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Systematic analysis of the impact of mixing locality on Mixing-DAC linearity for multicarrier GSM

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Abstract—In an RF transmitter, the function of the mixer and the DAC can be combined in a single block: the Mixing-DAC. For the generation of multicarrier GSM signals in a basestation, high dynamic linearity is required, i.e. SFDR > 85dBc, at high output signal frequency, i.e. $f_{out} \approx 4\text{GHz}$. This represents a challenge which cannot be addressed efficiently by current available hardware or state-of-the-art published solutions.

Mixing locality indicates if the mixing operation is executed locally in each DAC unit cell or globally on the combined DAC output signal. The mixing locality is identified as one of the most important aspects of the Mixing-DAC architecture with respect to linearity. Simulations of a current steering Mixing-DAC show that local mixing with a local output cascode can result in the highest linearity, i.e. $\text{IMD}_3 < -88\text{dBc}$ at $f_{out} = 4\text{GHz}$.

I. INTRODUCTION

A popular transmitter architecture is the zero-/low-IF transmitter. A functional overview of such a transmitter is shown in Fig. 1(a).

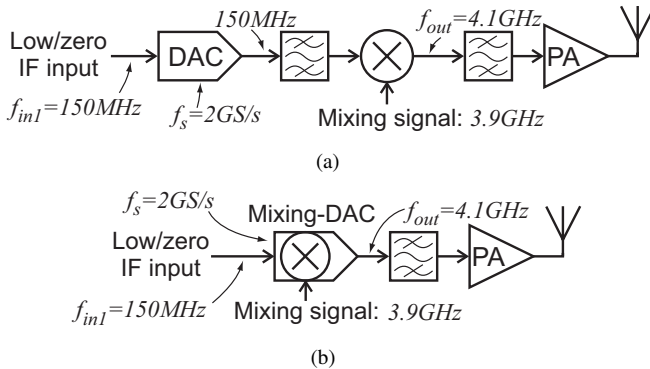


Fig. 1. Conventional transmitter signal chain (a) and new transmitter signal chain with Mixing-DAC (b)

Because of the constant improvement of CMOS process technology, the possibility to combine the function of the Mixer and the DAC has come within range [1]. A transmitter signal chain with this novel Mixing-DAC is shown in Fig. 1(b). Possible advantages of the Mixing-DAC over the classical approach due to the integration of both functions in one chip are: less noise, higher signal frequency, lower power consumption, lower cost. Moreover, various new architectures are available for implementing the combined DAC and mixer function, compared to just combining a DAC and a mixer.

An overview of the SFDR of recent Mixing-DAC publications and relevant DACs and Mixers (at $1V_{pp}$ output voltage) is given in Fig. 2. A possible application area for the Mixing-DAC is the generation of multicarrier GSM signals in basestations. For this specific application, the Mixing-DAC is required to have high spectral purity and linearity [2], i.e.

$\text{IMD} < -85\text{dB}$, up to an output frequency of approximately 4GHz. The bandwidth of the multicarrier GSM signal is limited to approximately 200MHz. Fig. 2 clearly shows that none of the current solutions can achieve this target. Above $f_{out} = 200\text{MHz}$, the highest linearity values are only achieved in a reduced bandwidth, e.g. [1], [3], using exotic technologies, e.g. GaAs [4], or at low output power, e.g. [5].

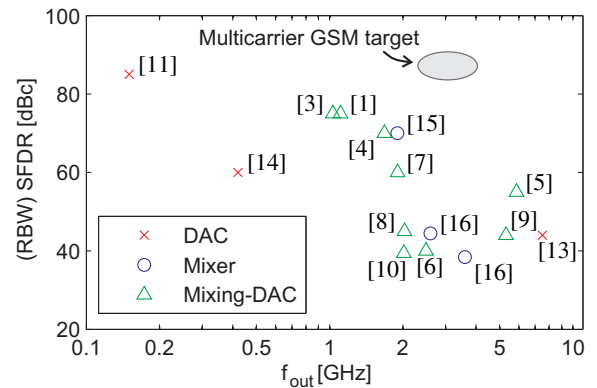


Fig. 2. Overview of the (reduced bandwidth) SFDR of state-of-the-art Mixing-DAC publications, DACs and mixers (at $1V_{pp}$ output signal amplitude)

This paper analyzes various Mixing-DAC architectures with a strong emphasis on high linearity at high frequencies, i.e. $\text{IMD} < -85\text{dB}$ at $f_{out} > 4\text{GHz}$. Section II discusses the importance of mixing locality for the linearity of a Mixing-DAC architecture and discusses two mixing locality options: ‘global mixing’ and ‘local mixing’. In section III simulation results are used to illustrate the trade-off between the two mixer locality options.

II. MIXING LOCALITY: GLOBAL AND LOCAL MIXING

Numerous Mixing-DAC linearity limitations exist. Simulations have shown that the mixing locality has a major impact on the linearity. Two main options for mixing locality are distinguished: global mixing and local mixing, see Fig. 3.

In global mixing, the output signals of the unit DAC functions are first combined before being mixed. When implementing global mixing with transistors, the non-linearity of the transistor results in a non-linear mixing function.

When local mixing is used, the mixing is executed inside the DAC unit cells before the signals are combined. These unit cells contain only 1-bit signals, hence the mixing operation is inherently linear even if real transistors are used. However, mismatch between the mixing operation in the unit cells can deteriorate the linearity of the Mixing-DAC.

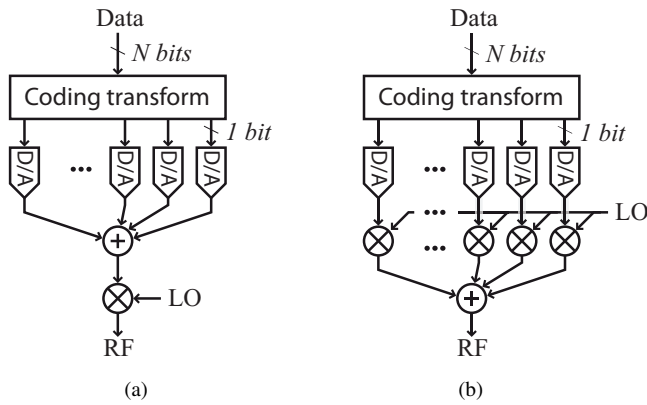


Fig. 3. General model of global mixing (a) and local mixing (b)

III. ANALYSIS AND SIMULATIONS

For the analysis of the two mixing locality options, a specific implementation is assumed, without loss of generality: a 65nm 1.2V/3.3V CMOS process with thin-oxide and thick-oxide transistors.

Since high linearity DACs are usually implemented as Current Steering(CS) DACs, the Mixing-DAC under investigation is chosen to be a CS Mixing-DAC. The simplified schematics of a CS Mixing-DAC with global mixing and local mixing are shown in Fig. 4(a) and Fig. 4(b) respectively

Table I summarizes the most important error sources of the CS Mixing-DAC which lead to non-linearity. The following subsections systematically analyze each error source separately, using the corresponding identification number in table I and Fig. 4. Unless otherwise indicated, simulations

TABLE I
MIXING-DAC ERROR SOURCES LEADING TO NON-LINEARITY

	#	Description
Output effects	1	Non-linear C_{gd} combined with output voltage swing
	2	Non-linear R_{db} combined with output voltage swing
Global mixing	3	Mixer input-current dependent mixing
Local mixing	4	Mixer data-dependent timing errors
	5	C_{cs} combined with the output-voltage dependent settling of the mixer common source nodes after data switching
Common	6	Common-source node disturbance due to LO transition combined with C_{cs} , dependent on output voltage swing
DAC effects	7	Data timing errors
	8	Disturbance due to data switching combined with C_{dcs}
	9	Mismatch between output current of current sources

use the following simulation setup. The load resistors (R_L) are 25Ω (50Ω double terminated) each and the maximum output current is 20mA, generating a differential output-signal amplitude of $1V_{pp}$. The input signal is a two-tone full scale signal at $f_{in1}=150MHz$ and $f_{in2}=165MHz$. Together with a mixing signal frequency (f_{LO}) of 4.02GHz, the resulting output signal frequencies (f_{out}) are 4.17GHz and 4.19GHz. In the simulations, the IMD3 of the output signal is used as a measure for the linearity.

A. Output effects

For isolating the Mixing-DAC non-linear output effects in simulation, the simulation setup of Fig. 5(a) is used. An ideal

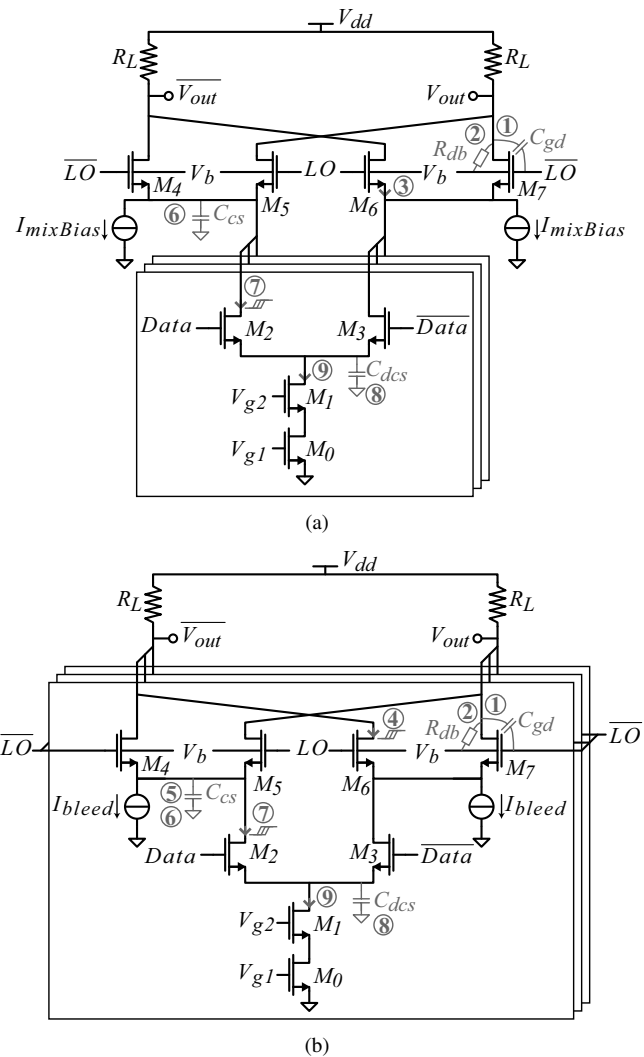


Fig. 4. Transistor model of two options for mixing locality: global mixing (a) and local mixing (b)

Mixing-DAC output signal is generated by I_{out} and R_L , while M_1 and M_2 model the output non-linearity of a Mixing-DAC. A sweep over the output common mode voltage (V_{out_dc}) for various values of the output signal frequency (f_{out}) is used to show the effect of the output non-linearities, see Fig. 5. This simulation clearly shows that an IMD3 of $-85dBc$ at 4GHz is achievable with CMOS output transistors.

The most limiting output effects are: gate-drain capacitance and drain-bulk leakage (error sources 1 and 2 in table I and Fig. 4). These two effects mainly depend on V_{out_dc} , f_{out} and output signal voltage swing.

B. Specific global mixing non-linearities

In the global mixing simulation model, only transistors M_4 to M_7 of Fig. 4(a) are real transistors. The other parts of the Mixing-DAC are implemented in Verilog-A.

Global mixing suffers from non-linearity errors due to the data-dependent current through the mixing transistors (error source 3). Global mixing can be linearized by optimizing the

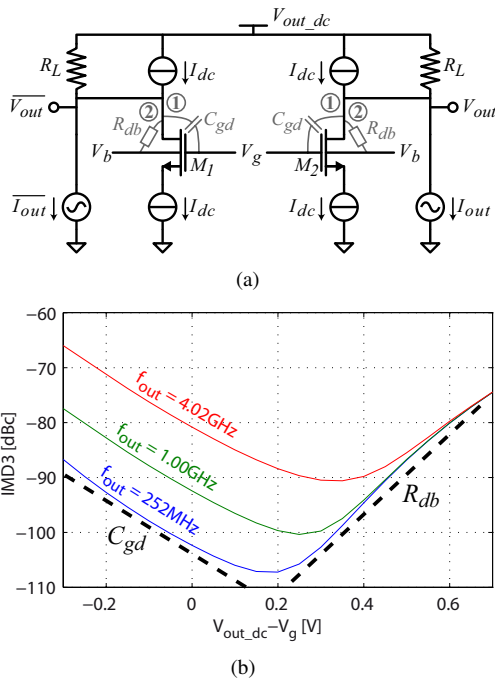


Fig. 5. Output effect simulation: circuit (a) and simulation results (b)

ratio between signal current and bias current, hence by adding bias current through the mixer ($I_{mixBias}$ in Fig. 4(a))

Fig. 6 shows the IMD3 dependence on $I_{mixBias}$. For equal bias voltage levels at each node, increasing $I_{mixBias}$ also means increases the size of the mixing transistors, which increases the output-related non-linearity. Therefore, the maximum achievable IMD3 for global mixing is -82dBc (see Fig. 6), which is worse than the required -85dBc .

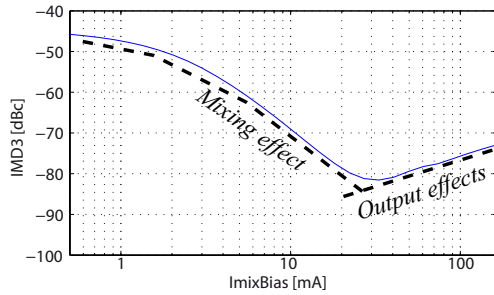


Fig. 6. With global mixing, the mixing operation linearity depends on the added bias current

C. Specific local mixing non-linearities

In the simulation model of the local Mixing-DAC, only transistors M_4 to M_7 of Fig. 4(b) are real transistors, the other Mixing-DAC parts are implemented using Verilog-A.

The current through a mixer transistor pair (e.g. M_4 - M_5) exhibits a large step if the input code of the corresponding data transistor (e.g. M_2) changes. This generates a large voltage step at the mixer common source node V_{cs} . Settling behavior of the V_{cs} step is dependent on the output voltage (error source 5), introducing an error charge on the parasitic capacitance C_{cs} . By optimizing I_{bleed} , this error source can be minimized.

Threshold voltage mismatch of the mixing transistors causes timing errors in the mixing operation between current cells,

generating non-linearity (error source 4). The results of a Monte Carlo (MC) mismatch simulation are shown in Fig. 7. In this simulation the transition time of the LO waveform is 50ps and R_L is chosen very small (0.25Ω) to isolate the mismatch non-linearity. The simulated standard deviation of the timing errors is approximately 0.8ps. In the corresponding IMD3 distribution, 99% of all IMD3 results is better than -93dBc . Therefore, it is concluded that the LO timing errors do not degrade the dynamic linearity of the CS Mixing-DAC below the required $\text{IMD3}=-85\text{dBc}$. The timing errors due to imperfect signal routing are assumed to be negligible and hence are not taken into account.

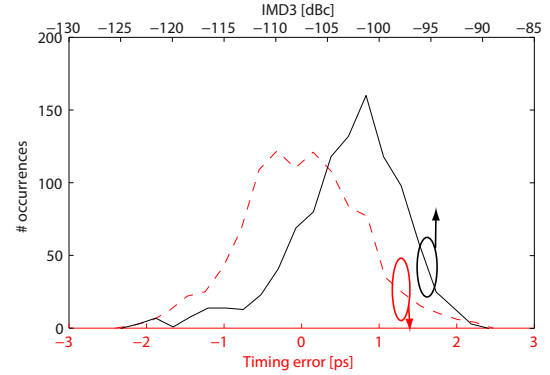


Fig. 7. Monte Carlo mismatch simulation: distribution of timing errors between two current cells and resulting IMD3 distribution

D. Common mixing non-linearities

Both local and global mixing are very sensitive to capacitance C_{cs} at the common source node of the mixer (error source 6). During a LO transition a disturbance occurs at the common source node of the mixer transistors. The size of this disturbance is dependent on the Mixing-DAC input signal, generating non-linear distortion. For local mixing, this data dependence originates from the finite isolation between the output voltage swing and the mixer common-source node. For global mixing, the signal current through the mixer causes the above mentioned data-dependence.

Fig. 8 shows the IMD3 dependence on the value of C_{cs} . In this simulation, the same models as given in section III-B and III-C are used. Realistic values for C_{cs} are 10-20fF for local mixing and 1-2pF for global mixing. In those regions, the linearity of the Mixing-DAC is reduced to $\text{IMD3}=-72\text{dB}$, which much worse than the required -85dBc .

E. DAC non-idealities

Non-linearities specifically related to the DAC function (e.g. error sources 7-9) are not discussed in this paper. Other authors have extensively discussed these effects [17]–[20]. Moreover, the DAC-function non-linearities are common to global mixing and local mixing.

F. Output cascode

For local mixing, the isolation between the output signal and the mixer common source node can be increased by adding a local output cascode to each cell. Fig. 9 shows the schematic

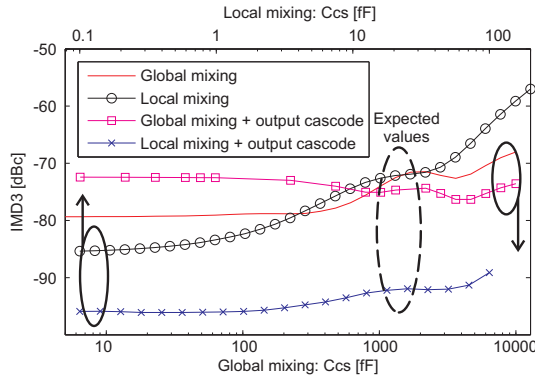


Fig. 8. Sensitivity of mixing linearity to capacitance at the mixer common-source node. Output cascode reduces sensitivity for local mixing.

of a local Mixing-DAC with output cascode. Careful biasing ensures all transistors do not exceed their maximum operating conditions. The new IMD3 dependence on mixer common source node capacitance is simulated using a simulation model where only M_4 - M_9 are real transistors, the results are shown in Fig. 8. It can be seen that the simulated performance is increased to $\text{IMD3} = -92\text{dBc}$.

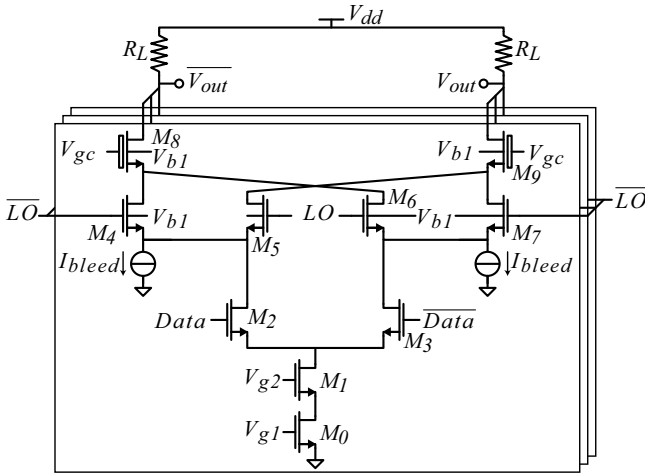


Fig. 9. Local CS Mixing-DAC with local output cascode

Using a simulation model where all Mixing-DAC current cell transistors (M_0 - M_9) are real transistors and assuming realistic wiring capacitances, the IMD3 is -88dBc , achieving the desired linearity.

For global mixing, adding additional isolation between the output and the mixer common-source node does not improve the linearity, since the C_{cs} dependent non-linearity is in global mixing is due to the data dependent current through the mixer. Fig. 8 confirms this claim.

IV. CONCLUSION

For high linearity Mixing-DACs, mixing locality is a major concern. For a current steering Mixing-DAC, the impact of the capacitance at the mixer common-source node (C_{cs}) dominates the Intermodulation Distortion (IMD) performance. For global mixing, this error source cannot be prevented. For local mixing, the IMD degradation due to C_{cs} originates from coupling from the mixer common-source node to the

output voltage. Implementing a local output cascode reduces the sensitivity to C_{cs} . The expected IMD3 performance of the exemplary local mixing CS Mixing-DAC is $< -88\text{dBc}$ at $F_{RF} > 4\text{GHz}$ output frequency, enabling the advantages of a Mixing-DAC for multicarrier GSM applications.

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