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A complete system to generate electrical noise with arbitrary power spectral density

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ABSTRACT

Reliability and performance of electronic devices are significantly dependent on their noise rejection capability that is usually investigated since their early production stage as well as during the scheduled maintenance. To this aim, white noise sources are mostly available on the market and usually to the purpose, whereas the use of generators capable of producing coloured noise (actually, very uncommon) should be advisable in most of applications. If arbitrary waveform generators (AWGs) are taken into account, either transient signals in single shot generation mode or periodic signals in continuous generation mode can only be produced due to the finite available memory; unfortunately, both modes are not suitable to emulate noise. To overcome the considered limitations, this work presents the design and implementation of a coloured noise generator that offers the possibility of tailoring the noise spectral content to the desired application. As it can be expected, performance of the generator changes according to different hardware selections; with specific regard to the proposed implementation, it performs as good as state of art solutions in terms of both bandwidth and flexibility. It is composed of a digital section implemented on field programmable gate arrays (FPGA) and a digital-to-analogue converter (DAC) mandated to generate the desired analogue output. The bandwidth of the generated noise can be selected up to a maximum of 50 MHz while the evolution of power spectral density versus frequency can be defined with a resolution equal to 0.4% of the bandwidth. Thanks to suitable digital signal processing techniques, spurious components laying outside the selected bandwidth are hardly attenuated.

1. Introduction

The analysis of internal and/or external mechanisms that produce disturbances with random characteristics, referred to as noise according to the current taxonomy, is a very important issue at the design stage of any electrical equipment and system. Nonetheless, the behavior of equipment and systems affected by noise has to be tested since the early production stage, as well as routinely during periodical maintenance actions, in order to assure their reliability and performance.

The opportunity of realizing noise sources has been addressed by the scientific community for many decades, and several proposals of systems able to generate Gaussian white noise signals can be found in the literature. Many contributions however are more oriented to hardware simulation than to prototyping, thus the noise is only synthesized in digital form [1–3]. For these contributions the emphasis is on the accurate reproduction of the Gaussian distribution in intervals that extend up to six

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standard deviations and beyond or on the fast generation of the digital samples to speed up the simulations [1].

The specificity of reproducing digital noise in the analogue domain is considered by a small subset of papers, and few solutions are available on the market. As an example, in [4] a complete system, composed of a digital noise generator and a digital to analogue converter, which produces white Gaussian noise and offers a maximum generation frequency equal to 500 kS/s is proposed. Further examples of systems that produce the noise in analogue form can be found in [5,6].

The majority of commercially available noise sources produce broadband white noise which cannot be controlled in terms of occupied bandwidth and power spectral density. They are based on a technology that exploits a low capacitance diode, biased into avalanche breakdown with a constant current, to generate broadband noise. This technology has reached a high degree of advancement that allows matching a variety of applications [7–9]. Typically, these noise sources are sold as auxiliary modules of noise figure analyzers or performance spectrum analyzers.

Many natural phenomena and mechanisms that take place in modern systems produce noise that differs from white noise and is generally referred to as coloured noise. Some contributions to the theory of coloured noise generation can be found in [4,10–13]. The scientific literature also proposes prototypes that face the issue of coloured noise generation [2,5,6,14]. In particular, in [2] a low performance digital circuit for the generation of comb filtered noise implemented using small-scale integration logic is proposed. A band-pass Gaussian noise generator, designed to test wireless receivers, is presented in [14]; the noise generator synthesizes digital noise which is stored in a flash memory and then played; the sample rate is very low, e.g. 100 kS/s, and the duration of the generated noise is limited to few seconds since the continuous reproduction of the noise stored in the memory leads to undesired periodicity. In [5] a 10 MS/s impulsive noise generator, capable of producing pulses with arbitrary distribution of amplitude, duration, and spacing, is proposed and implemented on field programmable gate arrays (FPGA). Finally, paper [6] presents a low speed system based on digital signal processors (DSPs) for the generation of pseudo random noise.

The aforementioned solutions do not allow the generation of arbitrary coloured noise and limit the reproduction speed to 10 MS/s. Besides, there are no commercially available noise sources capable of generating arbitrary coloured noise.

This paper proposes an analogue coloured noise generator that can be configured to produce noise characterized by arbitrary evolution of the power spectral density versus frequency. As an application example, the need of having such a generator can be experienced when the functionalities of RF and microwave communication systems that are susceptible to phase noise have to be verified. A usual approach to carry out the test consists in stimulating the system with a carrier characterized by controlled phase noise, which is obtained by modulating the phase of a pure carrier by means of a noise signal [15]. But, the use of flat spectrum noise generators as modulating source should be discouraged because phase noise generally exhibits a non-uniform power spectral density characterized by higher levels close to the carrier, i.e. at low baseband frequencies, and lower levels far from the carrier [16,17]. Moreover, the proposed generator can be utilized to replace the noise generators currently adopted in applications concerning noise sensitivity analyses, ADC characterization and performance improvement by means of dithering [18–20], test and analysis of sensors and actuators, and frequency domain identification of linear and time invariant systems [21,22]; in other words, it would grant the possibility of analyzing a variety of scenarios which cannot be emulated by means of flat spectrum noise sources [23].

The authors have been working on the generation of coloured noise and have shortly discussed about the feasibility of such a generator in [24]. In this paper all the implementation details to reproduce the noise generator are methodically illustrated, with special emphasis on the operating principles and metrological performance; nonetheless, a number of experimental results that characterize the system at various points of the processing chain are given. In fact, although it is universally recognized that more and more computing is moving into measurement instrumentation, it is very rare to have thorough descriptions of how, in measurement instrumentation, the embedded computer interacts with the support circuitry, memory, and peripherals to implement the designed measurement approach and how they all concur to determine the overall performance.

The system architecture of the generator includes a digital section implemented on FPGA and a digital-to-analog converter (DAC) to play in analogue form the coloured noise. The digital section is composed by (i) a pseudo random number generator with repetition period equal to $2^{63}-1$ samples, which assures non repetitive noise sequences in all practical applications, (ii) a digital FIR filter, which shapes the noise power spectral density according to the specifications given by the user, and (iii) further up-sampling and interpolation digital blocks, which control the bandwidth occupied by the noise played into analogue form. The generator offers a generation frequency equal to 100 MHz producing one noise sample per clock cycle. The Nyquist bandwidth of the generated noise is therefore equal to 50 MHz, but can be lowered to 50 MHz/N, where N is an integer selected by the user. The user can also define the spectral pattern of the noise in the occupied bandwidth by configuring the digital FIR filter. Upsampling and interpolation techniques, as described in the following, permit to reject the spurs that are outside the bandwidth in which the analogue noise is confined.

More specifically, the generator can produce coloured noise whose minimum and maximum occupied bandwidths are (0 Hz, 196 kHz) and (0 Hz, 50 MHz), respectively. Within the minimum bandwidth the evolution of the noise power spectral density versus frequency can be defined by the user with a resolution of 763 Hz while the generator, thanks to the conditioning of the data stream routed to the DAC in terms of upsampling and interpolation, is capable of providing up to 40 dB attenuation for