Appendix

A.1 Conservative Flow Networks

We start from the equations [Eq. (3.4)] for a conservative AC network with a known set of inflow and outflow nodes and obeying Ohm's law [Eq. (3.1)], namely,

$$\begin{cases} \vec{A} = \mathbf{G}(\rho)\,\vec{v} - \mathbf{G}(\sigma)\,\vec{w}, \\ \vec{B} = \mathbf{G}(\rho)\,\vec{w} + \mathbf{G}(\sigma)\,\vec{v}, \end{cases} \tag{A.1}$$

where $\vec{A}$ [$\vec{B}$] is the real [imaginary] part of the net flow (i.e., the sum of the inflows and outflows) at every node in the network (i.e., $A_k = \sum_{l=1}^{N} \Re\{I_{kl}\}$, $\Re\{I_{kl}\}$ being the real part of the current at the edge joining node k and l), $\mathbf{G}(\rho)$ [$\mathbf{G}(\sigma)$] is the Laplacian matrix that is derived from the network's conductance (susceptance) matrix ρ [σ], and $\vec{v}$ [$\vec{w}$] is the vector with the real part of the voltage potentials at each node in the network due to the particular location of the inflows and outflows that $\vec{A}$ and $\vec{B}$ provide. The aim is to calculate $\vec{v}$ and $\vec{w}$ as a function of $\vec{A}$ and $\vec{B}$.

Then, e.g., to find $\vec{w}$, we use the pseudo-inverse Laplacian matrix (see the definition in Sect. 2.3.1) of $\mathbf{G}(\rho)$, namely, $\mathbf{X}(\rho)$, and $\mathbf{G}(\sigma)$, namely, $\mathbf{X}(\sigma)$, as follows,

$$\begin{cases} \mathbf{X}(\rho)\,\vec{A} = \left(\mathbf{I} - \frac{1}{N}\mathbf{J}\right)\,\vec{v} - \mathbf{X}(\rho)\mathbf{G}(\sigma)\,\vec{w}, \\ \mathbf{X}(\sigma)\,\vec{B} = \mathbf{X}(\sigma)\,\mathbf{G}(\rho)\,\vec{w} + \left(\mathbf{I} - \frac{1}{N}\mathbf{J}\right)\,\vec{v}. \end{cases} \tag{A.2}$$

Thus, substracting these equations, we have that

$$\mathbf{X}(\sigma)\,\vec{B} - \mathbf{X}(\rho)\,\vec{A} = [\mathbf{X}(\sigma)\,\mathbf{G}(\rho) + \mathbf{X}(\rho)\mathbf{G}(\sigma)]\;\vec{w} \equiv \mathbf{L}\,\vec{w}. \tag{A.3}$$

The introduction of $\mathbf{L}$ is done in order to explicitly state that the remaining algebra to find $\vec{w}$ is solely related to the inversion of $\mathbf{L}$. In the case where the conductance and susceptance matrix commute (i.e., $[\rho,\,\sigma] = 0$), then, the respective Laplacian matrix commute as well (i.e., $[\mathbf{G}(\rho),\,\mathbf{G}(\sigma)] = 0$). Consequently, these matrices share a common eigenvectors base. Hence, $\mathbf{L}$ is a Laplacian matrix as well. Namely,

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$$L_{ij} = [\mathbf{X}(\sigma)\,\mathbf{G}(\rho)]_{ij} + [\mathbf{X}(\rho)\mathbf{G}(\sigma)]_{ij} = \sum_{k=1}^{N} \left([\mathbf{X}(\sigma)]_{ik}\,[\mathbf{G}(\rho)]_{kj} + [\mathbf{X}(\rho)]_{ik}\,[\mathbf{G}(\sigma)]_{kj}\right),$$

where, using Eq. (2.36),

$$[\mathbf{X}(\sigma)\,\mathbf{G}(\rho)]_{ij} = \sum_{k=1}^{N}\sum_{n=2}^{N}\left[\vec{\psi}_n\right]_i \frac{1}{\lambda_n(\mathbf{G}(\sigma))}\left[\vec{\psi}_n\right]_k^* \sum_{m=2}^{N}\left[\vec{\psi}_m\right]_k \lambda_m(\mathbf{G}(\rho))\left[\vec{\psi}_m\right]_j^*$$
$$\Rightarrow\quad [\mathbf{X}(\sigma)\,\mathbf{G}(\rho)]_{ij} = \sum_{n=2}^{N}\left[\vec{\psi}_n\right]_i \frac{\lambda_n(\mathbf{G}(\rho))}{\lambda_n(\mathbf{G}(\sigma))}\left[\vec{\psi}_n\right]_j^*.$$

This expression is the result of observing that $\sum_{k=1}^{N}[\vec{\psi}_n]_k^*[\vec{\psi}_m]_k = \delta_{nm}$. Moreover, because $[\vec{\psi}_n]_i = -\sum_{j\neq i}[\vec{\psi}_n]_j$ for all modes with $n > 1$ (see Sect. 2.2.1 for details on the eigenvector properties) due to the orthogonality with respect to the first mode, i.e., $\vec{\psi}_n \cdot \vec{\psi}_1 = 0\ \forall n > 1$, then, $L_{ii} = -\sum_{j\neq i} L_{ij}$ for the case where the matrices share a common eigenvector base. Consequently, $\mathbf{L}$ is a Laplacian matrix and its pseudo-inverse Laplacian matrix, $\mathbf{X}(L)$, is

$$[\mathbf{X}(L)]_{ij} = \sum_{n=2}^{N}\left[\vec{\psi}_n\right]_i \left(\frac{\lambda_n(\mathbf{G}(\rho))}{\lambda_n(\mathbf{G}(\sigma))} + \frac{\lambda_n(\mathbf{G}(\sigma))}{\lambda_n(\mathbf{G}(\rho))}\right)^{-1}\left[\vec{\psi}_n\right]_j^*. \tag{A.4}$$

We note that in Sect. 3.1.2 we name $\lambda_n(\mathbf{G}(\rho))$ $[\lambda_n(\mathbf{G}(\sigma))]$ as $\lambda_n(\rho)$ $[\lambda_n(\sigma)]$ and define R_n^2 as $R_n^2 \equiv \lambda_n(\rho)^2 + \lambda_n(\sigma)^2$ in Eqs. (3.6) and (3.7).

On the contrary, if the conductance and susceptance matrix do not commute (i.e., $[\rho,\ \sigma] \neq 0$), then, $\mathbf{X}(L)$ requires the calculation of the new eigenvalues and eigenvectors of $\mathbf{L}$. However, in any case, the solution for Eq. (A.3) is

$$\vec{w} = \mathbf{X}(L)\left[\mathbf{X}(\sigma)\,\vec{B} - \mathbf{X}(\rho)\,\vec{A}\right] + \langle w\rangle\,\vec{1}, \tag{A.5}$$

where $\langle w\rangle \equiv \frac{1}{N}\sum_{k=1}^{N} w_k$ and $\vec{1} = (1, \ldots, 1)^T$ are derived due to the pseudo-inverse Laplacian matrix third property [Eq. (2.39) in Sect. 2.3.1]. Similarly, for the real part of the node voltage potential, $\vec{v}$, we have

$$\vec{v} = \mathbf{X}(L)\left[\mathbf{X}(\sigma)\,\vec{A} + \mathbf{X}(\rho)\,\vec{B}\right] + \langle v\rangle\,\vec{1}, \tag{A.6}$$

A.2 AC Flow-Network Currents

From Eqs. (A.5) and (A.6) we derive an explicit expression for the real part of the voltage differences, i.e., $\Delta v_{kl} \equiv v_k - v_l$ ($\Delta w_{kl} \equiv w_k - w_l$ is derived analogously), in the case where conductance and susceptance matrix commute, namely, when Eq. (A.4) is valid. Moreover, the voltage differences allow to find straightforwardly the currents that are developed at every edge in the network using Ohm's law [Eq. (3.1)]. Using Eq. (A.6), we have that the voltage potential at node k is given by

$$v_k = \sum_{j=1}^{N} [\mathbf{X}(L)\,\mathbf{X}(\sigma)]_{kj}\ A_j + \sum_{j=1}^{N} [\mathbf{X}(L)\,\mathbf{X}(\rho)]_{kj}\ B_j + \langle v \rangle\,,$$

where

$$\begin{aligned}[\mathbf{X}(L)\,\mathbf{X}(\sigma)]_{kj} &= \sum_{l=1}^{N}\sum_{n=2}^{N} \left[\vec{\psi}_n\right]_k \left(\frac{\lambda_n(\rho)\,\lambda_n(\sigma)}{R_n^2}\right) \left[\vec{\psi}_n\right]_l^* \sum_{m=2}^{N} \left[\vec{\psi}_m\right]_l \frac{1}{\lambda_m(\sigma)} \left[\vec{\psi}_m\right]_j^* \\ &= \sum_{n=2}^{N} \left[\vec{\psi}_n\right]_k \frac{\lambda_n(\rho)}{R_n^2} \left[\vec{\psi}_n\right]_j^*,\end{aligned}$$

and analogously,

$$[\mathbf{X}(L)\,\mathbf{X}(\rho)]_{kj} = \sum_{n=2}^{N} \left[\vec{\psi}_n\right]_k \frac{\lambda_n(\sigma)}{R_n^2} \left[\vec{\psi}_n\right]_j^*.$$

Thus,

$$v_k = \sum_{j=1}^{N}\sum_{n=2}^{N} \left[\vec{\psi}_n\right]_k \frac{\lambda_n(\rho)}{R_n^2} \left[\vec{\psi}_n\right]_j^* A_j + \sum_{j=1}^{N}\sum_{n=2}^{N} \left[\vec{\psi}_n\right]_k \frac{\lambda_n(\sigma)}{R_n^2} \left[\vec{\psi}_n\right]_j^* B_j + \langle v \rangle\,. \tag{A.7}$$

Consequently, the voltage difference between nodes k and l, Δv_{kl}, in the AC steady-state is [Eq. (3.6)]

$$\Delta v_{kl} = \sum_{n=2}^{N} \left(\left[\vec{\psi}_n\right]_k - \left[\vec{\psi}_n\right]_l\right) \left(\sum_{j=1}^{N} \frac{\lambda_n(\rho)}{R_n^2} \left[\vec{\psi}_n\right]_j^* A_j + \frac{\lambda_n(\sigma)}{R_n^2} \left[\vec{\psi}_n\right]_j^* B_j\right). \tag{A.8}$$

Curriculum Vitae

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Education

Oct. 2011–Nov. 2014

Ph.D. in Physics
University of Aberdeen, Scotland
Thesis: Mathematical principles behind the Transmission of Energy and Synchronisation in Complex Networks.
Grade: Highest distinction.
Supervisors: Murilo S. Baptista and Celso Grebogi.
Courses: Mathematical modelling (95 %), Advanced Statistical Mechanics (95 %), Non-equilibrium Statistical Mechanics (80 %), Solar Power (87 %).
Extra-curricular: Hands-On Writing, Scientific Writing, Advanced Data Analysis, Exceptional Conference Presentations, Talking with the Media.

Aug. 2008–Jul. 2010

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M.Sc. in Physics
Universidad de la República, Uruguay
Thesis: Synchronisation of coupled electronic oscillators.
Grade: Mention (highest distinction).
Supervisors: Arturo C. Martí y Cecilia Cabeza.
Courses: Statistical Mechanics (10/12), Extended Systems and Turbulence (12/12), Phase Transitions and Critical Phenomena (11/12), Quantum Mechanics (12/12).

Aug. 2003–Jul. 2008
Licenciatura en Física opción Física (B.Sc.)

Universidad de la República, Uruguay

Courses: 32. *Average*: 9.25/12.

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Licenciatura en Física opcíon Astronomía

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Courses: 24. *Average*: 8.61/12.

Complementary Education

8 Apr. 2013–13 Apr. 2013
Joint CRM-Imperial College School and Workshop in Complex Systems
Universidad Autónoma de Barcelona, Spain

19 Mar. 2012–23 Mar. 2012

Imperial College Workshop on Critical Transitions in Complex Systems
Imperial College London, United Kingdom

Aug. 2010–Dec. 2010

Instituto de Mecánica de los Fluidos e Ingeniería Ambiental, Facultad de Ingeniería
Universidad de la República, Uruguay
Project: Numerical modelling of the Navier-Stokes equations.
Supervisors: Gabriel Usera y Rafael Terra.

21 Sep. 2009–25 Sep. 2009
ICTP International Workshop on Pseudochaos and Stable-Chaos in Statistical Mechanics and Quantum Physics

ICTP Trieste, Italy

Languages

Spanish	Native
English	Understands: very well—Speaks: very well—Writes: very well
Portugues	Understands: very well—Speaks: very well—Writes: regular
Swedish	Understands: regular—Speaks: regular—Writes: regular

Scholarships and Awards

Apr. 2015

Springer Theses award: "the best of the best"

Springer-Verlag, Germany

Award: Publication of the year's best Ph.D. theses as a Springer book.

http://www.springer.com/series/8790
Oct. 2011–Mar. 2015

Scottish Universities Physics Alliance (SUPA) studentship prize

University of Aberdeen, United Kingdom

Project: Transmission of Energy, Information, and Synchronisation in Complex Networks.
Supervisors: Murilo S. Baptista y Celso Grebogi.

Prize: 14,949£ (GBP) annually (SUPA prize 1802).
Aug. 2009–Jul. 2010

National Post-graduate Scholarships, A.N.I.I.

Universidad de la República, Uruguay

Project: Synchronisation of coupled non-linear oscillators.

Supervisors: Arturo C. Martí y Cecilia Cabeza.

Scholarship: 14,500$U monthly (BE_POS_2009_1000).
Mar. 2009–Jul. 2009

Research Initiation Scholarship, A.N.I.I.

Universidad de la República, Uruguay

Project: Numerical modelling of the interaction between stratified fluids and abrupt obstacles.

Supervisor: Luis G. Sarasúa.

Scholarship: 6,750$U monthly (BE_INI_2008_136).

Work Experience

Admission 4/2015	**Researcher level 3** PEDECIBA *Area Physics*
1/2015–1/2017	**Research Fellow** University of Aberdeen *Honorary*

12/2014–12/2016	**Adjunct Professor** UdelaR, Gr. 3 (N° 25009) *Exp. 240200-000813-14*
6/2011–6/2015	**Associate Researcher** A.N.I.I. *Code: SNI 2010 3413*
3/2011–7/2011	**Extension: 30 to 40 hs.** UdelaR, Gr. 2 (N° 22018) *Exp. 240200-000131-11*
12/2010–7/2012	**Researcher** UdelaR, Gr. 2 (N° 22018) *Exp. 240200-000735-10*
8/2009–12/2010	**Researcher Assistant** UdelaR, Gr. 1 (N° 21022) *Exp. 240200-000310-09*
9/2008–12/2008	**Extension: 20 to 30 hs.** UdelaR, Gr. 1 (N° 21303) *Exp. 240200-000674-08*
10/2007–12/2007	**Extension: 20 to 35 hs.** UdelaR, Gr. 1 (N° 21303) *Exp. 240200-000725-07*
10/2007–3/2009	**Researcher Assistant** UdelaR, Gr. 1 (N° 21303) *Exp. 240200-000602-07*

UdelaR Goverment Work

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09/2009–09/2010	**Student Delegate** Postgraduate Commission *Exp. 240200-000521-09*

Teaching Activity

Course UdelaR-IFFC	Period
Physics I Biosciences	Mar. 2015–Jun. 2015 Coordinator: Ernesto Blanco.
Wave Mechanic	Mar. 2010–Jun. 2010 Mar. 2011–Jun. 2011. Coordinator: Ernesto Blanco.
Analytic Mechanic	Mar. 2011–Jun. 2011. Coordinator: Arturo C. Martí.

Laboratory I	Mar. 2011–Jun. 2011. Coordinator: Nicolás Benech
Non-linear Physics	Aug. 2010–Dec. 2010 Coordinators: Arturo C. Martí y Cecilia Cabeza.
Workshop II	Aug. 2009–Dec. 2009 Aug. 2010–Dec. 2010. Coordinator: Cecilia Cabeza

Publications and Pre-prints
Citations: 61, h-index: 5, i10-index: 3

1. **N. Rubido**, *Stochastic dynamics and the noisy Brusselator behaviour*, in revision (2014) (arXiv: 1405.0390 [cond-mat.stat-mech]).
2. **N. Rubido**, C. Grebogi, and M.S. Baptista, *General analytical solutions for DC/AC circuit network analysis*, in revision (2014) (arXiv: 1405.1739 [physics.class-ph]).
3. R. García, **N. Rubido**, A.C. Martí, and C. Cabeza, *The role of intermediaries in the synchronisation of pulse-coupled oscillators*, Eur. Phys. J. Special Topics **223**, 1–11 (2014).
4. **N. Rubido**, A.C. Martí, E. Bianco-Martínez, C. Grebogi, M.S. Baptista, and C. Masoller, *Exact detection of direct links in networks of interacting dynamical units*, New J. Phys. **16**, 093010 (2014).
5. P.H.J. Nardelli, **N. Rubido**, C. Wang, M.S. Baptista, C. Pomalaza-Raez, P. Cardieri, and M. Latva-aho, *Models for the modern power grid*, Eur. Phys. J. Special Topics Review **10**, 1–15 (2014).
6. C. Cabeza, **N. Rubido**, and A.C. Martí, *Learning Physics in a Water Park*, Phys. Educ. **49**, 187–194 (2014).
7. **N. Rubido**, C. Grebogi, and M.S. Baptista, *Resiliently evolving supply-demand networks*, Phys. Rev. E, 012801 (2014).
8. A. Aragoneses, **N. Rubido**, J. Tiana-Alsina, M.C. Torrent, and C. Masoller, *Distinguishing signatures of determinism and stochasticity in spiking complex systems*, Sci. Rep. **3**, 1778 (2013).
9. **N. Rubido**, C. Grebogi, and M.S. Baptista, *Structure and function in flow networks*, Europhys. Lett. **101**, 68001 (2013).
10. **N. Rubido**, J. Tiana-Alsina, M.C. Torrent, J. García-Ojalvo, and C. Masoller, *Language organization and temporal correlations in the spiking activity of an excitable laser: Experiments and model comparison*, Phys. Rev. E **84**, 026202 (2011).
11. **N. Rubido**, C. Cabeza, S. Kahan, G.M. Ramírez Ávila, and A. C. Martí, *Synchronization regions of two pulse-coupled electronic piecewise linear oscillators*, Eur. Phys. J. D **62**, 51–56 (2011).

12. **N. Rubido**, C. Cabeza, G.M. Ramírez Ávila, and A. C. Martí, *Scaling laws in transient dynamics of firefly-like oscillators*, J. Phys. Conf. Series **285**, 012026 (2011).
13. **N. Rubido**, C. Cabeza, A.C. Martí, and G.M. Ramírez Ávila, *Experimental results on synchronization times and stable states in locally coupled light-controlled oscillators*, Phil. Trans. R. Soc. A **367**, 3267–3280 (2009).

Books

2006 **Notes on Wave Mechanics (pp 1–169)** Ondas (eva.universidad.edu.uy)
2015 **Energy Transmission and Synchronization in Complex Networks** Springer-Verlag

Participation in Events

9 Mar. 2015–13 Mar. 2015
Challenges of complex systems for technological applications

Universidade de Saõ Paulo, Saõ Paulo, Brazil

Invited talk: The modern power-grid from a Complex System perspective.
13 Oct. 2014–17 Oct. 2014

MEDYFINOL XVIII

Universidade Federal de Alagoas, Maceió, Brazil

Invited talk: Periodic collective behaviour: what matters is the coupling function.
22 Sep. 2014–26 Sep. 2014

European Conference on Complex Systems

Institute for Advanced Studies IMT Lucca, Italy

Talk: Exact detection of direct links in networks of interacting dynamical units.
25 Aug. 2014–28 Aug. 2014

13th Experimental Chaos and Complexity Conference

University of Aberdeen, Escocia

Poster: Exact detection of direct links in networks of interacting dynamical systems.
12 May 2014–4 Jul. 2014

Causality, Information transfer and Dynamical Networks

Max-Plank Institute for Complex Systems Dresden, Alemania

Poster: Resiliently evolving supply-demand networks.

Poster: Exact detection of direct links in networks of interacting dynamical units.

Talk: Network Inference from time-series measurements.

16 Sep. 2013–20 Sep. 2013

European Conference on Complex Systems

World Trade Center Barcelona, Spain

Talk: Resiliently evolving supply-demand networks.
17 Jun. 2013–21 Jun. 2013

Methods for Chaos Detection and Predictability

Max-Plank Institute for Complex Systems Dresden, Germany

Talk: Inferring network structure from non-linear method measurements.
3 Jun. 2013–7 Jun. 2013

Dynamic Days Europe 2013

Center for Biomedical Technology Madrid, Spain

Talk: Maintaining stable distribution in evolving supply-demand networks.
3 Dec. 2012–7 Dec. 2012

MEDYFINOL XVII

Universidad de los Ándes, Chile

Invited talk: Information capacities of complex weighted networks.
3 Sep. 2012–7 Sep. 2012

European Conference on Complex Systems

Université Libre de Bruxelles, Bélgium

Poster: Transmission of Energy and Information in Complex Networks.
3 Jun. 2012–8 Jun. 2012

International Conference on Delayed Complex Systems

Institute of Theoretical Physics Mallorca, Spain

Poster: Distinguishing determinism from stochasticity: ordinal analysis of the structure of the spiking activity of semiconductor lasers with optical feedback.
14 May 2012–18 May 2012

XXXV Encontro Nacional de Física da Matéria Condensada

Águas de Lindóia, Brazil

Poster: Symbolic statistical ordinal analysis distinguishes determinism from stochasticity in the spiking activity of semiconductor lasers with optical feedback.

Poster: Characterizing the spiking activity of semiconductor lasers with current modulation and optical feedback via ordinal time-series analysis.
3 Nov. 2010–5 Nov. 2010

XI Meeting on recent advances in Fluid Dynamics and their Applications

Colonia, Uruguay

Poster: Generation and analysis of solitary waves.
26 Jul. 2010–30 Jul. 2010

Dynamic Days South America 2010

Saõ José dos Campos, Brazil

Talk: Transients and Arnold tongues for synchronized electronic fireflies.

Poster: Synchronization of fireflies using a model of Light-Controlled Oscillators.
26 Jul. 2009–7 Aug. 2009

Hands-On Research in Complex Systems School

ICTP School and Workshop, Federal University of ABC, Brazil

Talk: Arnold tongues, scaling laws and limit cycles in optically coupled electronic oscillators.
11 May–15 May 2009

XXXII Encontro Nacional de Física da Matéria Condensada

Águas de Lindóia, Brazil

Poster: Arnold tongues, scaling laws and limit cycles in optically coupled electronic oscillators.
1 Dec.–5 Dec. 2008

MEDYFINOL XV

Universidad de la República, Punta del Este, Uruguay

Poster: Arnold tongues, scaling laws and limit cycles in optically coupled electronic oscillators.

Active Referee in Journals

Phys. Rev. Lett.	Impact Factor: 7.943
New J. Phys.	Impact Factor: 4.063
PLoS ONE	Impact Factor: 3.730
Phys. Rev. E	Impact Factor: 2.313
IEEE J. Quant. Elect.	Impact Factor: 1.830
Phys. Lett. A	Impact Factor: 1.766
Eur. J. Phys.	Impact Factor: 0.619

Collaboration Projects

- *Project*: Synchronisation in Quantum and Classical Hamiltonian systems (2014–2016).
  N. Rubido[1,2], J.A. Muniz[3], C.G. Antonopoulos[2], and L.P. García Pintos[4].

- *Project*: Fast encryption using an optical channel (2015–2017).
  N. Rubido[1,2], C. Masoller[5], and M.S. Baptista[2].
- *Project*: Community detection in complex networks (2014–2015).
  N. Rubido[1,2], Marcos G. Quiles[6], Elbert E. N. Macau[7].
- *Project*: Collective phenomena in networks of interacting electronic circuits (2014–2017).
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