Dynamic Range Improvement of Six-Port Interferometer Receivers

Bilel Mnasri* (1), Tarek Djerafi (2), Serioja Tatu (2) and Ke Wu (1)
(1) École Polytechnique, Montréal, Canada
(2) INRS-EMT, Montréal, Canada

Abstract

A receiver architecture based on the six-port concept with emphasis on improving demodulation capabilities in connection with dynamic range issues is studied and presented in this paper. In the proposed scheme, two six-port interferometric circuits are deployed where each is designed to demodulate a different region of a high-order constellation. This approach is validated experimentally and it shows a substantial enhancement of the receiver dynamic range. In this experimental demonstration, the error vector magnitude (EVM) is reduced from 16.73% when using a single conventional six-port circuit to 2.01% achieved with the proposed architecture at center frequency of 5 GHz.

1. Introduction

Next generation wireless systems are expected to provide higher data rates than current counterparts. Wireless transceiver architectures have played critical roles in the development of such systems, which are developed through either classical super-heterodyne or homodyne techniques or even emerging multi-port interferometer schemes. The six-port correlator has demonstrated a promising potential since its first introduction as a direct digital receiver [1]. Hence, it has become a candidate of interest for the development of high-data rate transceivers [2]. However, the limited square law region of power detectors, in connection with a limited dynamic range which are used for power reading in the multiport interferometer is a challenging issue in the deployment of six-port receivers [3]. To overcome this problem and also to support better data rates, some solutions have been introduced and presented in the literature. One technique, for example, focuses on the linearization of power detectors using polynomials so that high-order modulations can be handled in the same way as QPSK and QAM-16 schemes. Abul Hasan et al. have highlighted the foundation of such method and an experimental verification was performed showing the possibility of demodulating QAM-64 with an average error vector magnitude (EVM) of 1.66% around a center frequency of 2.4 GHz [3]. Another scheme, which aims to control the diode bias through a blind algorithm to reduce the EVM, was proposed by Lima et al [4]. Although both approaches have been successful in demodulating high-order modulations, it is important to mention that complicated digital algorithms are used to mitigate the limited square law region of the diode based detectors. Therefore, the digital information contained in the RF signals is no longer treated in the analog domain, and the complexity and cost of the receiver are inherently increasing. Moreover, Joakim Östh et al. presented a wideband six-port receiver operating over a bandwidth of 1 GHz around the center frequency of 7.5 GHz which is capable of offering data rates up to 1.7 Gbit/s with a bit error rate of 5.10^{-5} when applying an equalizer after the detection process while using conventional diode based power detectors [5]. In this paper, an alternative approach is proposed and studied aiming to increase the demodulation performances of six-port receivers without the need of digital algorithms and operating a relatively low frequency band. In fact, this work is developed to mitigate the limited square law region of power detectors while keeping the all analog operation of six-port receivers. An experimental prototype is developed to validate the anticipated dynamic range improvements.

2. Proposed Approach

The six-port interferometric circuit used in the design of RF and microwave receivers consists of two inputs connected to the unknown RF (a_6) and the local oscillator (a_5) signals, and four outputs which are connected to four power detectors operating under their square law region in order to generate DC voltages proportional to the power at their input [6]. Analog post processing is then performed to obtain information about the amplitude and/or relative phase of the unknown RF signal. Hence, all the information about the amplitude and relative phase of the unknown RF signal a_6 can be extracted by defining a Γ vector as it was introduced by Tatu et al. in [2].

$$\begin{aligned}\Gamma &= (V_3 - V_1) + \mathrm{j}.(V_4 - V_2)\\ &= \alpha.K.a^2.\exp(j\Delta\varphi)\end{aligned} \tag{1}$$

where V_i (i=1..4) refers to the voltage at the output of the four power detectors and the RF as well as the reference LO signals are defined as follows, while ω being the operating angular frequency:

$$a_6 = \alpha.a.\exp(j(\omega t + \Delta\varphi)) \tag{2}$$

$$a_5 = a.\exp(j\omega t) \tag{3}$$

Previous studies have focused on the characterization of the power detector dynamic range in order to determine the range of input RF power for which equation (1) holds true. In fact, it has been demonstrated that the square law region width of Schottky-diode detectors does not exceed 10 dB in best cases [3]. Therefore, this limitation would not allow

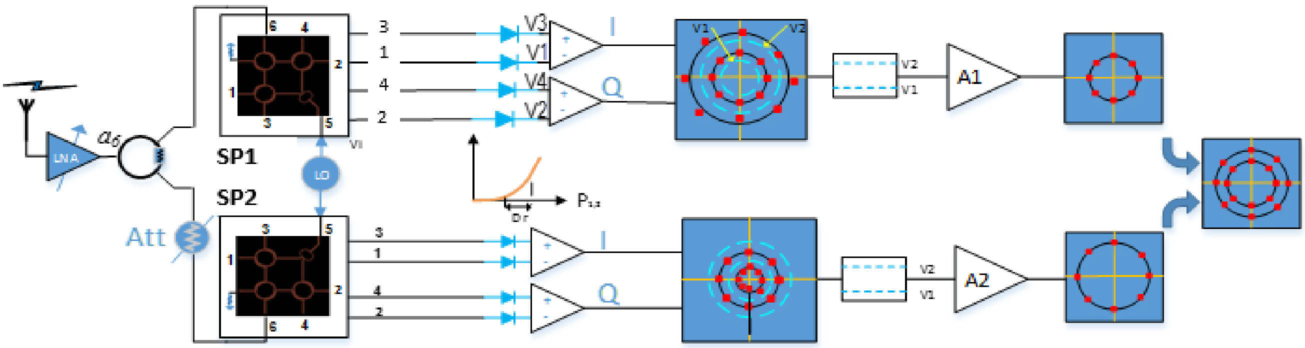

Figure 1. Schematic description of the proposed architecture

conventional six-port receivers to process high order modulations for which the peak–to-peak symbol power exceed 12dB for example and the automatic gain controller is unable to follow the change rate of the incoming RF signal, especially when dealing with high data rates and fast fading channels. In fact, for a high order constellation of complex symbols, only those received with RF power allowing the detectors to operate under their square law region will be demodulated properly. However, the symbols received at a higher RF power will be demodulated in the linear region of power detectors. Thus, the Γ vector is no more a representation of the original digital symbol. In this work, an architecture is introduced to increase the six-port receiver dynamic range, which allows a direct demodulation of high order modulations. In fact, a received amplified RF signal is equally split using a Wilkinson power divider as depicted in Fig. 1. The first of the twin signals is processed by first six-port circuit SP1 in a rather conventional manner. On the other hand, the second of the twin RF signals passes through an attenuator, with a fixed attenuation (Att) which is equal to the width of the detectors square law region, before being demodulated by the second six-port SP2. Hence, the first six-port SP1 would be responsible of demodulating the constellation symbols received at energy level P_1 satisfying the following condition.

$$|P_1 - P_{carrier}| \leq D_r \quad (4)$$

In the previous equation $P_{carrier}$ refers to the RF carrier power in dBm, and D_r denotes the width of the power detector square law region in dB. On the other hand, SP2 would be responsible for processing symbols received at power levels P_2 satisfying the following condition.

$$Dr \leq |P_2 - P_{carrier}| \leq 2D_r \quad (5)$$

The attenuator Att at the input of SP2 will reduce the power level P_2 so that the input modulated signal is processed within the square law region of power detectors. Followed by SP2, the DC voltages at the output will be simply amplified in the baseband by an operational amplifier A2 as shown in Fig. 1, where the gain of A2 would be greater than A1 in order to compensate the attenuator effect. In this way, both six-ports will instantaneously demodulate different segmented signals of the complex constellation. To overcome reading overlapped signals, DC voltage limiters [V1, V2] are added at the output of power detectors in order to create a partition of the symbols processed by SP1 and SP2. the goal of adding the DC voltage limiters is to divide the demodulation task between SP1 and SP2.It is also important to mention that if the constellation size is bigger, the proposed architecture could be extended and another six-port circuit SP3 should be added in series with an attenuator Att' to handle the remaining symbols of the constellation. According to the proposed approach, there is no need to apply any digital algorithm to either linearize the behavior of power detectors, or to control the biasing point of diode detectors in order to follow the RF signal dynamic range. As a consequence, the proposed scheme enables keeping the all analog treatment of digital signals.

3. Experimental Results

In order to validate the proposed concept, an experimental prototype was designed and implemented. The six port circuits were designed using Advanced Design System (ADS) software of Keysight Technologies. The substrate used for the circuit design is the RT/duroid 6002 with dielectric constant $\varepsilon_r = 2.94$ and height h=508 µm. The six-ports were designed to operate around a central frequency of 5 GHz. The S-parameter characterization through vector network analyzer measurements have been conducted and it has been shown that there is almost equal power division between the four output ports of the six-port circuit when either port 5 or 6 is excited (around -6dB over 500MHz of bandwidth) as well as a balanced phase distribution between these ports in order to ensure correct phase recovery of the oncoming RF signal. The squaring function needed to recover the baseband signal was performed by using eight power detectors (ZX47-60-S+) made by Mini-Circuits. Two Agilent digital oscilloscopes were used to visualize the demodulation results through theirs X-Y functionality and a set of measurements were conducted at 5 GHz at a data rate of 25 Mega symbols per second and with an RF carrier and LO power of -20 dBm. As for the

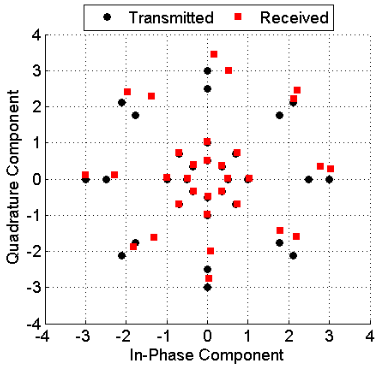

Figure 2. Demodulation results using one six-port circuit.

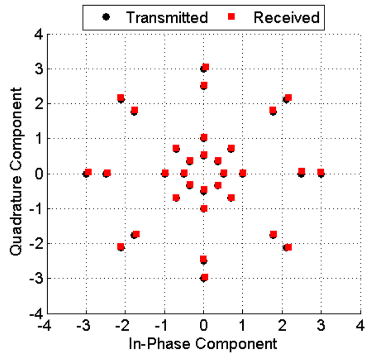

Figure 3. Demodulation results using the proposed architecture.

sensitivity of the proposed scheme, it is important to mention that it is directly related to the lower RF power that can be handled within the square law region of power detectors and which is equal to -20 dBm in our case. First, a modulation scheme following the Gray Code was defined. In fact, a constellation of 4 rings was constructed. Each ring is composed of eight symbols. The inner two rings contain symbols that satisfy the equation (4). These symbols are received at power levels less than *Dr* dB above the RF carrier and they are treated within the square law region of power detectors, namely by the junction SP1.The outer two rings are set in a way that the symbols they contain are received with power levels more than D_r dB above the RF carrier as highlighted by equation (5). Hence, they are processed by SP2 after being attenuated.
The inner rings radii were set to 0.5 and 1 and the outer two rings radii were chosen to be 2.5 and 3. Thus, the symbols of the outer rings would have power levels which is at least 10 dB more than those of the inner rings. This arrangement would make them to be treated out of the power detector square law region which is roughly equal to 8 dB. Hence, this constellation scheme enables us to highlight the distortion effect caused by the non-linearity of power detectors. In order to quantify the claims about the total receiver dynamic range improvement, the EVM metric as defined by equation (6) is computed for the defined constellation.

$$EVM = \sqrt{\left(E\left[|Z_k - X_k|^2 \right] / E\left[|X_k|^2 \right] \right)} \qquad (6)$$

where E denotes the mathematical mean function, and Z_k is the received version of each symbol X_k. The measured constellations when using both a six-port circuit and the proposed system are reported in Fig. 2 and Fig. 3 respectively. The EVM is computed for a set of 10^6 symbols sent randomly from the predefined constellation and it shows that it has been reduced from 16.73% when using a single six-port circuit to 2.01% in the case of the proposed approach. A comparison of the EVM enhancement with solutions reported in the literature is given by Tab. 1.

Table 1. Comparison of EVM improvement with existing solutions.

	Proposed solution	Frequency band	EVM improvement
[3]	Linearization	2.4 GHz	7.93 % to 1.66 %
[4]	Bias-control	Simulink model	6.3 % to 1.6 %
This work	Proposed approach	5 GHz	16.73 % to 2.01%

4. Conclusion

A six-port based interferometer receiver is presented in this paper. This architecture enables increasing the dynamic range of the whole receiver system, which has been always limited by the reduced square law region of power detectors. The EVM is evaluated for the single six-port receiver and for the proposed scheme and the results have demonstrated a substantial improvement from 16.73% to 2.01%. Hence, the proposed scheme could be a good alternative for six-port-based sensing and communication systems requiring a higher dynamic range.

5. References

1. J. Li, R. G. Bosisio, and K. Wu, “Dual-tone calibration of six-portjunction and its application to the six-port direct digital millimetric re-ceiver,” *IEEE Trans. Microw. Theory Tech*., vol. 44, no. 1, pp. 93–99, Jan. 1996.
2. S. O. Tatu, E. Moldovan, K. Wu, and R. G. Bosisio, “A new direct millimeter-wave six-port receiver,” *IEEE Trans. Microw. Theory Techn*., vol. 49, no. 12, pp. 2517–2522, Dec. 2001.
3. A. Hasan and M. Helaoui "Novel modeling and calibration approach for multi-port receivers mitigating system imperfections and hardware impairments," *IEEE Trans. Microwave Theory Tech*., vol. 60, no. 8, pp.2644 -2653, 2012.
4. J. A. Lima, John M. W. Rogers, and R. E. Amaya, "Optimization of EVM Through Diode Bias Control Using a Blind Algorithm Applied to Multiport Receivers ", *IEEE Trans. Circuits and Systems*, vol. 62, no. 3, Mar. 2015.
5. J. Osth, A. Serban, O. Owais, M. Karlsson, S. Gong, J. Haartsen, and P. Karlsson, “Six-port gigabit demodulator,” IEEE Trans. Microw.Theory Tech., vol. 59, no. 1, pp. 125–131, 2011.
6. T. Hentschel, “The six-port as a communications receiver”, *IEEE Trans. Microw. Theory Tech*., vol. 53, no. 3, pp. 1039 - 1047, Mar. 2005.