

# Manuscript Title: with Forced Linebreak\*

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(MUSO Collaboration)

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(CLEO Collaboration)  
(Dated: April 8, 2020)

An article usually includes an abstract, a concise summary of the work covered at length in the main body of the article.

**Usage:** Secondary publications and information retrieval purposes.

**Structure:** You may use the `description` environment to structure your abstract; use the optional argument of the `\item` command to give the category of each item.

## I. INTRODUCTION

## II. METHOD

### A. Graph Generalization

talk about how to map the original nanowire network on to a graph.

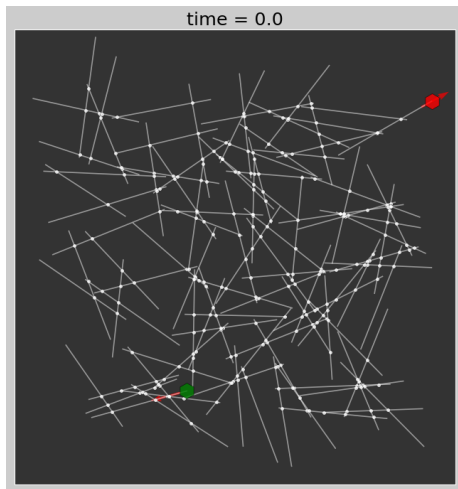


FIG. 1.

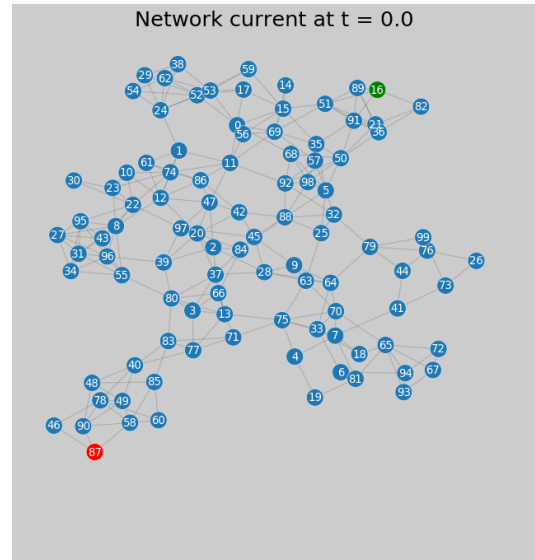


FIG. 2.

### B. Centrality

Centrality **Put some reference here** is an important measure that helps understand the fundamental structures and connectivities of networks. Betweenness centrality of nodes and edges in networks can demonstrate

\* A footnote to the article title

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.... Meanwhile, closeness centrality of nodes can be used to interpret the ..... [1].

A variation of centrality measures based on current flow model proposed by Brandes and Fleischer [2] is employed here. As the electrical dynamics in our networks fall in the class of **random walks** (not sure about here).

The betweenness centrality of an edge in the networks can be determined by:

$$c_{CB}(e) = \frac{\sum_{s \neq t \in V} \tau_{st}(e)}{(n-1)(n-2)}, \quad (1)$$

where  $\tau_{st}(e)$  is the current flow through edge  $e$  between nodes  $s$  and  $t$ , while  $n$  stands for number of nodes in the network.

The closeness centrality of a node in this context is structured in the same way as normal closeness centrality, with distance measured based on effective resistance rather than graphical distance. Therefore it is given by:

$$c_{CC}(v) = \frac{n-1}{\sum_{v \neq w \in V} R(v, w)}. \quad (2)$$

In the context of a unit  $st$ -current in the network,  $R(v, w)$  represents the effective resistance between nodes  $v$  and  $w$ .

### C. Transfer Entropy

Transfer entropy is an effective metric for information transduction ..... **cite Joe here.**

$$T_{Y \rightarrow X} = \sum_{u_n} p(u_n) \log \frac{p(x_{n+1} | x_n^{(k)}, y_n^{(l)})}{p(x_{n+1} | x_n^{(k)})}. \quad (3)$$

$n$  is a time index,  $u_n$  represents the state transition tuple  $(x_{n+1}, x_n^{(k)}, y_n^{(l)})$ ,  $x_n^{(k)}, y_n^{(l)}$  represent the  $k$  and  $l$  past values of  $x$  and  $y$  up to and including time  $n$ . **rephrase here.**

### D. Modularity

Modularity is a network metric that ..... **talk about it here** [3].

Recent studies in neuro-science demonstrated that modularity plays an important role in .... **talk about it here** [4].

Modularity ( $Q^w$ ) in a weighted network can be calculated by the Louvain method [5]:

$$Q^w = \frac{1}{I^w} \sum_{i,j} \left[ W_{ij} - \frac{k_i^w k_j^w}{I^w} \right] \delta(m_i, m_j), \quad (4)$$

in which  $w_{i,j}$  is the weight of the edge between nodes  $i$  and  $j$ ,  $I^w$  represents sum of all weights in the network,  $k_i^w$  stands for the weighted degree of node  $i$ ,  $m_i$  is the community where node  $i$  is located, and  $\delta$  is the Kronecker delta function.

## III. RESULTS

### A. Centrality and Dynamics

**100 nw is used here. Might have to use 700 nw for consistency.**

*a. Voltage distribution* Voltage distribution at a specific time  $t$  in the network can be roughly determined by the weighted current flow betweenness centrality. As shown in fig. 3, voltage and filament state as functions of centrality is plotted.

- **Rephrase here.**
- Two clustered groups (ON and OFF).
- Transition in between because of the continuity brought in by tunneling model.
- Maybe include power consumption here as well.

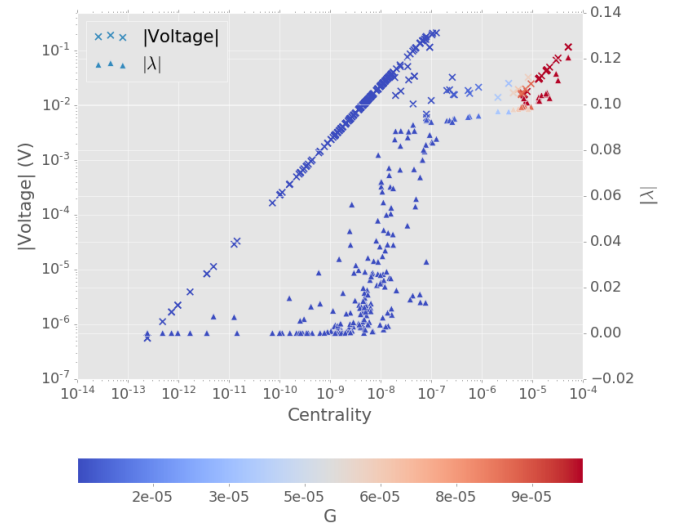


FIG. 3. T=2.9, around pathway formation. crosses are voltages and triangles are filament states.

*b. Current flow* **Maybe try power dissipation of nanowire as well.**

The cumulative current flow through nanowires shows are linear relationship versus node current flow betweenness centrality. fig. 4.

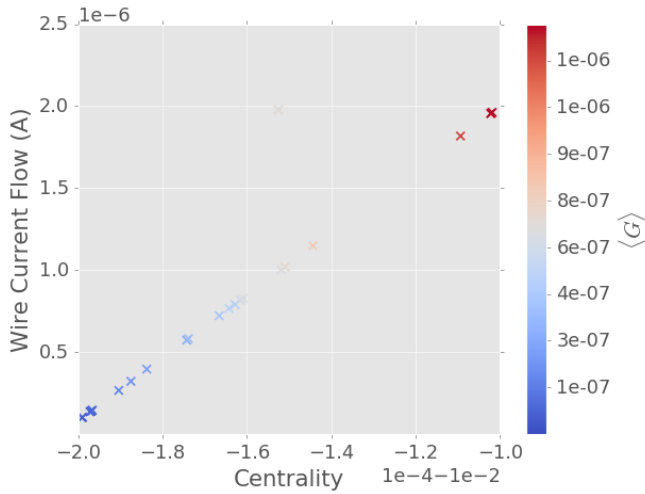


FIG. 4. Current flow on a nanowire vs node centrality

### B. Centrality and Functionality

*a. Mean communicability* Briefly Introduce the idea of communicability.

The communicability matrix ( $M$ ) is generated based on  $W$ .... Each entry represents .... **might cite some Comm paper here.**

The row sum of  $M$  can somehow interpret how communicable a node is to the rest of the network.

The plot of comm vs node closeness cent shows something .....

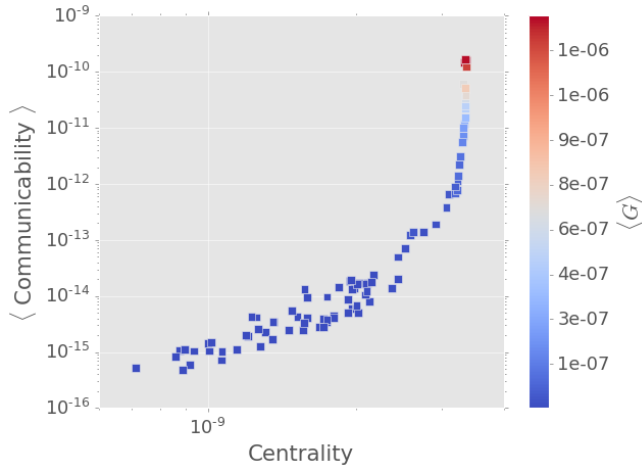


FIG. 5.

*b. Node Transfer Entropy* The wire closeness centrality also shows an interesting correlation with transfer entropy. More specifically, the capabilities of taking in and giving out information.

The transfer entropy across an edge ( $e_{i,j}$ ) is calculated by:

**Have to write these equations in a better man-**

ner.

$$TE_{i,j} = T_{V_i \rightarrow V_j} \quad (5)$$

And therefore the average outward TE and inward TE of a node can be calculated by:

$$\langle TE_{out_i} \rangle = \frac{\sum_{i,j, A_{i,j} \neq 0} TE_{out}}{\# \text{ of edges connected to } i} \quad (6)$$

With 50 repetitions of different source/target pairing (while keeping the graphical distance between them constant), TE shows a close to linear relationship with centrality as well:

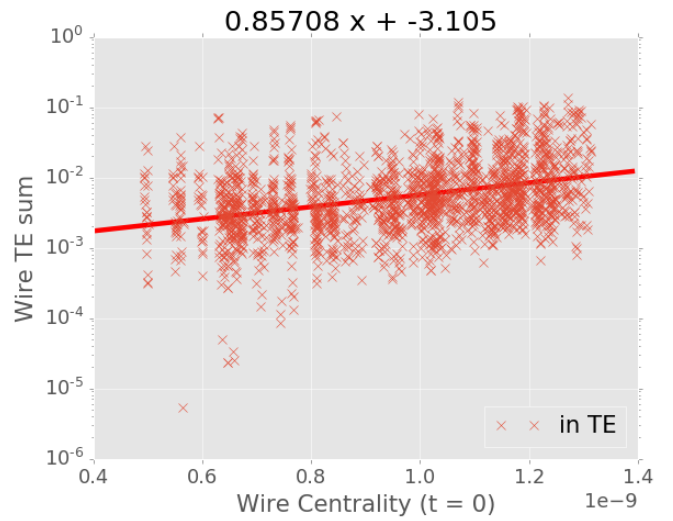


FIG. 6.

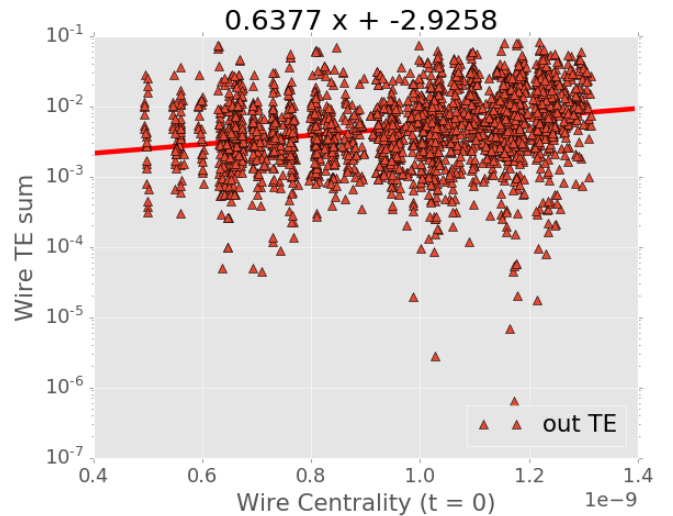


FIG. 7.

*c. Node Active Information Storage* **Not sure whether we need it here.**

### C. Time-series analysis

*a.  $\Delta G$*  The conductance time-series of the network reflects the activation stage of the network. Specifically,  $\Delta G$  can help identify the avalanche behaviors of the network.

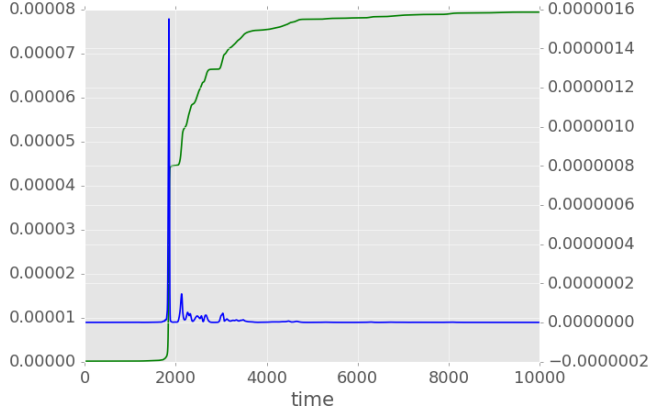


FIG. 8.

*b. TE time series* The transfer entropy across the whole network is calculated in the same way as before. The average is taken over the whole network the time series to obtain the time series.

Plotting TE time-series together with  $\Delta G$  in the same figure, the spikes of both curves coincide.

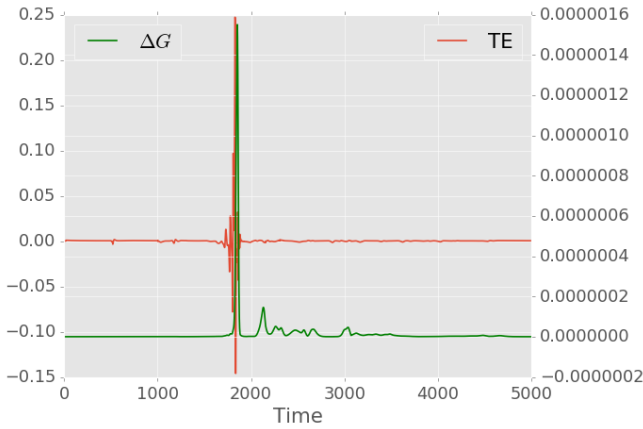


FIG. 9.

Different amplitude of voltage biases are applied to the network. The activation time and TE peak time in these realizations line-up pretty well.

*c. Modularity time series* Modularity of the network is calculated throughout the activation. The drop of Modularity coincide with  $\Delta G$  as well.

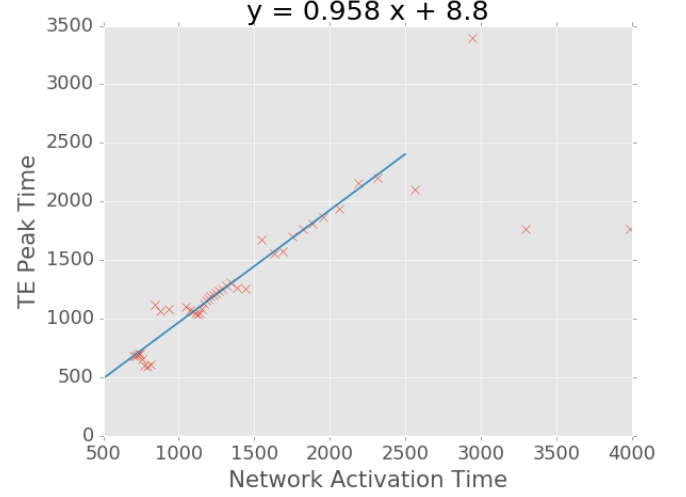


FIG. 10.

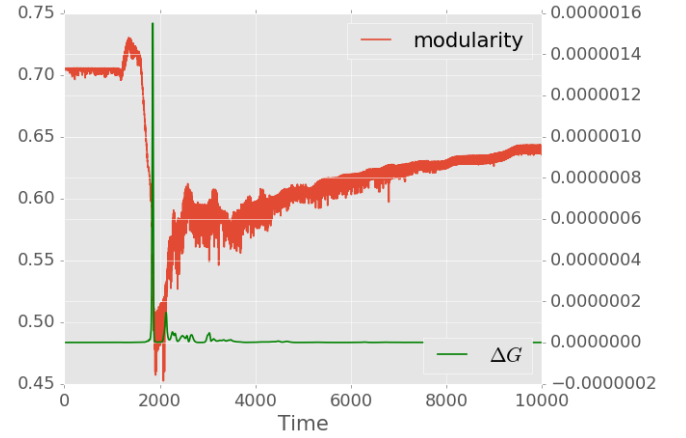


FIG. 11.

### D. Dual task

Pre-activate the network with Mackey-Glass signal, extract the state from different time-points. Then do a non-linear signal transform on it.

The Guirera [cite here](#) plots can be displayed as follow:

**Have to match the color bars here.**

## IV. DISCUSSION

## V. CONCLUSION

## ACKNOWLEDGMENTS

We wish to acknowledge the support of the author community in using REVTeX, offering suggestions and encouragement, testing new versions, . . .

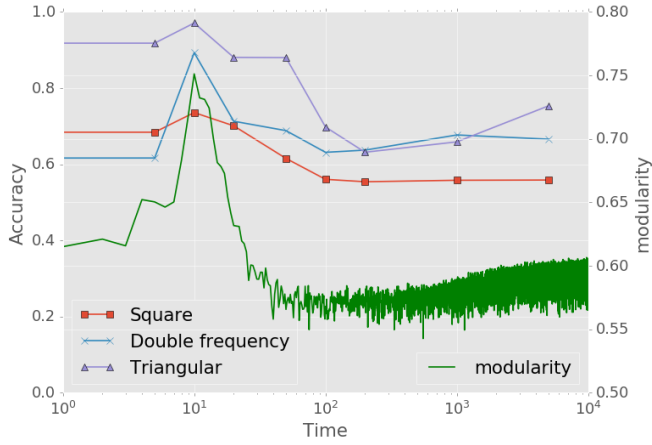


FIG. 12.

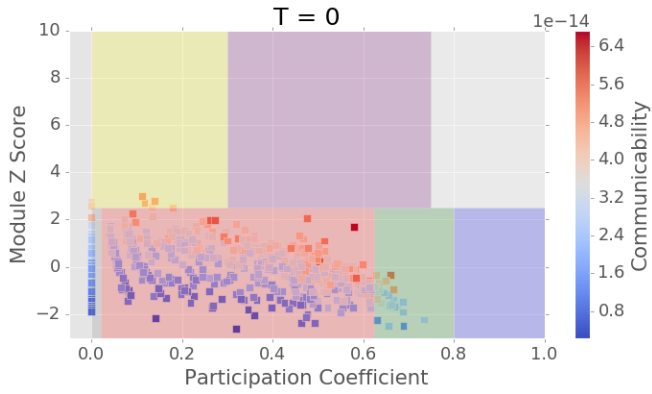


FIG. 13.

## Appendix A: Appendixes

## Appendix B: A little more on appendixes

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- [1] M. Newman, *Networks: An Introduction* (2010) pp. 1–784.
  - [2] U. Brandes and D. Fleischer, Centrality measures based on current flow, in *Lecture Notes in Computer Science*, Vol. 3404 (2005) pp. 533–544.
  - [3] M. Rubinov and O. Sporns, Complex network measures of brain connectivity: Uses and interpretations, *NeuroImage* **52**, 1059 (2009).
  - [4] D. Godwin, R. L. Barry, and R. Marois, Breakdown of the brain’s functional network modularity with awareness, *Proceedings of the National Academy of Sciences of the United States of America* **112**, 3799 (2015).
  - [5] V. D. Blondel, J. L. Guillaume, R. Lambiotte, and E. Lefebvre, Fast unfolding of communities in large networks, *Journal of Statistical Mechanics: Theory and Experiment* **2008**, 10.1088/1742-5468/2008/10/P10008 (2008), arXiv:0803.0476.

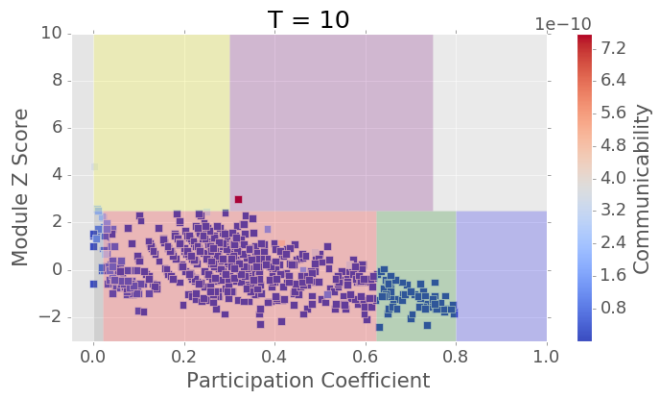


FIG. 14.

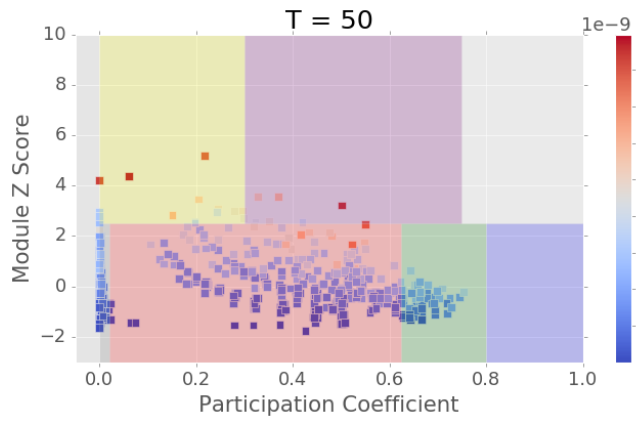


FIG. 15.