2022 IEEE 22nd Annual Wireless and Microwave Technology Conference (WAMICON) | 978-1-6654-2195-9/22/$31.00 ©2022 IEEE | DOI: 10.1109/WAMICON53991.2022.9786168

A Real Time RF Analog Signal Processor for Time Delay Estimation

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***Abstract*— In this paper, a time-delay estimator operating at RF frequency is proposed by designing a microwave Hilbert transformer and a correlator-based estimator. Comparing to conventional cross correlation, our proposed estimator enables zero crossing for time delay detection directly at its operating frequency without having complicated digital domain signal processing. The theoretical analysis is carried out to demonstrate the estimation function, and the transient-time simulation is conducted to demonstrate proposed novel concept.**

***Keywords*—Real-time analog signal processing (RAP), cross-correlation function (CCF), Hilbert transform, time delay estimation (TDE).**

I. INTRODUCTION

The time delay estimation for finding time-difference-of-arrival signals is key signal processing step in application of wireless communication, radar, sensor network, beamforming [1]-[3], distributed array time synchronization, and power amplifier digital pre-distortion. In digital signal processing domain, the time delay estimators can be implemented using cross correlation or discrete time Fourier transform. From observation of digital circuit revolution, transforming data and accessing memory storage are supper expensive as well cause data damage in parallel computation which limit the modern system, especially with high speed and wide operating bandwidth [4]. Analog signal processing provides intriguing opportunity to mitigate data deluge and reduce data movement in system input level. In recent, analog cross correlation approaches have been designed by detecting the peak of correlated signal [5]-[7]. However, in high SNR threshold system, the conventional cross correlation estimator causes ambiguation in selecting peak and require additional interpolation methods which decrease system performances [8]-[10]. To solve this problem, a mixed signal processing approach using digital Hilbert transform was designed to locate zero crossing for time delay estimation, which shows excellent performance for distorted noisy signal [11]. All above time delay estimators are realized in baseband signal either at analog form or digital form, which heavily relay on high performance analog-digital conversion and efficient digital signal processing [12]-[14]. Real-time RF signal processing attracts great interest in recent to realize operations as integration, differentiation, Fourier transform, time reverse, frequency compressor, frequency expender, spectrum sensing [15], and single side band modulation [16]-[19], where the signal is manipulated in its real time pristine RF/analog form without having assistant from analog-digital conversion and digital signal processing. These RF signal processors show great advantages for assisting conventional digital signal processing, especially with emerging high speed, wideband, and low latency wireless systems.

This work is sponsored by NSF under ECCS-2124531.

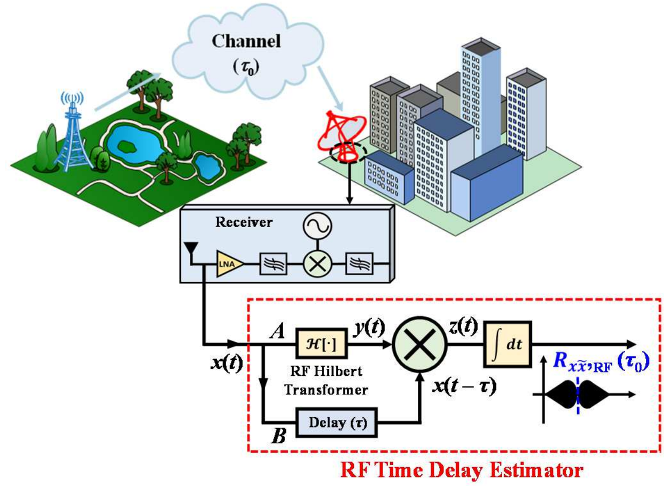

Fig. 1. Proposed RF signal processing circuit for time delay estimation

In this paper, a novel RF signal processor is proposed to work as time delay estimator (TDE) directly at its operating frequency without having digital signal processing. Our proposed estimator is composed of RF Hilbert transformer and time delay correlator network circuits. The theoretical analysis is carried out to derive the CCF resulting zero crossing at detected time delay τ_0, and corresponding simulation is conducted to prove the proposed concept.

II. DESIGN THOERY

The proposed RF analog signal processor for time delay estimation is shown in Fig. 1, where the coupled signal from receiver channel is divided into two channels passing through RF Hilbert transformer and RF delay line and mixed with each other before the integrator. The channel delay time is obtained by integrating the mixed signal across corresponding delay period. To realize this estimator in RF domain, the Hilbert transformer and correlator circuit (composed by delay, mixer, and integrator) are designed at microwave frequency.

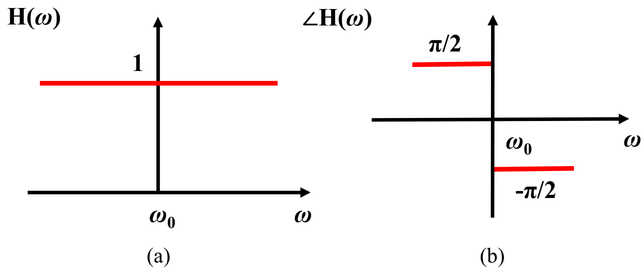

Fig. 2. Ideal Hilbert transform operating at center frequency ω_0: (a) Amplitude of transfer function. (b) Phase of transfer function

A. Microwave Hilbert Transformer

The ideal Hilbert transformation is a linear convolution of input signal $x(t)$ and impulse response:

$$h(t) = \frac{1}{\pi t} \tag{1}$$

The output signal is expressed as:

$$H[x(t)] = h(t) * x(t) = \frac{1}{\pi t} p.v.\int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau} d\tau \tag{2}$$

where *p.v.* denotes the Cauchy principal value, accommodating for the fact that $h(t)$ is not integrable at $t = 0$. In frequency domain, after the Fourier transform of ideal time-domain Hilbert transform, it can be derived as:

$$H(\omega) = \begin{cases} -j, & \omega > \omega_0 \\ 0, & \omega = \omega_0 \\ +j, & \omega < \omega_0 \end{cases} \tag{3}$$

Equation (3) shows the magnitude of input signal will not change in frequency domain while the total phase rotates 180° as shown in Fig. 2. In RF/Microwave frequency, the physical Hilbert transformer is realized based on microwave couplers, and resonant feedback delay loop. The signal flow chart is sketched in Fig. 3 (a), where T and C denote the transmission and coupling coefficients of coupler ($|T|^2 + |C|^2 = 1$), while D denotes the transmission coefficient of loop. Following standard flowchart rules [20], the transfer function is given as:

$$S_{21}(\omega) = T + \frac{C^2 D}{1 - T \cdot D} \tag{4}$$

Equation (4) reveals that the response of microwave Hilbert transformer is expressed as a function of coupling coefficient C. The phase response is also shown in Fig. 3 (b), where smaller coupling coefficient results faster phase rotation around the center frequency (ω_0). Based on this, a 3-dB microwave coupler ($|C| = 0.707$) and delay line can be applied to design the RF/microwave Hilbert transformer realizing Hilbert transform of $x(t)$ shown in Fig. 1 branch A, which is obtained as:

$$y(t) = H[x(t)] = \mathrm{Re}\{x_{BB}(t) \cdot e^{j(\omega_c t - \frac{\pi}{2})}\} \tag{5}$$

Where $x_{BB}(t)$ is the baseband envelope signal, and ω_c is carrier frequency.

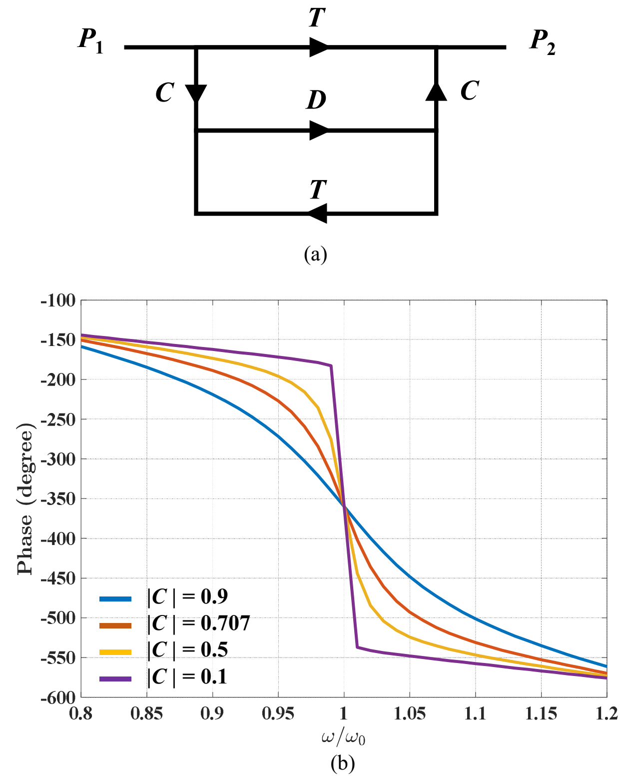

Fig. 3 Microwave Hilbert transformer (a) Signal flowchart. (b) Phase response with different coupling coefficient $|C|$.

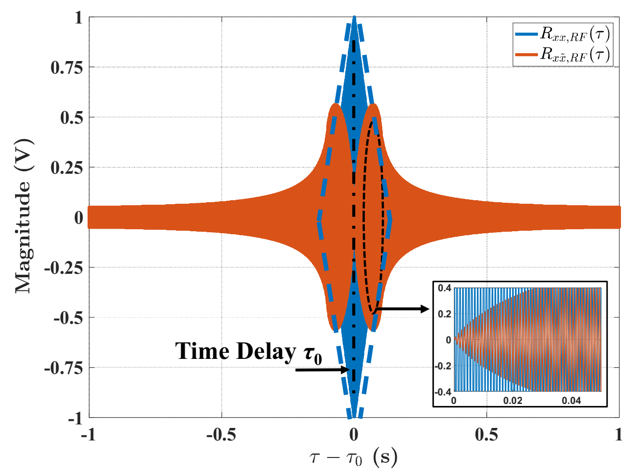

Fig. 4 Result of Cross-correlation RF signal: maximum peak at estimated channel time lag τ_0 converts into zero-crossing with Hilbert transform.

B. Design of RF Time Delay Estimater

Correlation is usually used to estimate the time delay of channel propagation, and the correlation function in general is

$$R_{xx}(\tau) = \int_{-\infty}^{+\infty} x(t)x(t-\tau)d\tau \tag{6}$$

where the inter-signal time delay (τ_0) caused in channel propagation can be determined by finding the peak point: $R_{xx}(\tau_0)$. However, even for a well-defined peak, it is normally found by evaluating the function at several points and approximate the derivative by taking their differences. This

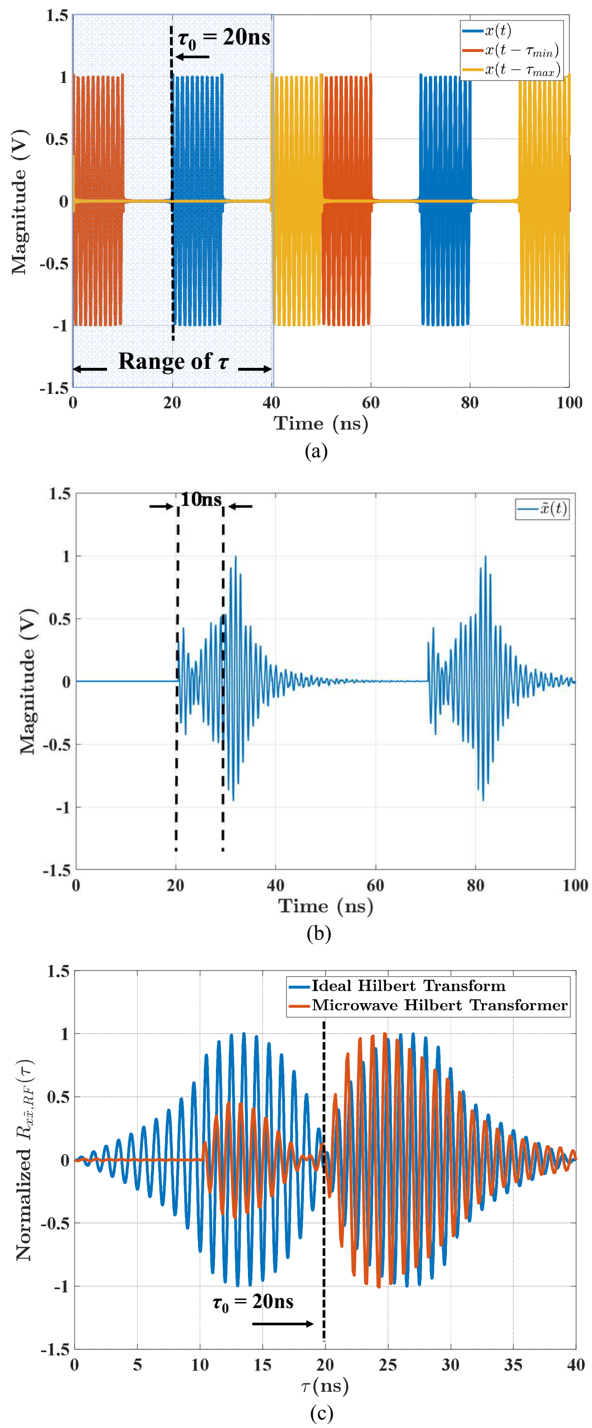

Fig. 5 Simulation Results: (a) Signal output from branch B: $x(t-\tau)$ with τ varied from 0 to 40ns. (b) Hilbert transform of input signal: $y(t) = H[x(t)]$. (c) Correlation results $R_{x\tilde{x},RF}(\tau)$ showing the specified delay at τ_0 = 20ns.

procedure normally requires additional operations when it is used in a servo control or radar system, which is not very convenient. In [11], it has been proved that the Hilbert transform of a correlation function is equivalent to the cross correlation between the signal and its Hilbert transform, which is:

$$R_{x\tilde{x}}(\tau) = \tilde{R}_{xx}(\tau) \tag{7}$$

where $\tilde{x}(t) \triangleq H[x(t)]$ denotes the Hilbert transform of $x(t)$. Correlating equation (7) and RF Hilbert transformer, the time delay estimator can be realized directly at its RF/Microwave frequency instead of converting to digital signal and using digital signal processing.

According to Fig. 1, the input signal $x(t)$, coupled from the receiver, is split into two branches under different operations. Through branch A, the signal at its pristine RF waveform will be transformed by HT function using equation (5). At the same time, the signal passing branch B will result time delay $x(t-\tau)$ in RF frequency domain, which is in form of

$$x(t-\tau) = \mathrm{Re}\{x_{BB}(t-\tau)\cdot e^{j(\omega_c t-\theta)}\} \tag{9}$$

Where $\theta = \omega_c \cdot \tau$ denotes phase shift acquired by the carrier. By multiplying $y(t)$ and $x(t-\tau)$, the output $z(t-\tau)$ can be obtained as:

$$z(t-\tau) = \mathrm{Re}\{x_{BB}(t)\cdot e^{j(\omega_c t-\frac{\pi}{2})}\}\cdot \mathrm{Re}\{x_{BB}(t-\tau)\cdot e^{j(\omega_c t-\theta)}\}$$

$$= \mathrm{Re}\{x_{BB}(t)\cdot x_{BB}(t-\tau)\cdot e^{j[2\omega_c t-(\frac{\pi}{2}+\theta)]}\} \tag{10}$$

The correlation result can be achieved through analog integration of $z(t-\tau)$, which is:

$$R_{x\tilde{x},RF}(\tau) = \int_0^t z(t-\tau)d\tau \tag{11}$$

Fig. 4 shows the result of RF cross correlation with RF Hilbert transform. The conventional cross correlation function $R_{xx,RF}(\tau)$ in blue line shows the maximum peak at the channel time lag τ_0. Our proposed RF Hilbert transform based $R_{x\tilde{x},RF}(\tau) \triangleq \tilde{R}_{xx,RF}(\tau)$ shows zero-crossing in orange line at channel delay τ_0, which provides an unambiguous determination of search.

III. Experimental Results and Analysis

To evaluate our proposed RF real-time analog time delay estimator as shown in Fig. 1, the simulation was carried using Keysight ADS. In simulation setup, input signal $x(t)$ is a pulse modulation signal $x(t)$ with pulse width of 10ns, and RF carrier frequency is set as 1GHz. In Fig. 5 (a), signal in orange line shows the $x(t)$, and its channel delay τ_0 is indicated in blue. The yellow line indicating the delay period for integration of cross correlation signal. Fig. 5 (b) shows the response of microwave Hilbert transformer in time domain, where the enhanced edges indicate the desired width of pulse, and signals within the pulse period get highly attenuated due to mutually canceling effect [18].

After integrating the output of multiplier, the normalized results of cross-correlation function $R_{x\tilde{x},RF}(\tau)$ are plotted on Fig. 5 (c), where the ADS simulation is conducted to compare microwave Hilbert transformer is with ideal Hilbert transform derived from equation (11). Both results show the estimated time delay of τ_0 = 20ns, demonstrating proposed circuit simulation aligns with derived RF time delay estimation theory.

IV. Conclusion

In this paper, a novel time delay estimator working at RF frequency is proposed. The microwave Hilbert transformer based on coupler and closed-loop resonator is implemented to generate cross correlation function with zero detecting. To prove our proposed design concept, simulation is conducted using Keysight ADS, and results are aligned well with the design theory.

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