An Improved Kahn Transmitter Architecture Based on Delta-Sigma Modulation

Yuanxun Wang

Department of Electrical Engineering, University of California Los Angeles,
405 Hilgard Ave., Los Angeles, CA 90095, U.S.A.

Abstract — **A new architecture for linear high efficiency power amplifiers and transmitters is proposed. The essential idea is to apply Delta-sigma modulation to the signal envelopes in the Kahn transmitters. While in traditional Kahn techniques the original signal envelope is restored before the final-stage power amplifier is modulated, in the proposed scheme, the power amplifier undergoes digital modulations and the signal envelope is restored from passing through a high Q bandpass filter at the output. Simulations based on power GaAs FET models show 31% improvements on power efficiency and 5 dB improvement in IM3 compared to traditional Kahn techniques.**

I. Introduction

Power efficiency and linearity of microwave power amplifiers have been the most important indices of transmitter performance. Traditional linear amplifiers such as Class A and Class AB amplifiers trade the power efficiency for the linearity. They usually operate at a significant backoff from the gain saturation region to avoid the nonlinearity. On the other hand, nonlinear amplifiers such as Class C, D, E, F can offer better power efficiency but with poor linearity. During the past, numerous researches have been carried out to combat either the linearity or the power efficiency problem [1], while the design of simultaneously linear and efficient power amplifiers remains as one of the most challenging goals.

Generally, power amplifiers will have the maximum efficiency working in the saturation region as switches. Since the product of current flow and voltage drop for a switch is always close to zero, the power dissipation of the transistor can be reduced to a minimum. From this understanding, so-called Class-S amplifiers or modulators have been proposed in conjunction with digital modulation concepts. When correctly manipulated, the signal integrity in Class-S amplifiers can be restored through signal processing or filtering techniques. Therefore these approaches have potential in providing the maximum efficiency without trading off the linearity performance. Among them the Kahn transmitter based on Envelope Elimination and Restoration (ERR) technique is one of the promising approaches [2-6]. Kahn's technique utilizes the separation of signal carrier and envelope. The signal envelope is amplified using a low frequency high efficiency amplifier. The final-stage RF power amplifier is acting as a modulator while the input is driven at the switching mode. The power efficiency of the envelope amplifier is crucial to the whole system efficiency. Thus it is often implemented in Class-S mode with pulse width modulation. The average power added efficiency of 57% has been reported at PEP [4] However, in the existing Kahn technique implementations, the signal envelope is restored through a low-pass filter before it is modulated on the carrier. It necessitates the linear modulation capability of the power transistor, which is often difficult to obtain especially for low input power level. Another promising approach worthy to mention is Asbeck's work based on bandpass delta-sigma modulators [7,8]. The idea is to simply digitize RF signal using delta-sigma modulators and the digitized waveform is used to drive amplifiers brute forth in class-S mode. The final RF signal is restored through a high Q bandpass filter. This technique is straightforward and is insensitive to the device non-linearity. However, digitizing RF frequency is not a easy task with the current semiconductor technology. The resulted wide bandwidth may also bring challenges in the design of microwave matching circuits.

To overcome the drawbacks of the above two approaches, a new transmitter architecture is proposed by combining the EER concept in Kahn technique and the digital modulation concept in the second approach. The proposed approach splits the envelope and carrier of the signal. The envelope rather than the RF signal is digitized using a delta-sigma modulator. Then the digitized envelope is directly modulated on a carrier without going through a low-pass filter. Thus the modulation non-linearity at the final stage won't affect the output signal linearity. The final RF output is obtained by passing the modulated signal through a bandpass filter. Because of the noise shaping property of delta-sigma modulators, most of the discretization error can be filtered out, which will assure reliable restoration of original signal envelope.

0-7803-7695-1/03/$17.00 © 2003 IEEE

In this paper, the propose architecture will be compared against existing architectures. To demonstrate the feasibility and advantages of the proposed scheme, circuit simulations are performed in Agilent ADS. From the simulation results, significant improvements in power efficiency and linearity are observed.

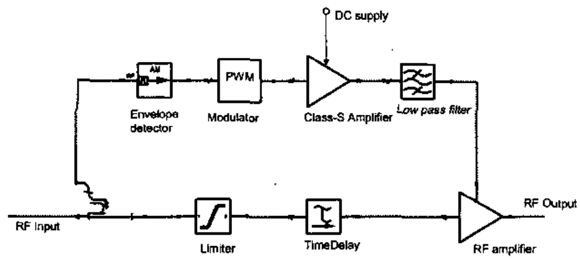


Fig.1 Block diagram of the conventional Kahn technique transmitter.

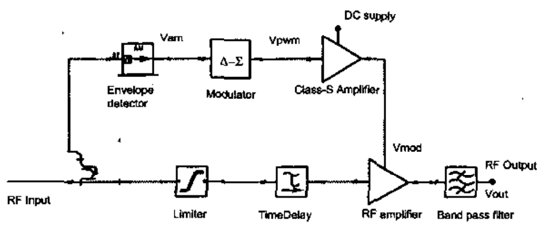


Fig.2 Block diagram of the proposed transmitter architecture No.1 (in modulator form).

II. SYSTEM ARCHITECTURE

The block diagram of conventional Kahn-technique transmitter is depicted in Fig.1. The signal is splitted into two branches. With the limiter, one branch is the constant envelope RF carrier with phase information. The other branch carries the amplitude information through the envelope detector. For efficient amplification of the signal envelope, a low frequency Class-S modulator is used. The envelope signal is first converted to pulse width modulation format through a sampler. After the pulses are amplified, they are filtered by a low pass filter, which restores the original signal envelope. The output of the Class-S modulator supplies the drain voltage of the RF power amplifier. Three limitations associated with this approach are in order. First, the simple pulse width modulation without noise shaping generates strong intermodulation terms in the spectrum. Second the linearity of the RF power amplifier affects the linearity of the output signal. Third, microwave amplifiers usually operate at an optimal drain voltage for best efficiency. However, for the traditional Kahn technique, the transistor power dissipation can not be minimized because of the continuous variation of the DC supply voltage.

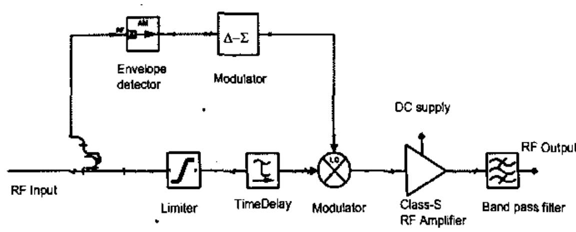


Fig3. Block diagram of the proposed transmitter architecture No.2 (in amplifier form).

The proposed transmitter architectures are shown in Fig.2 and Fig.3. In Fig.2, the transmitter is connected in the form of modulators. It has a similar block diagram as the conventional one, except two differences. First, the delta-sigma modulator is used instead of the simple pulse width modulator for noise shaping. Second, .the low pass filter at the Class-S modulator is removed and a band pass filter is inserted at the output, so the final stage amplifier work under digital modulation for better power efficiency and linearity performance. For high power applications where the implementation of high efficiency Class-S modulators is prohibited, the transmitter can be connected in the form of amplifiers instead of modulators, as shown in Fig.3. It has been shown in [9] that the saturation of amplifiers does not increase the intermodulation level of the final output, thus all the amplifiers can operate in switching modes. This type of architecture is more similar to those in [7,8] while the sampling speed requirement for delta-sigma modulators in the proposed approach is significantly reduced for microwave or millimeter wave carriers.

III. SIMULATION RESULTS

To validate the proposed transmitter architectures, a circuit simulation of the proposed architecture no.1 is set up in Agilent ADS. A generic Statz GaAs FET model is used to simulate the RF power amplifier and the Class-S modulator. For RF power amplifier, a single-ended transistor is used. Transient simulations are carried out for a two-tone input. The carrier frequency is at 1GHz and the two tones are at 995 MHz and 1.005 GHz respectively.

The output band pass filter is designed to have 20 MHz pass band bandwidth with 3 resonators. A First order delta-sigma modulator is used. The delta-sigma modulator sampling rate is chosen to be 10 times of the RF bandwidth, which is about 100MHz. The observation time is from 200 ns to 400 ns. It should be noted that the ADS design guide includes a traditional Kahn transmitter simulation example. Therefore, for comparison purposes, the above parameters are intentionally chosen to agree with the example file. The simulated power efficiency and the linearity performance of the proposed approach are compared against the results provided in the example file.

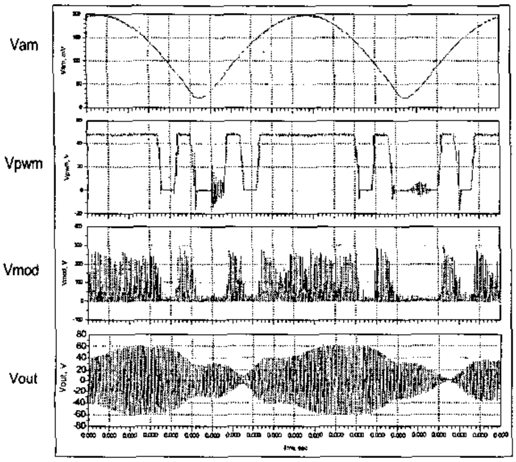


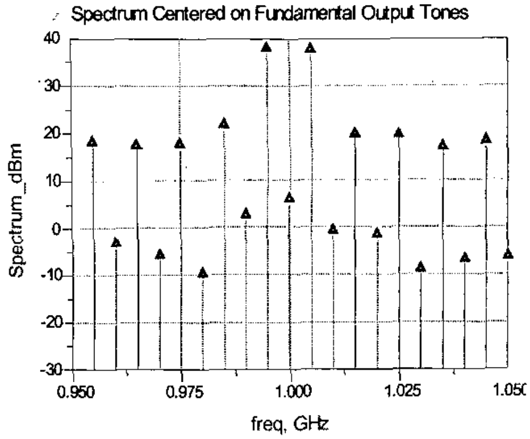
Fig.4. Voltage waveforms at different positions in the proposed circuit.

A. Voltages

The simulated voltages at different positions are shown in Fig.4. The first graph shows the voltage after the envelope detector, followed by the pulse waveform discretized by

	Available Source Power, Watts, from Both Input Tones	Power Delivered to Load Resistor, Watts, at Both Fundamentals	Total DC Power Consumption	Power-Added Efficiency
	Pinput	Poutput	Pdc	PAE
Proposed scheme	0.011	18.666	20.227	92.223
	Pinput	Poutput	Pdc	PAE
Traditional Kahn	0.011	17.128	28.211	60.673

Table.1 Comparison of power efficiencies.



Fig,5 Output spectrum of the traditional Kahn technique transmitter.

delta-sigma modulator. The pulse chain is then used as power supply of the RF power amplifier to modulate the

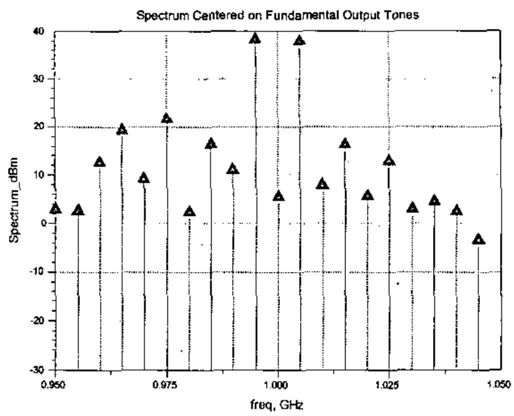


Fig.6 Output spectrum of the proposed transmitter.

carrier, as shown in the third graph. The last graph is the waveform at the filter output, e.g. the final output, which reproduces the two tone signal quite well.

B. Power efficiency

The simulation shows a high power added efficiency of 92% at PEP, which is 31% higher than the reference case using traditional Kahn technique. This high efficiency is achieved mainly because the digital modulation of the RF power amplifier drives the amplifier in a more efficient switching mode, which significantly reduces the transistor power dissipation. Table.1 is generated from the simulation results.

C. Intermodulation

The spectrums of the final output for both cases are shown in Fig.5 and Fig.6. The figures show the third order intermodulation levels are reduced from 17dBc to 22dBc. The main reason of the improvement is because the noise shaping of delta-sigma modulation spreads the sampling/discretization error out of the interested frequency band. The digital modulation of the RF power amplifier also benefits the linearity of output signal by eliminating the non-linearity effects of the amplifier modulation.

V. CONCLUSION

A novel transmitter architecture for both high power efficiency and linearity is proposed. The essential idea is to combine conventional Kahn technique with the delta-sigma modulators. Simulations in Agilent ADS have shown promising results. More detailed study for different amplifier architectures and hardware implementation are currently in process.

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