Self-organized synchronisation in massive MIMO inspired by biological systems

Lucas Wetzel[†‡], Alexandros Pollakis[*‡], David J. Jörg[†‡], Wolfgang Rave[*‡], Gerhard Fettweis[*‡], and Frank Jülicher[†‡]
[*]Technische Universität Dresden, Vodafone Chair, Dresden, Germany
[†]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany
[‡]Center for Advancing Electronics Dresden cfAED, Dresden, Germany

***Abstract*—Components of electronic networks can be orchestrated using a common time reference. For instance, antenna arrays in massive multiple-input multiple-ouput (MIMO) applications require synchronous carrier frequencies for all antennas. We show that mutually coupled digital phase-locked loops (DPLLs) can self-organize to provide frequency-synchronous clocking in large-scale systems. We develop a phase description of individual and coupled DPLLs that takes into account filter impulse responses and delayed signal transmission. We find that transmission delays between DPLLs can stabilize in-phase and other frequency-synchronized states, while instantaneously coupled DPLLs do not maintain synchrony. In such networks filtering and transmission delays have profound effects on the collective frequency and the time scale of synchronization. To test our theoretical predictions, we designed and carried out experiments using networks of off-the-shelf DPLL integrated circuitry. We show that the phase model can quantitatively predict the existence and stability of synchronized states. Our results demonstrate that mutually delay-coupled DPLLs can provide robust and self-organized synchronous clocking.**

I. Introduction

In large spatially extended electronic systems that rely on coordination of many components, it is a challenge to provide a global time reference, e.g., for network-on-chips and antenna arrays. In wireless communications, the multiple-input multiple-output (MIMO) concept is established in modern wireless communication standards such as Long-Term Evolution (LTE) [1] and IEEE 802.11n (WiFi) [2]. MIMO communications allows to exploit situations where several data streams can be transmitted in parallel on the same time-frequency resource, known by the notion of spatial multiplexing. This concept can be exploited to increase data rate, reliability, energy efficiency, and interference handling [3]. However, in large antenna systems, one major challenge is to ensure phase synchrony of the carrier signals for all antennas [4]. Traditional hierarchical clock distribution concepts rely on a *single* master node distributing a clocking signal using a tree-like structure to multiple slave nodes. Such structures become space and energy inefficient with an increasing system size and are vulnerable to errors due to noise and cross-talk [4]. In order to overcome these limitations, novel clocking concepts are needed.

Biological systems can provide inspiration, especially if complex systems operating in noisy environments are considered. Systems exhibiting self-organized synchronization such as neuron clusters and coupled genetic oscillators have attracted a wide experimental and theoretical research interest [5], [6]. Through mutual coupling of their oscillatory dynamics, these systems synchronize robustly despite operating in highly noisy environments and in the presence of communication time delays.

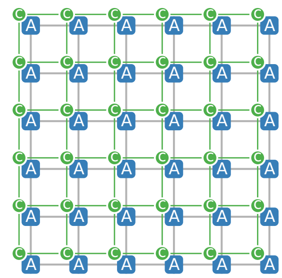

Fig. 1: Clocking network architecture of 36 nearest-neighbour coupled clocks (C), each with a local antenna (A).

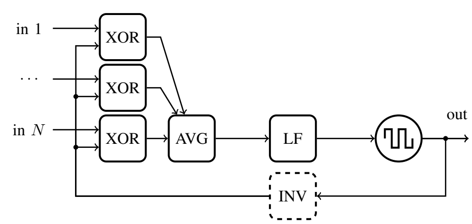

Fig. 2: Signal flow of a DPLL with multiple delayed input signals with a phase detector (PD), loop filter (LF), voltage-controlled oscillator (VCO), and optionally an inverter (INV).

Utilizing the understanding of the synchronization dynamics in a biological system, we propose a massive MIMO clocking concept in which each node/antenna is equipped with a local clock. These clocks are mutually coupled such that each clock sends its signal to at least one other clock and receives an input from at least one other clock of the network, e.g. nearest-neighbour coupling, and form a clock distribution network that is able to synchronize in a self-organized way (Fig. 1) [7]. As the system size increases and/or the clock frequencies become large, transmission delays have to be considered within the clock distribution network and become of functional relevance. Even for signalling with propagation speeds close to the speed of light, only a few centimetres are bridged in a nanosecond, the period of a 1GHz clock.

II. Theory of Self-Organized Synchronization

Each node contains a digital phase-locked loop (DPLL) with a phase detector (PD), see Fig. 2, consisting of multiple XOR gates and an averaging block [8]. Additionally there can be a delay component in each input path to control the values of the transmission delays, not shown here. For a VCO with a digital output signal, an ideal low-pass as LF, and a linear VCO frequency response, the time evolution of the phase of DPLL k is governed by

$$\dot{\phi}_k(t) = \omega + \frac{K}{n(k)} \sum_{l=1}^{N} c_{kl} \int_0^\infty \mathrm{d}u\, p(u) \times \Delta\big(\phi_l(t-\tau-u) - \phi_k(t-u)\big) \;, \tag{1}$$

where ω is the intrinsic frequency of the VCO, K the denotes the VCO's sensitivity, $c_{kl} \in \{0,1\}$ encode the network topology, $p(u)$ denotes the LF impulse response, and $n(k) = \sum_l c_{kl}$ the averaging factor. The triangular function Δ is defined by $\Delta(\phi) = 2|\phi|/\pi - 1$ in the range $-\pi \leq \phi \leq \pi$ and satisfies $\Delta(\phi + 2\pi) = \Delta(\phi)$ for all ϕ. Here we have considered identical transmission delays τ between coupled DPLLs.

The global in-phase synchronized state is characterized by all DPLLs evolving with the same collective frequency Ω and without phase lags, $\phi_k(t) = \Omega t$. The collective frequency of these states is given by the solutions to

$$\Omega = \omega + K\Delta(\Omega\tau). \tag{2}$$

This solution is independent of the number N of DPLLs and the network topology. The global frequency Ω deviates from the intrinsic frequency in dependence of the transmission delay τ and the sensitivity K of the VCO.

Whether an in-phase synchronized state can be achieved depends on its stability properties. We find that a small additive phase perturbation decays or grows with a complex frequency λ, where $\mathrm{Re}(\lambda)$ is the exponential decay or growth rate and $\mathrm{Im}(\lambda)$ is a modulating frequency. The complex frequency λ depends on the characteristic length scale of the perturbation in relation to the network size. Using the phase model Eq. (1) the complex frequencies λ can be obtained as solutions to

$$\lambda/\hat{p}(\lambda) + K\Delta'(\Omega\tau)(1 - \zeta e^{-\lambda\tau}) = 0 \;, \tag{3}$$

where $\hat{p}(\lambda)$ is the LF's transfer function. The length scale of a perturbation enters through the eigenvalues ζ of the network topology matrix. The in-phase synchronised state is stable only if $\mathrm{Re}(\lambda) < 0$ for all λ and for all ζ. Hence, we can use Eq. (3) to determine the stability of the in-phase synchronised states and the times scales of synchronisation.

III. Numerical Example and Prototype Setup

As an example we show a quadratic grid of 6x6 nearest-neighbour coupled DPLLs with open boundary conditions (Fig. 1). Figure 3A shows the collective frequency of all clocking nodes in dependence of the transmission delay. For large transmission delays multiple solutions can coexist with different collective frequencies. Which solution is attained depends on the initial conditions. Fig. 3B shows the perturbation decay rate and stable regions corresponding to the in-phase synchronized solution in Eq. (2) for active and inactive inverter. The perturbation response rates and stability depend on all system parameters. The inverter is used to achieve stability of the in-phase synchronized state for a wide range of transmission delays.

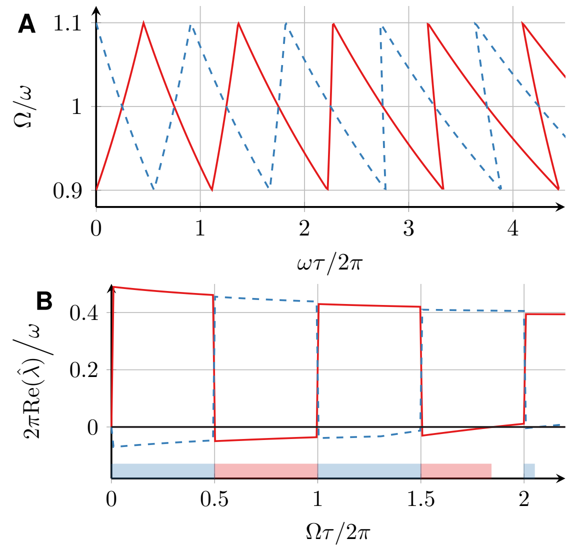

Fig. 3: (A) Collective frequency as a function of the transmission delay. (B) $\mathrm{Re}(\hat{\lambda})$, the slowest decaying perturbation mode, for a 6x6 nearest-neighbour coupled quadratic grid of delay-coupled DPLLs vs $\Omega\tau$. In both plots solid red lines show the results with inactive inverter, blue dashed lines the results with active inverter. The red and blue bars indicate stable regions with active or inactive inverter. DPLL parameters: $\omega/2\pi = 1\,\mathrm{GHz}$, $K/2\pi = 100\,\mathrm{MHz}$, first order butterworth LF with $50\,\mathrm{MHz}$ cut-off frequency.

Using a prototype 3x3 network of coupled DPLLs with nearest neighbour coupling we obtain the frequency and the perturbation decay from the measured phase time series of the DPLLs which are in quantitative agreement with the phase model predictions.

IV. Future Work

We currently investigate the robustness of the synchronized state against phase noise within the phase description. In addition, we develop algorithms to tailor the network topology to given system requirements and investigate strategies to efficiently boot large networks. To further test our model we plan to implement massive MIMO prototype antenna arrays and compare these with Master-Slave clock trees.

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