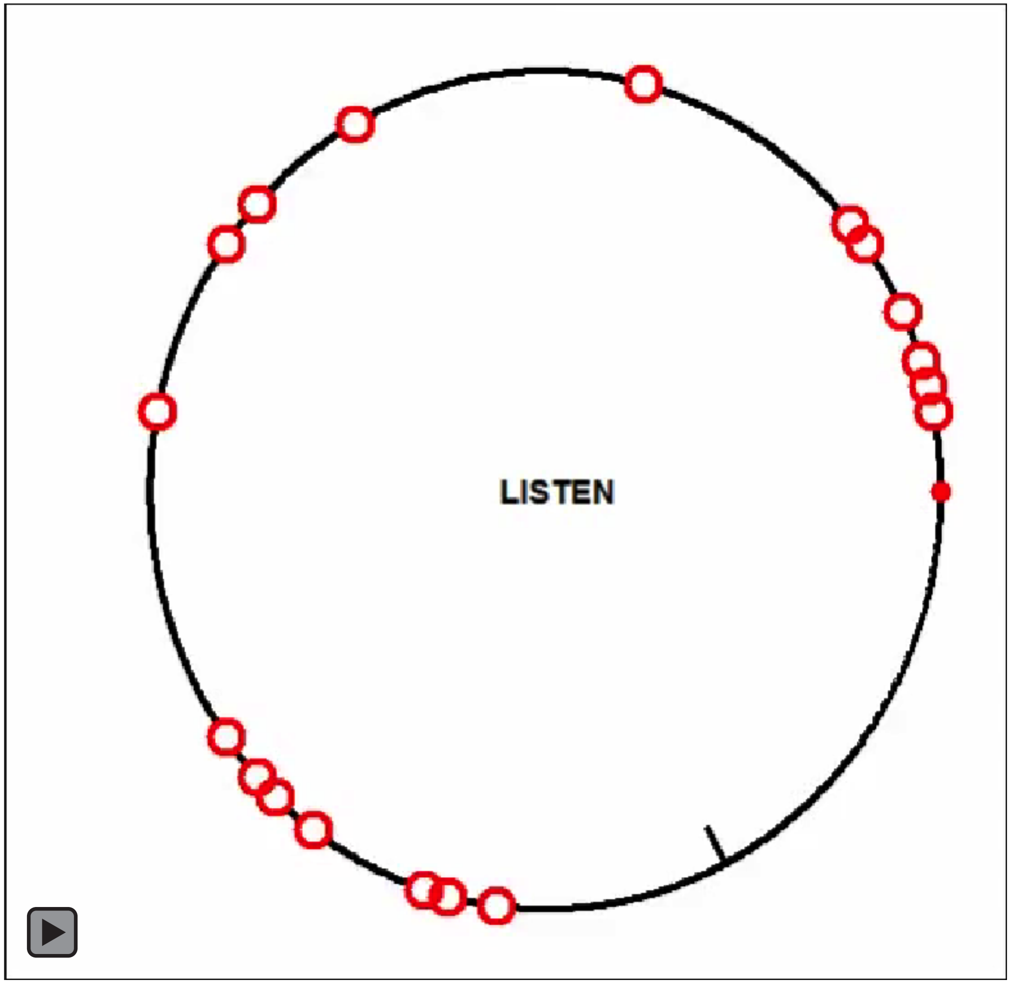
$$\Phi \rightarrow \Phi + \Delta$$

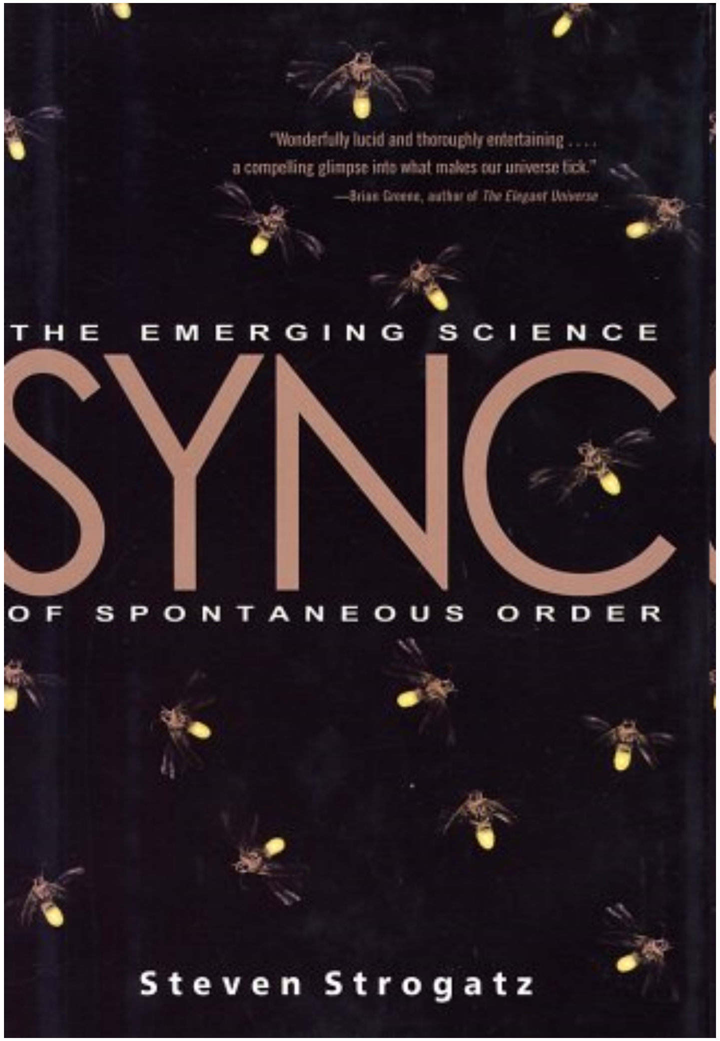
Update function:

$$H(\Phi) = \Phi + \Delta$$



Several coupled oscillators





- Firefly swarms
- Brain activity
- Sleep cycles
- Hands clapping
- Bridge vibrations
- Cardiac pacemaker cells

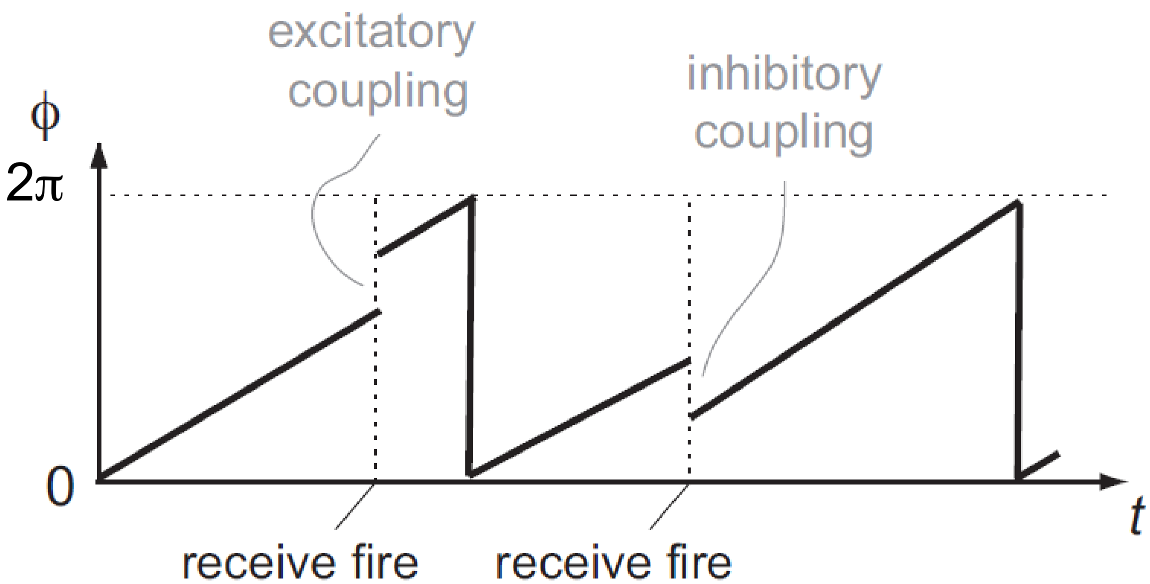
… and many other phenomena.

Synchronization with generalized assumptions

Extending the Mirollo-Strogatz model

- Concept can be used with sync words instead of short pulses.
- Certain delays make the synchronization process unstable. Solution is to apply refractory periods in each oscillator.
- Generalization from all-to-all coupling to multihop topologies
- Generalization from perfect channels to erroneous channels
- Generalization from identical and time-invariant oscillators to non-identical and time-varying oscillators
- Tuning of the update function

Inhibitory and excitatory coupling

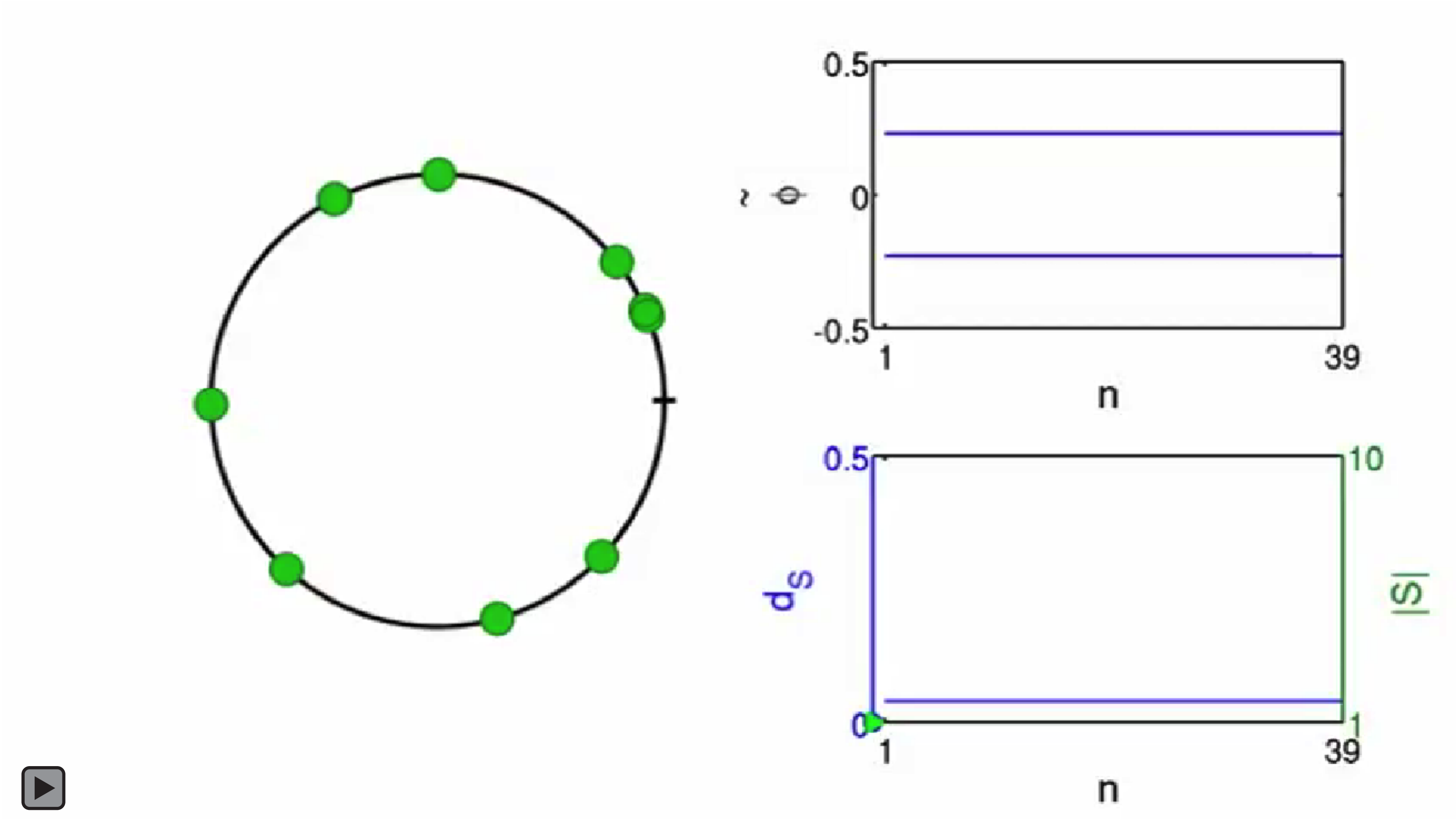


Van Vreeswijk, Abbott, Ermentrout: When inhibition not excitation synchronizes neural firing. *J. Computational Neuroscience*, Dec. 1994.

Nischwitz, Glünder: Local lateral inhibition: a key to spike synchronization? *Biological Cybernetics*, 1995.

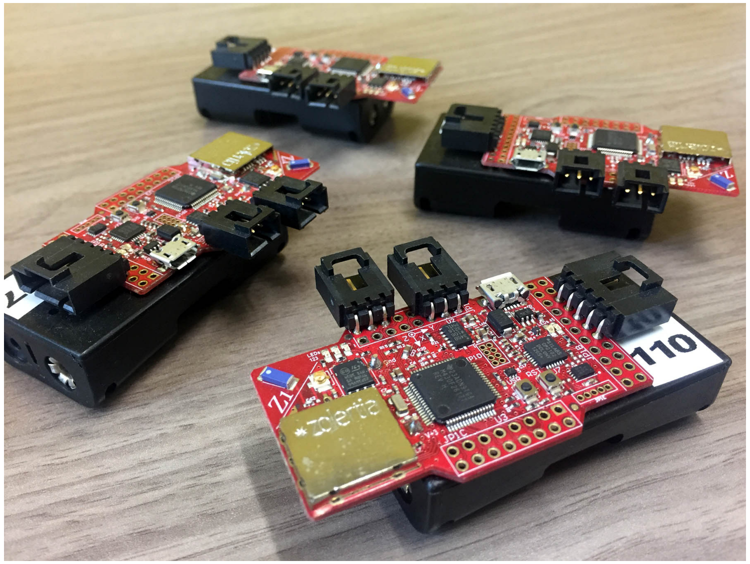
Van Vreeswijk, Sompolinsky: Chaos in neuronal networks with balanced excitatory and inhibitory activity. *Science*, 1996.

Inhibitory and excitatory coupling

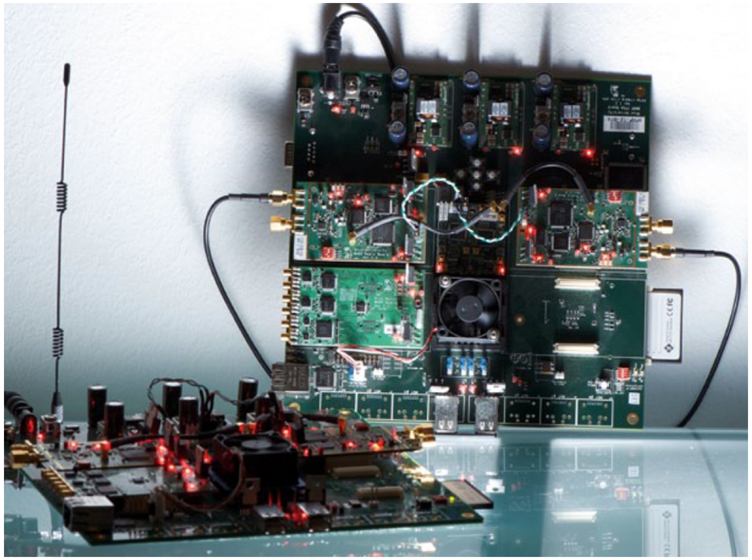


Synchronization in wireless networks

Our experimental performance studies



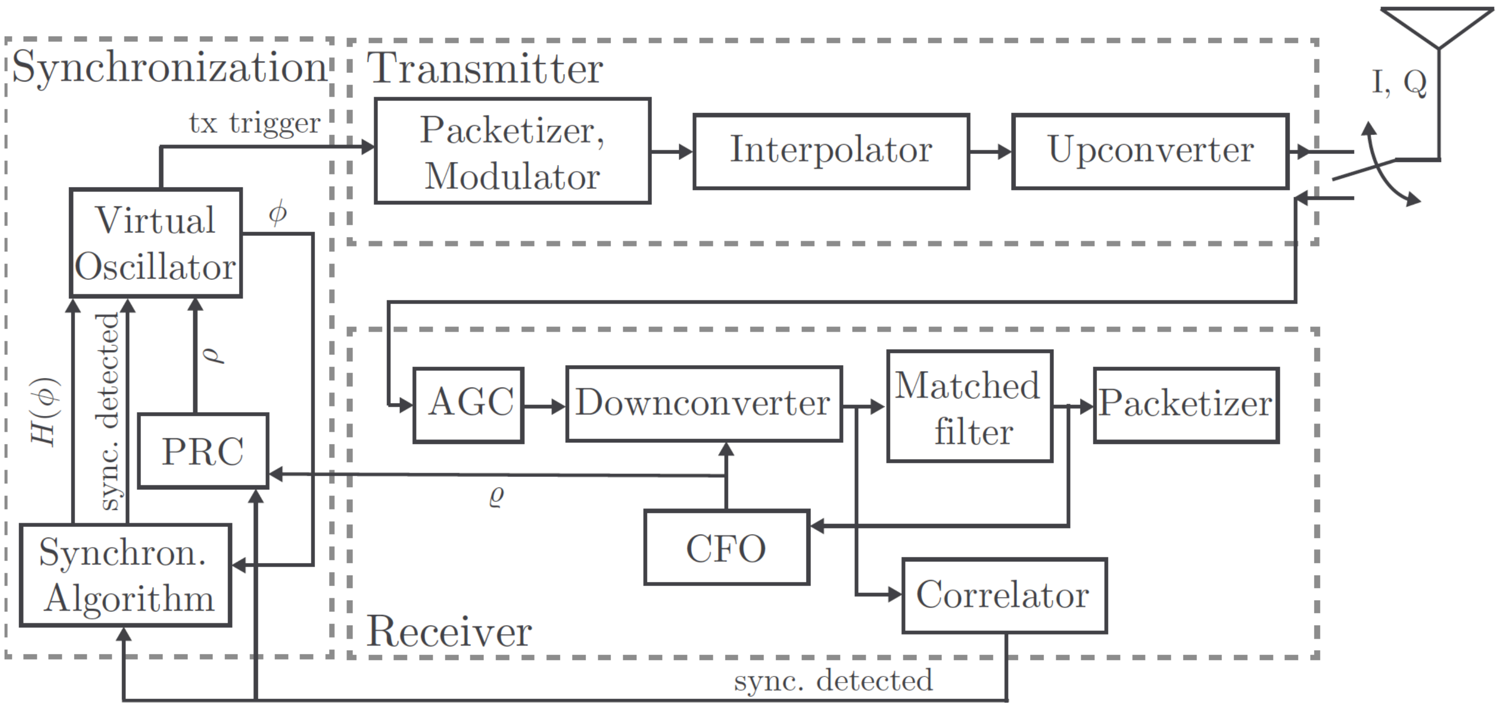
Sensor network with 100 Zolertia Z1 devices (IEEE 802.15.4)



System with five FPGA-based programmable radio boards (WARP)

Synchronization in wireless networks

Implementation on WARP boards

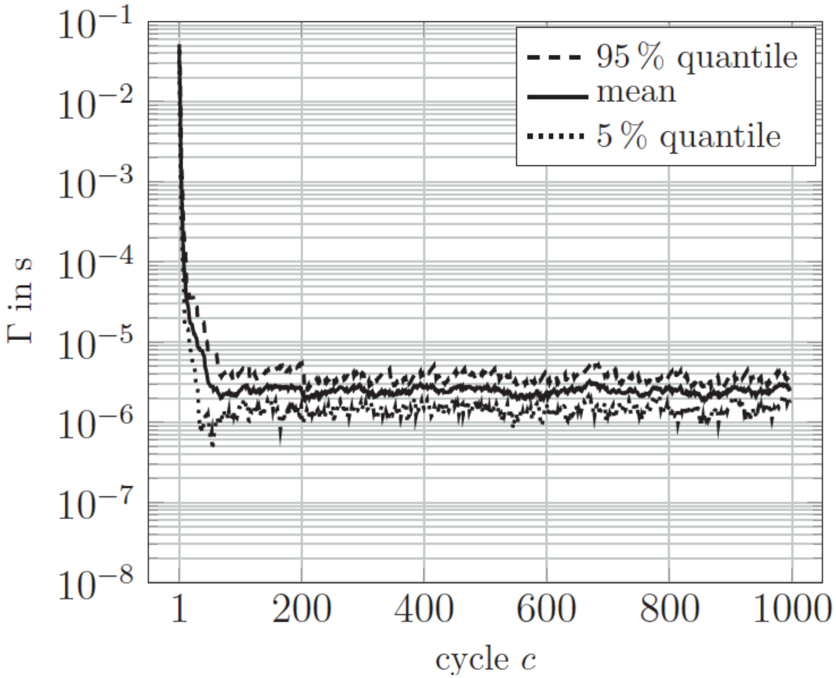


CFO: Carrier frequency offset

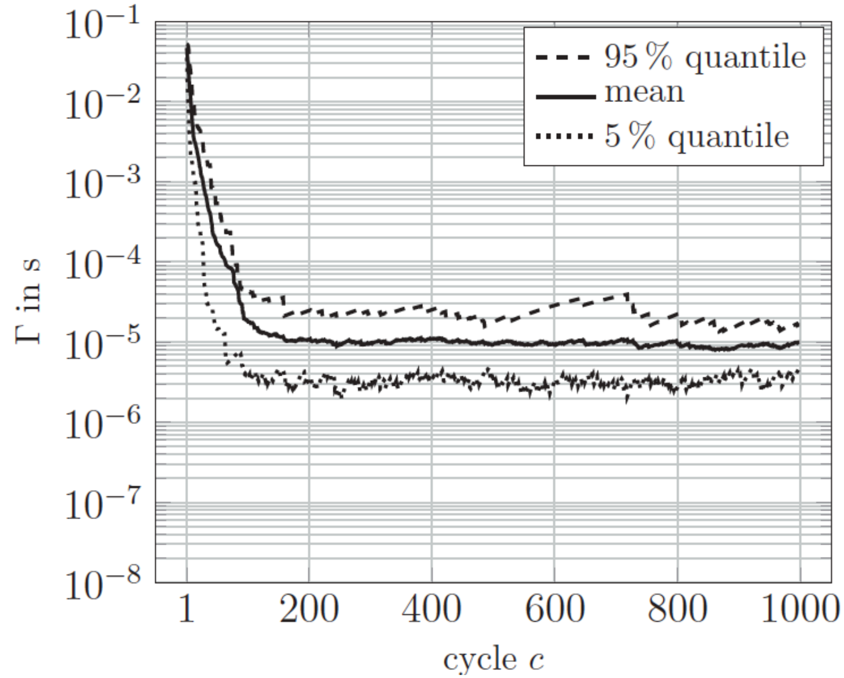
PRC: Phase rate correction

Synchronization in WARP networks

Precision with inhibitory-excitatory coupling



Fully connected topology

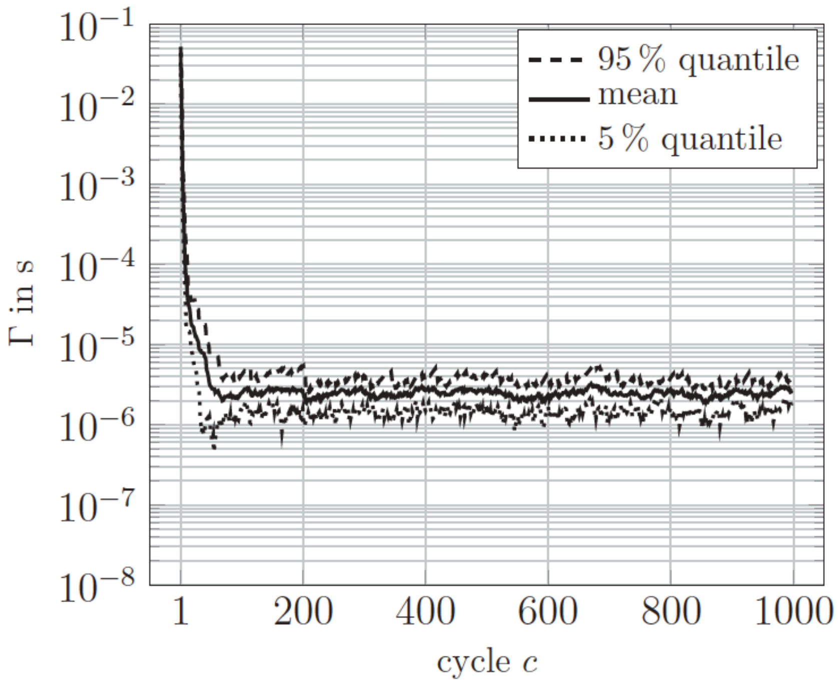


Star topology

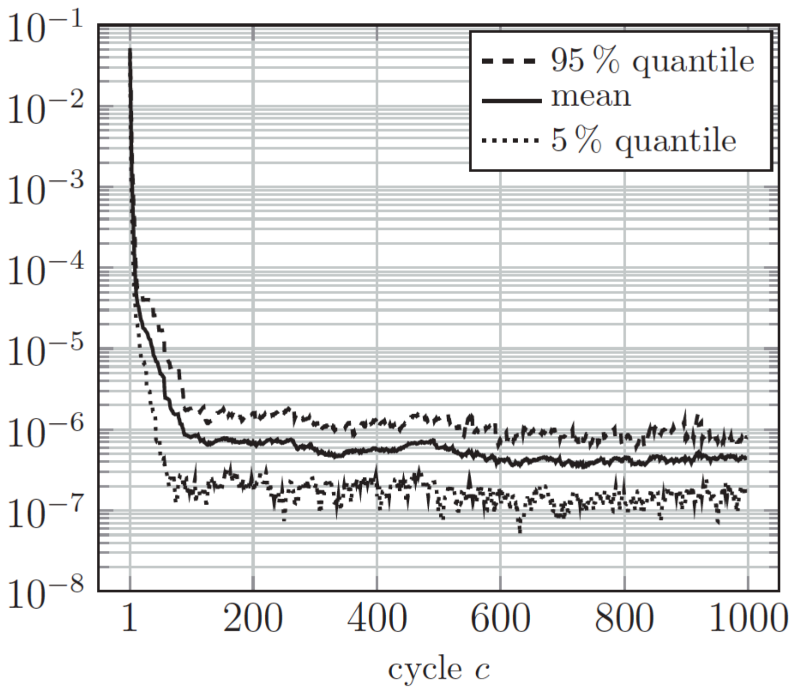
Brandner, Schilcher, Bettstetter: Firefly synchronization with phase rate equalization and its experimental analysis in wireless systems. *Computer Networks*, March 2016.

Synchronization in WARP networks

Precision with IE coupling and phase rate correction



Without phase rate correction



With phase rate correction (PRC)

Fully connected topology

Proofs of convergence to synchrony

"Does it always work?"

Publication	MS90	TWG02	NF11	KB12	KKBT12
Coupling	**E**	**I**	**EI**	**I**	**EI**
Delays	zero	fixed same for all	yes	**random** **different**	**random** **different**
Initial phases	almost all	subinterval	subinterval	**arbitrary**	**arbitrary**
Phase rates	identical	identical	identical	**different**	identical
Topology	all-to-all	**arbitrary**	**arbitrary**	all-to-all	**arbitrary**

E: Excitatory coupling **I**: Inhibitory coupling

Mirollo, Strogatz: Synchronization of pulse-coupled biological oscillators. *SIAM J. Applied Mathematics*, 1990.

Timme, Wolf, Geisel: Coexistence of regular and irregular dynamics in complex networks of pulse-coupled oscillators. *Phys. Rev. Lett.*, 2002.

Nishimura, Friedman: Robust convergence in pulse-coupled oscillators with delays. *Phys. Rev. Lett.*, 2011.

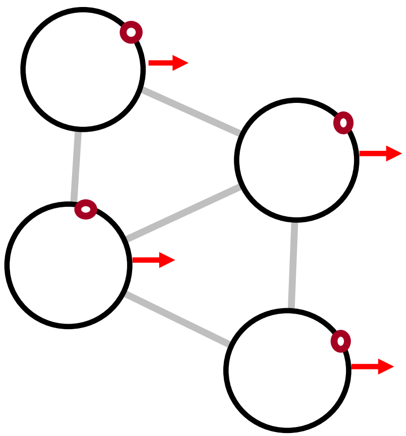
Klinglmayr, Bettstetter: Self-organizing synchronization with inhibitory-coupled oscillators. *ACM Trans. Auton. Adapt. Syst.*, 2012.

Klinglmayr, Kirst, Bettstetter, Timme: Guaranteeing global synchronization in networks with stochastic interactions. *New J. Physics*, 2012.

Stochastic coupling

An interesting phenomenon (1/3)

Ideal coupling



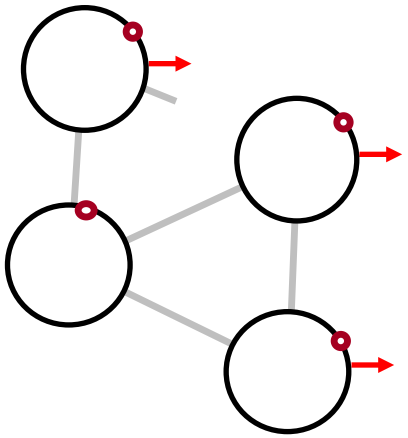
- Reliable firing
- Reliable channels
- Reliable reception

… can lead to non-convergence in multihop networks.

Stochastic coupling

An interesting phenomenon (2/3)

Stochastic coupling



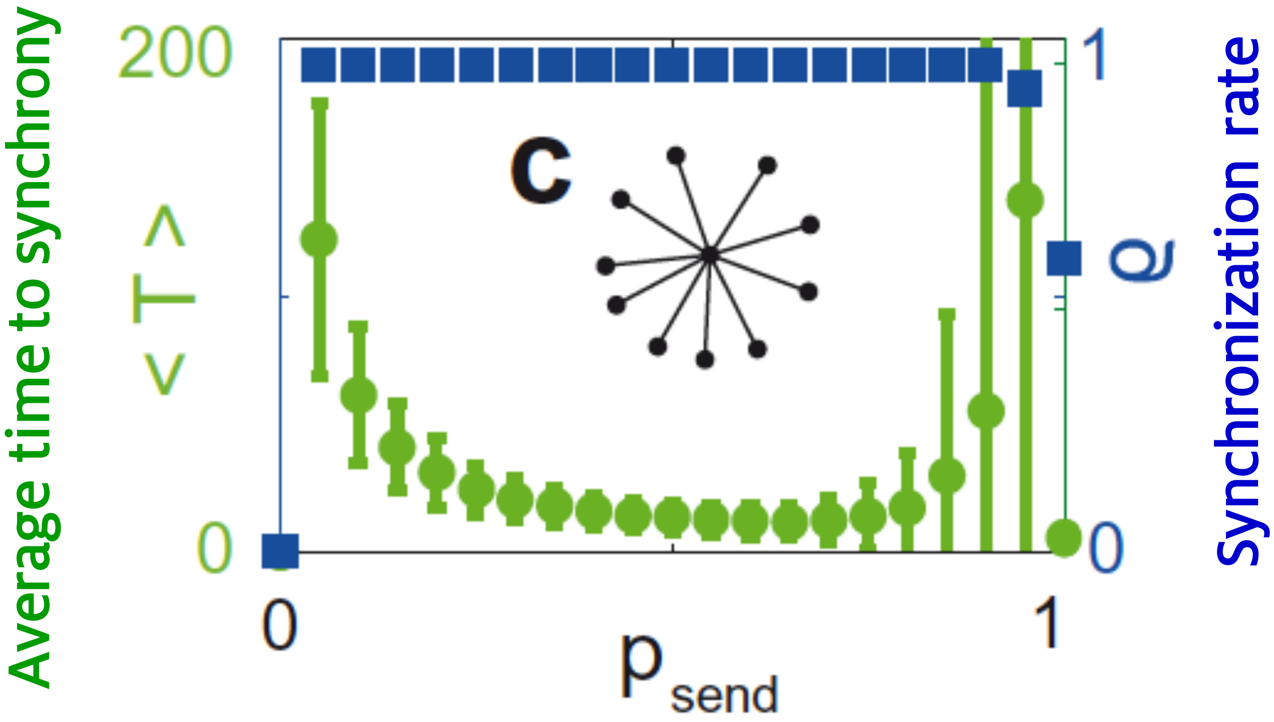
- Unreliable firing *or*
- Unreliable channels *or*
- Unreliable reception

- Is a requirement for our convergence proofs.
- Can have beneficial effects for sync guarantees, time, precision.
- Opens new design approach (intentionally stochastic coupling).

Stochastic coupling

An interesting phenomenon (3/3)

Fire pulse is sent with probability p_{send}



Design guidelines

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1. Use refractory periods in systems with delays.
2. Use combination of excitatory and inhibitory coupling.
3. Use stochastic coupling to enable convergence guarantees.
4. Use phase rate correction to improve precision in systems with non-identical and time-varying oscillators.
5. Balance fast synchronization versus robustness.

Lakeside Labs

Take-home messages

Sync from biology and physics to wireless systems

- Phenomena of self-organizing synchronization can be modeled using pulse coupled oscillators (PCO).
- Schemes are adaptive and scalable with the number of entities.
- Systems of identical oscillators with (fixed) delay can achieve perfect synchrony.
- More general systems were proven to converge. Their precision is determined e.g. by different phase rates and delay jitter.
- Precise synchronization was demonstrated in wireless networks.

Team

Predoctoral researchers

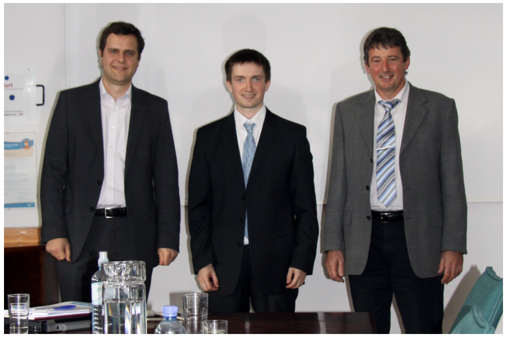
- Alexander Tyrrell (2005-09)
- Johannes Klinglmayr (2009-13)
- Günther Brandner (2008-15)
- Wasif Masood (2012-16)

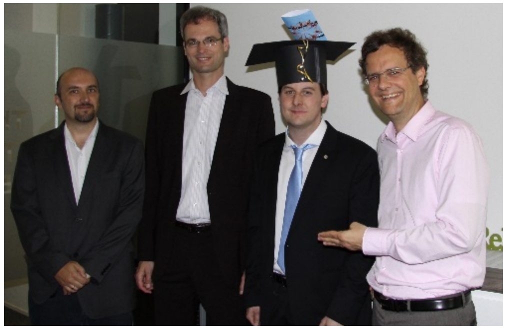
Postdoctoral researchers

- Udo Schilcher
- Jorge Friedrich Schmidt

Collaborators

- Gunther Auer (DOCOMO, now Ericsson)
- Marc Timme (MPI Göttingen)
- Christoph Kirst (Rockefeller)





Outlook

Theory

- Derive convergence proof for most general assumptions
- Investigate stochastic coupling as new design dimension
- Study robustness against malicious entities
- Extend insights to other forms of self-organizing coordination
- Study de-synchronization problems

Technology

- Synchronization in power grids
- Synchronization in mini-drone swarms

Moreira, Mathur, Diermeier, Amaral. Efficient system-wide coordination in noisy environments. *PNAS*, 2004.

Rohden, Sorge, Timme, Witthaut: Self-organized synchronization in decentralized power grids, *Phys. Rev. Lett.*, 2012.

Literature

Some general work

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- Buck, Buck: Synchronous fireflies. *Scientific American*, 1976.
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Some publications with emphasis on wireless systems

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- Werner-Allen, Tewari, Patel, Welsh, Nagpal: Firefly-inspired sensor network synchronicity with realistic radio effects. In *Proc. ACM SenSys*, 2005.
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- Wang, Nunez, Doyle: Statistical analysis of the pulse-coupled synchronization strategy for wireless sensor networks. *IEEE T. Signal Process.*, 2013.

Some publications by my team

- Tyrrell, Auer, Bettstetter. Fireflies as role models for synchronization in ad hoc networks. In *Proc. BIONETICS*, 2006.
- Tyrrell, Auer, Bettstetter: Emergent slot synchronization in wireless networks. *IEEE Trans. Mobile Comput.*, 2010.
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- Brandner, Schilcher, Bettstetter: Firefly synchronization with phase rate equalization and its experimental analysis … . *Computer Networks*, 2016.
- Klinglmayr, Bettstetter, Timme, Kirst: Convergence of self-organizing pulse coupled oscillator synchronization … . *IEEE Trans. Automat. Contr.*, 2017.