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Nonlinear Channelizer: A Frequency Agile and Adaptive Receiver for RF Communication

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Abstract— The Nonlinear Channelizer is an integrated circuit made up of large parallel arrays of analog nonlinear oscillators which has the ability to receive complex signals containing multiple frequencies. The concept is based on the generation of internal oscillations in coupled nonlinear systems that do not normally oscillate in the absence of coupling. In particular, the system consists of unidirectionally coupled (overdamped) bistable nonlinear elements, where the frequency and other dynamical characteristics of the emergent oscillations depend on the system's internal parameters and the received signal. These properties and characteristics are employed to develop a system capable of locking onto any arbitrary input Radio Frequency (RF) signal over a wide bandwidth. The developed system is efficient by eliminating the need to rely on high-speed, high-accuracy Analog-to-Digital Converters (ADC's), and compact by making use of nonlinear coupled systems to act as a channelizer (frequency binning and channeling), a low noise amplifier, and a frequency down-converter in a single step which, in turn, will reduce the size, weight, power, and cost of the entire communication system. In addition, configuring the channel's attributes in terms of its location in the spectrum and its bandwidth are done with the simple controls of the coefficients of the nonlinear terms in the system via resistor settings which can afford the system the flexibility to reconfigure the channels' characteristics through command lines. This paper covers the summary of the work by discussing the concept of the nonlinear channelizer, the dynamics of the system and its associated bifurcations that give rise to the behaviors used for channeling, and finally the experimental results for a system operating between 500 MHz to 4 GHz. The complete detail of the work and the engineering details are reported in the journal paper [1].

1. Introduction

A traditional approach to creating a linear version of the channelizer is to directly digitize the signal using high-speed (and highly accurate, i.e., lots of bits) analog-to-digital converters (ADC's) [2–4]. The signal is then processed using dedicated digital signal processing hardware and software [5]. Due to speed and accuracy limitations, many ADC's may be required to digitize "chunks" of the spectrum in parallel. Although this approach is straight forward and can offer some significant benefits in performing specific functions (such as processing correlated spread spectrum signals that are below the ambient noise level), the resulting systems tend to be large, expensive, and power hungry. In addition, this requirement places high demand on high-speed, high-accuracy ADC's for such purposes, but the low-power and low-cost devices needed to meet the current signal processing needs remain elusive.

The Nonlinear Channelizer circumvents the traditional solution by taking advantage of the properties of the nonlinear oscillators and oscillating arrays. Of particular utility is the phenomenon of synchronization [6, 7]. The system employs synchronization similar to a two-dimensional Van der Pol system [8, 9], but is constructed of three or more one-dimensional (overdamped) bistable elements. As a result, the N dimensional arrayed system, which can also demonstrate oscillatory behavior, shows a wider variety of synchronization behaviors and characteristics beyond that of a single two-dimensional oscillator.

In a nutshell, a Nonlinear Channelizer can be described simply as a RF spectrum analyzer contained on an analog microchip, which can perform its function on a massively parallel scale, as denoted in the Channelizer IC in Figure 1. Each chip is capable of having hundreds of discrete arrays

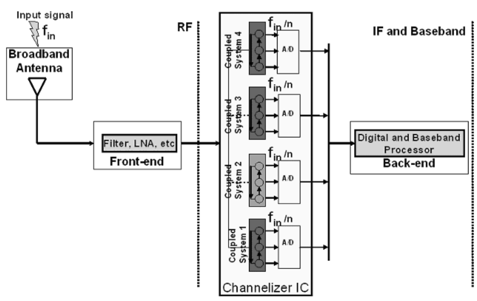

Figure 1: *Schematic concept of a Nonlinear Channelizer. The device is essentially a RF spectrum analyzer made up of hundreds of discrete arrays of coupled nonlinear oscillators. Each array is tuned to cover a specific frequency range for signal interception.*

of coupled nonlinear oscillators, with each array adjusted to cover a specific frequency range for signal interception. Figure 2 shows how the channels are stacked over a wide

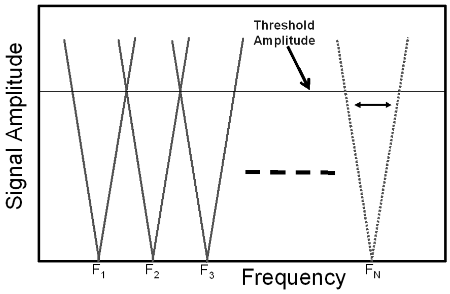

Figure 2: *Stacking channels give the channelizer the ability to intercept a wide spectrum of frequencies. During regular operation an external signal with frequency f_i is first sent to all channels. Then only the oscillators in the array that cover that particular frequency f_i would change their natural oscillation to lock onto the signal while the remaining channels continue to oscillate, unaffected, at their natural frequencies.*

range of frequencies to cover the spectrum of interest. In operation, the entire incoming frequency spectrum gathered by an antenna or the system's front-end is fed to all the banks (channels) of oscillators for channelizing. If the incoming signal has frequency content which falls within the range (within the V-shape or bandwidth) of a specific bank (channel), then the oscillators in that bank would change their natural oscillation's characteristics to lock onto that signal in response; even though, the incoming signal may be off from the natural oscillation's frequency. While responding to the input signal, each oscillator in the channel array oscillates at f_{in}/N, where f_{in} is the input signal frequency and N is the number of nonlinear oscillators coupled in the array (N is odd and greater than 1). This effect provides an automatic frequency down-conversion function to bring the intercepted signal from high to low without using the commonly employed method of frequency mixing in the state-of-the-art communication systems. The lowering of the frequency makes it easy for signal digitization via a commonly available Analog-to-Digital converters. Afterward the responding channels outputs can be passed onto the Control and Logic electronics for further signal processing, which are denoted as the back-end in Figure 1.

This new technology relies on the dynamical properties of carefully constructed nonlinear circuits. These circuits, which possess a few generic but necessary nonlinear qualities, are used to lock onto a specific band of frequencies. Additionally, the circuits have a useful quality that allows them to operate in a quiescent state. In the presence of an appropriate radio frequency (RF) signal, the nonlinear circuit undergoes a dynamical change known as a bifurcation, resulting in oscillatory behavior that is phase and frequency locked to the incoming signal (carrier signal).

The remaining part of the paper is organized as follows. In Section 2 the dynamics of the coupled system is presented along with the bifurcation analysis and the numerical simulation results. In Section 3 the experimental setup and the results are discussed. Lastly, in Section 4 some concluding remarks are presented.

2. Dynamics, Bifurcation, and Simulation Results

We now provide an overview of the behaviors of a coupled array of nonlinear elements whose dynamics is derived from the circuit analysis. The basic dynamics of the N-element array can be modeled through the following system of differential equations,

$$C_L \dot{V}_i = -gV_i + I_s \tanh(cV_i) - I_c \tanh(cV_{i+1}) + I_g \tanh(cs(t)), \quad (1)$$

where $i = 1, \ldots, N$. Note that we have cyclic boundary conditions, the array is actually an N-element "ring" with unidirectional or forward coupling only. C_L is the effective load capacitance of the entire circuit, which sets the maximum response time of the circuit. I_s is nonlinear coefficient that defines the bistability of the circuit when tuned past a threshold value. I_c is the coupling coefficient between the nonlinear oscillators. I_g controls the gain of an input signal $s(t)$, and c is a constant based on the microchip fabrication process. The parameter values used throughout this paper, unless otherwise noted, are: $C_L = 0.1pF$, $g = 0.001\Omega$, $c = 7$, $I_s = 900\mu A$, $I_c = 650\mu A$, and $I_g = 100\mu A$.

We now consider $s(t) = \varepsilon \sin(2\pi\omega t)$, where ε represents the amplitude of the incoming signal and ω is the frequency. In the absence of the external signal ($\varepsilon = 0$), the system is known to exhibit quiescent steady-state behavior as well as oscillatory behavior. In the oscillatory state, each component switches between its two stable states, leading or lagging its neighboring component by $2\pi/N$ radians. Again, this pattern is referred to as the out-of-phase or traveling wave pattern. A theoretical understanding of the oscillator's response to an incoming signal is available based on recent developments [10–12]. Figure 3 illustrates three regions of response to a signal as a function of the amplitude ε and the parameter I_c. In the supercritical region (I) the oscillator array is not frequency locked to the incoming signal, rather it oscillates at its natural frequency but the amplitudes are modulated by the input signal. In region (II) the oscillator array is frequency locked to the incoming signal so that each oscillator in the array switches at a frequency that is ω/N, where ω is the frequency of the incoming signal. In region (III) the dynamics of each oscillator in the array is over-driven by the incoming signal, resulting in an in-phase response with respect to each other and the signal. The significance of regions (II) and (III) is that the response of the oscillators is overwhelmingly driven by the characteristics of the incoming signal $s(t)$ in terms of phase and frequency. In this sense the oscillator channels the significant qualities of the incoming signal. Even in the case of frequency down-conversion, which occurs in region (II), the phase information of the input signal is preserved via the synchronization effect. Thus, a theoretical and experimental understanding of the parametric control over the regions of synchronization and the bifurcation qualities will be necessary to design the channelizing devices that accurately target the signals with precise frequency and amplitude characteristics.

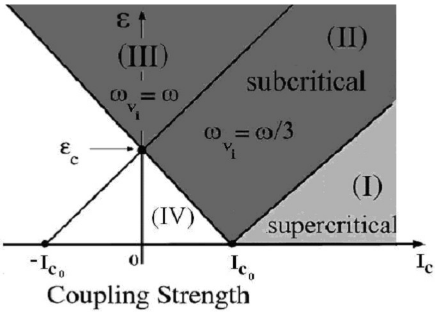

Figure 3: *Bifurcation diagram depicting different regions of behavior in a channelizer, with three elements per array, as a function of inter-component coupling strength I_c and signal strength ε. Regions (II) and (III) represent synchronization between the oscillators in the array and an external signal with frequency ω. In region (II) each oscillator oscillates at $\omega/3$. In region (IV) the system does not oscillate without an external signal. In Region (I) the oscillators in the array do not lock onto the incoming signal. Instead, they oscillate at their natural frequencies.*

As indicated earlier, the center frequency of the channelizer can be adjusted by changing the parameters I_s and I_c, mostly adjusting I_c once I_s is established to guarantee bistability. Figure 4 illustrates, through the numerical simulations, the effect of tuning the coupling parameter I_c for different values, $I_c = 650\mu A$, $I_c = 750\mu A$ and $I_c = 850\mu A$, to create the stacking effect, i.e., building the channelizer to cover a wide spectrum of interest as illustrated in Figure 2. Other parameters may be tuned in a similar fashion to customize the shape of the channel (V-shape) to either widening or narrowing the channels as determined by a designer. The parameter that primarily controls this effect is the I_g.

3. Experimental Results

The experimental system is designed so that each element in the array can oscillate at about 365MHz with the proper setting of the system parameters C_L, g, I_s, I_c, and I_g. This means that the 3-coupled array can respond to an input signal around 1GHz depending on the bandwidth configuration of the channel. To aid in setting up the correct parameters, a model of the experiment was simulated in SPICE (Simulation Program with Integrated Circuit Emphasis). Once those parameters are determined and set, the behavior is readily established when the circuit is powered up. The experimental board, in particular, was powered with a 3.3V power supply. I_c, I_s, and I_g were set by adjusting potentiometers and were measured directly with a multimeter. The parameters I_c, I_s, and I_g were set to $195\mu A$,

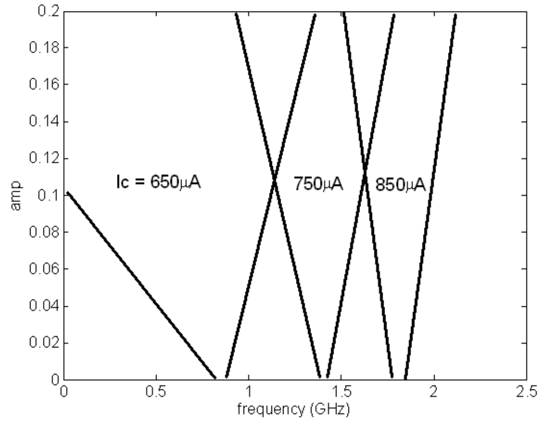

Figure 4: *Arnold's tongue showing the V shaped region of synchronization defined by the amplitude of the input signal ε and the difference between the signals frequency ω and the natural frequency ω_N of the oscillator. A "channelizing" array can be constructed by using multiple oscillator arrays with the natural frequencies spread evenly across the spectrum of interest.*

$384\mu A$ and $96\mu A$, respectively. The parameter C_L is set by the total node parasitic capacitance of 0.1 pF, and g is set to 0.002 Siemens.

The concept of constructing many channels over a wide frequency (as is shown in Figure 2) is realized in numerical simulations through Figure 4 and confirmed in Figure 5, where the stacking of the channels can be achieved by tuning the system's accessible parameters via the I_c, I_g, and I_s. Figure 5 demonstrates that increasing I_c results in increasing the oscillation frequency which shifts the center of the V shape to the right. For example, setting $I_c = 407\mu A$ the center is around 900 MHz. Then adjusting I_c to $542\mu A$ the center shifts to 1.20 GHz and so on in shifting to 1.50 GHz and 1.80 GHz as indicated in the figure. Notice that the width of the channel decreases as the system moves to higher frequencies, which was also observed in numerical simulations shown in Figure 4. To configure the bandwidth of the channel, I_g may be tuned to widen or narrow the channel via a similar control of the feedback current.

Figure 6 shows an input and response of a sample Binary Phase Shift Keying (BPSK) modulation signal being provided to one of the channels on the microchip. For ease of digitization of the signal, the frequency of the experimental system is scaled down to operate in the kilo-Hertz range. Notice that when the modulated signal is phase shifted by 180 degrees to represent either the 0-bit or the 1-bit, the phase shift is captured in the response of the channelizer. This response signal is produced by summing the digitized signals of the three outputs from the coupled oscillators. Similar results can be seen in a much more complex modulation such as the Frequency Hop Spread Spectrum (FHSS) type.

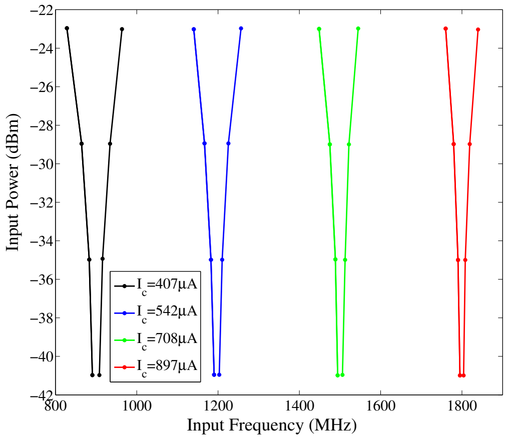

Figure 5: *(Color online) Experimental results of V-shape displacements, through changes in coupling strength I_c, are carried out to create the stacking effect to build a channelizer.*

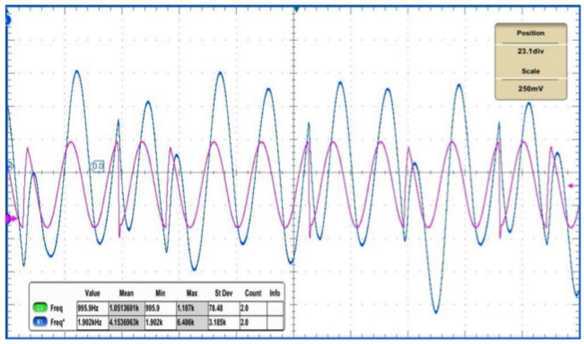

Figure 6: *(Color online) Experimental results for capturing a sample BPSK modulated signal. The frequency of the oscillation in this case is scaled down to 4 KHz for ease of capturing the signal and for displaying purposes. The input BPSK modulated signal is in RED and the response from the channelizer (summing all three outputs from the three nonlinear oscillators) is represented in BLUE. The summed response shows a good representation of the input signal where all of the phase information from the input signal is preserved.*

4. Conclusion

The nonlinear channelizer surpasses the traditional solution by taking advantage of the nonlinear properties of a generic nonlinear system, in particular its bifurcation qualities and its ability to synchronize to an incoming signal (while synchronized, the phase and frequency dynamics of the oscillator is overwhelmingly dominated by the incoming signal). In addition to taking advantage of these dynamical qualities, nonlinear tools concerning the topology of the coupling between the oscillator and the RF signal input, as well as between the oscillator and other oscillator arrays, allow for a significant increase in the utility of the nonlinear channelizer. These tools, which are group-theoretic in nature, allow the designer to virtually dictate the behaviors of the oscillators with regard to the input signal, as well as the behavior of interconnected oscillator arrays. The approach often results in coupled oscillator systems that retain specific topological symmetries, as well as time-shift invariant symmetries, that can be used for specific purposes. Examples that have been demonstrated include signal detection at high frequencies using lower frequency components and nearly arbitrary signal frequency up-conversion and down-conversion.

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