Compensation of DC-Offsets and RF-Self-Mixing Products in Six-Port-Based Analog Direct Receivers

Marko Mailand and Hans-Joachim Jentschel

Dresden University of Technology
Institute of Traffic Information Systems
01069 Dresden, Germany
Email: {mailand, jentschel}@vini.vkw.tu-dresden.de
Telephone: ++49 351 36753

***Abstract*—The cancellation of DC-offsets and 2nd-order-type RF-self-mixing products (RFS2) is presented for six-port-based, analog direct receiver front-ends. It is shown that the signal dependent RFS2 comprising a dynamic DC-offset as well as the front-end dependent static DC-offset are generated systematically and not only by spurious effects unlike conventional, mixer-based front-ends. Due to this fact, it is possible to remove the DC-offsets and RFS2 before analog-to-digital conversion. In this article, it is explained how the DC-offset/RFS2 compensation can be mainly reduced to path mismatch cancellation within the front-end. For that purpose, appropriate front-end architectures are presented. In the ideal case, the proposed technique enables complete DC-offset and RFS2 cancellation.**

I. Introduction

Future mobile communication devices will have to enable multi-protocol applications. There are a lot of analog receiver front-end architectures as well as component realization possibilities which ought to perform this task. Due to several implementation limitations within analog integration e.g., tunable band-pass filters etc., recent investigations of front-end architectures focus on low intermediate frequency (IF) [1] or direct conversion techniques [2]. But also wideband-IF concepts are still of interest [3].

A promising candidate for the implementation of a broadband, multi-protocol-capable direct receiver front-end is the so called six-port receiver [4]-[7]. There, direct conversion is usually realized, although IF reception was possible too. In the use as communication receiver front-end, the former *six-port* structure was reduced to a *five-port* but also expanded to a *seven-port*. We use the respective terms, if they are especially addressed. For general descriptions, the term *six-port-based* is used.

One of the most crucial factors within any analog direct conversion receiver front-end is the direct current (DC) offset. The DC-offset comprises a static and a dynamic component. It has to be removed from the received signal to be able to regenerate the respective wanted information properly. The static DC-offset originates from the circuitry of the front-end and can be considered as quasi-constant within short time periods. On the other hand, the dynamic DC-offset permanently changes, since it is caused by the RF-signal. The dynamic DC-offset within a six-port-based receiver is a part of the unwanted 2nd-order-type RF-self-mixing products (RFS2) which are produced systematically as portion of the rectified wave.

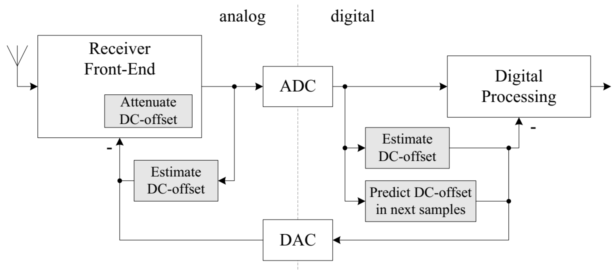

Fig. 1. General possibilities of DC-offset cancellation.

In this paper, the cancellation of these DC-offsets and RFS2 within six-port-based direct reception is investigated. After some issues of state-of-the-art DC-offset compensation, descriptions of novel five-port and seven-port front-end architectures will be given. Afterwards, the DC-offset/RFS2 cancellation will be explained which is enabled by the novel front-end architectures.

II. Compensation of DC-Offsets within Direct Receivers

The realizations of DC-offset compensation are manifold as the different front-end implementations are. Preferably, the DC-offset should be removed before the analog-to-digital conversion (ADC) in order to gain dynamic range for the wanted signal.

One widespread method is to determine an average value for the DC-offset in the analog domain. General, realizations use a large time-constant to extract the DC-offset. Then, this DC value is subtracted from the input to form a closed-loop system. Large DC-loop-gain will reduce the output offset. However, these R-Cs are usually external as their corner is near DC [8]. To speed up the setting time of the DC-offset cancellation loop, a dual, adjustable bandwidth structure can be utilized with variable MOS resistors [9]. Moreover, low-pass filters or gain-attenuation concepts are used for analog DC-offset compensation. There, the unwanted DC-components

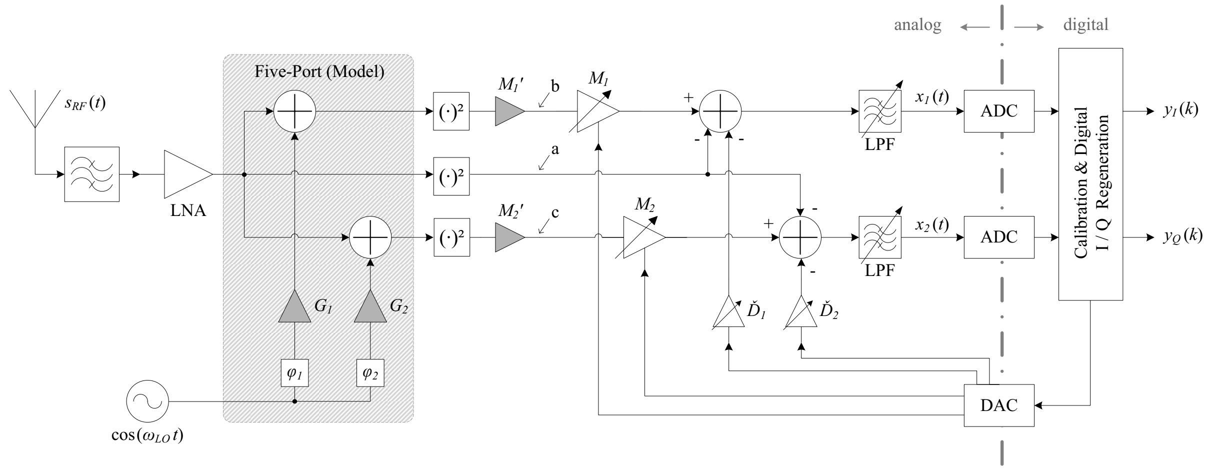

Fig. 2. Five-Port front-end with reduced circuitry effort; Note: the boxed φ_i symbolize phase shifts; the grayly grounded elements only model system inherent mismatches, they are not discrete components.

are attenuated whereas the required signal-components are amplified in the analog domain.

On the other hand, there are several techniques of DC-offset compensation in the digital domain. Well-known methods are based on adaptive filters which estimate the DC-offset [10], [11].

Further realizations combine analog and digital DC-offset cancellation techniques [12]. In Fig. 1 the natures of these techniques are given.

Although it is possible to eliminate the static DC-offset with only analog effort, the dynamic component can only be treated by an estimate. Thus, there remains a portion of the dynamic DC-offset even in the ideal, theoretical case. Methods which attenuate the offsets also leave over some portions of DC-components. The digital techniques are able to predict the dynamic DC-offset quite precisely. But even there, only an estimate can be removed from the wanted signal. Hence, in the best case, a portion of dynamic DC-offset still remains within the wanted signal in analog domain. To date, no technique or concept is known which can completely remove the spurious DC-offsets in analog domain.

We will show that within six-port-based font-ends one can generate a base-band signal without DC-offset distortions (static and dynamic) as well as without nonlinear distortions due to RFS2 even before ADC.

III. Six-Port-Based Receiver Front-Ends

By the implementation of six-port-based receiver front-ends, it is possible to realize simple, broadband and multi-protocol devices [4]-[7]. Such a front-end performs a homodyne reception with additive mixing. Advantages of six-port-based front-ends are that no mixers are needed and that the broadband capability is achievable more easily e.g., in [6] bandwidths of up to 20 MHz with a RF-frequency region of (2-5)GHz are reported. Furthermore, such front-ends are significantly more robust against deviations of the RF-level.

In order to reduce the number of expensive analog devices, a five-port front-end was suggested [13]. The front-end architecture is shown in Fig. 2. Within the receiver the RF-signal, i.e. $s_{RF}(t) = Re\{s(t)\cdot\exp(j\,\omega_{RF}\,t)\}$ with $s(t) = s_I(t) + j\cdot s_Q(t)$ ($I\ldots$in-phase and $Q\ldots$quadrature-phase channel of the wanted signal), is superimposed by the phase-shifted and scaled local oscillator (LO) signal $s_{LO}(t) = Re\{G_i\,\exp(-j\,(\omega_{LO}\,t - \varphi_i))\}$. The output signal of the front-end can be written as ($\omega_{RF} = \omega_{LO}$):

$$x_i(t) = \underbrace{G_i^2\,M_i'\,M_i + (M_i'\,M_i - 1)\cdot(s_I^2(t) + s_Q^2(t))}_{\text{rectified wave including DC-offsets}} - \check{D}_i + \underbrace{2\;M_i'\,M_i\cdot\big(s_I(t)\,G_i\,\cos(\varphi_i) + s_Q(t)\,G_i\,\sin(\varphi_i)\big)}_{\text{wanted signal components}} \qquad (1)$$

The M_i' in (1) and Fig. 2 reflect the respective path mismatches of path b and c with respect to path a. These mismatches are caused e.g., by imperfect circuitry realization because of production deviations. The variable amplifiers M_i shall be utilized to compensate the path mismatches.

For further investigations, we rewrite (1) in matrix form.

$$\mathbf{x} = \begin{bmatrix} A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \end{bmatrix} \begin{bmatrix} s_I(t) \\ s_Q(t) \\ s_I^2(t) + s_Q^2(t) \end{bmatrix} + \begin{bmatrix} D_1 \\ D_2 \end{bmatrix} \qquad (2)$$

with $\mathbf{x} = [x_1(t), x_2(t)]^T$. This notation is more advantageous since any deviation and distortion of the wanted signal is modelled. Here, the system coefficients A_i to D_i stand for the front-end specific transmission (1) as well as for deviations of e.g., φ_i, G_i, phase and amplitude errors due to imperfect LO, etc. The A_i and B_i coefficients reflect the portions of the I-channel and the Q-channel within the front-end outputs $x_i(t)$. Moreover, it shows that the unwanted RF-self-mixing product comprising some dynamic DC-offset and the quasi-static DC-offset (represented by $C_i \neq 0$ and $D_i \neq 0$) originate from different sources (RF-signal and circuitry, respectively). D_i can be considered as quasi-static (static) DC-offset since it only changes either slowly by environmental variations (e.g. temperature) or by the receiver setup (e.g. LO-frequency, etc.) being significantly changed.

Different from other front-end concepts, the six-port-based architectures enable to treat the static DC-offset and the RFS2 (inclusive dynamic DC-offset) separately. The reason is given by (1). Apparently, within the rectified wave, the static DC-offset, i.e. $G_i^2\, M_i'\, M_i$, and the RFS2, i.e. $(M_i'\, M_i - 1) \cdot (s_I^2(t) + s_Q^2(t))$, are produced systematically and not only by spurious effects unlike mixer-based front-ends. Thus, they can be treated with direct signal manipulation.

Hence, it is possible to realize combined DC-offset/RFS2 compensation just by providing an appropriate front-end architecture like e.g., the systems in Fig. 2 or Fig. 3.

IV. Front-End Calibration - Cancellation of DC-Offsets and RF-Self-Mixing Products

At first, we will concentrate on the front-end of Fig. 2. In [13], the calibration of this type of front-end is investigated in detail. The calibration procedure can be realized without any test-signals e.g., by a DSP.

The cancellation of the RFS2 and hence the dynamic DC-offset is directly related to the removal of the path mismatches M_i'. The signal path a (Fig. 2) is essential, which directly feeds the squared RF-signal to the signal paths b and c. Without path mismatch, this would remove the RFS2 including the dynamic DC-offset. But, as there are mismatches to be expected, they will have to be cancelled within the front-end calibration. If we switch off the LO and set $M_1 = 1$, $M_2 = 0$ or $M_1 = 0$, $M_2 = 1$, we can determine the respective path mismatch cancellation values digitally:

$$M_i' = 1 + f\big(\frac{x_1(k)}{x_2(k)}\big) \tag{3}$$

$$\text{with e.g.,}\quad f\big(\frac{x_1(k)}{x_2(k)}\big) = \sqrt{\mathrm{E}\left\{\frac{x_1^2(k)}{x_2^2(k)}\right\}}\quad .$$

whereas $\mathrm{E}\{\times\}$ denotes the expectation of the argument. $f(\times)$ can be any appropriate function of its argument [13]. Updates for M_i' can be calculated during the stand-by phase of the receiver. As soon as the M_i are set to the required values, the front-end removes systematically the dynamic DC-offset. In the ideal case, the path mismatches are completely cancelled and hence the dynamic DC-offset. At this point, the superiority of six-port based receivers shows up. This is because the systematically generated dynamic DC-component is removed systematically in the analog domain. The removal depends only on the quality of the path mismatch cancellation and not on the origin of the offset, i.e. the fast changing RF-signal. Therefore, the dynamic DC-offset can be removed completely (without estimating or predicting it) before the ADC.

If the RF-signal is switched off, i.e. $s_I(t) = 0$ and $s_Q(t) = 0$, the static DC-offset is simply obtained by

$$\check{D}_i = \mathrm{E}\big\{x_i(k)\big\}\ . \tag{4}$$

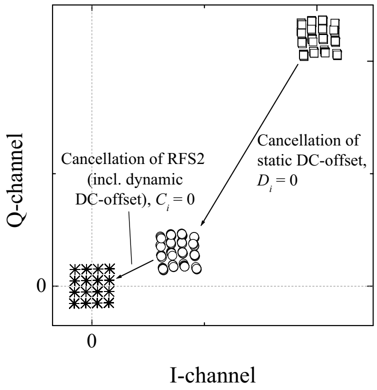

Fig. 4. Schematic relocation/reshaping of a 16QAM modulated IQ-constellation due to the cancellation of the different DC-offsets and 2nd-order-type RF-self-mixing products (RFS2).

After the digital determination of the respective DC-components, the amplification values in the front-end, i.e. $\check{D}_i$, are set to these values. Thus, the static DC-offset is removed before ADC. This method is sufficient for the static DC-component for comparably slowly changing environments.

After DC-offset compensation, the front-end transmission of (2) reduces to

$$\mathbf{x} = \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} \approx \begin{bmatrix} A_1 & B_1 \\ A_2 & B_2 \end{bmatrix} \begin{bmatrix} s_I(k) \\ s_Q(k) \end{bmatrix}\ . \tag{5}$$

The A_i and B_i are not known and there is no need to utilize test-signal measurements to obtain them. These parameters can be determined by blind signal separation algorithms [14].

In Fig. 4 the effect of the DC-offsets and RFS2 and their removal within the five-port receiver front-end (Fig. 2) is shown schematically.

A further possibility of static DC-offset cancellation is related to a different front-end architecture. In Fig. 3, a seven-port is shown. The former paths for the $\check{D}_i$ are removed and two more n-port output paths and two power detectors, i.e. square-law devices are inserted. With this architecture, the static DC-offset compensation is reduced to another path mismatch cancellation for M_{si}' like for the paths b and c with M_i' or M_{ri}', respectively. The advantage of this method is that all DC-offset/RFS2 compensations are reduced to path mismatch cancellations and hence any deviation of the offsets' origins is directly feed to the compensation. Consequently, all changes of the LO- and RF-signal are considered within the DC-offset/RFS2 cancellation. This is the case even if the signals changes within a single data sequence. Therefore, all DC-offsets and 2nd-order-type RF-self-mixing products can be removed.

Unlike the architecture in Fig. 2, the presented seven-port front-end considers any change of the unwanted DC-offsets and RFS2. Therefore, also transmission protocols with e.g., fast frequency-hopping schemes and hence, permanently changing LO-signals, i.e. short-time-static DC-offset can be processed without incessant updates for the compensation

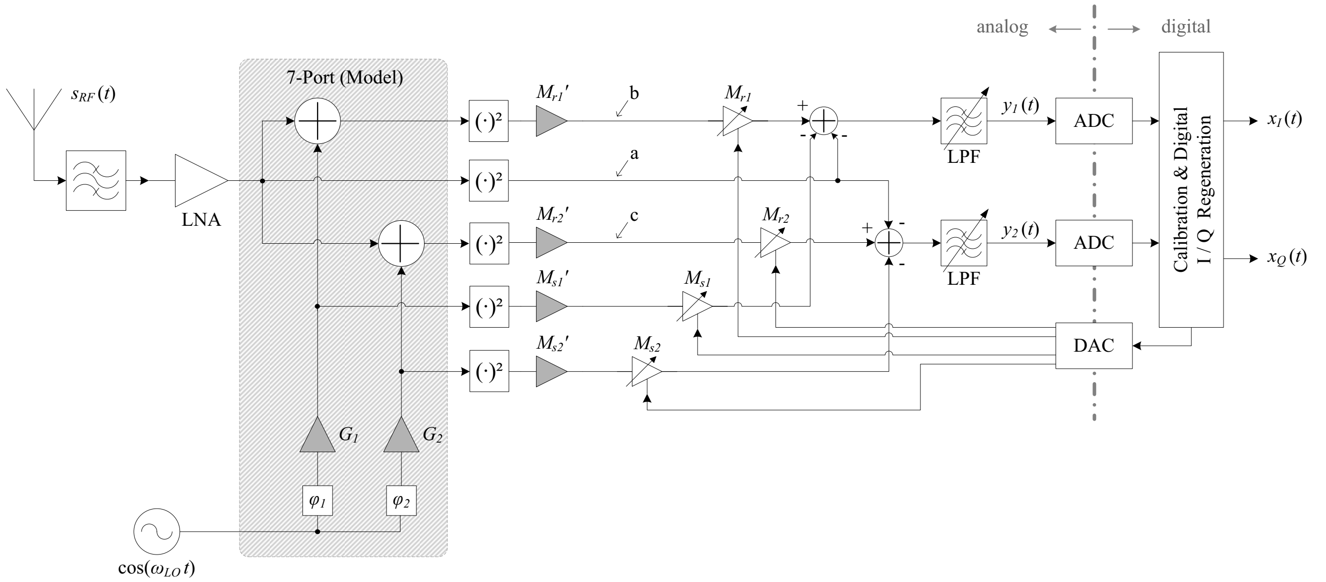

Fig. 3. Seven-Port front-end for complete online, analog DC-offset/RFS2 compensation; Note: the grayly grounded elements only model system inherent mismatches, they are not discrete components.

values $\check{D}_i$. In addition, approximately the same circuitry effort is utilized, since the tuneable amplifiers are only replaced and the two new square-law devices can be implemented quite simply e.g., by RF-diodes. Hence, only the quality of path mismatch cancellation and its dependence on temperature and deterioration will influence the compensation of DC-offsets and RF-self-mixing products.

Moreover, it is to underline that additional, spurious RF-self-mixing and LO-self-mixing as source of DC-offsets are no problem at all within six-port-based reception since the receiver performs additive mixing. Any superposition of RF-signals and LO-signals only increases the level of the respective input but does not cause additional distortions. In other words, (2) also includes such self-mixing effects. Further, the requirements are lowered for very linear elements within the front-end. All second order nonlinearities before the power detectors do only influence marginal the six-port output signals.

V. Influence of Incomplete Mismatch Cancellation

If portions of the recitified wave, i.e. DC-offsets and RFS2 remain within the wanted signal, then the performance e.g., symbol-error-rate (SER) of the receiver will decrease.

We conducted a simulation with the front-end of Fig. 2 in order to demonstrate the consequences of incomplete compensation of the dynamic DC-offset and nonlinear distortions due to RFS2. A 16QAM modulated signal was transmitted over an AWGN channel. The raised cosine pulse shaping filter has a rolloff-factor of 0.3 and a 16^{th} order FIR low-pass-filter is realized, where $f_{RF} = \omega_{RF}/(2\,\pi) \approx$ 2GHz. The front-end parameters were selected as $M_1' = 0.92$, $M_2' = 0.97$, $\varphi_1 = \pi/7$, $\varphi_2 = \pi/3$, $G_1 = 0.8$ and $G_2 = 0.9$. The IQ-regeneration, i.e. the digital blind signal estimation of the

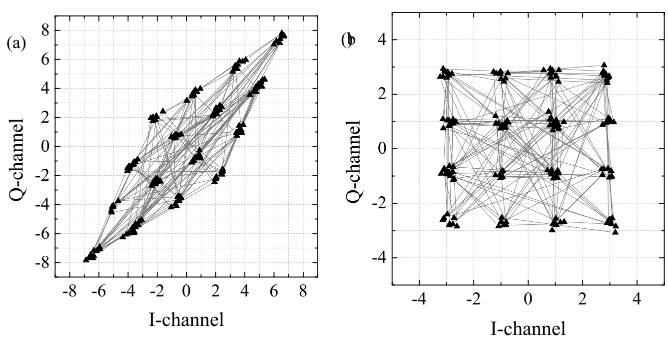

Fig. 5. IQ-constellations before (a) and after (b) IQ-regeneration; AWGN: SNR=20dB.

front-end parameters A_i and B_i in (5) was performed by a recursive Gram-Schmidt orthonormalization followed by a trained phase synchronization [14].

The received signal and the regeneration of the 16QAM IQ-constellation after the front-end utilizing converged blind signal parameter estimation is shown in Fig. 5(a) and Fig. 5(b), respectively. In this example, the path mismatch cancellation is assumed to be perfect. In Fig. 5(a), the distortion of the IQ-constellation is due to the five-port parameters φ_i and G_i including amplitude and phase imbalances of the LO.

For realistic investigation, we have to expect incomplete path mismatch cancellation and hence remaining DC-offset/RFS2 in the analog domain. This results in a degradation of the SER versus signal-to-noise ratio (SNR) performance of the whole receiver. In the different cases of Fig. 6, the receiver performance is compared to the ideal, 'theoretical boundary' for a 16QAM modulated signal. The second curve was obtained without any mismatch under the condition of the

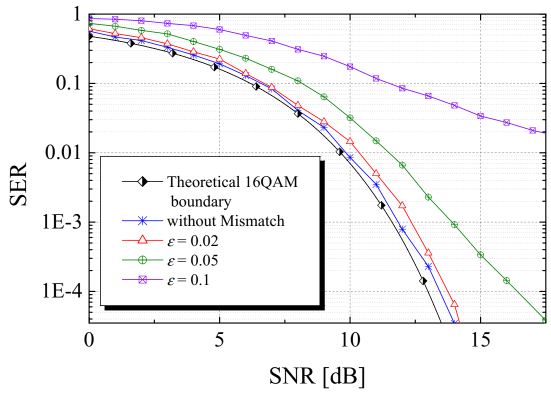

Fig. 6. Symbol error rate for different remaining DC-offsets/RFS2 due to path mismatch; Recursive Gram-Schmidt orthonormalization is utilized for IQ-regeneration.

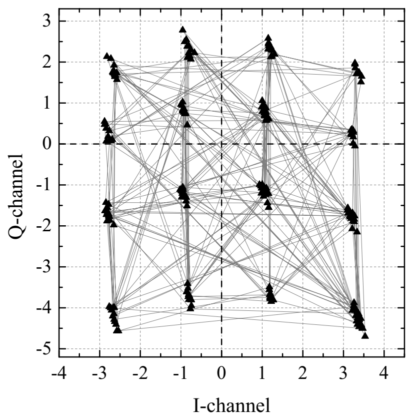

Fig. 7. Shifted and distorted IQ-constellation for $\varepsilon = 0.17$ (17% mismatch); AWGN: SNR=30dB.

system parameters given above. For the other three curves, we introduced path mismatch with an relative error of

$$\varepsilon = \pm\Big(M_i \cdot M_i' - 1\Big) \quad \text{(ideally: } M_i\, M_i' = 1) \qquad (6)$$

within each of the paths b and c. As it can be seen in Fig. 6, the SER performance degrades as the path mismatch error increases. The reasons are a shifting and a distortion of the IQ-constellation due to remaining DC-offset and RFS2. For severe mismatches ($\geq 5\%$), the degradation of the SER for larger SNR is due to the shifting and distortion of the whole IQ-constellation and an additional variation of the respective symbols. Since $\varepsilon \approx 0.02$ is an realistically achievable value for a mismatch-cancelled circuit realization, the front-end architectures are expected to be able to work without accessory DC-offset/RFS2 compensation.

Fig. 7 shows the shifted IQ-constellation for $\varepsilon = 0.17$ with $SNR_{AWGN} = 30$dB. Afterwards, the I-channel and the Q-channel can not be demodulated anymore in our example since the IQ-symbols cross their respective demodulation limit.

VI. Conclusion

In this article, we have shown that DC-offset and RF-self-mixing product compensation within six-port-based direct receivers differs from techniques for mixer-based receiver. This is due to DC-offset/RFS2 being generated systematically in six-port-based front-ends. We have presented two novel analog front-end architectures. These front-ends reduce the DC-offset/RFS2 compensation mainly to a path mismatch cancellation, especially for the crucial dynamic DC-offset. Moreover, the influence of imperfect mismatch cancellation with respect to the remaining portions of DC-offset/RFS2 was investigated.

The presented, novel architectures enable the analog compensation even for the dynamic DC-offset within direct reception.

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