Kahn EER Technique With Single-Carrier Digital Modulations

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***Abstract*—The Kahn envelope elimination and restoration (EER) technique allows for linear RF power amplification by combining nonlinear, but efficient, radio frequency (RF) and audio frequency (AF) power amplifiers. The EER technique requires a coordinate transform of the Cartesian digital in-phase and quadrature (I & Q) signals to polar amplitude (A) and phase-modulated RF (RF-P) signals. An ideal recombination of the A and RF-P signals in the output stage of the transmitter yields perfect amplificated I & Q signals in the output of the transmitter. However, any small mismatch of the delay between A and RF-P paths or bandwidth restrictions within the A path reveal the dominant nonlinearity inherent with the coordinate transform, resulting in out-of–band (OOB) radiation. In this paper, the EER technique is investigated for single-carrier digital modulations. It is shown that the characteristics of the resulting OOB radiation merely depends on the size of the hole in the vector diagram of the digital modulation and is practically independent of other parameters of a digital modulation. Universal curves are given, which can be useful for developing and aligning EER digital transmitters.**

***Index Terms*—Amplifier, band-limited communications, delay effects, envelope elimination and restoration (EER), Kahn technique, phase modulation, single-carrier modulation, spectral regrowth, transmitter.**

I. Introduction

DIGITAL cellular transmission systems of second and higher generations use single-carrier modulation schemes with not constant envelopes. The transmitter power amplifier (PA) has to operate in linear mode for these modulations. Linear amplifiers are of very low efficiency [2], which reduces battery recharge time of the handset considerably. On the other hand, the envelope elimination and restoration (EER) technique, which uses amplifiers in the switched mode [1], [4], [5], has high efficiency. Applying the EER technique necessitates the digital in-phase and quadrature (I & Q) signals being converted to their amplitude (A) and phase-modulated RF (RF-P) signals, which is equivalent to a coordinate transform from Cartesian to polar [6]. Both A and RF-P signals have increased bandwidths compared to the I & Q signals. In the PA stage of the transmitter, the A and RF-P signals are multiplied, which is the coordinate transform backward. This multiplication process is technically imperfect due to delay differences of the A and RF-P signals and linear distortions in the A path of the transmitter. Therefore, the EER technique is prone to out-of–band (OOB) radiation resulting from delay mismatch and linear distortion of the A path [3]. In a previous paper [6], it is shown that the OOB radiation can be reduced if the vector diagram of the digital modulation has no zero crossings and shows a "hole" at the origin, as do offset modulations.

This paper shows how the amount of the shoulder distance, which is the difference in the spectrum between the wanted and unwanted parts at the corner of the nominal bandwidth, depends on the delay difference between the A and RF-P signals. It is further shown that the slope of the OOB spectrum only depends upon the size of the hole in the vector diagram of the digital modulation scheme, and all the other details of the modulation, e.g., single carrier or multicarrier, have only very minor effects on the shoulder distance. Furthermore, the slope of the OOB spectrum is identical to the slope of the RF-P spectrum. Since the delay mismatch does have such a great influence, the A path, which is, for technical reasons, band limited, necessarily needs a constant group delay. Here, the influence on the OOB resulting from the bandwidth and rolloff factor ϱ_A, which describes, in this context, the shape of the transition from the passband to stopband, are investigated. It is shown that a limited bandwidth in the A path results in a reduced shoulder distance. However, the influence of the delay mismatch can be seen, provided the effects thereof exceed those from the bandwidth limitation of the A path. In this way, only a few measurements are necessary for characterizing an EER transmitter for digital transmission.

- The delay difference between A and RF-P signals gives the maximum achievable shoulder distance to the OOB spectrum.
- The hole in the vector diagram determines the slope of the OOB spectrum.
- The bandwidth limitations of the A path gives a lower limit for the OOB spectrum.
- Whichever effect results in a, say, 3-dB higher OOB spectrum is dominating the others.
- The idealized curves given coincide with the simulations within ±3 dB.
- In a real transmitter, also the ”normal” nonlinearities have to be regarded, which are masked by the coordinate transform nonlinearities, if they are approximately 3 dB smaller.

In this paper, however, only the nonlinearities introduced by the EER technique are regarded, and "normal" nonlinearities of amplifiers, as well as A to phase conversions in the PA are omitted. The results derived in a MATLAB simulation give the optimum performance of EER transmitters as functions of delay mismatch and A path bandwidth limitations.

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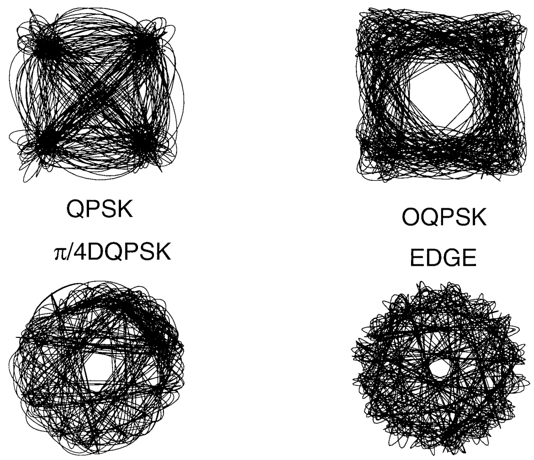

Fig. 1. Vector diagrams of QPSK, OQPSK, $\pi/4$ DQPSK, and EDGE.

II. Vector Diagrams of Typical Single-Carrier Modulations

Four typical digital modulation schemes are regarded, which are as follows:

- *quadrature phase-shift keying* (QPSK): with rolloff $\varrho = 0.2$ (in this context, symbol shaping: $\varrho = 0$ brick-wall shape, $\varrho = 1$ root-raised cosine shape);
- *offset quadrature phase-shift keying* (OQPSK): ($\varrho = 0.2$);
- $\pi/4$ *differential quadrature phase shift keying* (DQPSK): with $\pi/4$ shifting, as used for TETRA mobile communication ($\varrho = 0.35$);
- EDGE: enhanced data rates for GSM and TDMA/136 evolution ($\varrho = 0.6$).

The QPSK is a modulation without a vector hole (Fig. 1). Other modulation schemes without a vector hole, however, like DQPSK or 8-ary phase-shift keying (8PSK), lead to nearly identical results as QPSK with respect to OOB radiation, and are not presented here. OQPSK has a vector hole of approximately 35% of its diameter, and $\pi/4$ DQPSK as well as EDGE still have holes, but with a smaller size of approximately 13% or 5%, respectively. All modulations were root-raised cosine filtered, which is the filtering at the transmitter's side. This is in the case of EDGE, not the exact pulse shaping [7], but has no influence on the OOB spectrum.

III. OOB Spectra for Different Delays

An EER transmitter has been analyzed with a MATLAB simulation for different modulation schemes. The MATLAB simulation is written as an ".m" file. The data were randomly chosen and combined to symbols according to the modulations. The transmitter model comprises function files, e.g., for Cartesian to polar conversion, A signal-filtering phase-modulation time shifting of the RF-P signal, quadrature double-sideband (QDSB) modulation, i.e., polar to Cartesian, up and down sampling, and Welch spectrum estimation, according to the EER transmitter's block diagram [6].

In the case of QPSK, the spectra for different values of the delay are shown in Fig. 2. The ideal spectrum has the parameter Delay $= 0$.

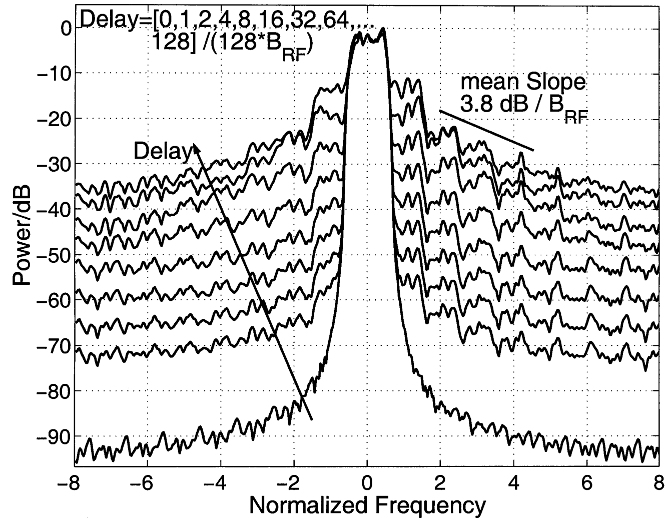

Fig. 2. Spectra of QPSK with different values of delay between A and RF-P paths.

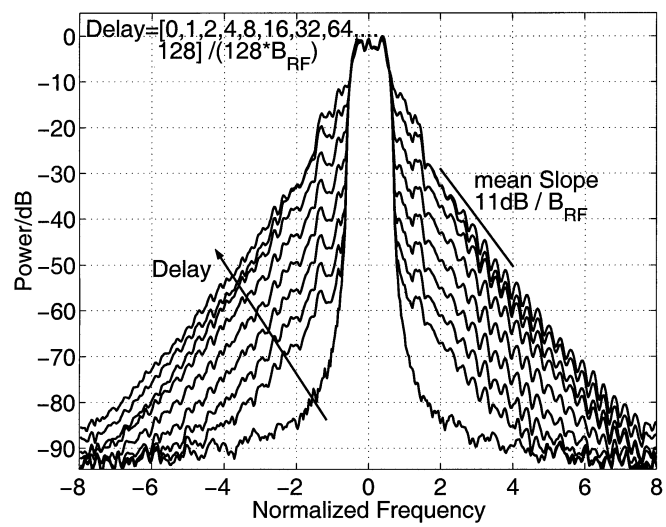

Fig. 3. Spectra of OQPSK with different values of delay beetween A and RF-P paths.

While QPSK has no vector hole at all, OQPSK has a very large vector hole. Nevertheless, the shoulder distances are practically identical (Fig. 3). This might be astonishing. However, if the trajectory in the vector diagram has to pass from, let us say, the upper left to the lower right corner, for both modulation schemes, QPSK and OQPSK, it takes nearly the same time if the same symbol rate is transmitted. In the case of OQPSK, no wedges in the A signal and no phase jumps occur. Therefore, higher spectral components are weaker than in the case of QPSK. While this can be observed directly in the spectrum of the A signal, in the modulated QPSK respective OQPSK signals, this comes up farther off on both sides from the carrier frequency. Thus, this is the reason for steeper slopes in the spectrum of the OOB for OQPSK with respect to QPSK. A vector hole gives no gain for shoulder distance, as can be seen by a comparison with Fig. 2, but only results in a steeper slope of the OOB spectrum (11 dB/B_{RF} compared to 3.8 dB/B_{RF}).

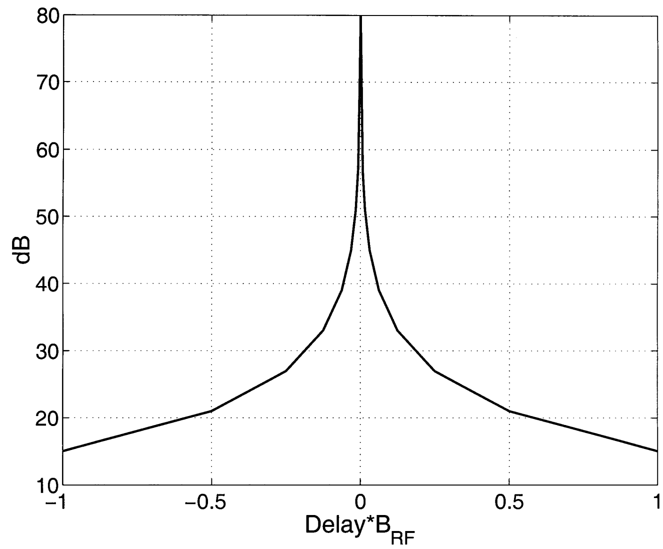

Fig. 4. Shoulder distance as a function of delay beetween A and RF-P paths.

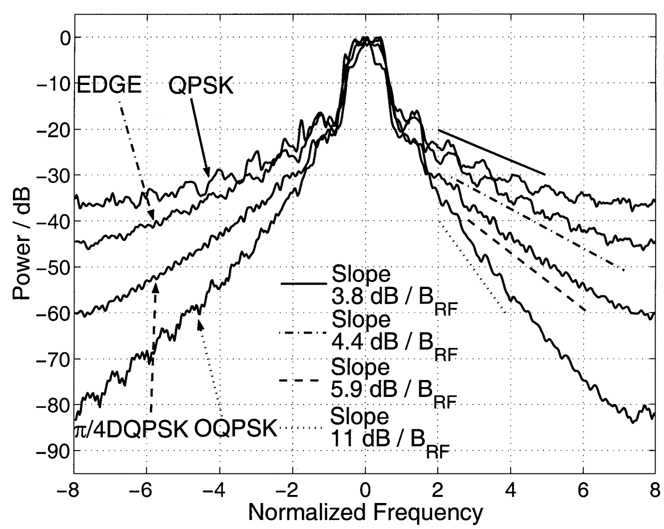

Fig. 5. Spectra of RF-P signals for QPSK, OQPSK, $\pi/4$ DQPSK, and EDGE.

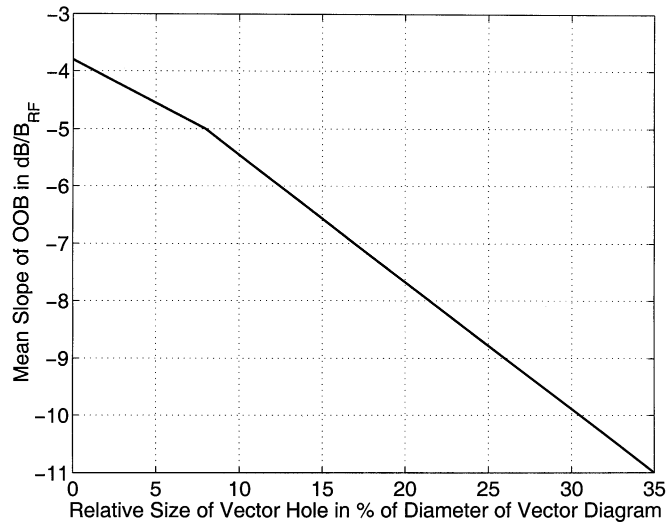

Fig. 6. Mean slope of the OOB spectrum @2–4 of normalized frequency.

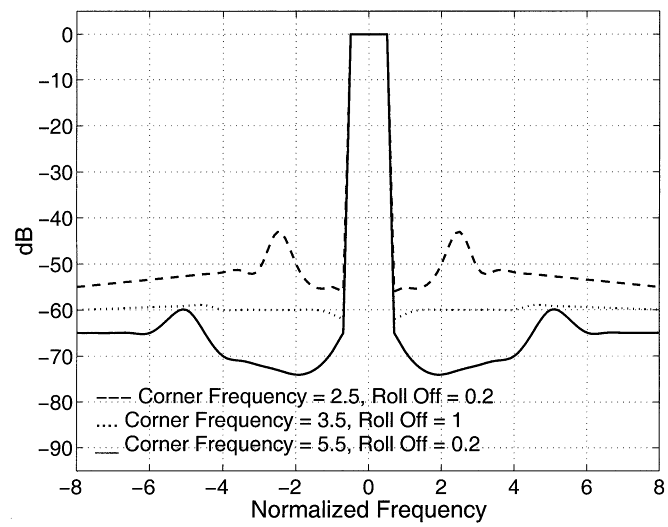

Fig. 7. Lower limit for QPSK spectra with A path band limited and best delay matching.

In an examination of both spectra plots (see Figs. 2 and 3), it can be seen that a progressive delay mismatch of $2^n \cdot T_d$ leads to an equidistant decrease of the shoulder distance by 6 dB each time; T_d being the minimum delay time step that can be realized. From these results coinciding with other modulation schemes, not presented here, a graph can be made, where the shoulder distance is related to the RF bandwidth $B_{\rm RF}$ of the digital signal (Fig. 4). This graph shows the maximum of the shoulder distance, which is achievable if no other nonlinear effect comes up. It can be seen how critical the matching of the delay difference between A and RF-P signals is, and it gets more difficult, the broader the bandwidth $B_{\rm RF}$ becomes.

IV. OOB Slopes and RF-P Spectra

In Figs. 2 and 3, as well as in Fig. 4, the delay is $\leq 1/B_{\rm RF}$. Simulations show that Delay $= 1/B_{\rm RF}$ is an upper limit in the OOB spectrum. If this limit is compared to the spectrum of the RF-P signal, it is shown to be practically identical (Fig. 5). Therefore, only Fig. 4 and the RF-P spectrum (Fig. 5) are necessary if an OOB spectrum shall be determined. In this figure, RF-P spectra for typical single-carrier modulations are given. However, for single-carrier modulations, the OOB spectrum has two big ripples close to the channel. Therefore, the slope can only be estimated at relative frequencies 2–4 (Fig. 6). A comparison to the RF-P spectra of noise-like modulations, e.g., OFDM, taken at the same relative frequencies, shows that only the size of the vector hole determines the slope of the RF-P spectra, which is, again, an astonishing result. However, on the other hand, this underlines how dominant the nonlinearity due to the coordinate transform is.

V. Bandwidth Limitations in the A Path

While in an EER transmitter the bandwidth limitation in the RF Path only plays a minor role [6], the bandwidth limitation in the A path is essential. Because the delay matching between A and RF-P signals is critical as shown above, it is necessary to equalize the A path for a constant group delay. In the simulation the group delay is absolutely constant, and the corner

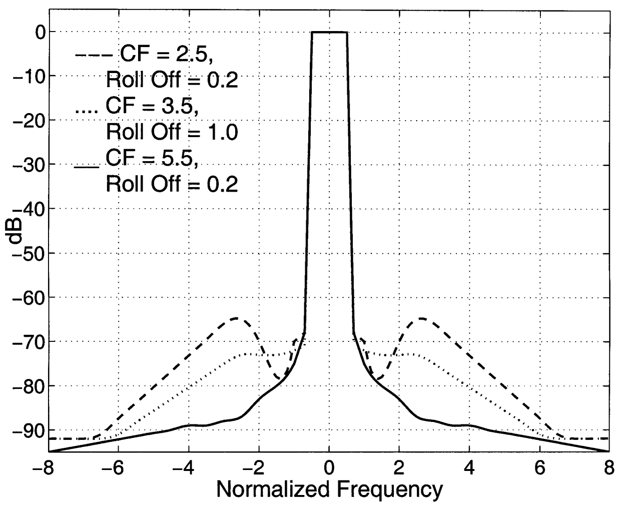

Fig. 8. Lower limit for OQPSK spectra with A path band limited and best delay matching.

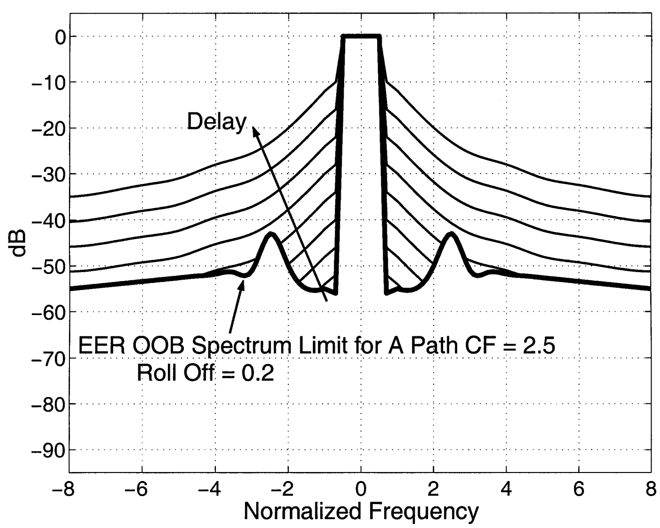

Fig. 9. QPSK delay spectra with A path band limited to a corner frequency 2.5 and rolloff 0.2.

frequency is defined as the −6-dB point. The rolloff is symmetrical to this point. The spectrum now is calculated for best delay matching. The result shows a lower limit of the OOB spectrum which can not be fallen short of. The limit itself depends on the corner frequency and the rolloff. Fig. 7 shows results for QPSK modulation (smoothed curves).

This figure shows some specific results.

- If the rolloff is steep, say, $0 \leq \varrho_A < 0.6$, there is a hump in the spectrum at the position of the corner frequency (cases 2.5 and 5.5).
- If the corner frequency is increased, the hump moves outside and only slightly reduces its relative height (case 5.5).
- Increasing the corner frequency gives lower values for OOB (cases 3.5 and 5.5).
- Increasing the rolloff $0.8 \leq \varrho_A < 1$ reduces the hump without reducing the lower limit (case 3.5)
- It is beneficial to realize rolloff $\varrho_A = 1$ at a reduced absolute bandwidth when a certain limit has to be met, e.g., an International Telecommunications Union (ITU) spectrum mask (compare case 3.5 with 5.5).

The shape of the lower limit spectrum curves is dependent on the size of the vector hole. The correspondent curves for OQPSK are given in Fig. 8, and it shows that these become very much more favorable if the modulation has a vector hole (in this case, 35%).

VI. OOB Spectra With A Path Band Limited

If two effects produce nonlinearities, such as in the case of delay mismatch and bandwidth limitation of the A path, the repercussion on the OOB spectrum is dominated by the stronger effect. For big delay mismatch, the OOB spectrum is identical to the delay spectra (see Figs. 2 and 3). For small delay mismatch, the OOB spectrum cannot become better than the limit given by the effects of the bandwidth limitations of the A path. That means, for constructing the whole OOB spectrum the limit curves (Figs. 7 or 8) are additionally necessary. In an idealized graph, this is shown for QPSK with rolloff $\varrho_A = 0.2$ and A bandwidth of 2.5 (Fig. 9).

VII. Conclusions

For the Kahn EER technique with digital modulations, the maximal achievable shoulder distance depends on the delay mismatch between A and RF-P signals. For delays $\geq 1/B_{\mathrm{RF}}$, the digital spectrum is practically identical to the RF-P spectrum, which is the upper limit for OOB in the spectrum. The slope of the OOB spectrum practically depends only on the size of the hole in the vector diagram of the digital modulation, and the modulation scheme itself is of secondary significance. According to the importance of a delay mismatch, the A path needs to have a constant group delay. A transfer function of the A path with limited bandwidth gives a lower limit for the OOB spectrum. The shape of this limit curve depends on the size of the vector hole. An A path transfer function with a constant A in combination with a rolloff $\varrho_A \leq 0.6$ gives a hump in the OOB spectrum at frequencies corresponding to the corner frequency of the A path. This hump smooths out for $\varrho_A = 1$. With a limited realizable bandwidth in the A path, a combination of lower corner frequency and $\varrho_A = 1$ is beneficial to higher corner frequency and lower rolloff. When delay mismatch and A path bandwidth limitations occur at the same time, the OOB spectrum is dominated by the effect, which is approximately 2–3 dB higher.

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