Gate Network Dynamics: Ultra-Wideband Sources

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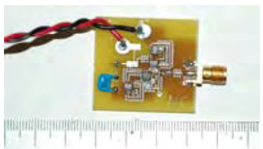
Revolutionary Research . . . Relevant Results

Background: Boolean Networks

Boolean networks consist of nodes connected by directed edges, which link the outputs of nodes to the inputs of nodes. The most common physical realization of the nodes is found in logic gates. A given node has *k* inputs, which determine its output via a truth table associated with the node. Each input is "true" or "false" (0 or 1), as is the output, so for a *k*-input node there are 2^(2^k) possible truth tables. In the ideal case, simultaneous update of all of the nodes in a network is assumed. Boolean networks have been used as a model for gene regulatory networks, and S.A. Kauffman, who first investigated the properties of random Boolean networks, proposed that *k*=2 networks are on the "edge of chaos". We investigate physical realizations of such networks.

Below left: An example of a Boolean network. Note the directed edges. (J.E.S. Socolar and S.A. Kauffman, Phys. Rev. Lett 90, 068702 (2003).)

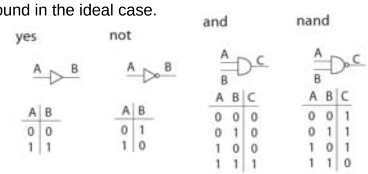
Below right: Photo of one circuit, in this case the not-nand-2not circuit. The smallest tics on the bottom scale denote millimeters.

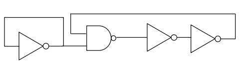


Implementation: Logic Gates

To implement physical realizations of Boolean networks, we use logic gates, connecting their inputs and outputs together to form the network, and associating the Boolean variable "true" with the high voltage of the gates, and "false" with the low voltage. Our current set-up consists of logic gates (NOTs, NANDs, and XORs) from the Tiny Logic family, soldered onto custom designed printed circuit boards. We have also used logic gates from the 74AC series on a breadboard. The 74AC series oscillates in the 0-200 MHz range, while the Tiny Logic gates are faster, in the 0-2 GHz range. We have focused on NAND networks, since they have 2 inputs (and so networks of them potentially lie on the "edge of chaos") and since the NAND is a universal logic gate: all other gates can be constructed from some number of NANDs. Non-idealities arise as a result of the analog nature of the circuits, asynchronous updates of the logic gate states, noise in the circuit, and capacitive coupling between elements, leading potentially to a wider range of behaviors than is found in the ideal case.

Right: Circuit diagrams and truth tables for some simple logic gates.

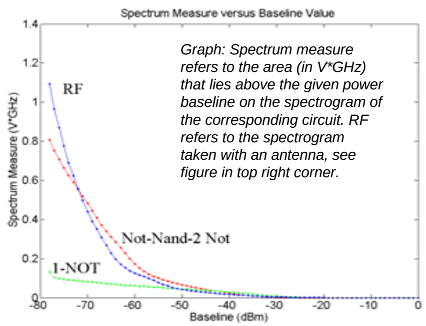




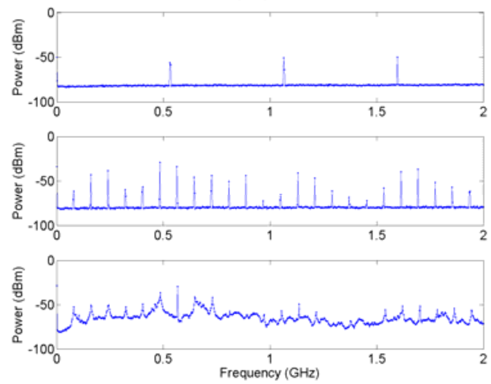
Left: Circuit diagram of not-nand-2not circuit, which exhibits broadband behavior at certain supply voltages.

Results

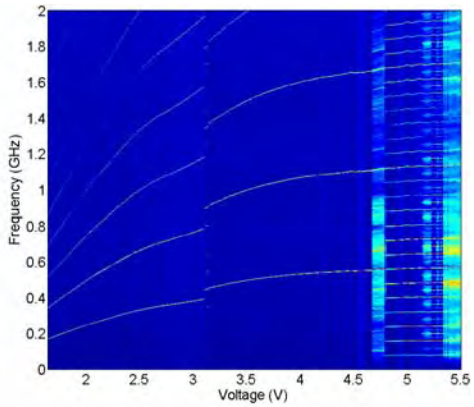
To date we have investigated a number of simple networks consisting of between 1 and 5 elements, using NOT, NAND, and XOR gates. In our current set-up, we use a spectrum analyzer to study the behavior of the circuits. We also have a variable power supply. We have seen both fixed point and simple periodic behavior, as expected from the behavior of the corresponding ideal networks. In addition, for some power supply voltages we also see quasi-periodic and broadband behavior, possibly corresponding to chaos, which is not possible in the ideal case (for which only periodic or fixed point behavior is possible after transients). The broadband behavior is of particular interest in possible sensor applications. One way we quantify the behavior is with a measure of the area on a spectrogram that lies above a given power.



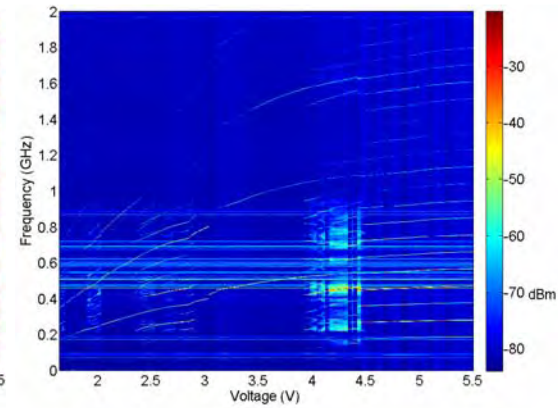
*Graph: Spectrum measure refers to the area (in V*GHz) that lies above the given power baseline on the spectrogram of the corresponding circuit. RF refers to the spectrogram taken with an antenna, see figure in top right corner.*



Above: Spectra for the not-nand-2not circuit for three different voltages, showing, from top to bottom, simple periodic, periodic with sub-harmonics, and broadband behavior.



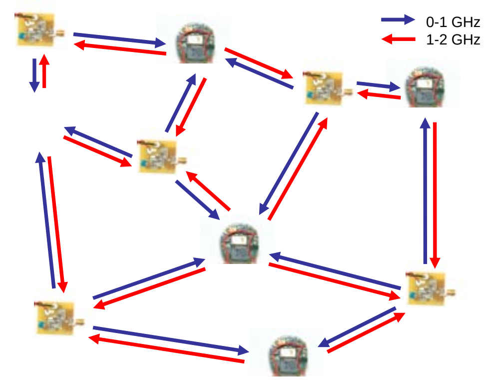
Spectrogram for the not-nand-2not circuit, with spectra plotted in vertical slices in color, with the power supply voltage along the horizontal axis.



Spectrogram taken with an antenna on the spectrum analyzer input, and the not-nand-2not circuit connected to an oscilloscope and another antenna, approximately 30 cm away. Note the "lab" signature, the constant horizontal features. Also, note the shift in the location of the broadband states as compared to the spectrogram on the left, due to coupling with the oscilloscope and antenna.

Left: An example of a smart particle, consisting of sensors, power supply, and transmitter (ENS-Lyon/Maryland collaboration).

Below: Example of a possible network of sensors, consisting of two different types that transmit and receive in different bands (as a method of avoiding the problem of self-coupling washing out the effect of other circuits in the network).



Conclusions:

•Broadband behavior in the 0-200 MHz and 0-2 GHz ranges is possible in circuits with a small number of elements.

Future Plans:

•Characterize interaction via antennas of 2 or more circuits, and investigate antenna design and optimization.

•Explore battery power options for circuits (resulting in reduced noise in the circuit, but a fixed voltage).

•Investigate more network topologies, guided by theory and results for behavior of ideal networks (looking at length and number of attractors in ideal case).

•Medium and long term: engineer circuits into smart particles, investigate large network implementations.