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(54) Self-synchronizable network

Selbst-synchronisierbares Netzwerk

Réseau auto-synchronisable

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- **F.M. ORSATTI; R. CARARETO; J.R.C. PIQUEIRA: "Mutually connected phase-locked loop networks: dynamical models and design parameters", IET CIRCUIT DEVICES SYST., vol. 2, no. 6, 2008, pages 495-508, XP002733443,**

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Description

Field of the invention

[0001] The present invention relates to a synchronizable network. The present invention specifically relates to clock distribution and self-organized synchronization in large scale networks, like high performance Multiprocessor System-on-Chips (MPSoCs) architectures.

Background of the invention

[0002] Enabled by sub-micrometer semiconductor device fabrication technologies, MPSoCs have become a key component for modern communications and computation systems. Lately, the trend to integrate more and more processing cores in a single silicon die has gained momentum, aided by promising benefits in mechanical footprint, computational performance, energy and cost efficiency. Hence, increasing the number of cores directly translates into high performance through parallel processing and high efficiency compared to single-core solutions.

[0003] Nowadays, hundreds of thousands of cores are integrated on one single chip. To ensure a stable and well defined system a common synchronization strategy is to separate clocking of the processing blocks. The globally asynchronous locally synchronous (GALS) clocking yields a simplified clock tree and allows clock generation on-chip to minimize the number of required I/O pins. Hence, the clock frequencies and supply voltages, within a heterogeneous MPSoC, can be dynamically adjusted per core. However, the flexibility, scalability and other benefits of GALS clocking technique goes along with performance penalties caused by additional communication latencies between disjoint clock domains. This exactly describes the bottleneck of the GALs approach.

[0004] In contrast, for high performance microprocessors a globally synchronous design as shown in Fig. 1, where all cores 12 of a clocking network 11 share one master clock 13, is used. The communication latencies between cores are drastically reduced compared to GALS clocking. Considering next generation MPSoCs, a very large chip area has to be clocked synchronously. Implementing a master clock based clock tree, see Fig. 1, the clock signals within MPSoCs have to be transmitted over ranges of some millimeters, which is a well-known bottleneck for speed, power and reliability. Furthermore, traditional globally synchronous clocking circuits have become too difficult for large MPSoCs with many cores, constantly growing chip size and wire induced delays. In addition, the clock trees consume a significant amount of power which is critical for mobile communication systems.

[0005] Both clocking techniques, GALS and the globally synchronous design, reach their limits at large scale networks like massive MPSoCs.

[0006] Another strategy for network synchronization and clock distribution relates to self-organized synchronization of distributed network nodes in absence of an entraining master clock.

[0007] "Mutually connected phase-locked loop networks: dynamical models and design parameters" by F.M. Orsatti, R. Carareto, J.R.C. Piqueira, IET Circuit Devices Syst.,2008, Vol. 2, No. 6, pp. 495-508 relates to distributing clock signals by using mutually connected architectures instead of master-slave type architectures. Mutually connected digital PLL networks are studied and conditions for the existence of synchronized states are derived, depending on individual node parameters and network connectivity, considering that the nodes are nonlinear oscillators with nonlinear coupling conditions.

[0008] "Multiple synchronous states in static delay-free mutually connected PLL networks" by F.M. Orsatti, R. Carareto, J.R.C. Piqueira, Signal Processing 90 (2010) 2072-2082 relates to mutually connected networks of digital phase-locked loops. Even for static networks without delays, different synchronous states may exist for the network.

[0009] However, these papers deal with networks for which a time delay between oscillators is not present or negligible. Hence, the solution presented there cannot be applied to networks exhibiting a significant time delay between network nodes.

[0010] WO 2013/178237 A1 relates to a communication network of interconnected communication nodes, each node comprising an oscillator that is mutually coupled to oscillators of other communication nodes. The oscillator generates periodic synchronization pulses. The communication node further comprises a transmitter for transmitting the synchronization pulses to other communication nodes; a receiver for receiving synchronization pulses from other communication nodes; and a synchronization unit for synchronizing the phase of the synchronization pulses generated by the oscillator with the phase of the synchronization pulses received from other communication nodes by adjusting the phase of the synchronization pulses generated by the oscillator upon receipt of synchronization pulses from other communication nodes. The synchronization unit adjusts the phase of the synchronization pulses generated by the oscillator in such a way that a guaranteed network-wide synchronization is achieved for all communication nodes of the communication network.

[0011] However, WO 2013/178237 A1 explicitly limits a transmission time delay of the synchronization pulses between the communication nodes to one eighth of the period of the oscillator. Hence, this disclosure does not provide a suitable solution for networks exhibiting a transmission time delay exceeding one eighth of the period of the oscillator, e.g., highly integrated chip networks. Moreover, this solution assumes pulse coupling. Stochastic synchronization pulse emission is required to guarantee synchronization. Hence, this solution is not suitable for clock distributions with time-continuous coupling.

Disclosure of the invention

[0012] It is an objective of the present invention to provide a solution for synchronizing a network comprising a plurality of interconnected nodes that provides a stable synchronized state, especially for large scale networks.

[0013] This objective is achieved with a node according to the independent apparatus claim and a method for synchronizing a network according to the independent method claim.

[0014] The present invention relates to a node for a network comprising a plurality of interconnected nodes. The node comprises a controllable oscillator generating a time-continuous synchronization signal for synchronizing the plurality of interconnected nodes of the network. The node further comprises a controller for comparing and synchronizing a phase of the time-continuous synchronization signal generated by the controllable oscillator, which is transmitted to other nodes of the network, with the phase of an external time-continuous synchronization signal received from other nodes of the network by adjusting a frequency of the time-continuous synchronization signal generated by the controllable oscillator. The external time-continuous synchronization signal received from another node of the network is delayed with respect to the time-continuous synchronization signal transmitted by the other node by a total time delay. The total time delay is a transmission time delay resulting from a transmission time between the transmission of the external time-continuous synchronization signal by the other node and the following receipt of the external time-continuous synchronization signal by the node. The total time delay also comprises any tunable additional time delays in addition to the transmission time delay. The controller iteratively adjusts the frequency of the time-continuous synchronization signal generated by the controllable oscillator such that a network-wide synchronization of oscillators is achieved for all nodes of the network. At least one of the following parameters: the total time delay τ_T, the feedback delay τ_f, a free running frequency ω of the controllable oscillator (33), a coupling strength K, an impulse response $p(u)$ of a filter (32) within the controller (31, 32), is tuned to yield a desired perturbation response rate λ, i.e. perturbation response rate λ with $\mathrm{Re}(\lambda)<0$, and/or collective frequency Ω. The desired perturbation response rate λ solves

$$e^{\lambda\tau_T}\left(\frac{\lambda}{\alpha\hat{p}(\lambda)}+e^{-\lambda\tau_f}\right)=\zeta \quad ,$$

wherein ζ denotes an eigenvalue of a normalized coupling matrix $\mathbf{\tilde{D}} = (\tilde{d}_{kl})$ with $\tilde{d}_{kl}=d_{kl}/n_k$, $d_{kl}\in\{0,1\}$, where $d_{kl}=1$ indicates a connection between node k and node l, n_k denotes a number of received external time-continuous synchronization signals;

$\alpha=Kh'(-\Omega[\tau_T-\tau_f])$, wherein h' denotes a first derivative of a coupling function h;

$$\hat{p}(\lambda)=\int_0^\infty du\; p(u)\, e^{-\lambda u}$$

denotes a Laplace transform of an impulse response $p(u)$ of the filter within the controller; and

wherein the collective frequency Ω solves:

$$\Omega=\omega+Kh(-\Omega[\tau_T-\tau_f]) \ .$$

[0015] The synchronization is thus achieved in a continuous self-organized process in interaction with other nodes of the network.

[0016] The controller may be any control system with feedback of the continuous synchronization signal generated by the tunable oscillator.

[0017] Specifically, the controller in combination with the controllable oscillator may form a phase locked loop (PLL). PLLs are electronic components able to synchronize their synchronization signals by evaluating mutual phase differences and adjusting their frequencies accordingly. The controller then comprises a phase detector (PD) and a loop filter (LF). The controllable oscillator may be a voltage controlled oscillator (VCO). The phase detector compares the phase of the external time-continuous synchronization signal with the phase of the time-continuous synchronization signal generated by the controllable oscillator.

[0018] A model for mutually coupled PLLs is described below using an analog PLL as an example. The present invention is not restricted to analog PLLs.

[0019] The VCOs output a sinusoidal with constant amplitude, which can be set to 1 without loss of generality,

$$x_k(t)=\sin\phi_k(t) \tag{1}$$

where $\phi_k(t)$ denotes the phase of the oscillatory signal and k=1,2 indexes the PLL. The phase detector multiplies an external input signal x_l with the output signal x_k of the VCO. Total time delays, for example resulting from transmission time delays and/or tunable additional time delays between the PLLs are accounted for by a delay τ_T of the received signal. Moreover, a feedback delay between the VCO and the PD is accounted for by a delay τ_f in the VCO signal. However, the feedback delay may be zero.

$$\begin{aligned}x_k^{PD}(t)&=x_l(t-\tau_T)\cdot x_k(t-\tau_f)\\&=\frac{1}{2}[\cos(\phi_l(t-\tau_T)-\phi_k(t-\tau_f))-\cos(\phi_l(t-\tau_T)+\phi_k(t-\tau_f))]\end{aligned} \tag{2}$$

[0020] This signal x_k^{PD} is filtered by the loop filter

$$x_k^C(t)=\int_0^\infty du\; p(u)\, x_k^{PD}(t-u) \tag{3}$$

according to the impulse response $p(u)$ of the LF. The output x_k^C of the LF yields the control signal for the VCO. The dynamic frequency of the VCO is given by its intrinsic frequency ω, which is modulated by the control signal x_k^C,

$$\dot{\phi}_k(t)=\omega+K_{VCO}x_k^C(t) \tag{4}$$

where K_{VCO} is the sensitivity of the VCO. In Eq. (2), the first term containing a phase difference describes low frequency components of the signal, while the second term containing a sum of phases describes high frequency components. Approximating the LF as ideal, these high frequency components are fully damped and can therefore be omitted. Hence, the dynamic frequency of the VCO is given by

$$\dot{\phi}_k(t)=\omega+K\int_0^\infty du\; p(u)\cos(\phi_l(t-\tau_T-u)-\phi_k(t-\tau_f-u)) \tag{5}$$

where $K=K_{VCO}/2$ is the coupling strength and has the dimension of a frequency. The cosine function containing the phase difference is called the coupling function. This is a closed phase equation for two mutually delay-coupled PLLs.

[0021] Eq. (5) can be extended to a phase model for N delay coupled PLLs with transmission delays between coupled oscillators. A standard state-of-the-art PLL handles only a single input signal. The controller then compares and synchronizes a phase of the time-continuous synchronization signal generated by the controllable oscillator with the phases of external time-continuous synchronization signals received from a plurality of other nodes of the network by adjusting a frequency of the time-continuous synchronization signal generated by the controllable oscillator.

[0022] One aspect of the present invention relates to a combiner for combining external time-continuous synchronization signals received from other nodes of the network to generate a combined external time-continuous synchronization signal. The phase detector compares the phase of the time-continuous synchronization signal generated by the controllable oscillator with the phase of the combined external time-continuous synchronization signal. The combiner may be part of the phase detector (PD). The combiner may be a noninverting adder. The phase detector (PD) may be a multiplier for analog signals or an XOR gate for digital signals. Alternatively, the phase detector may compare the phase of the time-continuous synchronization signal generated by the controllable oscillator with the phase of each external time-continuous synchronization signal individually to generate a plurality of phase detector signals. The combiner then combines the phase detector signals to control the controllable oscillator.

[0023] The phase model for N coupled analog PLLs reads

$$\dot{\phi}_k(t) = \omega_k + \frac{K}{n_k}\sum_{l=1}^{N} d_{kl}\int_0^{\infty} du\ p(u)\cos(\phi_l(t-\tau_T-u)-\phi_k(t-\tau_f-u)) \qquad (6)$$

[0024] The connections between PLLs are described by the coupling matrix **D**=(d_{kl}) with $d_{kl}\in\{0,1\}$, where $d_{kl}=1$ indicates a connection between *k* and *l*. The coupling strength is normalized by the number of input signals $n_k = \sum_l d_{kl}$. Two examples of coupling matrices are given for global coupling with *N* =4 oscillators and for nearest-neighbor coupling on a 2x2 lattice with periodic boundary conditions:

$$\mathbf{D}_{\text{global}} = \begin{pmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix}, \quad \mathbf{D}_{\text{nearest-neighbor}} = \begin{pmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{pmatrix} \qquad (7)$$

[0025] In global in-phase synchronous states, the phase of all oscillators satisfy

$$\phi_k(t) = \Omega t \quad \forall k, \qquad (8)$$

where Ω denotes a global / collective frequency. The global / collective frequency Ω satisfies

$$\Omega = \omega + K\cos(\Omega[\tau_T - \tau_f]) \quad , \qquad (9)$$

where $\omega_k = \omega \forall k$, with $\int_0^{\infty} du\ p(u) = 1$, and $\sum_{l=1}^{N} d_{kl} = n_k$. This result is valid for any coupling topology if there is no disjoint set of nodes.

[0026] One aspect of the present invention relates to tuning the total time delay between mutually coupled PLLs. A stable in-phase synchronized solution, Eq. (8), with global frequency Ω cannot be achieved for arbitrary total time delays between coupled synchronizers. The total time delay is a design parameter and can be tuned by an additional delayer and the design of the network. A node may comprise a delayer for inducing an additional time delay to a transmission time delay. The total time delay effectively induces a frequency-dependent phase shift to a synchronization signal and, if appropriately tuned, changes the coupling properties such that stable synchronized states become possible. A delayer may be any means suitable to induce such phase shifts. The delayer may need to be specifically tuned for each input path.

[0027] The total time delay may comprise a period of the controllable oscillator. Specifically, it may exceed one eighth of a period of the controllable oscillator. Thus, networks with large delays can be synchronized.

[0028] The node may further comprise a feedback delayer for inducing a feedback delay τ_f in a feedback path between the controllable oscillator and the phase detector. The feedback delay may compensate for the total time delay. The collective frequency then depends on the difference between the total time delay and the feedback delay.

[0029] Furthermore, the total time delay may be tuned such that it minimizes a perturbation response rate λ in order to arrive at an in-phase synchronized state with maximum stability as will be explained.

[0030] For a phase perturbed by a perturbation $q_k(t)$

$$\phi_k(t) = \Omega t + \varepsilon q_k(\mathrm{t}) \quad \forall k, \qquad (10)$$

where ε is small, Taylor expansion of Eq. (6) to first order in ε at $\varepsilon=0$ yields the linear dynamics of the perturbation,

$$\dot{q}_k(t)=\frac{\alpha}{n_k}\sum_{l=1}^{N}d_{kl}\int_0^{\infty}du\; p(u)\,[q_l(t-\tau_T-u)-q_k(t-\tau_f-u)] \tag{11}$$

where

$$\alpha=K\sin(\Omega[\tau_T-\tau_f]) \tag{12}$$

[0031] Substituting the exponential ansatz $q_k(t)=c_k e^{\lambda t}$, where λ is complex, into Eq. (11) the characteristic equation is given by

$$\lambda c_k=\frac{\alpha}{n_k}\hat{p}(\lambda)\sum_{l=1}^{N}d_{kl}(c_l e^{-\lambda\tau_T}-c_k e^{-\lambda\tau_f})\ , \tag{13}$$

where $\hat{p}(\lambda)=\int_0^{\infty}du\; p(u)\,e^{-\lambda u}$ is the Laplace transform of the impulse response $p(u)$ of the LF. The in-phase synchronized state Eq. (8) is linearly stable if and only if $\mathrm{Re}(\lambda)<0$ for all solutions to Eq. (13). In the absence of a total time delay and a feedback delay, no stable synchronized can exist: for τ_T-τ_f=0, Eq. (12) implies α=0 and Eq. (13) only permits the solution λ=0. This indicates neutral stability, where any small perturbation persists. Hence, only a non-zero difference of total time delay and feedback delay allows for stable in-phase synchronized states. It shall be remarked that two unfavorable effects for in-phase synchronization (non-attractive coupling, total time delay induced by transmission delay) combined yield a desirable technical effect.

[0032] Solutions for λ can be obtained by rewriting Eq. (13) in vector form

$$e^{\lambda\tau_T}\left(\frac{\lambda}{\alpha\hat{p}(\lambda)}+e^{-\lambda\tau_f}\right)\mathbf{c}=\tilde{\mathbf{D}}\mathbf{c} \tag{14}$$

with $\mathbf{c}=(c_1...c_N)^T$ and the normalized coupling matrix $\tilde{\mathbf{D}}=(\tilde{d}_{kl})$ with $\tilde{d}_{kl}=d_{kl}/n_k$. For any solution λ, the scalar coefficient on the left hand side of Eq. (14) is an eigenvalue of $\tilde{\mathbf{D}}$. A strategy to solve Eq. (14) is thus to solve the equation $e^{\lambda\tau_T}(\lambda/\alpha\hat{p}(\lambda)+e^{-\lambda\tau_f})=\zeta$ for each eigenvalue ζ of $\tilde{\mathbf{D}}$. The corresponding eigenvectors **c** are collective perturbation modes for which the linearized dynamics decouple.

[0033] For an arbitrary 2n-periodic coupling function *h*, the term α in Eq. (14) satisfies:

$$\alpha=Kh'(-\Omega[\tau_T-\tau_f])\ , \tag{15}$$

wherein *h'* denotes a first derivative of coupling function *h,* and *K* denotes the coupling strength. The collective frequency Ω solves:

$$\Omega=\omega+Kh(-\Omega[\tau_T-\tau_f])\ . \tag{16}$$

[0034] Thus, for a desired collective frequency Ω the total time delay τ_T in combination with the feedback delay τ_f may be tuned such that a maximum perturbation decay can be achieved by optimizing the perturbation response rate λ, see Eq. (9).

[0035] Moreover, further design parameters for optimizing the perturbation response rate λ are the free running frequency ω of the controllable oscillator, the coupling strength *K,* and the impulse response *p(u)* of a filter within the controller, i.e., the loop filter.

[0036] One aspect of the present invention relates to optimizing the perturbation response by tuning the cut-off frequency of the loop filter.

[0037] A large class of loop filters can be described by an impulse response $p(t)$, here given by the Gamma distribution,

$$p(t)=t^{a-1}\frac{e^{-t/b}}{b^a\Gamma(a)} \qquad (17)$$

where $\boldsymbol{a}$ corresponds to the order of the utilized loop filter and b determines the cut-off frequency ω_c according to $\omega_c=(ab)^{-1}$. The transfer function is given by

$$\hat{p}(\lambda)=\int_0^\infty dt\; p(t)\, e^{-\lambda t}=\frac{1}{(1+\lambda b)^a} \quad . \qquad (18)$$

[0038] Substituting into Eq. (14), the characteristic equation is given by:

$$\lambda(1+\lambda b)^a+\alpha(e^{-\lambda\tau_f}-\zeta e^{-\lambda\tau_T})=0\,. \qquad (19)$$

[0039] This equation can have multiple solutions in λ for each eigenvalue ζ.

[0040] The time-continuous synchronization signal may be a digital signal or an analog signal. The node may be a clocking node and the time-continuous synchronization signal may be a clock signal for clocking the clocking node.

[0041] The present invention further relates to a usage of a node as described above within a network comprising a plurality of interconnected nodes that are continuously coupled. The network may be designed to yield a desired perturbation response rate and/or collective frequency. A design parameter of the network is the distance between a node and another node that determines the total time delay. The total time delay corresponding to an optimum perturbation response rate may be achieved either by adjusting the distance alone and/or the additional time delay induced by a delayer.

[0042] The present invention further relates to a method for synchronizing a network comprising a plurality of interconnected nodes. The method comprises generating a time-continuous synchronization signal in each node; transmitting the time-continuous synchronization signal of each node to other nodes of the network; receiving in each node a delayed external time-continuous synchronization signal from other nodes of the network; synchronizing in each node a phase of the time-continuous synchronization signal with a phase of the external time-continuous synchronization signal received from another node by delaying the external time-continuous synchronization signal received from another node of the network with respect to the external time-continuous synchronization signal transmitted by the other node by a total time delay comprising a transmission time delay resulting from a transmission time between the transmission of the external time-continuous synchronization signal by the other node and the following receipt of the external time-continuous synchronization signal by the node and any tunable additional time delay in addition to the transmission time delay, iteratively adjusting the frequency of the time-continuous synchronization signal such that a network-wide synchronization is achieved for all nodes of the network in a continuous self-organized process in interaction with the other nodes of the network, and tuning at least one of the following parameters: the total time delay τ_T, the feedback delay τ_f, a free running frequency ω of the controllable oscillator (33), a coupling strength K, an impulse response $p(u)$ of a filter (31) within the controller (31, 32), to yield a desired perturbation response rate λ, i.e. perturbation response rate λ with $\mathrm{Re}(\lambda)<0$, and/or collective frequency Ω.

[0043] Therein the desired perturbation response rate λ solves $e^{\lambda\tau_T}\left(\frac{\lambda}{\alpha\hat{p}(\lambda)}+e^{-\lambda\tau_f}\right)=\zeta$, wherein ζ denotes an eigenvalue of a normalized coupling matrix $\tilde{\mathbf{D}}=(\tilde{d}_{kl})$ with $\tilde{d}_{kl}=d_{kl}/n_k$, $d_{kl}\in\{0,1\}$, where $d_{kl}=1$ indicates a connection between node k and node l, n_k denotes a number of received external time-continuous synchronization signals, $\alpha=Kh'(-\Omega[\tau_T-\tau_f])$, wherein h' denotes a first derivative of a coupling function h, $\hat{p}(\lambda)=\int_0^\infty du\; p(u)\, e^{-\lambda u}$ denotes a Laplace transform of an impulse response $p(u)$ of the filter within the controller; and wherein the collective frequency Ω solves:

$$\Omega = \omega + Kh(-\Omega[\tau_T - \tau_f]) \ .$$

Brief description of the drawings

[0044] Node, network and related method according to the invention are described in more detail herein below by way of exemplary embodiments and with reference to the attached drawings, in which:

Fig. 1	shows a prior art approach for clock distribution on a globally synchronous network involving a master clock;
Fig. 2	shows an approach of a dynamic clocking network involving mutually coupled nodes, which are able to globally synchronize in a self-organized manner;
Fig. 3	shows a block diagram of a network node comprising a delay-coupled PLL according to a first embodiment;
Fig. 4	shows a block diagram of a network node comprising a delay-coupled PLL and an additional delayer according to a second embodiment;
Fig. 5	shows a block diagram of a network node comprising a delay-coupled PLL, an additional delayer for each input and a combiner to combine a plurality of phase detector signals according to a third embodiment;
Fig. 6	shows a block diagram of a network node comprising a delay-coupled PLL, an additional delayer for each input and a combiner to combine a plurality of input signals according to a fourth embodiment;
Fig. 7	shows a block diagram of a network node comprising a delay-coupled PLL and a feedback delayer according to a fifth embodiment;
Fig. 8	shows a diagram showing a global frequency of the in-phase and anti-phase synchronized state versus the transmission delay; and
Fig. 9	shows a diagram showing global synchrony measured using the Kuramoto order parameter as a function of time;
Fig. 10	shows a diagram showing the perturbation response rate versus the transmission delay; and
Fig. 11	shows a diagram showing the perturbation response rate versus the transmission delay for different cut-off frequencies of the loop filter.

Detailed description of the invention

[0045] Fig. 2 shows a dynamic clocking network 22 comprising a plurality of interconnected clocking nodes 21 that are continuously delay-coupled. Each clocking node is implemented as a PLL. Thus, the clocking network 22 is network of mutually delay-coupled PLLs with continuous coupling.

[0046] Referring to Fig. 3, the PLL comprises a phase detector 31, a loop filter 32 and a voltage controlled oscillator 33 that generates a time-continuous clocking signal $x_k(t)$. The PLL synchronizes the phase of the clocking signal generated by the VCO 33 with the phase of the external clocking signal $x_l(t-\tau_s)$ which is delayed by the transmission time delay τ_s, indicated by transmission delayer 34, by adjusting the frequency of the clocking signal of the VCO such that a network-wide synchronization of the VCOs is achieved for all clocking nodes of the dynamic clocking network. To do so, the phase detector 31 compares the phase of the external clocking signal $x_l(t-\tau_s)$ with the phase of the clocking signal $x_k(t)$ generated by the VCO 33 to generate a phase detector signal $x_k^{PD}(t)$. After filtering with the loop filter 32 this yields the control signal $x_k^C(t)$ for the VCO 33.

[0047] Fig. 4 shows the node of Fig. 3 comprising an additional delayer 45 to adjust the total time delay. Transmission time delay τ_s and additional time delay τ_d yield the total time delay τ_T. The phase detector 41 compares the phase of the additionally delayed external clocking signal $x_l(t-\tau_T)$ with the phase of the clocking signal $x_k(t)$ generated by the VCO

43 to generate the phase detector signal $x_k^{PD}(t)$. After filtering with the loop filter 42 this yields the control signal $x_k^{C}(t)$ for the VCO 43. By properly inducing an additional time delay, stable solutions for the collective frequency of the network can be achieved.

[0048] Fig. 5 shows a clocking node with a plurality of external clocking signals $x_1(t)$, $x_2(t)$, $x_3(t)$, ..., $x_n(t)$. Each input path comprises an individual delayer 551, 552, 553, 554 that induces an additional time delay to the transmission time delay indicated by transmission delayers 541, 542, 543, 544. Each phase detector 511, 512, 513, 514 compares the phase of the clocking signal $x_k(t)$ generated by the controllable oscillator 53 with the phase of each external clock signal individually to generate a plurality of phase detector signals. The combiner 56 combines the phase detector signals to generate a combined phase detector signal to control the controllable oscillator. The combined phase detector signal is filtered by the loop filter 52 to yield the control signal $x_k^{C}(t)$ for the VCO. The PLL of each clocking node thus adjusts the frequency of the clocking signal of each VCO such that a network-wide synchronization of the VCOs is achieved for all clocking nodes of the dynamic clocking network. By properly inducing individual additional time delays to each input path, stable solutions for the collective frequency of the network can be achieved.

[0049] Fig. 6 shows a clocking node with a plurality of external clocking signals $x_1(t)$, $x_2(t)$, $x_3(t)$, ..., $x_n(t)$. Each input path comprises an individual delayer 651, 652, 653, 654 that induces an additional time delay to the transmission time delay indicated by transmission delayers 641, 642, 643, 644. In contrast to the embodiment as shown in Fig. 5, where a combiner combines a plurality of phase detector signals, in this embodiment the combiner 66 combines the plurality of external clocking signals to generate a combined external clocking signal. The phase detector 61 compares the phase of the clocking signal generated by the VCO 63 with the phase of the combined external clocking signal to generate the phase detector signal $x_k^{PD}(t)$. After filtering with the loop filter 62 this yields the control signal $x_k^{C}(t)$ for the VCO 63.

[0050] Fig. 7 shows the clocking node of Fig. 4 comprising a feedback delayer 77 for introducing a time delay in the feedback loop of the PLL comprising the phase detector 71, loop filter 72 and VCO 73. The feedback delay may be induced to compensate for a total time delay.

[0051] The individual total time delays τ_T in any of the described embodiments are design parameters. Only if chosen properly, a stable synchronous state can be achieved as will be explained with reference to Fig. 8 which shows the global frequency Ω of the in-phase and anti-phase synchronized state as a function of the total time delay τ_T for a clocking network comprising two clocking nodes. The anti-phase synchronized state is characterized by $\phi_1(t)=\phi_2(t)-\pi$. Full lines denote stable solutions and dashed lines denote unstable solutions. Hence, for a desired global frequency of the clocking network, the total time delay can be chosen for a given free running frequency of the VCO in order to achieve a desired synchronous state and global frequency of the network. If no additional time delay is induced, the transmission time delay corresponds to the total time delay. Thus, by choosing the distances between the coupled nodes of the network accordingly, a transmission time delay can be achieved that yields a stable synchronous state.

[0052] The curves of Fig. 8 are shown for the following system parameters: VCO free running frequency $\omega = 2n \times 3.55$ GHz, coupling strength $K = 2n \times 1.11$ GHz, LF order a = 1, LF cut-off frequency $\omega_c = 2n \times 355$ MHz. The frequencies of the different solutions can be obtained by letting the clocking network evolve from different initial phase differences. For example, for $\tau_T=0.2\cdot 2\pi/\omega$, all initial phase differences lead to the in-phase synchronized state, see Fig. 8, wherein an order parameter of zero means no synchrony and wherein a value of one implies full synchrony. For values of the total time delay for which both solutions are stable, the clock network evolves towards one solution according to its initial condition.

[0053] Moreover, the total time delay may be chosen such that a perturbation response rate given by Re(λ) is minimized, see Eq. (14).

[0054] Fig. 10 shows a diagram showing the perturbation response rate versus the total time delay for a clocking network comprising two clocking nodes. The coupling matrix corresponding to two mutually coupled PLLs is given by $\tilde{\mathbf{D}}=\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ and has eigenvalues $\zeta_1=1$ and $\zeta_2=-1$. It shows a distinct minimum in the region of stable solutions which corresponds to a total time delay that is optimal with respect to the perturbation response rate. It shall be mentioned that for a desired global frequency, a maximum perturbation decay of the clock network can be achieved by simultaneously adjusting the total time delay and the free running frequency of the VCO, which shifts the curve of the global frequency, see Fig. 8, up or down.

[0055] The coupling strength and the cut-off frequency of the loop filter also affects the stability of the clock network. Fig. 11 shows the perturbation response rate versus the total time delay for different cut-off frequencies of the loop filter.

[0056] Thus, by properly tuning the total time delay in combination with the cut-off frequency a minimum perturbation response rate can be achieved.

[0057] The present invention proposes a novel synchronization strategy, specifically for spatially distributed clocks. These clocks are synchronized by networks of mutually coupled phase-locked loops. An important feature is the total time delay in the time-continuous coupling between phase-looked loops which enables synchronized states in the presence of a non-attractive coupling mechanism. As the transmission time delay is not limited to one eighth of a period of the oscillator as is the case with the solution disclosed in WO 2013/178237 A1, networks with larger total time delays between nodes can be synchronized. Important applications are, e.g., high performance MPSoCs architectures, distributed antenna arrays, and other large scale electronic clocking systems communicating by means of time-continuous signals.

[0058] The present invention specifically provides a simplified clock network compared to the prior art tree structure. The synchronized network thus enables an increased energy efficiency due to shorter connections and less amplification. Moreover, it exhibits increased robustness towards failure of individual components due to decentralized architecture. Furthermore, the synchronized network is designed for high quality of oscillations. The synchronized network can be realized using readily available hardware components. Thus, this solution works with readily available hardware combined in a novel way and additionally simplifies clock distribution, thereby reducing power consumption and increasing scalability.

Claims

1. Node (21) for a network (22) comprising a plurality of interconnected nodes, each node (21) comprising:

a controllable oscillator (33) generating a time-continuous synchronization signal for synchronizing the plurality of interconnected nodes (21) of the network (22);
a controller (31, 32) for comparing and synchronizing a phase of the time-continuous synchronization signal generated by the controllable oscillator (33), which is transmitted to other nodes (21) of the network (22), with the phase of an external time-continuous synchronization signal received from other nodes (21) of the network (22) by adjusting a frequency of the time-continuous synchronization signal generated by the controllable oscillator (33),
characterized in that the external time-continuous synchronization signal received from another node (21) of the network (22) is delayed with respect to the external time-continuous synchronization signal transmitted by the other node (21) by a total time delay comprising a transmission time delay resulting from a transmission time between the transmission of the external time-continuous synchronization signal by the other node (21) and the following receipt of the external time-continuous synchronization signal by the node (21) and any tunable additional time delay in addition to the transmission time delay;
wherein the controller (31, 32) iteratively adjusts the frequency of the time-continuous synchronization signal generated by the controllable oscillator (33) such that a network-wide synchronization of oscillators (33) is achieved for all nodes (21) of the network (22) in a continuous self-organized process in interaction with the other node (21) of the network (22),
wherein at least one of the following parameters: the total time delay τ_T, the feedback delay τ_f, a free running frequency ω of the controllable oscillator (33), a coupling strength K, an impulse response $p(u)$ of a filter (32) within the controller (31, 32), is tuned to yield a desired perturbation response rate λ, i.e. perturbation response rate λ with $\mathrm{Re}(\lambda)<0$, and/or collective frequency Ω; and
wherein the desired perturbation response rate λ solves $$e^{\lambda\tau_T}\left(\frac{\lambda}{\alpha\hat{p}(\lambda)}+e^{-\lambda\tau_f}\right)=\zeta \quad ,$$ wherein ζ denotes an eigenvalue of a normalized coupling matrix $\tilde{\mathbf{D}}=(\tilde{d}_{kl})$ with $\tilde{d}_{kl}=d_{kl}/n_k$, $d_{kl}\in\{0,1\}$, where $d_{kl}=1$ indicates a connection between node k and node l, n_k denotes a number of received external time-continuous synchronization signals;
$\alpha=Kh'(-\Omega[\tau_T-\tau_f])$, wherein h' denotes a first derivative of a coupling function h;

$$\hat{p}(\lambda)=\int_0^\infty du\ p(u)\,e^{-\lambda u}$$

denotes a Laplace transform of an impulse response $p(u)$ of the filter within the controller; and wherein the collective frequency Ω solves:

$$\Omega=\omega+Kh(-\Omega[\tau_T-\tau_f]) \ .$$

2. Node according to claim 1, wherein the controller (31, 32) comprises a phase detector (31) configured to compare the phase of the external time-continuous synchronization signal with the phase of the time-continuous synchronization signal generated by the controllable oscillator (33).

3. Node according to claim 1 or 2, wherein the controller (61, 62) compares and synchronizes a phase of the time-continuous synchronization signal generated by the controllable oscillator (63), which is transmitted to other nodes (21) of the network (22), with the phases of external time-continuous synchronization signals received from other nodes (21) of the network (22) by adjusting a frequency of the time-continuous synchronization signal generated by the controllable oscillator (33),
wherein the external time-continuous synchronization signals received from other nodes (21) of the network (22) are delayed with respect to the time-continuous synchronization signal transmitted by the other nodes (21) by a total time delay; and
wherein the controller (61, 62) iteratively adjusts the frequency of the time-continuous synchronization signal generated by the controllable oscillator (63) such that a network-wide synchronization of oscillators is achieved for all nodes (21) of the network (22) in a continuous self-organized process in interaction with the other nodes (21) of the network (22).

4. Node according to claim 3, further comprising a combiner (66) to combine the external time-continuous synchronization signals received from other nodes (21) of the network (22) to generate a combined external time-continuous synchronization signal and wherein the phase detector compares (61) the phase of the time-continuous synchronization signal generated by the controllable oscillator (63) with the phase of the combined external time-continuous synchronization signal.

5. Node according to claim 3, wherein the phase detector (511, 512, 513, 514) compares the phase of the time-continuous synchronization signal generated by the controllable oscillator (53) with the phase of each external time-continuous synchronization signal individually to generate a plurality of phase detector signals; and wherein the combiner (56) combines the phase detector signals to control the controllable oscillator (53).

6. Node according to claim 4 or 5, wherein the controller comprises the combiner (56; 66).

7. Node according to any of claims 1 to 6 comprising a delayer (45) for inducing an additional time delay in addition to a transmission time delay to yield the total time delay.

8. Node according to any of claims 3 to 6 comprising a plurality of delayers (551, 552, 553, 554; 651, 652, 653, 654) for inducing an additional time delay in addition to a transmission time delay to yield the total time delay for each received external time-continuous synchronization signal.

9. Node according to any of claims 1 to 8 comprising a feedback delayer (77) for inducing a feedback time delay in a feedback path between the controllable oscillator (73) and the phase detector (71).

10. Node according to any of claims 1 to 9, wherein the time-continuous synchronization signal is a digital signal or an analog signal.

11. Node according to any of claims 1 to 10, wherein the node (21) is a clocking node and wherein the time-continuous synchronization signal is a clock signal for clocking the clocking node (21).

12. Node according to any of claims 1 to 11 used in a Network (22) comprising a plurality of interconnected nodes (21) that are time-continuously coupled comprising a distance between a node (21) and another node (21) determining total time delays to yield the desired perturbation response rate and/or collective frequency.

13. Method for synchronizing a network (22) comprising a plurality of interconnected nodes (21), the method comprising:

generating a time-continuous synchronization signal in each node (21);
transmitting the time-continuous synchronization signal of each node (21) to other nodes (21) of the network (22);
receiving in each node (21) a delayed external time-continuous synchronization signal from other nodes (21) of the network (22);

characterized by

synchronizing in each node a phase of the time-continuous synchronization signal with a phase of the external time-continuous synchronization signal received from another node (21) by delaying the external time-continuous synchronization signal received from another node (21) of the network (22) with respect to the external time-continuous synchronization signal transmitted by the other node (21) by a total time delay comprising a transmission time delay resulting from a transmission time between the transmission of the external time-continuous synchronization signal by the other node (21) and the following receipt of the external time-continuous synchronization signal by the node (21) and any tunable additional time delay in addition to the transmission time delay;
iteratively adjusting the frequency of the time-continuous synchronization signal such that a network-wide synchronization is achieved for all nodes (21) of the network (22) in a continuous self-organized process in interaction with the other nodes (21) of the network (22),
tuning at least one of the following parameters: the total time delay τ_T, the feedback delay τ_f, a free running frequency ω of the controllable oscillator (33), a coupling strength *K,* an impulse response *p(u)* of a filter (31) within the controller (31, 32), to yield a desired perturbation response rate λ, i.e. perturbation response rate λ with Re(λ)<0, and/or collective frequency Ω;

wherein the desired perturbation response rate λ solves

$$e^{\lambda\tau_T}\left(\frac{\lambda}{\alpha\hat{p}(\lambda)}+e^{-\lambda\tau_f}\right)=\zeta \quad ,$$

wherein ζ denotes an eigenvalue of a normalized coupling matrix $\tilde{\mathbf{D}}=(\tilde{d}_{kl})$ with $\tilde{d}_{kl}=d_{kl}/n_k$, $d_{kl}\in\{0,1\}$, where $d_{kl}=1$ indicates a connection between node k and node *l*, n_k denotes a number of received external time-continuous synchronization signals;
$\alpha=Kh'(-\Omega[\tau_T-\tau_f]$, wherein *h*' denotes a first derivative of a coupling function *h*;

$$\hat{p}(\lambda)=\int_0^\infty du\; p(u)\, e^{-\lambda u}$$

denotes a Laplace transform of an impulse response *p(u)* of the filter (33) within the controller (31, 32); and
wherein the collective frequency Ω solves:

$$\Omega=\omega+Kh(-\Omega[\tau_T-\tau_f])\ .$$

Patentansprüche

1. Knoten (21) für ein Netz (22) mit mehreren miteinander verbundenen Knoten, wobei jeder Knoten (21) folgendes umfasst:

   einen steuerbaren Oszillator (33), der ein zeitkontinuierliches Synchronisationssignal zum Synchronisieren der mehreren miteinander verbundenen Knoten (21) des Netzes (22) erzeugt;
   eine Steuereinheit (31, 32) zum Vergleichen und Synchronisieren einer Phase des zeitkontinuierlichen Synchronisationssignals, das durch den steuerbaren Oszillator (33) erzeugt wird, das zu anderen Knoten (21) des Netzes (22) gesendet wird, mit der Phase eines externen zeitkontinuierlichen Synchronisationssignals, das von anderen Knoten (21) des Netzes (22) empfangen wird, durch Einstellen einer Frequenz des zeitkontinuierlichen Synchronisationssignals, das durch den steuerbaren Oszillator (33) erzeugt wird,
   dadurch gekennzeichnet, dass das externe zeitkontinuierliche Synchronisationssignal, das von einem anderen Knoten (21) des Netzes (22) empfangen wird, in Bezug auf das externe zeitkontinuierliche Synchronisationssignal, das durch den anderen Knoten (21) gesendet wird, um eine Gesamtzeitverzögerung mit einer Sendezeitverzögerung, die sich aus einer Sendezeit zwischen dem Senden des externen zeitkontinuierlichen Synchronisationssignals durch den anderen Knoten (21) und dem folgenden Empfang des externen zeitkontinuierlichen Synchronisationssignals durch den Knoten (21) ergibt, und irgendeiner abstimmbaren zusätzlichen Zeitverzögerung zusätzlich zur Sendezeitverzögerung verzögert wird;
   wobei die Steuereinheit (31, 32) die Frequenz des zeitkontinuierlichen Synchronisationssignals, das durch den steuerbaren Oszillator (33) erzeugt wird, iterativ einstellt, so dass eine netzweite Synchronisation von Oszillatoren (33) für alle Knoten (21) des Netzes (22) in einem kontinuierlichen selbstorganisierten Prozess in Zusammenwirkung mit dem anderen Knoten (21) des Netzes (22) erreicht wird,
   wobei mindestens einer der folgenden Parameter: die Gesamtzeitverzögerung τ_T, die Rückkopplungsverzögerung τ_f, eine Freilauffrequenz ω des steuerbaren Oszillators (33), eine Kopplungsstärke *K*, eine Impulsreaktion p(u) eines Filters (32) innerhalb der Steuereinheit (31, 32) abgestimmt wird, um eine gewünschte Störungsre-

aktionsrate λ, d. h. eine Störungsreaktionsrate λ mit $\mathrm{Re}(\lambda)<0$, und/oder eine kollektive Frequenz Ω zu erbringen; und

wobei die gewünschte Störungsreaktionsrate λ $e^{\lambda\tau_T}\left(\frac{\lambda}{\alpha\hat{p}(\lambda)}+e^{-\lambda\tau_f}\right)=\zeta$ löst, wobei ζ einen Eigenwert einer normierten Kopplungsmatrix $\tilde{\mathbf{D}}=(\tilde{d}_{kl})$ mit $\tilde{d}_{kl}=d_{kl}/n_k$, $d_{kl}\in\{0,1\}$ bezeichnet, wobei $d_{kl}=1$ eine Verbindung zwischen dem Knoten *k* und dem Knoten *l* angibt, n_k eine Anzahl von empfangenen externen zeitkontinuierlichen Synchronisationssignalen bezeichnet;

$\alpha=Kh'(-\Omega[\tau_T-\tau_f])$, wobei *h'* eine erste Ableitung einer Kopplungsfunktion *h* bezeichnet;

$\hat{p}(\lambda)=\int_0^\infty du\, p(u)\, e^{-\lambda u}$ eine Laplace-Transformation einer Impulsreaktion *p*(*u*) des Filters innerhalb der Steuereinheit bezeichnet; und

wobei die kollektive Frequenz Ω Folgendes löst:

$$\Omega=\omega+Kh(-\Omega[\tau_T-\tau_f]).$$

2. Knoten nach Anspruch 1, wobei die Steuereinheit (31, 32) einen Phasendetektor (31) umfasst, der dazu konfiguriert ist, die Phase des externen zeitkontinuierlichen Synchronisationssignals mit der Phase des zeitkontinuierlichen Synchronisationssignals zu vergleichen, das durch den steuerbaren Oszillator (33) erzeugt wird.

3. Knoten nach Anspruch 1 oder 2, wobei die Steuereinheit (61, 62) eine Phase des zeitkontinuierlichen Synchronisationssignals, das durch den steuerbaren Oszillator (63) erzeugt wird, das zu anderen Knoten (21) des Netzes (22) gesendet wird, mit den Phasen von externen zeitkontinuierlichen Synchronisationssignalen, die von anderen Knoten (21) des Netzes (22) empfangen werden, vergleicht und durch Einstellen einer Frequenz des zeitkontinuierlichen Synchronisationssignals, das durch den steuerbaren Oszillator (33) erzeugt wird, synchronisiert,
wobei die externen zeitkontinuierlichen Synchronisationssignale, die von anderen Knoten (21) des Netzes (22) empfangen werden, in Bezug auf das zeitkontinuierliche Synchronisationssignal, das durch die anderen Knoten (21) gesendet wird, um eine Gesamtzeitverzögerung verzögert werden; und
wobei die Steuereinheit (61, 62) die Frequenz des zeitkontinuierlichen Synchronisationssignals, das durch den steuerbaren Oszillator (63) erzeugt wird, iterativ einstellt, so dass eine netzweite Synchronisation von Oszillatoren für alle Knoten (21) des Netzes (22) in einem kontinuierlichen selbstorganisierten Prozess in Zusammenwirkung mit den anderen Knoten (21) des Netzes (22) erreicht wird.

4. Knoten nach Anspruch 3, der ferner einen Kombinator (66) umfasst, um die externen zeitkontinuierlichen Synchronisationssignale, die von anderen Knoten (21) des Netzes (22) empfangen werden, zu kombinieren, um ein kombiniertes externes zeitkontinuierliches Synchronisationssignal zu erzeugen, und wobei der Phasendetektor die Phase des zeitkontinuierlichen Synchronisationssignals, das durch den steuerbaren Oszillator (63) erzeugt wird, mit der Phase des kombinierten externen zeitkontinuierlichen Synchronisationssignals vergleicht (61).

5. Knoten nach Anspruch 3, wobei der Phasendetektor (511, 512, 513, 514) die Phase des zeitkontinuierlichen Synchronisationssignals, das durch den steuerbaren Oszillator (53) erzeugt wird, mit der Phase jedes externen zeitkontinuierlichen Synchronisationssignals individuell vergleicht, um mehrere Phasendetektorsignale zu erzeugen; und wobei der Kombinator (56) die Phasendetektorsignale kombiniert, um den steuerbaren Oszillator (53) zu steuern.

6. Knoten nach Anspruch 4 oder 5, wobei die Steuereinheit den Kombinator (56; 66) umfasst.

7. Knoten nach einem der Ansprüche 1 bis 6 mit einem Verzögerer (45) zum Induzieren einer zusätzlichen Zeitverzögerung zusätzlich zu einer Sendezeitverzögerung, um die Gesamtzeitverzögerung zu erbringen.

8. Knoten nach einem der Ansprüche 3 bis 6 mit mehreren Verzögerern (551, 552, 553, 554; 651, 652, 653, 654) zum Induzieren einer zusätzlichen Zeitverzögerung zusätzlich zu einer Sendezeitverzögerung, um die Gesamtzeitverzögerung für jedes empfangene externe zeitkontinuierliche Synchronisationssignal zu erbringen.

9. Knoten nach einem der Ansprüche 1 bis 8 mit einem Rückkopplungsverzögerer (77) zum Induzieren einer Rückkopplungszeitverzögerung in einem Rückkopplungspfad zwischen dem steuerbaren Oszillator (73) und dem Phasendetektor (71).

10. Knoten nach einem der Ansprüche 1 bis 9, wobei das zeitkontinuierliche Synchronisationssignal ein digitales Signal oder ein analoges Signal ist.

11. Knoten nach einem der Ansprüche 1 bis 10, wobei der Knoten (21) ein Taktknoten ist und wobei das zeitkontinuierliche Synchronisationssignal ein Taktsignal zum Takten des Taktknotens (21) ist.

12. Knoten nach einem der Ansprüche 1 bis 11, der in einem Netz (22) mit mehreren miteinander verbundenen Knoten (21) verwendet wird, die zeitkontinuierlich mit einem Abstand zwischen einem Knoten (21) und einem anderen Knoten (21) gekoppelt sind, der Gesamtzeitverzögerungen bestimmt, um die gewünschte Störungsreaktionsrate und/oder kollektive Frequenz zu erbringen.

13. Verfahren zum Synchronisieren eines Netzes (22) mit mehreren miteinander verbundenen Knoten (21), wobei das Verfahren Folgendes umfasst:

Erzeugen eines zeitkontinuierlichen Synchronisationssignals in jedem Knoten (21);
Senden des zeitkontinuierlichen Synchronisationssignals jedes Knotens (21) zu anderen Knoten (21) des Netzes (22);
Empfangen eines verzögerten externen zeitkontinuierlichen Synchronisationssignals in jedem Knoten (21) von anderen Knoten (21) des Netzes (22);
gekennzeichnet durch
Synchronisieren einer Phase des zeitkontinuierlichen Synchronisationssignals mit einer Phase des externen zeitkontinuierlichen Synchronisationssignals, das von einem anderen Knoten (21) empfangen wird, in jedem Knoten durch Verzögern des externen zeitkontinuierlichen Synchronisationssignals, das von einem anderen Knoten (21) des Netzes (22) empfangen wird, in Bezug auf das externe zeitkontinuierliche Synchronisationssignal, das durch den anderen Knoten (21) gesendet wird, um eine Gesamtzeitverzögerung mit einer Sendezeitverzögerung, die sich aus einer Sendezeit zwischen dem Senden des externen zeitkontinuierlichen Synchronisationssignals durch den anderen Knoten (21) und dem folgenden Empfang des externen zeitkontinuierlichen Synchronisationssignals durch den Knoten (21) ergibt, und irgendeiner abstimmbaren zusätzlichen Zeitverzögerung zusätzlich zur Sendezeitverzögerung;
iteratives Einstellen der Frequenz des zeitkontinuierlichen Synchronisationssignals, so dass eine netzweite Synchronisation für alle Knoten (21) des Netzes (22) in einem kontinuierlichen selbstorganisierten Prozess in Zusammenwirkung mit den anderen Knoten (21) des Netzes (22) erreicht wird,
Abstimmen mindestens eines der folgenden Parameter: der Gesamtzeitverzögerung τ_T, der Rückkopplungsverzögerung τ_f, einer Freilauffrequenz ω des steuerbaren Oszillators (33), einer Kopplungsstärke K, einer Impulsreaktion $p(u)$ eines Filters (31) innerhalb der Steuereinheit (31, 32), um eine gewünschte Störungsreaktionsrate λ, d. h. eine Störungsreaktionsrate λ mit $\mathrm{Re}(\lambda)<0$, und/oder eine kollektive Frequenz Ω zu erbringen; und
wobei die gewünschte Störungsreaktionsrate λ $e^{\lambda\tau_T}\left(\frac{\lambda}{\alpha\hat{p}(\lambda)}+e^{-\lambda\tau_f}\right)=\zeta$ löst, wobei ζ einen Eigenwert einer normierten Kopplungsmatrix $\tilde{\mathbf{D}}=(\tilde{d}_{kl})$ mit $\tilde{d}_{kl}=d_{kl}/n_k$, $d_{kl}\in\{0,1\}$ bezeichnet, wobei $d_{kl}=1$ eine Verbindung zwischen dem Knoten k und dem Knoten l angibt, n_k eine Anzahl von empfangenen externen zeitkontinuierlichen Synchronisationssignalen bezeichnet;
$\alpha=Kh'(-\Omega[\tau_T-\tau_f])$, wobei h' eine erste Ableitung einer Kopplungsfunktion h bezeichnet;
$\hat{p}(\lambda)=\int_0^\infty du\, p(u)\, e^{-\lambda u}$ eine Laplace-Transformation einer Impulsreaktion $p(u)$ des Filters (33) innerhalb der Steuereinheit (31, 32) bezeichnet; und
wobei die kollektive Frequenz Ω Folgendes löst:

$$\Omega=\omega+Kh(-\Omega[\tau_T-\tau_f]).$$

Revendications

1. Noeud (21) pour un réseau (22) comprenant une pluralité de noeuds interconnectés, chaque noeud (21) comprenant :

un oscillateur commandable (33) générant un signal de synchronisation continu dans le temps pour synchroniser la pluralité de noeuds interconnectés (21) du réseau (22) ;
un contrôleur (31, 32) pour comparer et synchroniser une phase du signal de synchronisation continu dans le temps généré par l'oscillateur commandable (33), qui est transmis à d'autres noeuds (21) du réseau (22), avec la phase d'un signal de synchronisation continu dans le temps externe reçu depuis d'autres noeuds (21) du réseau (22) en ajustant une fréquence du signal de synchronisation continu dans le temps généré par l'oscillateur commandable (33),
caractérisé en ce que le signal de synchronisation continu dans le temps externe reçu d'un autre noeud (21) du réseau (22) est retardé par rapport au signal de synchronisation continu dans le temps externe transmis par l'autre noeud (21) d'un délai total comprenant un délai de transmission résultant d'un temps de transmission entre la transmission du signal de synchronisation continu dans le temps externe par l'autre noeud (21) et la réception suivante du signal de synchronisation continu dans le temps externe par le noeud (21) et n'importe quel délai supplémentaire accordable en plus du délai de transmission ;
où le contrôleur (31, 32) ajuste de manière itérative la fréquence du signal de synchronisation continu dans le temps généré par l'oscillateur commandable (33) de manière à ce qu'une synchronisation à l'échelle du réseau des oscillateurs (33) soit réalisée pour tous les noeuds (21) du réseau (22) dans un processus auto-organisé continu en interaction avec l'autre noeud (21) du réseau (22),
où au moins l'un des paramètres suivants : le délai total τ_T, le délai de rétroaction τ_f, une fréquence libre ω de l'oscillateur commandable (33), une résistance de couplage K, une réponse impulsionnelle p(u) d'un filtre (32) à l'intérieur du contrôleur (31, 32), est réglé pour conduire à un taux de réponse de perturbation souhaité λ, c'est-à-dire un taux de réponse de perturbation λ avec $\mathrm{Re}(\lambda) < 0$, et/ou une fréquence collective Ω ; et
où le taux de réponse de perturbation souhaité λ est solution de l'équation suivante :

$e^{\lambda\tau_T}\left(\frac{\lambda}{\alpha\hat{p}(\lambda)} + e^{-\lambda\tau f}\right) = \zeta,$ où ζ désigne une valeur propre d'une matrice de couplage normalisée $\tilde{D} = (\tilde{d}_{kl})$ avec $\tilde{d}_{kl} = \frac{d_{kl}}{n_k}, d_{kl} \in \{0,1\}$, où $d_{kl} = 1$ indique une connexion entre le noeud k et le noeud l, n_k désigne un nombre de signaux de synchronisation continus dans le temps externes reçus ;
$\alpha = Kh'(-\Omega[\tau_T - \tau_f])$, où h' désigne une dérivée première d'une fonction de couplage h ;
$\hat{p}(\lambda) = \int_0^\infty du\, p(u) e^{-\lambda u}$ désigne une transformée de Laplace d'une réponse impulsionnelle p(u) du filtre à l'intérieur du contrôleur ; et
où la fréquence collective Ω est solution de l'équation suivante :

$$\Omega = \omega + Kh\left(-\Omega\left[\tau_T - \tau_f\right]\right).$$

2. Noeud selon la revendication 1, dans lequel le contrôleur (31, 32) comprend un détecteur de phase (31) configuré pour comparer la phase du signal de synchronisation continu dans le temps externe avec la phase du signal de synchronisation continu dans le temps généré par l'oscillateur commandable (33).

3. Noeud selon la revendication 1 ou la revendication 2, dans lequel le contrôleur (61, 62) compare et synchronise une phase du signal de synchronisation continu dans le temps généré par l'oscillateur commandable (63), qui est transmis à d'autres noeuds (21) du réseau (22), aux phases de signaux de synchronisation continus dans le temps externes reçus d'autres noeuds (21) du réseau (22) en ajustant une fréquence du signal de synchronisation continu dans le temps généré par l'oscillateur commandable (33),
où les signaux de synchronisation continus dans le temps reçus d'autres noeuds (21) du réseau (22) sont retardés, d'un délai total, par rapport au signal de synchronisation continu dans le temps transmis par les autres noeuds (21) ; et
où le contrôleur (61, 62) ajuste de manière itérative la fréquence du signal de synchronisation continu dans le temps généré par l'oscillateur commandable (63) de manière à ce qu'une synchronisation des oscillateurs à l'échelle du réseau soit réalisée pour tous les noeuds (21) du réseau (22) dans un processus auto-organisé continu en interaction avec les autres noeuds (21) du réseau (22).

4. Noeud selon la revendication 3, comprenant en outre un combineur (66) pour combiner les signaux de synchronisation continus dans le temps externes reçus d'autres noeuds (21) du réseau (22) pour générer un signal de synchronisation continu dans le temps externe combiné et où le détecteur de phase compare (61) la phase du signal de synchronisation continu dans le temps généré par l'oscillateur commandable (63) à la phase du signal de synchronisation continu dans le temps externe combiné.

5. Noeud selon la revendication 3, dans lequel le détecteur de phase (511, 512, 513, 514) compare la phase du signal de synchronisation continu dans le temps généré par l'oscillateur commandable (53) à la phase de chaque signal de synchronisation continu dans le temps externe, individuellement, pour générer une pluralité de signaux de détecteur de phase ; et où le combineur (56) combine les signaux de détecteur de phase pour commander l'oscillateur commandable (53).

6. Noeud selon la revendication 4 ou la revendication 5, dans lequel le contrôleur comprend le combineur (56 ; 66).

7. Noeud selon l'une quelconque des revendications 1 à 6, comprenant un retardateur (45) pour induire un délai supplémentaire en plus d'un délai de transmission pour conduire au délai total.

8. Noeud selon l'une quelconque des revendications 3 à 6, comprenant une pluralité de retardateurs (551, 552, 553, 554 ; 651, 652, 653, 654) pour induire un délai supplémentaire en plus d'un délai de transmission pour conduire au délai total pour chaque signal de synchronisation continu dans le temps externe reçu.

9. Noeud selon l'une quelconque des revendications 1 à 8, comprenant un retardateur de rétroaction (77) pour induire un délai de rétroaction dans un trajet de rétroaction entre l'oscillateur commandable (73) et le détecteur de phase (71).

10. Noeud selon l'une quelconque des revendications 1 à 9, dans lequel le signal de synchronisation continu dans le temps est un signal numérique ou un signal analogique.

11. Noeud selon l'une quelconque des revendications 1 à 10, dans lequel le noeud (21) est un noeud d'horloge et où le signal de synchronisation continu dans le temps est un signal d'horloge pour synchroniser le noeud d'horloge (21).

12. Noeud selon l'une quelconque des revendications 1 à 11 utilisé dans un réseau (22) comprenant une pluralité de noeuds interconnectés (21) qui sont couplés de manière continue dans le temps, comprenant une distance entre un noeud (21) et un autre noeud (21) déterminant des délais totaux pour conduire au taux de réponse de perturbation souhaité et/ou à une fréquence collective.

13. Procédé de synchronisation d'un réseau (22) comprenant une pluralité de noeuds interconnectés (21), le procédé comprenant les étapes suivantes :

générer un signal de synchronisation continu dans le temps dans chaque noeud (21) ;
transmettre le signal de synchronisation continu dans le temps de chaque noeud (21) à d'autres noeuds (21) du réseau (22) ;
recevoir dans chaque noeud (21) un signal de synchronisation continu dans le temps externe retardé provenant d'autres noeuds (21) du réseau (22) ;
caractérisé par les étapes suivantes :

synchroniser dans chaque noeud une phase du signal de synchronisation continu dans le temps avec une phase du signal de synchronisation continu dans le temps externe reçu d'un autre noeud (21) en retardant le signal de synchronisation continu dans le temps externe reçu d'un autre noeud (21) du réseau (22) par rapport au signal de synchronisation continu dans le temps externe transmis par l'autre noeud (21) d'un délai total comprenant un délai de transmission résultant d'un temps de transmission entre la transmission du signal de synchronisation continu dans le temps externe par l'autre noeud (21) et la réception suivante du signal de synchronisation continu dans le temps externe par le noeud (21) et n'importe quel délai supplémentaire accordable en plus du délai de transmission ;
ajuster de manière itérative la fréquence du signal de synchronisation continu dans le temps de manière à ce qu'une synchronisation à l'échelle du réseau soit réalisée pour tous les noeuds (21) du réseau (22) dans un processus auto-organisé continu en interaction avec les autres noeuds (21) du réseau (22),
accorder au moins l'un des paramètres suivants : le délai total τ_T, le délai de rétroaction τ_f, une fréquence libre ω de l'oscillateur commandable (33), une résistance de couplage K, une réponse impulsionnelle p(u) d'un filtre (31) à l'intérieur du contrôleur (31, 32), pour conduire à un taux de réponse de perturbation souhaité λ, c'est-à-dire un taux de réponse de perturbation λ avec $\mathrm{Re}(\lambda) < 0$, et/ou une fréquence collective Ω ;

où le taux de réponse de perturbation souhaité λ est solution de l'équation suivante :

$e^{\lambda\tau_T}\left(\frac{\lambda}{\alpha\hat{p}(\lambda)} + e^{-\lambda\tau f}\right) = \zeta,$ où ζ désigne une valeur propre d'une matrice de couplage normalisée $\tilde{D} = (\tilde{d}_{kl})$ avec $\tilde{d}_{kl} = \frac{d_{kl}}{n_k}, d_{kl} \in$ {0,1}, où d_{kl} = 1 indique une connexion entre le noeud k et le noeud l, n_k désigne un nombre de signaux de synchronisation continus dans le temps externes reçus ; $\alpha' = Kh'(-\Omega[\tau_T - \tau_f])$, où h' désigne une dérivée première d'une fonction de couplage h ; $\hat{p}(\lambda) = \int_0^\infty du\, p(u) e^{-\lambda u}$ désigne une transformée de Laplace d'une réponse impulsionnelle p(u) du filtre (33) à l'intérieur du contrôleur (31, 32) ; et

où la fréquence collective Ω est solution de l'équation suivante :

$$\Omega = \omega + Kh\big(-\Omega\left[\tau_T - \tau_f\right]\big).$$

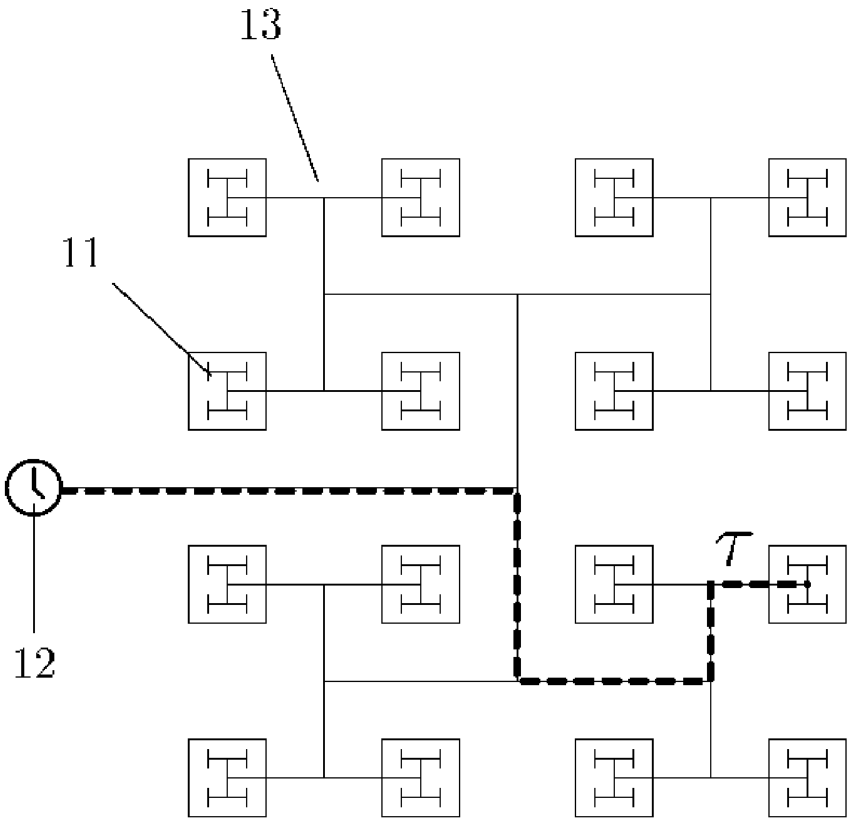

Fig. 1

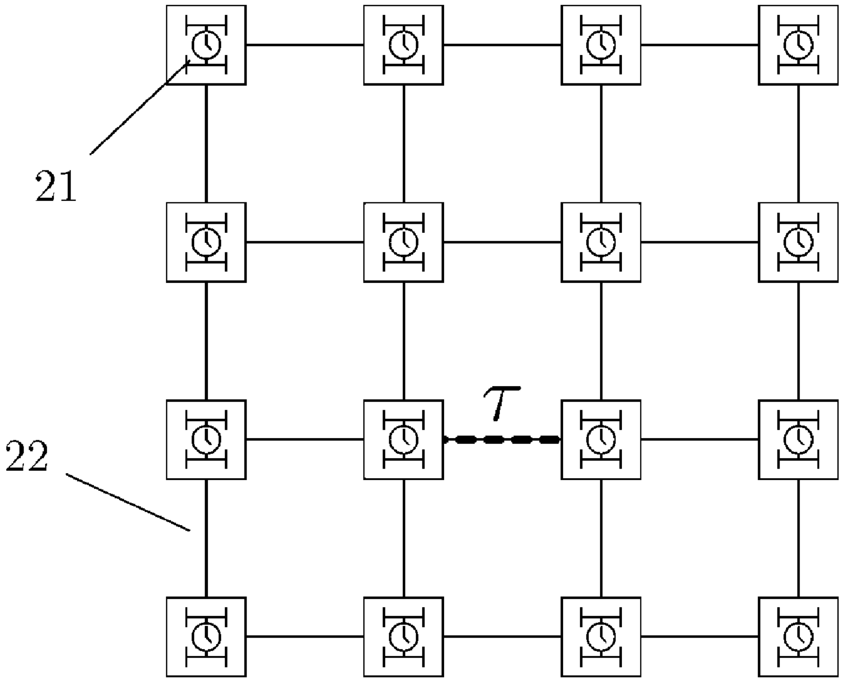

Fig. 2

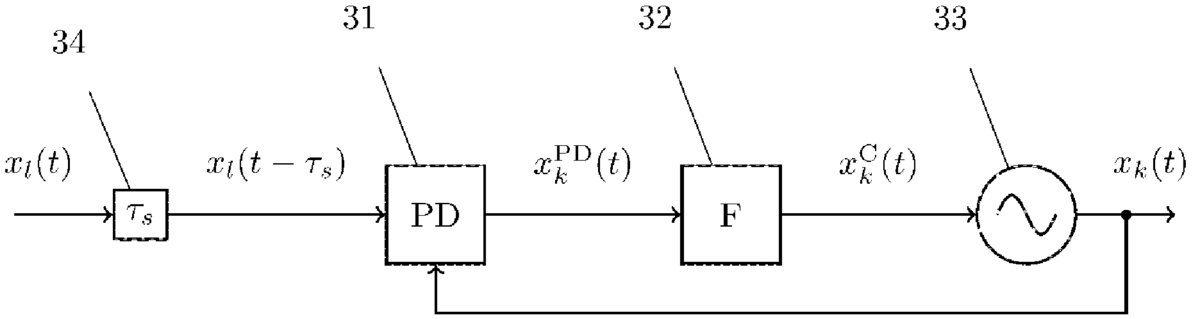
34
31
32
33
$x_l(t)$
τ_s
$x_l(t-\tau_s)$
PD
$x_k^{\mathrm{PD}}(t)$
F
$x_k^{\mathrm{C}}(t)$
$x_k(t)$

Fig. 3

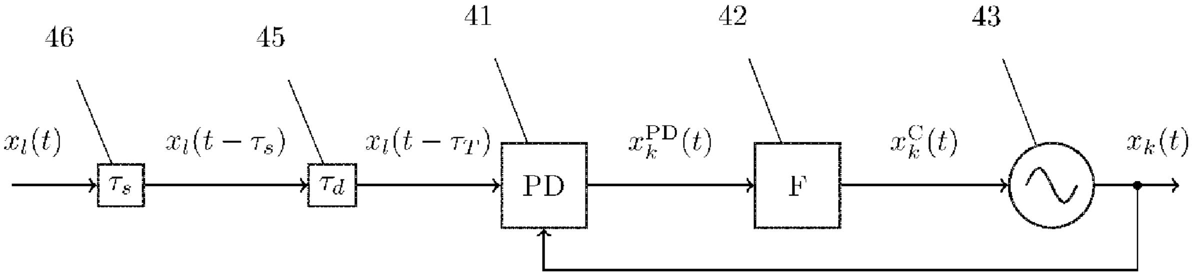
46
45
41
42
43
$x_l(t)$
τ_s
$x_l(t-\tau_s)$
τ_d
$x_l(t-\tau_T)$
PD
$x_k^{\mathrm{PD}}(t)$
F
$x_k^{\mathrm{C}}(t)$
$x_k(t)$

Fig. 4

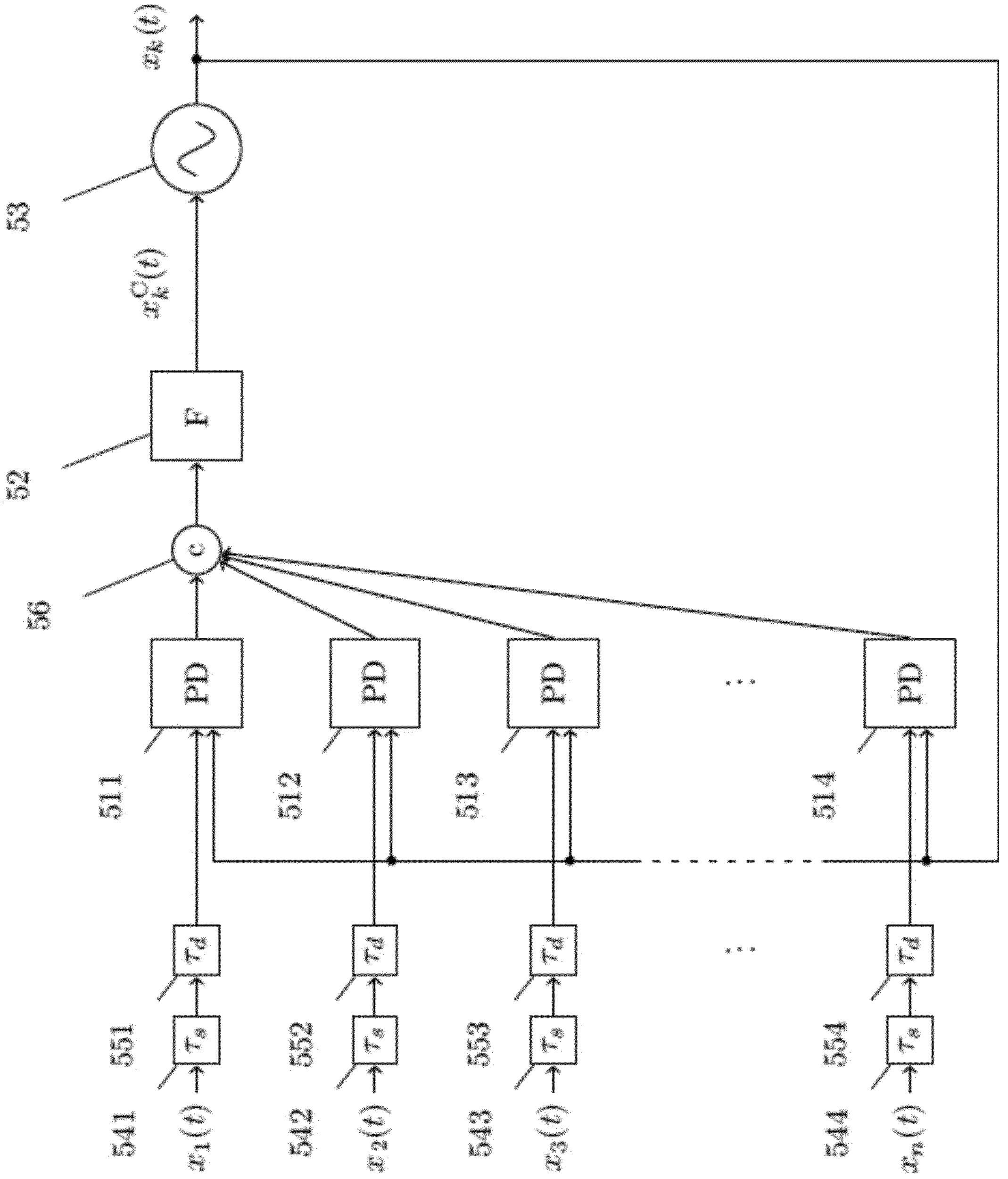
53
52
56
$x_k(t)$
$x_k^C(t)$
F
c
PD
PD
PD
PD
511
512
513
514
τ_d
τ_d
τ_d
τ_d
551
552
553
554
τ_s
τ_s
τ_s
τ_s
541
542
543
544
$x_1(t)$
$x_2(t)$
$x_3(t)$
$x_n(t)$

Fig. 5

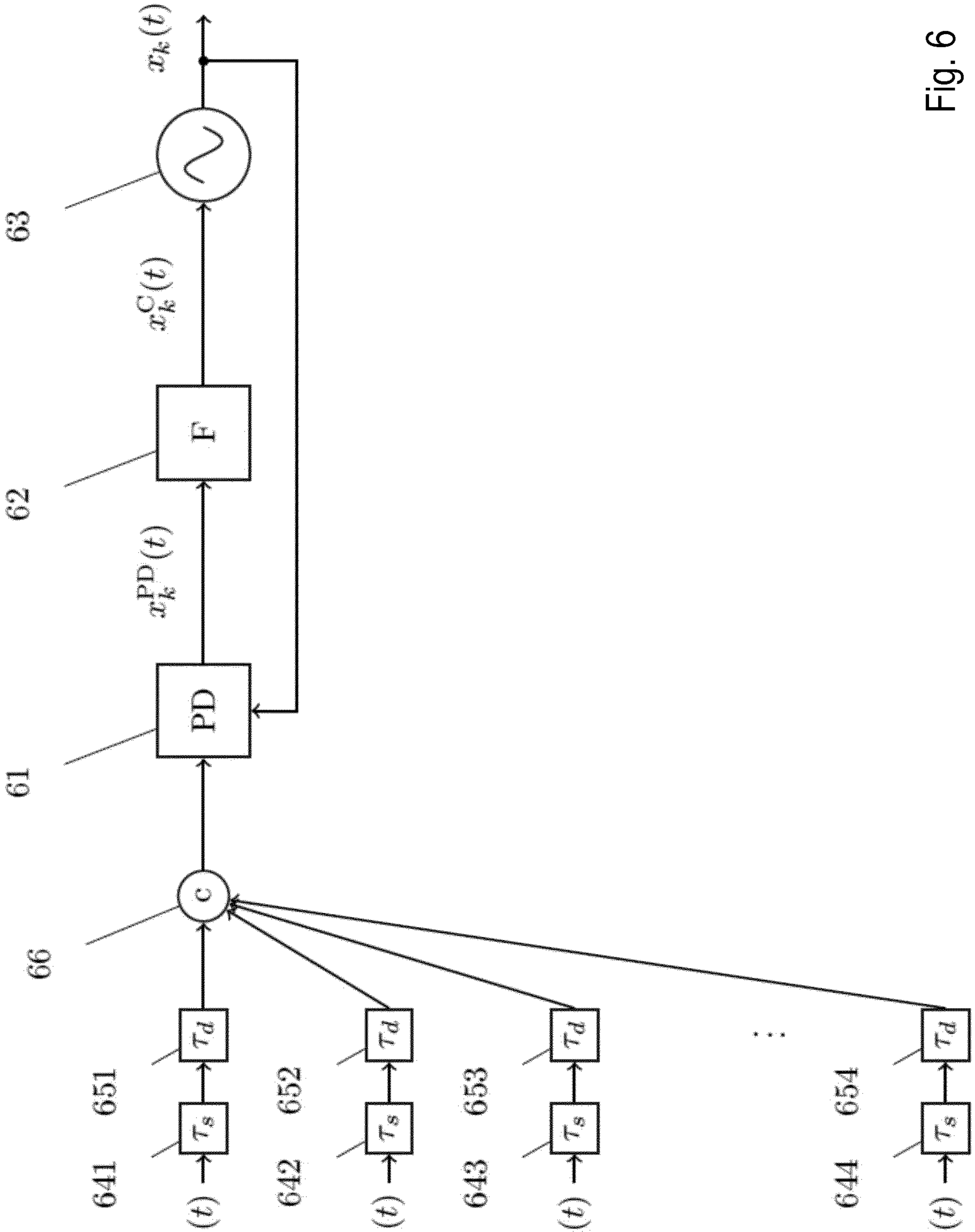
$x_k(t)$
63
$x_k^{\mathrm{C}}(t)$
62
F
$x_k^{\mathrm{PD}}(t)$
61
PD
66
c
651
τ_d
641
τ_s
$x_1(t)$
652
τ_d
642
τ_s
$x_2(t)$
653
τ_d
643
τ_s
$x_3(t)$
654
τ_d
644
τ_s
$x_n(t)$

Fig. 6

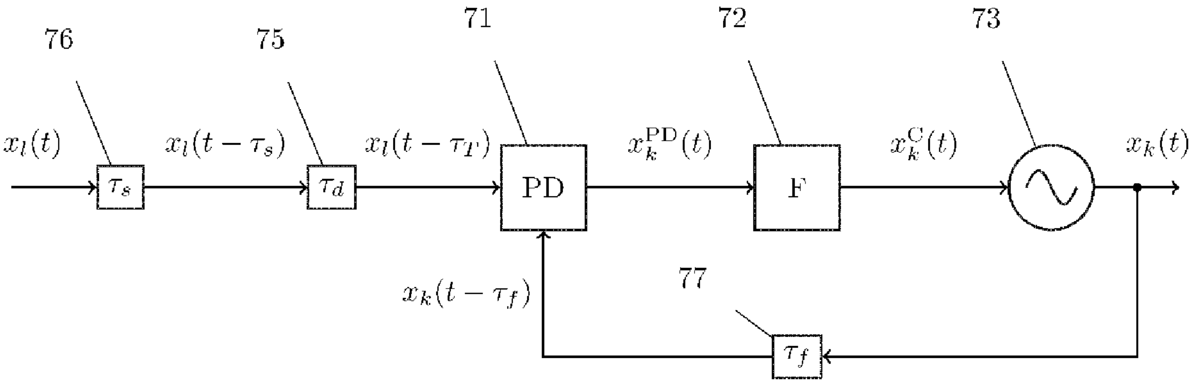
76
75
71
72
73
$x_l(t)$
τ_s
$x_l(t-\tau_s)$
τ_d
$x_l(t-\tau_T)$
PD
$x_k^{\mathrm{PD}}(t)$
F
$x_k^{\mathrm{C}}(t)$
$x_k(t)$
$x_k(t-\tau_f)$
77
τ_f

Fig. 7

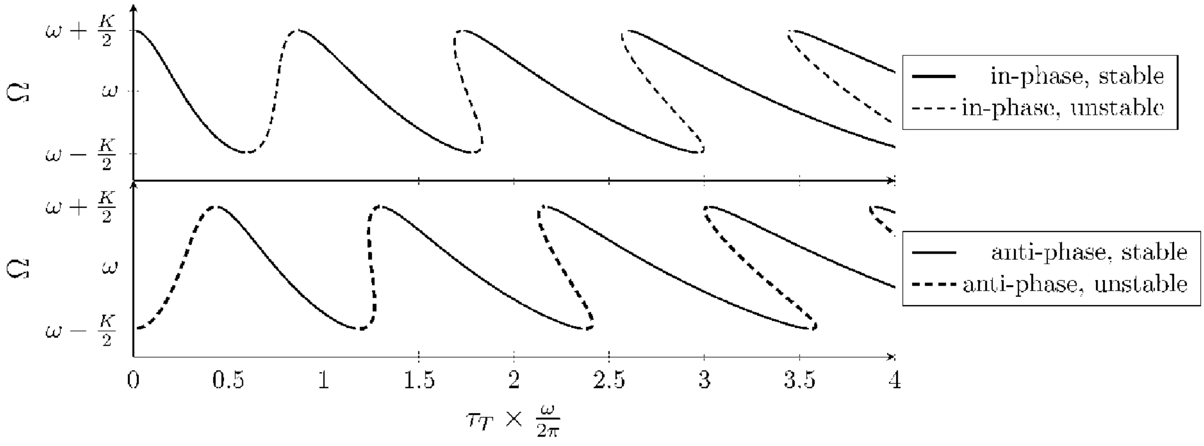
Ω
$\omega+\frac{K}{2}$
ω
$\omega-\frac{K}{2}$
in-phase, stable
in-phase, unstable
Ω
$\omega+\frac{K}{2}$
ω
$\omega-\frac{K}{2}$
anti-phase, stable
anti-phase, unstable
0
0.5
1
1.5
2
2.5
3
3.5
4
$\tau_T \times \frac{\omega}{2\pi}$

Fig. 8

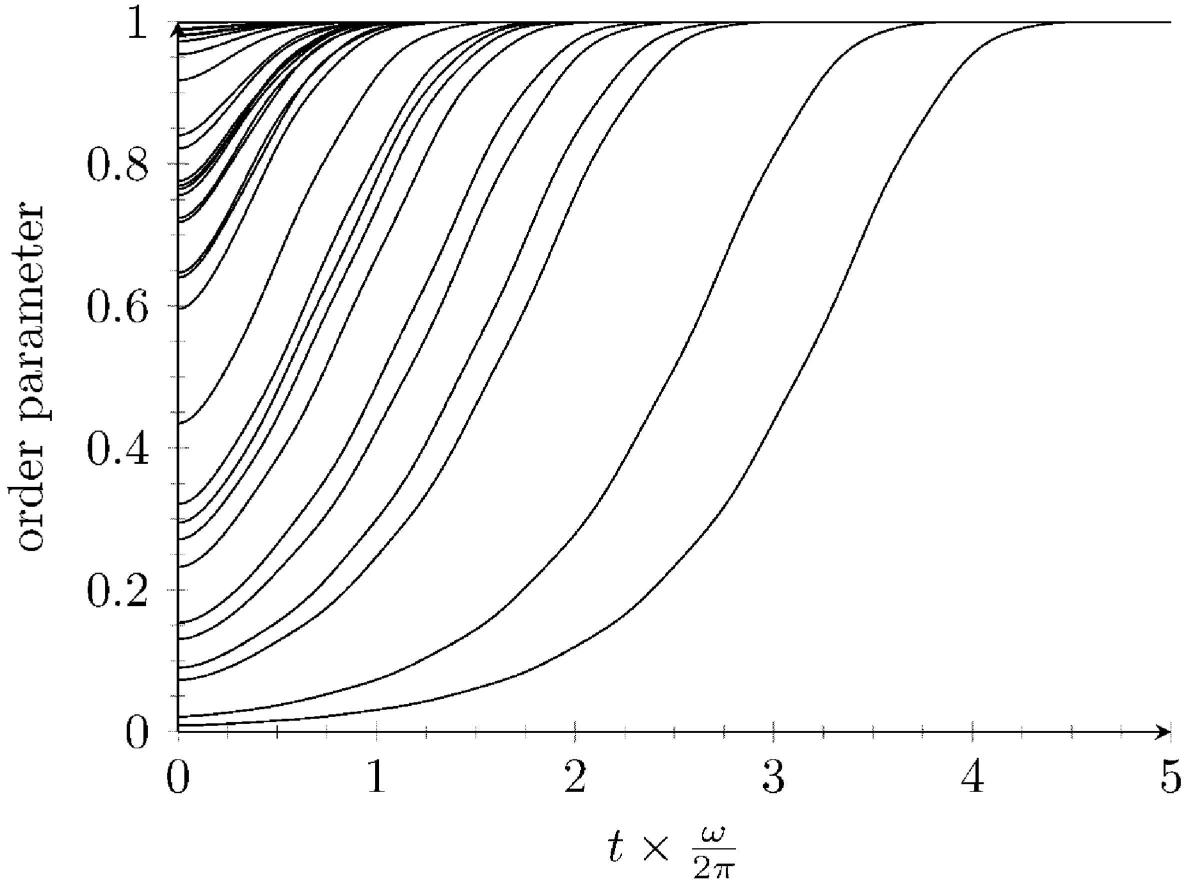

Fig. 9

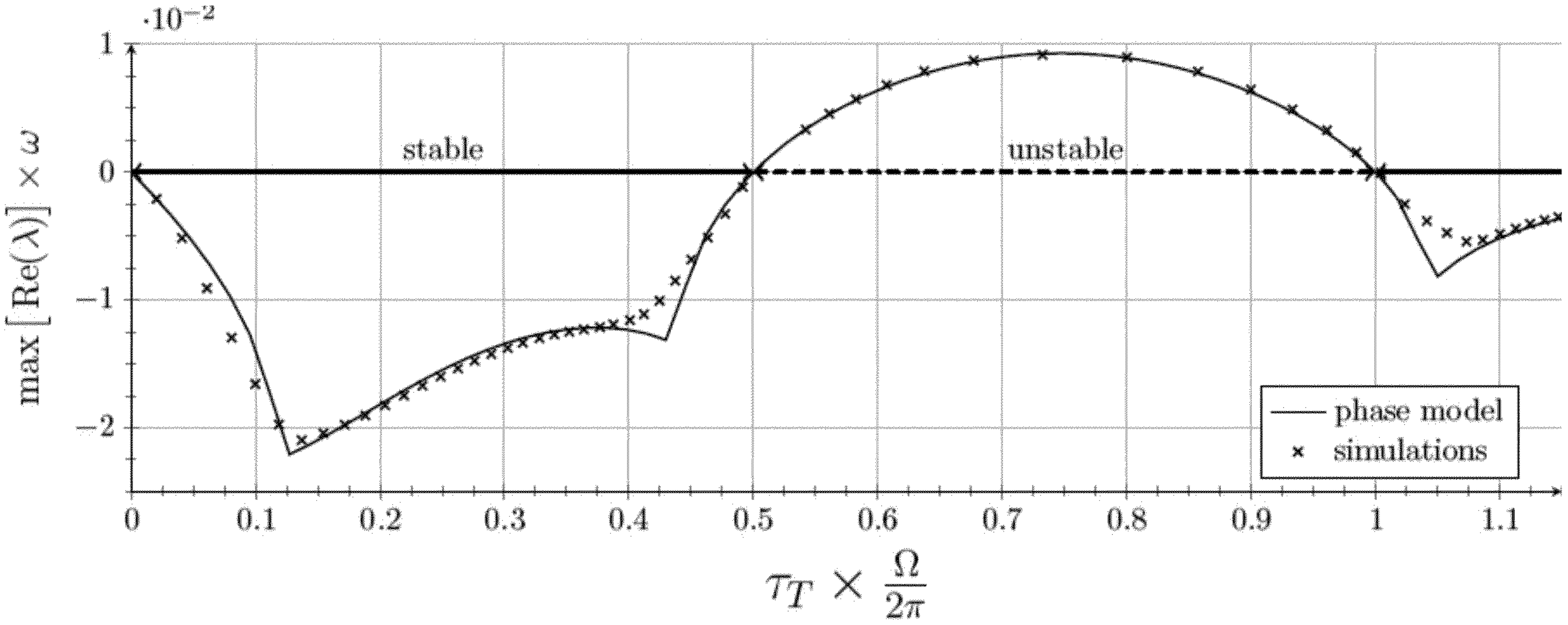
$\cdot 10^{-2}$
1
0
−1
−2
max [Re(λ)] × ω
stable
unstable
phase model
simulations
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
$\tau_T \times \frac{\Omega}{2\pi}$

Fig. 10

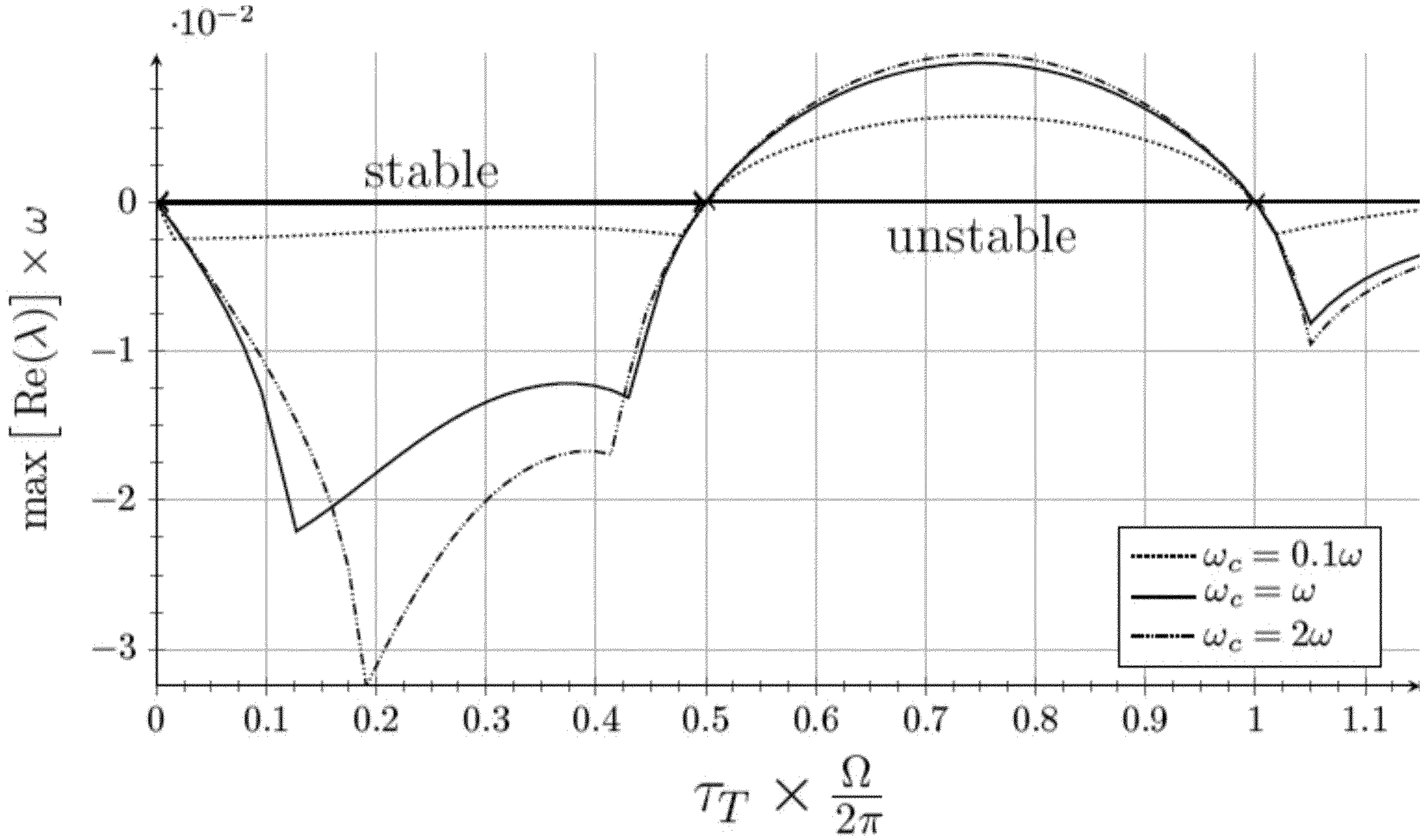
$\cdot 10^{-2}$
stable
unstable
0
-1
-2
-3
$\max\left[\mathrm{Re}(\lambda)\right] \times \omega$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
$\tau_T \times \frac{\Omega}{2\pi}$
$\omega_c = 0.1\omega$
$\omega_c = \omega$
$\omega_c = 2\omega$

Fig. 11

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- WO 2013178237 A1 **[0010] [0011] [0057]**

Non-patent literature cited in the description

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- **F.M. ORSATTI ; R. CARARETO ; J.R.C. PIQUEIRA.** Multiple synchronous states in static delay-free mutually connected PLL networks. *Signal Processing,* 2010, vol. 90, 2072-2082 **[0008]**