High-Resolution Real-Time Spectrum Sniffer for Wireless Communication

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Abstract—**A high-resolution real-time spectrum sniffer based on a novel dispersive delay structures (DDSs) design technique is presented. In this technique, the required stepped group delay response is realized as the superposition of a linear response and sawtooth response. To validate the proposed technique, a spectrum sniffer with 60 MHz frequency resolution is demonstrated. The simulation results show that the spectrum sniffer can determine the availability of three different channels in real-time.**

I. INTRODUCTION

Radio analog signal processing (ASP) is a novel technology for high-speed and real-time systems operating at microwave and millimeter wave frequencies. Several ASP applications have been reported in radar, sensor, instrumentation and wireless communication systems [1]–[14]. One of the most promising of these applications might be spectrum sniffers [14], which devices probing their wireless environment in real-time and instantaneously determining the availability of frequency bands for cognitive radio.

The core of an ASP system, and hence of a spectrum sniffer, is a dispersive delay structure (DDS). A DDS is a component exhibiting a specified group delay response over a given frequency band and therefore resolving in the time domain the different spectral components of a broadband input signal. In order to provide clear discrimination between the input frequencies, a DDS must feature a sufficiently high ground delay versus frequency slope response. However, increasing this slope results in pulse spreading, which is defeating the original purpose of resolution enhancement. A solution to this issue is to use a stepped group delay DDS, exhibiting a flat response across the frequency bands of the signals and steep response between these bands [14]. Unfortunately, the DDS reported in [14] has a low frequency resolution, in the order of 2 GHz.

This paper introduces a novel stepped group delay DDS, based on the cascading of a DDS with a linear group delay and a DDS with a sawtooth group delay, that exhibits a frequency resolution increased by a factor of about 30.

II. LINEAR-SAWTOOTH DDS PRINCIPLE

It has been found that coupled-line, or C-section, based DDS exhibit a number of superior features compared to other microwave technologies, such as surface-acoustic wave, magnetostatic wave, metamaterial and chirped transmission line technologies. However, as mentioned in Sec. I, such DDS's, which are transmission-type DDS (input and output signals at different ports), are restricted to relatively small frequency resolution (broadband) responses (no resolution at all in the limit case of zero coupling, where the C-section degenerates into a simple transmission line). This is due to the inherent broadband response of coupled-line couplers, which is itself due to the small amount of achievable coupling between the two lines [1], [7].

Reflection-type (input and output signals at the same port) DDS's provide a much higher frequency resolution because this resolution is now proportional to the *smallness* of the coupling coefficient (a very high resolution exists for a very small coupling level because the smaller the coupling the longer the wave reflects back and forth in the resonator). Moreover, a closed-form synthesis technique is now available for reflection-type DDS's [2]. However, if the technique proposed in [2] would be directly applied for the design of a stepped group delay DDS, a high-order, and hence large and lossy, structure would be ensue. To avoid this issue, we introduce here the linear-sawtooth DDS synthesis approach depicted in Fig. 1, where the stepped response is simply obtained as a superposition of the superposition of a linear and of a (practically smoothed) sawtooth responses produced by two cascaded reflection-type DDS's.

The linear group delay response (dotted purple line of Fig. 1) can be synthesized directly using the method provided in [15]. For the sawtooth group delay response, two approaches are possible. In wide-band cases, it might be realized by using the harmonics of reflection-type resonators or transmission-type coupled lines. In narrow-band cases, as the one we are dealing with here, it can be realized by cascading reflection-type resonators resonating at different frequencies, where the sawtooth peaks correspond to different resonant frequencies.

III. DDS IMPLEMENTATION EXAMPLE

Let us now consider an illustrative example with the following specifications: 1) 3-step group delay with steps centered
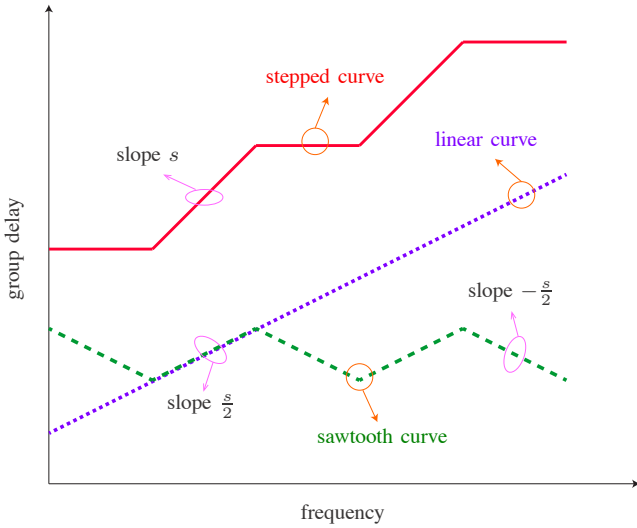
Fig. 1. Stepped group delay response realized as the superposition of a linear response and a sawtooth response.
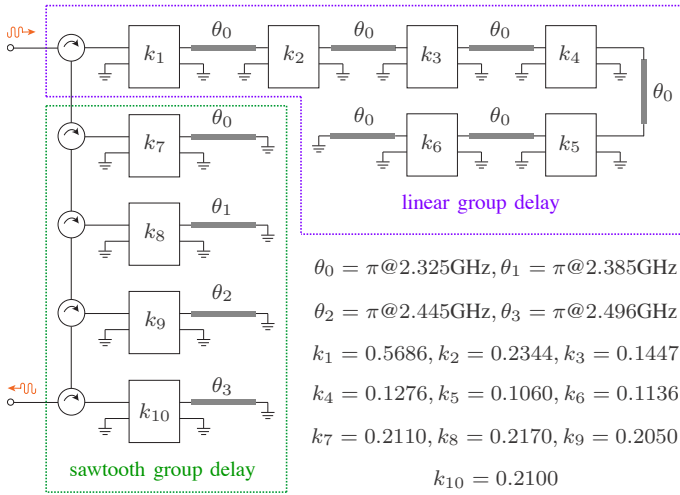

Fig. 3. Simulated group delay response for the DDS implementation of Fig. 2.

$\theta_0 = \pi @ 2.325\text{GHz}, \theta_1 = \pi @ 2.385\text{GHz}$

$\theta_2 = \pi @ 2.445\text{GHz}, \theta_3 = \pi @ 2.496\text{GHz}$

$k_1 = 0.5686, k_2 = 0.2344, k_3 = 0.1447$

$k_4 = 0.1276, k_5 = 0.1060, k_6 = 0.1136$

$k_7 = 0.2110, k_8 = 0.2170, k_9 = 0.2050$

$k_{10} = 0.2100$

Fig. 2. Possible circuital implementation of the reflection-type DDS for stepped group delay response.

Fig. 4. High-resolution real-time spectrum sniffer using the stepped group-delay DDS shown in Fig. 3.

at $2.34, 2.40, 2.46$ GHz; 2) 30 MHz passband for each step; 3) at least 4 ns group delay difference between the steps.

The DDS may be implemented as shown in Fig. 2. The circuit is composed of two parts, corresponding to linear and sawtooth group delay responses. The linear group delay part is designed using the synthesis method in [15] and all its resonators resonate at 2.325 GHz. In the sawtooth part, resonators resonating at $2.325, 2.385, 2.445, 2.496$ GHz are cascaded.

The simulated DDS group delay response is shown in Fig. 3. It is observed to well follow the specified response with step differences of 4.2 ns and 4.5 ns, satisfying the specifications.

IV. SPECTRUM SNIFFER DEMONSTRATION

Figure 4 shows the schematic of a high-resolution real-time spectrum sniffer incorporating stepped group-delay DDS of
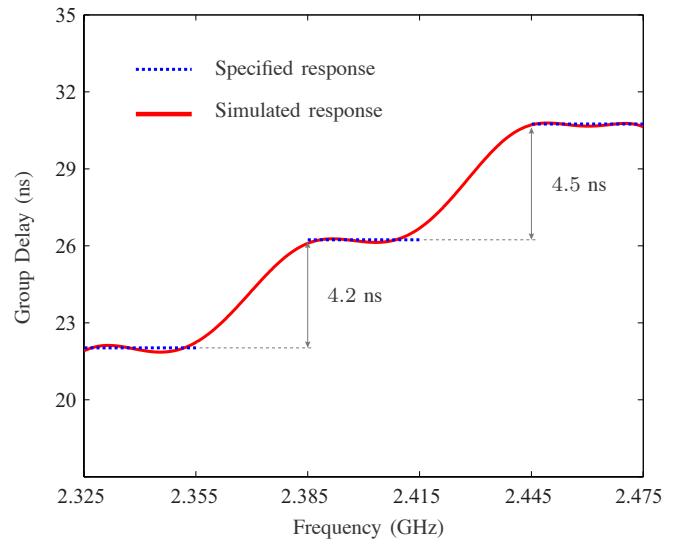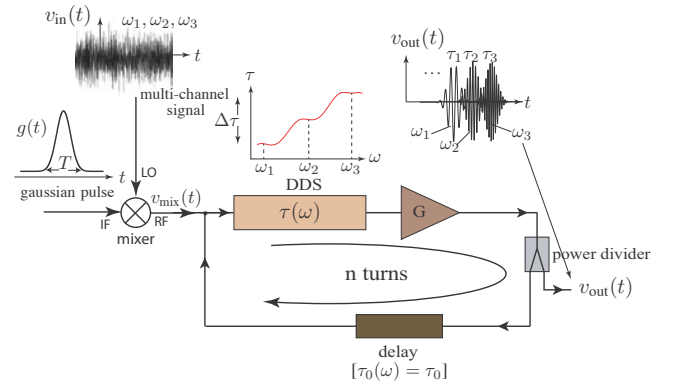
Fig. 3 and using the loop scheme proposed in [16] to increase the group delay slope without increasing the frequency band.

The global signal in the environment of the sniffer, $v_{\text{in}}(t)$, assumed to include several communication channels supporting phase or amplitude modulated signals, is received at the local oscillator port of the mixer and mixed with a baseband gaussian pulse $g(t)$ whose bandwidth must be smaller than the bandwidth of the flat steps of the DDS response. This produces the multi-tone pulse $v_{\text{mix}}(t)$. The signal $v_{\text{mix}}(t)$ travels next across the DDS, which temporally discriminates its different frequency components, corresponding to the different channels, finally generating the signal $v_{\text{out}}(t)$. Since the channel discrimination resolution of the system after one pass through the DDS is generally not sufficiently high, the signal is re-injected into the DDS the loop. The essential function of the loop is to enhance the group delay difference in a given frequency range from the delay amount $\Delta\tau$ provided by a single DDS to $n\Delta\tau$ after n passes. A constant delay τ_0 in the loop avoids self-overlapping of the between successive turns.
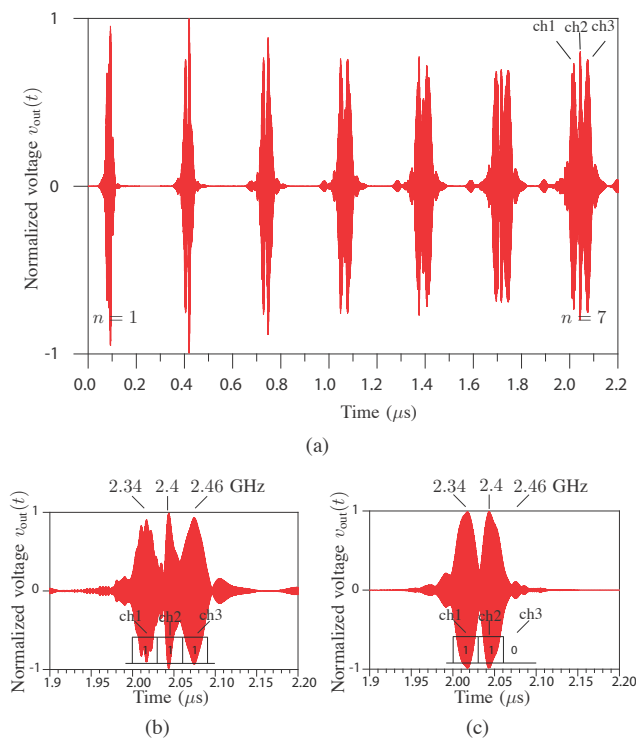
Fig. 5. Simulated output voltage $v_{out}(t)$ for the spectrum sniffer of Fig. 4 for an input signal $v_{in}(t)$ including three channels centered at $f_1 = 2.34\ GHz$, $f_2 = 2.40\ GHz$, $f_3 = 2.46\ GHz$, using Advanced Design System (ADS 2011.05) (a) Output signal for the first 7 turns in the loop with the three channels ON. (b) Zoom on the 7th output pulse for the same situation as (a). (c) Zoom on the 7th output pulse for channels 1, and 2 ON and channel 3 OFF.

In this experiment, the input gaussian pulse has a width 50 ns and the constant delay in the loop is set as $\tau_0 = 300$ ns. The output signal $v_{out}(t)$ for an input signal $v_{in}(t)$ consisting of the three channels centered at the frequencies $f_1 = 2.34$ GHz, $f_2 = 2.40$ GHz and $f_3 = 2.46$ GHz, is shown in Fig. 5(a). The output signal features a frequency resolution of about 60 MHz. The pulse discrimination is enhanced by increasing the number of turns from $n = 1$ to $n = 7$ in the loop, where divider can be replaced by a switch to select out the discriminated signal. Figure 5(b) shows a zoom on $v_{out}(t)$ after 7 turns in the loop for channels 1, 2, and 3 ON. Figure 5(c) shows a zoom on $v_{out}(t)$ after 7 turns in the loop for channels 1, 2 ON, and channel 3 OFF.

V. CONCLUSION

A high-resolution real-time spectrum sniffer based on novel linear-sawtooth DDS has been presented. In the corresponding design technique, the stepped group delay response was decomposed into a linear and sawtooth responses. To illustrate the proposed technique, a spectrum sniffer with 60 MHz frequency resolution has been designed. The simulation results show that the spectrum sniffer could real-timely check the availability of three different channels centered at $2.34, 2.40, 2.46$ GHz.

REFERENCES

[1] S. Gupta, D. L. Sounas, H. V. Nguyen, Q. Zhang, and C. Caloz, "CRLH-CRLH C-section phaser with enhanced group delay swing for higher analog signal processing resolution," *IEEE Trans. Microw. Theory Tech.*, accepted.

[2] Q. Zhang, S. Gupta, and C. Caloz, "Synthesis of narrowband reflection-type phasers with arbitrary prescribed group delay," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 8, pp. 2394–2402, 2012.

[3] Y. Horii, S. Gupta, B. Nikfal, and C. Caloz, "Multilayer broadside-coupled dispersive delay structures for analog signal processing," *IEEE Microw. Wireless Compon. Lett.*, vol. 22, no. 1, pp. 1–3, Jan. 2012.

[4] S. Gupta, B. Nikfal, and C. Caloz, "Chipless RFID system based on group delay engineered dispersive delay structures," *IEEE Antennas Wirel. Propagat. Lett.*, vol. 10, pp. 1366–1368, Dec. 2011.

[5] C. Caloz, "Metamaterial dispersion engineering concepts and applications," *Proc. IEEE*, vol. 99, no. 10, pp. 1711–1719, Oct. 2011.

[6] B. Nikfal, S. Gupta, and C. Caloz, "Increased group-delay slope-loop system for enhanced-resolution analog signal processing," *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 6, pp. 1622–1628, Jun. 2011.

[7] S. Gupta, A. Parsa, E. Perret, R. V. Snyder, R. J. Wenzel, and C. Caloz, "Group delay engineered non-commensurate transmission line all-pass network for analog signal processing," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 9, pp. 2392–2407, Sept. 2010.

[8] S. Gupta, S. Abielmona, and C. Caloz, "Microwave analog real-time spectrum analyzer (RTSA) based on the spectral-spatial decomposition property of leaky-wave structures," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 12, pp. 2989–2999, Dec. 2009.

[9] S. Abielmona, S. Gupta, and C. Caloz, "Compressive receiver using a CRLH-based dispersive delay line for analog signal processing," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 11, pp. 2617–2618, Nov. 2009.

[10] H. V. Nguyen and C. Caloz, "Composite right/left-handed delay line pulse position modulation transmitter," *IEEE Trans. Microw. Theory Tech.*, vol. 18, no. 5, pp. 527–529, Aug. 2008.

[11] S. Abielmona, S. Gupta, and C. Caloz, "Experimental demonstration and characterization of a tunable CRLH delay line system for impulse/continuous wave," *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 12, pp. 864–866, Dec. 2007.

[12] M. A. G. Laso, T. Lopetegi, M. J. Erro, D. Benito, M. J. Garde, M. A. Muriel, M. Sorolla, and M. Guglielmi, "Real-time spectrum analysis in microstrip technology," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 3, pp. 705 – 717, 2003.

[13] J. D. Schwartz, J. Azaña, and D. V. Plant, "Experimental demonstration of real-time spectrum analysis using dispersive microstrip," *IEEE Microw. Wireless Compon. Lett*, no. 4, pp. 215–218, Apr. 2006.

[14] B. Nikfal, D. Badiere, M. Repeta, B. Deforge, S. Gupta, and C. Caloz, "Distortion-less real-time spectrum sniffing based on a stepped group-delay phaser," *IEEE Microwave and Wireless Components Letters*, Nov. 2012.

[15] Q. Zhang, S. Gupta, and C. Caloz, "Synthesis of reflection-type phaser with arbitrary prescribed group delay," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 8, pp. 2394 –2402, Aug. 2012.

[16] B. Nikfal, S. Gupta, and C. Caloz, "Increased group-delay slope-loop system for enhanced-resolution analog signal processing," *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 6, Jun. 2011.