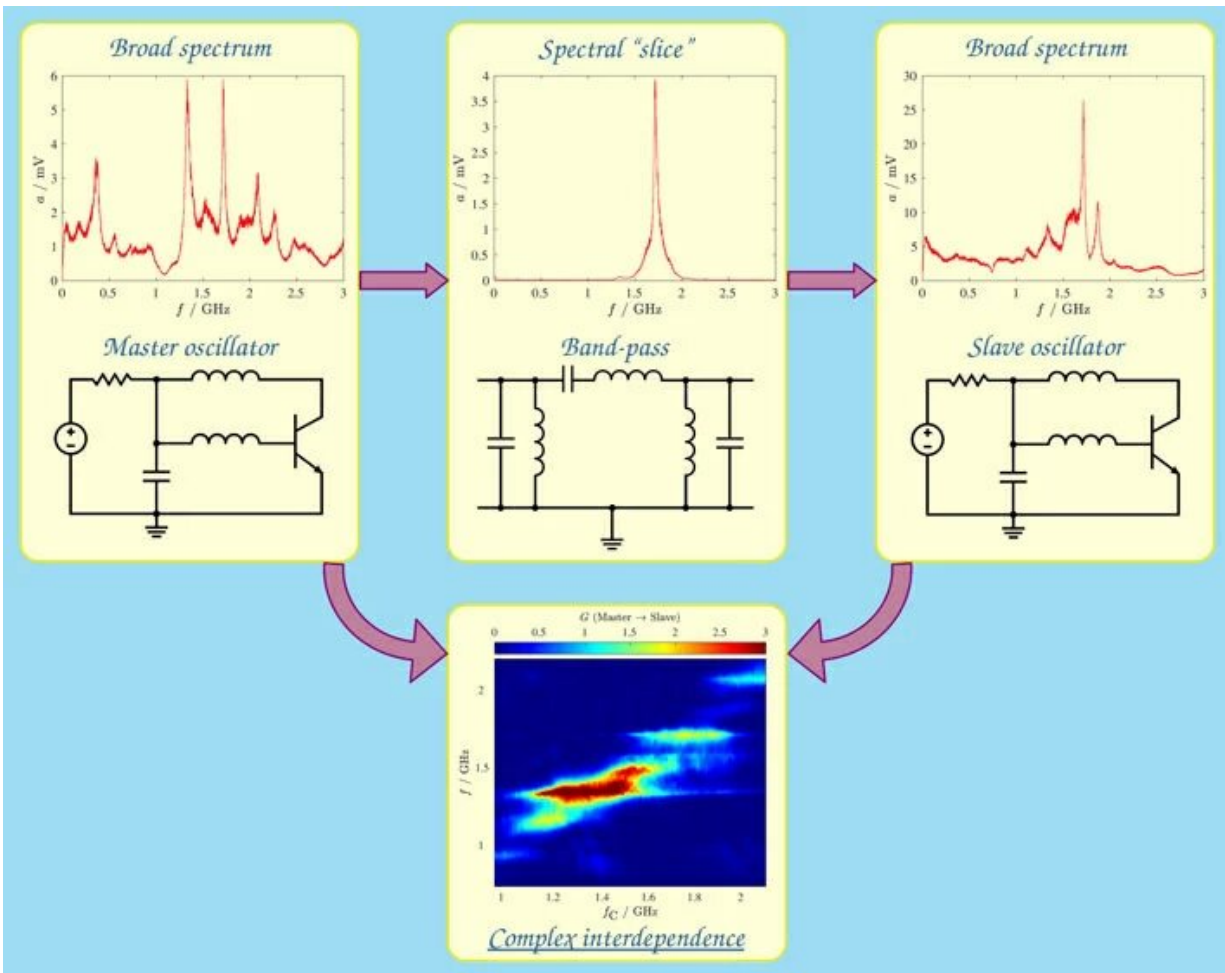


Synchronizing chaos through a narrow slice of the spectrum

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Conceptual overview of the coupling scheme between a master and a slave chaotic oscillator via a band-pass filter, and the resulting complex interdependence between their activities. Credit: *Chaos, Solitons & Fractals* (2022). DOI: 10.1016/j.chaos.2022.112854

The abstract notion that the whole can be found in each part of something has for long fascinated thinkers engaged in all walks of philosophy and experimental science, from Immanuel Kant on the essence of time to David Bohm on the notion of order, and from the self-similarity of fractal structures to the defining properties of holograms.

It has, however, remained understandably extraneous to [electronic engineering](#), which strives to develop ever more specialized and efficient circuits exchanging signals that possess highly controlled characteristics. By contrast, across the most diverse complex systems in nature, such as the brain, the generation of activity having features that present themselves similarly over different temporal scales, or frequencies, is nearly a ubiquitous observation.

In a quest to explore new and unorthodox approaches to designing systems capable of solving difficult computation and control problems, physicists and engineers have, for decades, been investigating networks made up of chaotic oscillators. These are systems that can be easily realized using analog electronic, optical, and mechanical components.

Their striking property is that, despite being quite simple in their structure, they can generate behaviors that are, at the same time, incredibly intricate and far from random.

"Chaos entails an extreme sensitivity to initial conditions, meaning that the activity at each point in time is effectively unpredictable. However, a crucial aspect is that the geometrical arrangements of the trajectories generated by chaotic signals have well-defined properties which, alongside the distribution of frequencies, are rather stable and repeatable. Since these features can change in many ways depending on the voltage input or parameter settings like a resistor value, these circuits are interesting as a basis for realizing new forms of distributed computation, for example, based on sensor readings," explains Dr.

Ludovico Minati, lead author of the study.

"In our recent work, we showed that they could be effectively used to realize the kind of physical reservoirs that can simplify neural network training," adds Mr. Jim Bartels, doctoral student at the Nano Sensing Unit, where the study was conducted.

When two or more chaotic oscillators are coupled together, the most interesting behaviors emerge as they attract and repulse their activities while trying to find an equilibrium, in ways that usual periodic oscillators simply cannot access. "Two years ago, work done in our laboratory demonstrated that these behaviors could, at least in principle, be used as a means to gather readings from distant sensors and directly provide statistics such as the average value," adds Dr. Ludovico Minati.

However, the complex nature of chaotic signals implies that they generally feature broad frequency spectra, which are very different from those, narrow and neatly delineated, that are typically used in modern wireless communication. "As a consequence, it becomes very difficult, if not impossible, to realize couplings over the air. That's not only because antennas are often highly tuned for specific frequencies, but also and especially because radio regulations do not allow broadcasting except within tightly-defined regions," explains Mr. Boyan Li, master student and second author of the study.

To date, there is a substantial body of literature covering the many effects that can arise in ensembles of chaotic oscillators. For example, small groups of nodes that preferentially synchronize with each other can appear, a little like groups of people coalescing together at a party, together with unexpected remote inter-dependencies that remind us of the binding problem in the brain.

However, surprisingly, almost no studies have considered the possibility

(or otherwise) of coupling chaotic oscillators via a mechanism, basically a filter, that transfers only a narrow range of frequencies. For this reason, the researchers at Tokyo Tech decided to explore the behavior of a pair of chaotic oscillators. They coupled them using a filter that they could easily tune to let through only a narrow range of frequencies, while for the time being retaining a wired connection between them.

"We decided to use a type of chaotic oscillator that is extraordinarily simple, involving only one transistor and a handful of passive components, and known as the Minati-Frasca oscillator. This family of oscillators was introduced about five years ago by researchers from Italy and Poland, and has many remarkable properties, as outlined in a recent book. Recently, we become interested in understanding them and their several potential applications," explains Dr. Hiroyuki Ito, head of the Nano Sensing Unit where the study was conducted.

Based on simulations and measurements, the research team was able to demonstrate that it is in fact possible to synchronize these oscillators even without transferring the entire broad spectrum, but just a relatively narrow "slice" of it. They like to compare this to a situation where the whole is found, at least partially, in a part.

When operating in the lower gigahertz region, close to where first-generation wireless devices work, the oscillators could synchronize when conveying only a few point percent of the bandwidth. As expected, the synchronization was not complete, meaning that the oscillators did not completely follow each other's activity.

"This sort of incomplete, or weak, interdependence is precisely the region where the most interesting effects can appear at the level of a network of nodes. It is quite similar between oscillators and neurons, as one of our previous works showed. These are the mechanisms that represent the next frontier for implementing distributed computation

based on emergent behaviors, as many research groups worldwide are pursuing," adds Dr. Mattia Frasca from the University of Catania in Italy, who initially co-discovered these circuits with Dr. Minati, later analyzing together their behaviors and relationship to other systems in nature, and provided several [theoretical foundations](#) which were used for the study by the Tokyo Tech researchers.

The researchers observed that while a narrow slice of the spectrum was enough to obtain some detectable synchronization, the center location and width of the filter had important effects. Using a multitude of analysis techniques, they could see that over some regions, the activity of the slave [oscillator](#) tracked the filter setting in an evident way, whereas in others, different and rather more complex effects appeared.

"This is a good example of the richness of behaviors available to these circuits, which remain not widely known in the electronic engineering community. It is quite different compared to the simpler responses of periodic systems, which are either locked or not to each other. It is a long way before we are really able to realize effective applications using these phenomena, so it must be said that this is fundamental research at the moment. However, it is very fascinating to think that in the future we may realize some aspects of sensing also using these unusual approaches," adds Zixuan Li, doctoral student, and co-author of the study.

After this interview, the team explained that this type of research will firstly need to be extended by understanding more deeply the phenomena and how they can be used to generate interesting collective activity. Then, the two main engineering challenges will be to demonstrate couplings over an actual wireless link, while meeting all radio requirements, and to substantially minimizing the power consumption, also using some results from their previous research.

"If successful solutions are found to these challenges, then one of our main goals is to demonstrate usable distributed sensing in applications that are important to society, such as monitoring the condition of land in precision agriculture," concludes Dr. Hiroyuki Ito. The methodology and results are reported in a recent article published in *Chaos, Solitons & Fractals*, and all of the experimental recordings have been made freely available for others to use in future work.

More information: Ludovico Minati et al, Incomplete synchronization of chaos under frequency-limited coupling: Observations in single-transistor microwave oscillators, *Chaos, Solitons & Fractals* (2022). [DOI: 10.1016/j.chaos.2022.112854](https://doi.org/10.1016/j.chaos.2022.112854)

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