Tech Notes

Nonlinear Equalization for Receiver Dynamic Range Extension

MIT Lincoln Laboratory has achieved significant increases in receiver dynamic range by applying nonlinear equalization techniques.

Modern sensing and communications systems must operate over wide bandwidths and with high sensitivity in order to capture and distinguish signals in the complex environment created by the proliferation of data transmitted throughout the atmosphere. In all systems, the need for accurate data collection is important. But, in sensing operations particularly, the need for a high dynamic range is driven by the ratio of strong signals, which may be extraneous to the desired operation, to weaker signals, which may be coming from small targets of interest. For example, to an air traffic controller seeking radar information of current aircraft movements, strong signals masking vital ones could spell disaster.

MIT Lincoln Laboratory has developed solutions to enhancing the dynamic range of radar, signal intelligence, and electronic intelligence systems, all of which must detect small signals in the presence of strong background and interference signals. One technique, nonlinear equalization (NLEQ), has already shown significant advances in extending the dynamic range of RF and mixed-signal electronic systems (Figure 1). Increases in dynamic range between 5 to 20 decibels (dB) have been demonstrated (Figure 2). Since industry has historically been making about 1 dB a year in dynamic range improvement, Lincoln Laboratory's work could be seen as advancing the field five to twenty years ahead.

What Is Nonlinear Equalization?

A major limiter in detecting weak signals in the presence of strong signals is the distortion created by spurious interferences caused by the "mixing" of strong signals. For example, consider what happens in a radar receiver when two in-band tones are injected into the front-end of the receiver. If the receiver is what is known as linear, the two tones remain separated and do not interact with each other. However, analog circuits and analog-to-digital converters unavoidably exhibit "nonlinear" behavior, i.e., additional contributions to the tones, called intermodulation products or "intermods," are introduced. Although the energy in the intermods is usually small, some intermods will fall into the receiver band where signals may be present. In fact, as signal processing techniques attempt to uncover smaller and smaller signals, nonlinear intermods or other distorting effects can actually mask the signals of interest.

The challenge for analog designers is to find a way to reduce nonlinear distortions in receivers. Traditionally, designers attempt to use better analog components.

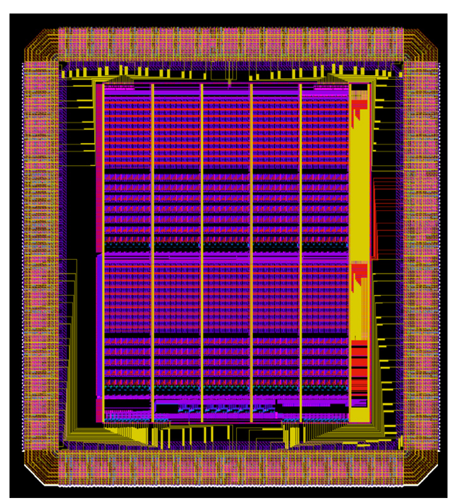

Figure 1. Computer-aided design (CAD) drawing of Lincoln Laboratory's nonlinear equalization very-large-scale integrated circuit.

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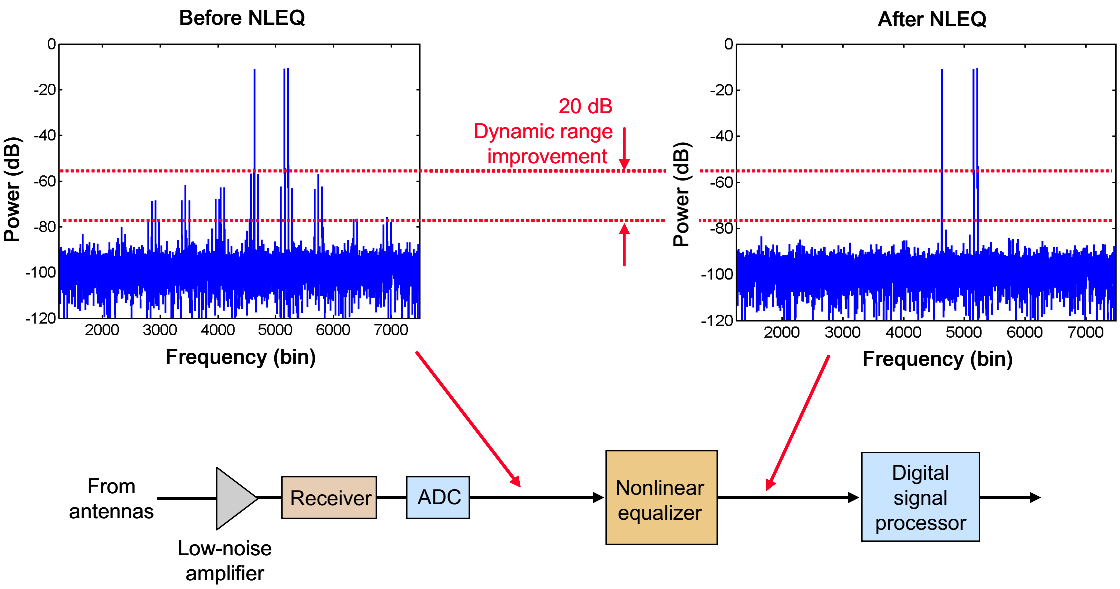

Figure 2. Before nonlinear equalization filtering is applied, intermods obscure the signals of interest (left-hand graph). After the data is processed through the nonlinear equalizer, the intermods are substantially suppressed, increasing the dynamic range by 20 dB (right-hand graph).

System performance is thus limited by the state-of-the-art in analog devices. Alternatively, various digital compensation techniques have emerged to "nullify" the distortions, either through coding/decoding that is designed to alleviate the intermodulation of signals or through equalizing algorithms that filter the nonlinear effects.

Classical linear filtering techniques are ineffective at removing nonlinear intermods. Rather, an adaptive nonlinear polynomial filter must be applied to the system to reduce the distortions by inverting the nonlinear system response without harming the desired linear input-signal component. Unfortunately, a straightforward polynomial filter implementation requires a prohibitive number of computations and is not practical for systems requiring real-time response.

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Lincoln Laboratory Approach

Lincoln Laboratory has applied a novel hardware-algorithm co-design approach to implement a nonlinear equalizer that overcomes this limitation. Unlike the conventional polynomial filter, the nonlinear equalizer designed with this approach has a significantly reduced computational complexity, enabling its implementation into two state-of-the-art NLEQ processors—NLEQ-500 and NLEQ-4000. The NLEQ-4000 processor relies upon a highly efficient systolic architecture and low-threshold voltage dynamic-logic circuits to perform over 1 trillion operations per second to enhance analog-to-digital converters of sampling rates up to 4 billion samples per second, while consuming less than 1 W of power (at 1.5 billion samples per second). This performance is about 1000 times better than that of a typical microprocessor used in a computer.

These NLEQ processors are programmable by a set of coefficients so that they can be applied to different systems. To prepare an NLEQ processor for a new system, a one-time process is applied to identify its coefficients by injecting signals that excite all relevant nonlinear modalities throughout the entire system bandwidth and input signal levels. This approach is very general as it does not require detailed knowledge of the system being equalized.

The benefits of the nonlinear equalization technology were successfully demonstrated in an electronic warfare (EW) receiver system. The real-time performance of an EW receiver system incorporating the NLEQ-4000 processor was verified against a suite of realistic threat scenarios generated under a contractor's airborne environment simulator.

In order to ensure that NLEQ technology can be applied to different types of receiver systems for significant performance enhancements at low additional cost, the NLEQ algorithm and processors have been verified with analog-to-digital converters of different architectures and sampling rates. For existing systems, as well as for systems yet to be developed, the NLEQ processor will provide substantial improvements for the entire digital receiver chain at minimal cost and negligible size, weight, and power overhead. ■

Additional Reading

J.I. Goodman, B.A. Miller, M.A. Herman, G.M. Raz, and J. Jackson, "Polyphase Nonlinear Equalization of Time-Interleaved Analog-to-Digital Converters," *IEEE Journal of Selected Topics in Signal Processing*, vol. 3, no. 3, pp. 362–373, 2009.

W.S. Song, J.I. Kramer, J.R. Mann, K.M. Gettings, G.M. Raz, J.I. Goodman, B.A. Miller, M.A. Herman, T.B. Emberley, L.L. Retherford, and A.H. Horst, "Nonlinear Equalization Processor IC for Wideband Receivers and Sensors," *Proceedings of the 13th Annual High Performance Embedded Computing Workshop*, 2009, available online at http://www.ll.mit.edu/HPEC/agendas/proc09/agenda.html.

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