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Demodulation of aggregated RF Signals with a Unique Rx Chain

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***Abstract*— In the next generation of the mobile radio systems, the information will be distributed on discontinuous frequency bands. To demodulate the RF signal, a possible architecture is to use a number of receivers Rx equal to that of the discontinuous RF frequency bands. This paper demonstrates that this operation can be made with a single receiver Rx. The method is based on the mixing of the RF signal with a local oscillator (LO) signal constituted by several Continuous Wave (CW) signals. The technique is studied theoretically and then applied to the case of RF signal constituted of two frequency bands. The CW frequencies of the LO signal are selected to convert both bands of the RF signal in Zero Intermediate Frequency (ZIF) and LOW Intermediate Frequency (LIF).**

I. Introduction

The International Telecommunication Union of Radiocommunication (ITU-R) recommended that the 4th generation network must reach the data rate of 1 Gbit/s for the downlink (base station to mobile station) and 500 Mbit/s for the uplink (mobile station to base station)[1],[2]. This data rate requires a frequency bandwidth between 70 MHz and 100 MHz. The availability of this frequency range is not always guaranteed, especially for RF carrier frequency below 3 GHz. The solution is spectrums aggregation which consists in distributing the information on multiple discontinuous frequency bands. Nowadays, the proposed architecture is to use a number of Rx receiver equal to the number of frequency bands of the RF signal. In the case of 2 bands, another way is to use the architecture of the Weaver demodulator and a LO frequency equals approximately to the half of both carrier frequencies [3], [4]. This last technique is not applicable for the demodulation of more than 2 frequency bands.

In parallel with our research works, a team of NTT published in [5] practical results on the transposition by a mixer of a RF signal constituted of 2 frequency bands. The used technique is similar to that developed in this paper and consists in using a LO signal constituted of 2 frequency tones. It is shown in [5] that power levels of the IF signals may be identical even if the RF signal is composed of two frequency bands of different power levels. This property is obtained by monitoring the relative power of CW signals of the LO. However, that involves a degradation of the signal to noise ratio for one of the bands by increasing the conversion loss of the mixer.

In the work presented in this paper this technique is applied directly for the demodulation of RF signal aggregated in frequency and without any control of the power level of the LO signal.

The principle of transposition in baseband of a RF signal constituted of discontinuous frequency bands is demonstrated in section II. Finally the section III gives a validation of the theoretical results by the measure. The variation of the quality of the In phase and Quadrature (IQ) constellation of the demodulated signals is given according to the relative power level of both frequency bands of the RF signal.

II. Theory And Technique Of The Down Conversion Of The Rf Signal

The transposition of a RF signal to baseband is done by the mixing with a LO signal. Assuming the RF signals is constituted of 2 discontinuous frequency bands, respectively centered at the frequencies f_1 and f_2 and of bandwidth BW_1 and BW_2; the expression of the aggregated RF signal is expressed thus:

$$v_{RF}(t) = \mathrm{Re}[Z_1(t)e^{j2\pi f_1 t} + Z_2(t)e^{j2\pi f_2 t}] \qquad (1)$$

with $Z_j(t) = a_j(t)e^{j\theta_j(t)}$, $j=1,2$ the complex envelope of 2 carrier frequencies f_1 and f_2.

In our case the objective is to lower the frequency bandwidth of the converted signals to relax the required performances of the Analog to Digital Converter (ADC). The strategy is consequently to convert both frequency bands of the RF signal to ZIF for one band and LIF at frequency Δf_2 for the second one. In that way, both CW frequencies of the LO

signal are equal to f_1 and f_2- Δf_2 with $\Delta f_2 > BW_1/2$. The expression of the LO signal is defined as follows:

$$v_{LO}(t) = \mathrm{Re}[V_{LO}(e^{j(2\pi f_1 t+\phi_1)} + e^{j(2\pi(f_2-\Delta f_2)t+\phi_2)})] \quad (2)$$

with V_{LO} the amplitude of the CW signals and angles ϕ_i *(i=1,2)* representing phase shifts between RF and LO signals. Assuming that $f_2 > f_1$ so that we obtain the following condition:

$$\left| f_2 - f_1 \right| > f_{LPF} \quad (3)$$

where $$f_{LPF} = \Delta f_2 + BW_2 / 2 \quad (4)$$

is the cutoff frequency of the low-pass filter.

The expression to the output signal of the low-pass filter is expressed as follows:

$$v_k(t) = V_{LO} \begin{Bmatrix} A_{k1} a_1 \cos(\theta_1(t) - \phi_1) + \\ A_{k2} a_2 \cos(\theta_2(t) + 2\pi\Delta f_2 t - \phi_2) \end{Bmatrix} \quad (5)$$

where A_{kj}, *j=1,2* are gains that include the conversion gain of the mixer and the losses of splitters, phase shifters and filters. And k represents the output path of the mixer.

The equation (5) shows that the first frequency band is transposed directly to baseband around zero, it is a ZIF demodulation. The second band is transposed to the intermediate frequency Δf_2, it is a LIF demodulation.

Moreover the separation between both baseband spectrums is possible if:

$$\Delta f_2 - BW_2 / 2 > BW_1 / 2 \quad (6)$$

This technique is applied to the Three Phase Demodulator (TPD) instead of the Classical IQ (CIQ) demodulator. Indeed, a previous paper [6] has shown TPD gives a gain of 20 dB in second-order inter-modulation distortion (IMD2) rejection in comparison with CIQ. The operation mode of TPD differs from the CIQ. The RF and LO signals are divided into three paths instead of two. The phase shift between the LO signals is equal to ± 120° for the TPD instead of 90 ° for the CIQ. The CIQ delivers directly the IQ baseband signals. In the case of the TPD, the output signals are three low frequency signals, named $v_1(t)$, $v_2(t)$ and $v_3(t)$. The TPD (Fig. **1**) was essentially realized using COTS components. The phase shifters were made with microstrip propagation lines. The phase shift varies from 60 ° to 150 ° in function of frequency in the range 2 to 4.2 GHz. The splitters insertion loss is 5dB. The mixers present the following characteristics: RF/LO inputs (DC=2-7 GHz), FI output (DC-1.3 GHz), LO power (7dBm), Conversion Loss (7dB) and intercept point of order 2 (IIP2 = 27dBm).

[7], [8] demonstrate that if $v_2(t)$ output is symmetric in comparison with 2 others, the three output signals of the TPD can be added by an analog circuit of IQ regeneration performing the following operations:

$$I_{out}(t) = \mu_I \cdot [-V_1(t) + 2 \cdot V_2(t) - V_3(t)] \quad (7)$$

$$Q_{out}(t) = \mu_Q \cdot [V_1(t) - V_3(t)] \quad (8)$$

Both constants μ_I and μ_Q are determined by a classical equalization procedure. In this work this operation is done thanks to a training sequence. Finally the transmitted *I(t)* and *Q(t)* signals are recovered.

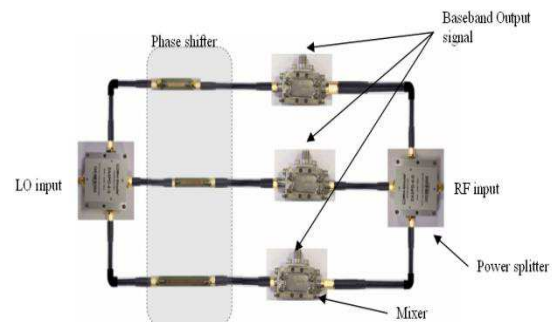

Fig. 1. Three Phase Demodulator

The mismatch between the paths of the demodulator depends upon the deviation in symmetric conditions of amplitude and phase. In [7], the simulated results demonstrate that a phase asymmetry at port3 of value $\Delta\Phi$ introduces an amplitude error on IQ output. For example, a phase imbalance, $\Delta\Phi=\pm 10°$ gives ± 3 *dB* imbalance IQ output as shown in the Fig.3 of [7].

III. Measurement Results

The Fig. **2** presents the test bench. The digital *I(p)* and *Q(p)* data are generated from Matlab software. These data are transmitted to both generators (Agilent Technologies E8267) via a Local Area Network (HP J2600A HUB). The generators operate in the mode ARB (arbitrary waveform generator). The modulated signals are added by a combiner (PULSAR PS-20-450/10S). In our experience, the RF signal is the aggregation of two modulated signals of carrier frequencies 2 GHz and 2.3 GHz. The numerical frame is composed of a 16 symbols training sequence with Constant Amplitude Zero Autocorrelation (CAZAC) followed by a pseudorandom PN9 data sequence. The modulation format is Quadrature Phase Shift Keying (QPSK) with a symbol rate of 100 kS/s for each aggregated signal. The *I(p)* and *Q(p)* data are filtered by a Square Root Raised Cosine filter (SQRC) with a roll-off equal to 0.35.

The test is performed using baseband signals with low frequency bandwidths. However, the TPD can also demodulate RF signals with modulation signals of high bandwidth.

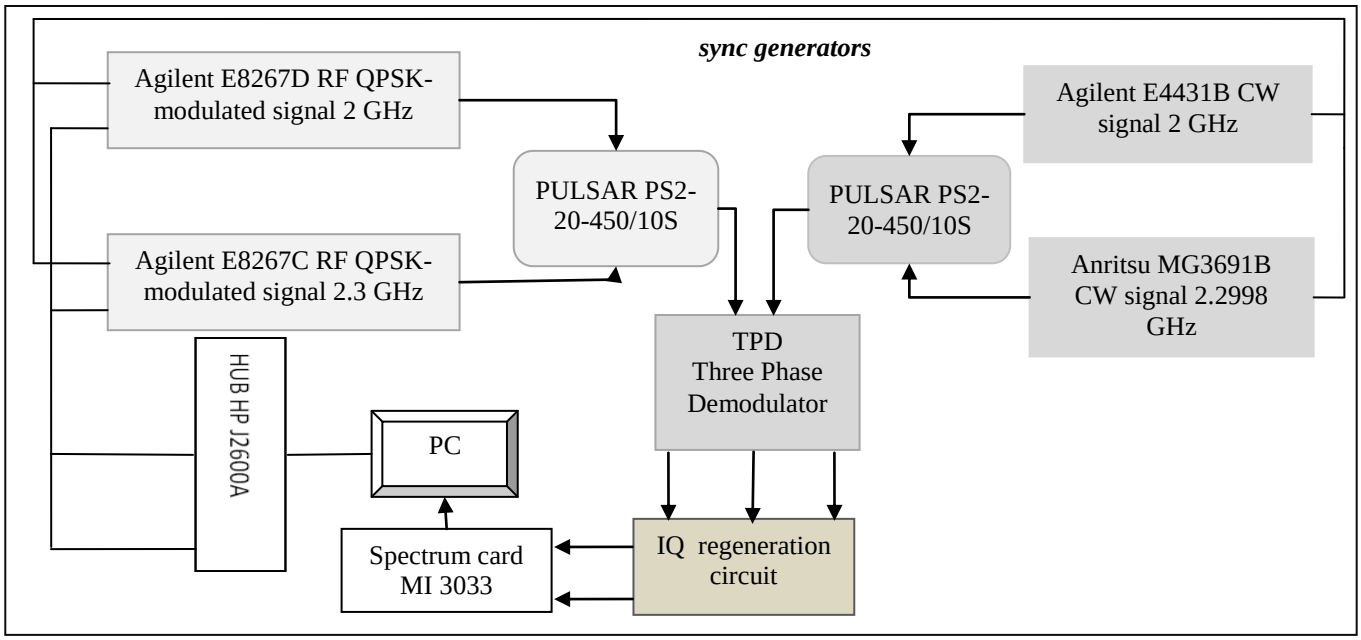

Fig. 2. Test Bench for the demodulation of RF signal aggregated in frequency

For example, Fig. 3 shows the measured baseband spectrums of a RF signal constituted of carrier frequencies 2 and 2.3 GHz modulated with signals of 20 MHz bandwidth. The digital signals are generated and filtered by a SQRC of roll-off equal to 0.35. The latter reduces the frequency band of the RF signal. Thus, the spectrum of the output signal V_3 of the TPD is composed of two bands: 0-13.5 MHz (ZIF configuration) and 36.5-63.5 MHz (LIF configuration) (Fig. 3).

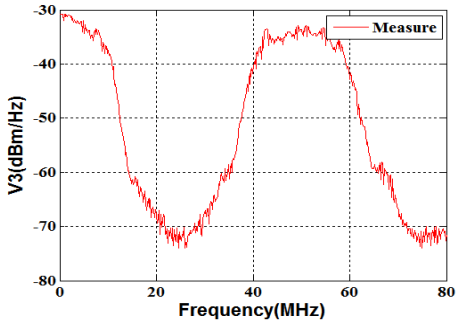

Fig. 3. Power Spectral Density in dBm/Hz of V_3 signal in function of frequency for bandwidth to 20 MHz.

Due to components limitations (data acquisition card, Low Frequency amplifiers, PC…) the measurements were made with data rate of 100 kS/s.

The frequency conversion of the aggregated RF signal is performed by the mixing with a LO signal constituted of two CW signals. According to section II, the first CW frequency is 2 GHz to convert the first band to ZIF and the second CW frequency is 2.2998 GHz to convert the second band to LIF. The synchronization of the generators is performed by a common clock signal of frequency 10 MHz (Fig. 2).

The RF signal is demodulated by the TPD. The three outputs signals of the TPD are combined in the IQ-regeneration circuit (Fig. 2).

The spectrum of the baseband Iout signal shows two distincts bands centered respectively between 0-67kHz (ZIF configuration) and 133-267 kHz (LIF configuration) (Fig. 4).

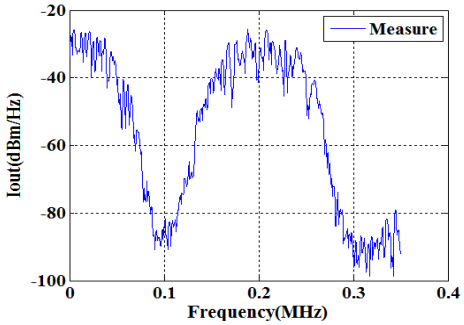

Fig. 4. Power Spectral Density in dBm/Hz of Iout signal in function of frequency for bandwidth to 100 KHz.

The sampling frequency of the data acquisition card (MI3033) is equal to 800 KHz. The Iout and Qout signals are oversampled with a factor equal to 8. Then equalization of I_{out} and Q_{out} is performed using the training sequence. Fig. 5 shows that the two QPSK constellations are recovered and centred. The red points show that the synchronization with the CAZAC sequence functions correctly. These results validate the theoretical assumptions developed in II.

The performances of this receiver are evaluated using the Error Vector Magnitude (EVM). We call ZIF signal (resp. LIF), the signal of carrier frequency 2 GHz (resp. 2.3 GHz), which is transposed to ZIF (resp. LIF). The results show a gain of 2 to 3 dB in sensitivity (defined here for EVM=-15dB), for the LIF signal in comparison with the ZIF signal (Fig. 6).

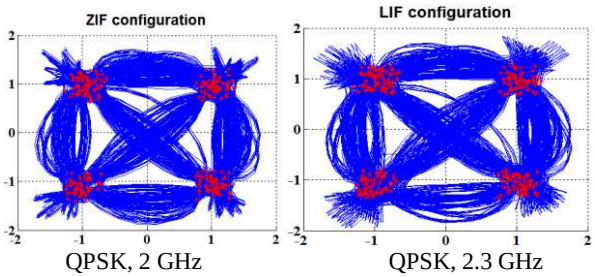

Fig. 5. Phase constellation of 2 discontinuous frequency bands RF signal translated Zero-IF and 200 KHz LIF

The results of the EVM presented in the Fig. 6 were performed by varying simultaneously the input power level of the ZIF and LIF signals. The Fig. 7 and the Fig. 8 show the scenarios where one of the power level of a signal (ZIF or LIF) is fixed to -47 dBm and the other varies.

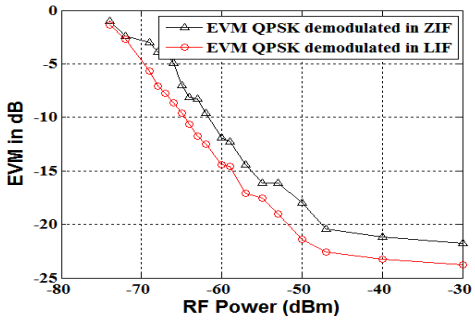

Fig. 6. EVM in dB in function of RF input signal in dBm constituted of 2 carriers modulated by QPSK signals.

By comparing the EVM results of ZIF signal in Fig. 6 and Fig. 7, there is a degradation of about 5 dB when the fixed (-47 dBm) power level of the LIF signal is greater than the power level of the ZIF signal. For the same limit value of -47 dBm, there is only a drop of about 2.5 dB for the EVM of the LIF signal in Fig. 6 and Fig. 8. Thus the LIF signal influences more the quality of the converted ZIF signal. This can be explained by second-order inter-modulation distortion (IMD2), which is more important in the ZIF converted band than in the LIF one. This effect has been checked by theoretical study and by spectrum measurement but is not described here due to space limit of the paper.

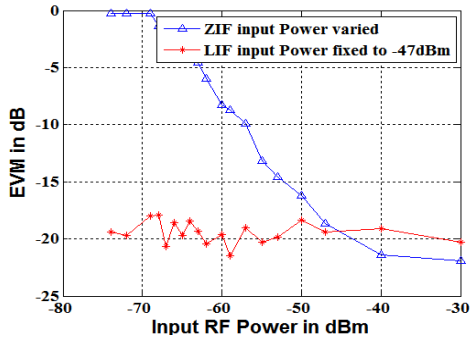

Fig. 7. EVM in dB in function of RF input signal in dBm constituted of 2 carriers modulated by QPSK signals, so the power of signal RF to frequency 2.3 GHz fixed to -47 dBm.

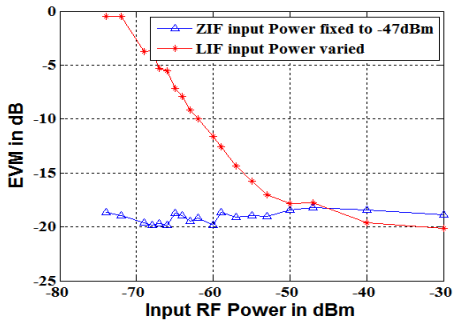

Fig. 8. EVM in dB in function of RF input signal in dBm constituted of 2 carriers modulated by QPSK signals, so power of signal RF to frequency 2 GHz fixed to -47 dBm.

VI. Conclusion

This paper demonstrates that it is possible to demodulate a RF signal constituted of two discontinuous frequency bands with a single Rx chain. However, this technique can be extended to a greater number of bands. The used technique is based on a LO signal composed of several CW signals. The used method is demonstrated theoretically and confirmed by measurements results. The demonstration has been done for two useful signals centered at 2 GHz and 2.3 GHz and QPSK modulated with a symbol rate of 100Ks/s. The signals have been respectively converted to ZIF and LIF in such a way the ADC has to convert low frequencies signals of frequency bandwidth 300 kHz.

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