Six-Port Receiver for mm-Wave – Concept, Evaluation and Implementation

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***Abstract* — A six-port receiver uses simple power detectors to realize a direct conversion or a zero-IF receiver. This paper reveals the theory about six-port receivers, which are suited to realize a low cost architecture for mm-wave applications. Further, a comparison between different possible receiver architectures is presented. The RF characteristics and boundary limitations show that the six-port receiver is an interesting alternative to existing mixer based architectures. The implementation, especially the effort in the digital base band processing is presented, which allowed a first demonstrator to receive 10^4 error free symbols.**

***Index Terms* — six-port, multi-port, direct conversion, multi standard receiver, additive mixing, software radio**

I. Introduction

THE requirements on receiver architectures are increasing constantly. Receivers are expected to become more broadband, as well as the transmission frequency is increasing steadily, e.g. Nx100MHz @ 60 GHz in the WIWGAM project [8]. Latest research in mm-wave has declared that activities at 60 GHz are just the opener for wireless application up to 150 GHz [1].

A contrary trend claims to become smaller and cheaper, which eliminates conventional heterodyne concepts. Smaller and cheaper forces a reduction of monolithically not integrable components, as well as the avoidance of adjustment work. Further, the amount of different communication standards that has to be implemented is increasing enormously. Especially in the automotive area, a multi-standard receiver platform has the potential to reduce size and cost, whereas it offers update possibility to future standards.

Conventional heterodyne receivers are mostly working with real band pass signals in frequency regions far above the modulated base band signal. One ore more monolithically not integrable filters are required. The implementation considering financial aspects with the focus on a multi-band/mode-receiver architecture is impossible with current and expectable technological progress.

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Homodyne or direct conversion receivers, and zero-IF or low-IF receivers respectively, are an alternative and promising realization possibility. Thereby, the analog signal processing is essentially moved down to low frequencies and the number of monolithically not integrable filters is reduced to a minimum.

An alternative to conventional architectures is offered by the six-port technology. It promises to be cheap and extremely broadband and can be used at highest frequencies to realize a direct conversion receiver as well as a zero-IF receiver. This is achieved by the combination of a simple and cheap analog frontend – active mixers are replaced by power measurements via diodes – with subsequent digital signal processing, i.e. the boundary regarding upper frequency limit will be set by realizable diodes to detect the signal power.

II. The Six-Port Theory

A. Additive Mixing

Contrary to conventional multiplicative mixer, the input signals are added and subsequently squared. The squaring is done on a nonlinear element, e.g. a schottky diode.

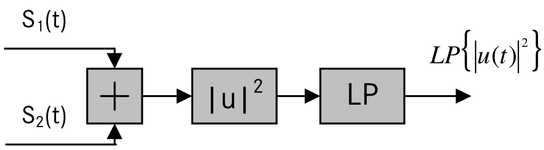

Fig. 1.Principle of additive mixing

The local oscillator signal $s_1(t)$

$$s_1(t) = A_{LO} \cdot \cos(\omega_{LO} t + \varphi_{LO}) \tag{1}$$

with amplitude A_{LO}, frequency ω_{LO} and initial phase φ_{LO}, is added to the received RF bandpass signal $s_2(t)$

$$\begin{aligned} s_2(t) &= x_{BP}(\mathrm{t}) \\ &= \mathrm{Re}\{\underline{x}_{BB}(t) \cdot e^{j\omega t}\} \\ &= |\underline{x}_{BB}(t)| \cdot \cos(\omega t + \varphi_x(t)) \\ &= x_I(t) \cdot \cos(\omega t) - x_Q(t) \cdot \sin(\omega t) \end{aligned} \tag{2}$$

with the carrier frequency ω and phase $\varphi_x(t)$ or inphase x_I and quadratur x_Q amplitude. The added signal gets squared and low-pass filtered to the complex baseband bandwidth.

$$
\begin{aligned}
LP\left\{|u(t)|^2\right\} &= \tfrac{1}{2}A_{LO}{}^2 + \tfrac{1}{2}\left|\underline{x}_{BB}(t)\right|^2 + A_{LO}\cdot\left|\underline{x}_{BB}(t)\right|\cdot\cos(\Delta\omega t+\varphi_{LO}-\varphi_x(t)) \\
&= \tfrac{1}{2}\left(A_{LO}{}^2 + \boldsymbol{x_I(t)^2} + \boldsymbol{x_Q(t)^2}\right) + \ldots \qquad (3) \\
&\ldots + A_{LO}\cdot\left[\boldsymbol{x_I(t)}\cdot\cos(\Delta\omega t+\varphi_{LO}) - \boldsymbol{x_Q(t)}\cdot\sin(\Delta\omega t+\varphi_{LO})\right]
\end{aligned}
$$

A linear dependency of the lowpass signal power $LP\left\{|u(t)|^2\right\}$ to $\boldsymbol{x_I(t)}$, $\boldsymbol{x_Q(t)}$ and $\boldsymbol{x_I(t)^2} + \boldsymbol{x_Q(t)^2}$ can be seen. Therefore, the calculation of the complex base band signal $\underline{x}_{BB}(t) = x_I(t) + jx_Q(t)$ by applying a linear equation system requires at least three power measurements with independent phase relations.

B. *Multi-Port Receiver*

Introducing phase shifts ψ_i in one input path, allows creating linear independent power measurements.

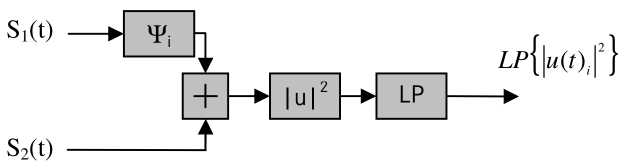

Fig. 2.Principle of a multi-port receiver

At least three independent paths are needed to calculate the complex baseband signal $y(t)$

$$y(t) = x_I(t) + j\cdot x_Q(t) \equiv \sum_i \underline{c}_i \cdot LP\left\{|u_i(t)|^2\right\} \qquad (4)$$

by introducing a complex calibration coefficient $\underline{c}_i$. A general multi-port receiver equation is formulated in matrix notation.

$$
\mathrm{y}(t) = \begin{bmatrix}\underline{c}_1\\ \underline{c}_2\\ \vdots\\ \underline{c}_n\end{bmatrix}^T \left[A_{LO}\cdot\begin{bmatrix}\cos(\Theta(t)+\psi_1) & -\sin(\Theta(t)+\psi_1)\\ \cos(\Theta(t)+\psi_2) & -\sin(\Theta(t)+\psi_2)\\ \vdots & \vdots\\ \cos(\Theta(t)+\psi_n) & -\sin(\Theta(t)+\psi_n)\end{bmatrix}\cdot\begin{bmatrix}x_I(t)\\ x_Q(t)\end{bmatrix} + \begin{bmatrix}1\\1\\ \vdots\\1\end{bmatrix}\cdot\frac{x_I(t)^2+x_Q(t)^2+A_{LO}{}^2}{2}\right] \qquad (5)
$$

with $\Theta(t) = \Delta\omega t + \varphi_{LO}$, $\Delta\omega = \omega_{LO} - \omega$

Choosing $\psi = \left[0^\circ, 90^\circ, 180^\circ, 270^\circ\right]$ and assuming $\Theta(t) = 0$ leads to $\underline{c} = \begin{bmatrix}1 & -j & -1 & j\end{bmatrix}^T \cdot\left(\frac{1}{A_{LO}}\right)$

Equation 5 shows that in any case

$$\sum_i \underline{c}_i \equiv 0 \qquad (6)$$

in order to eliminate the rectified part $(x_I(t)^2 + x_Q(t)^2 + A_{LO}{}^2)/2$.

Assuming that the phase shifts are done by a simple delay line an error ε is introduced by deviating from the design frequency. The initial local oscillator phase φ_{LO}, as well as the frequency difference $\Delta\omega$ is unknown.

$$\psi = \left[0^\circ, 90^\circ+\varepsilon, 180^\circ+2\varepsilon, 270^\circ+3\varepsilon\right]$$
$$\Theta(t) \neq 0$$

With ψ and $\Theta(t)$ follows:

$$
\mathrm{y}(t) = A_{LO}\cdot\begin{bmatrix}\underline{c}_1\\ \underline{c}_2\\ \underline{c}_3\\ \underline{c}_4\end{bmatrix}^T\cdot\begin{bmatrix}\cos(\Theta(t)) & -\sin(\Theta(t))\\ \sin(\Theta(t)+\varepsilon) & \cos(\Theta(t)+\varepsilon)\\ -\cos(\Theta(t)+2\varepsilon) & -\sin(\Theta(t)+2\varepsilon)\\ \sin(\Theta(t)+3\varepsilon) & \cos(\Theta(t)+3\varepsilon)\end{bmatrix}\cdot\begin{bmatrix}x_I(t)\\ x_Q(t)\end{bmatrix}
$$
$$\wedge \quad \sum_i \underline{c}_i \equiv 0 \qquad (7)$$

Equation 7 reveals the possibility of calibration by sending a known training symbol sequence, presupposed the linear equation system is at least of rank three.

C. *Five-Port vs. Six-Port*

Equation 3 shows that three output ports are enough to realize a multi-port receiver. With respect to subsection *B*, it can be shown that linear independency can not be taken for granted, which may be caused by errors of the phase shifts ψ_i.

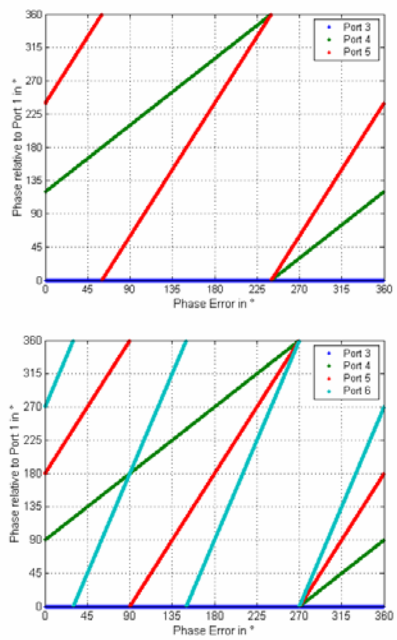

Fig. 3. Influence of the phase error to five/six-port

Fig. 3 shows that a five-port has only two linear independent output ports already at 60° phase error, whereas a six-port shows this behavior at 90° phase error for the first time. Furthermore, a six-port shows a uniform relative phase distribution at multiples of 180° relating to the center frequency f_0. Thus, it possesses identical receiving characteristics at the frequencies f_0, $1.5f_0$, $2f_0$, $2.5f_0$ …, assuming that the phase shifts are realized by delay lines. This corresponds to the requirement of broadband multi-mode and multi-standard receiver.

D. *Realization of a Six-Port*

A common method to realize the four independent phase shifts is using 90°-hybrid couplers as shown in Fig. 4 [5], with the two inputs connected to the local oscillator (LO) and the RF bandpass signal.

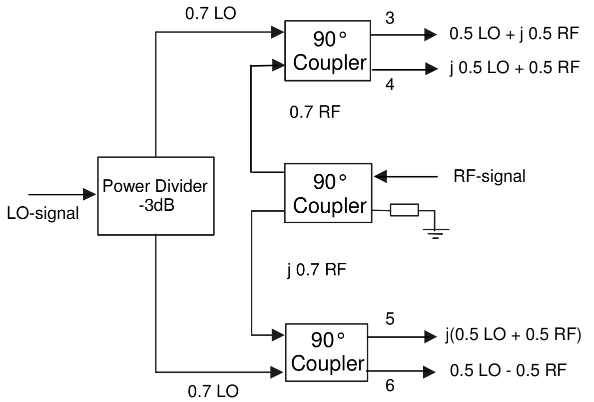

Fig. 4. Realization of a six-port

Fig. 5 shows a simple power detector circuit with appropriate lowpass filtering to detect the power of each six-port output.

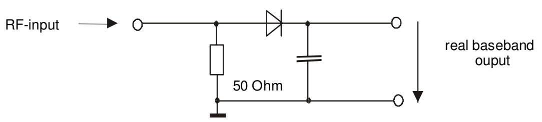

Fig. 5. Simple power detector circuit

The layout for a 24 GHz six-port with power detectors is shown in Fig. 6, where the right picture shows a magnified depiction of the of the power detector realization.

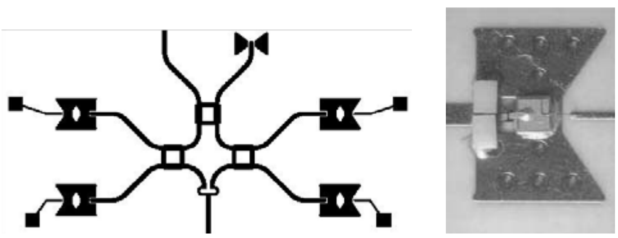

Fig. 6. Six-port layout and power detector realization

III. Six-Port Receiver Architecture in Comparison to Conventional Receiver Architectures

A. *Overview Receiver Architectures*

The introduction of six-port technology in microwave receivers seems to push the boundaries regarding price and upper frequency limit. To enable a serious validation of six-port technology we have to benchmark it with existing receiver architectures.

Looking on applications intended to use with six-port technology the most important alternative receiver concepts are the direct conversion receiver and the IF sampling receiver. Both are depicted in Fig. 7 and Fig. 8, where LO is the local oscillator, LP a lowpass filter and BP a bandpass filter. The six-port receiver is well described in section II. All three receiver concepts generate an I/Q data stream, which is further processed to recover the binary data.

Direct sampling receivers are actually not applicable with state of the art technology for the herein addressed frequency range, so this architecture will not be discussed further.

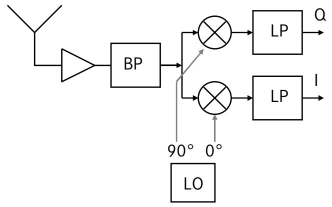

Fig. 7 Direct conversion receiver

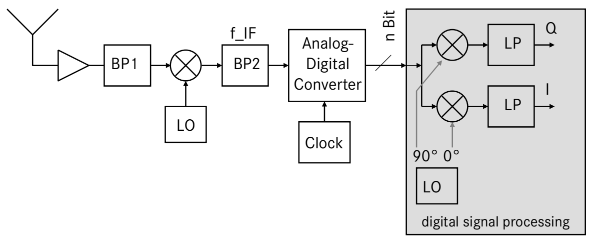

Fig. 8 IF sampling receiver

B. *Comparison of RF Performance*

Phase accuracy: In all receiver architectures phase noise of the local oscillator (LO) will be directly transformed to phase noise in the complex baseband. In case of the IF sampling receiver, jitter of the sampling clock may lead to additional phase noise [6]. This kind of phase noise will also lead to neighbor channel interference, caused by reciprocal mixing and therefore reduce the selectivity of the receiver.

In all three cases channel selection is usually done by setting the first local oscillator, therefore the requirements and the phase noise will be about the same. Only the IF sampling receiver makes it principally possible to design the first LO with fixed frequency by taking a wide bandpass filter BP2 and perform the channel selection in the digital domain. This could enhance the performance significantly.

In case of the six-port receiver and the direct conversion receiver additional phase inaccuracy will be introduced by inaccurate calibration. Because of always existing phase imbalance in direct conversion receivers, phase distortion has also to be reduced by calibration.

Noise figure: All discussed receiver architectures approve the use of a low noise amplifier (LNA) stage. In this case the noise figure will be defined by the LNA. For frequencies where no LNA is available we have to compare the noise of a mixer to the noise of a power detector receiver. For frequencies beyond 50 GHz both are usually built up using Schottky diodes. The noise figure for diode mixers [2] [7] is comparable to its conversion loss that is typically about 7dB. Simulations on microwave power detectors using a beam lead GaAs Schottky diode have shown that the noise figure goes down to 4.8dB for input powers smaller than -20dBm.

LO power: To obtain a good conversion gain, the power of the local oscillator should be in range of 0 to 10dBm for most mixers [2]. Best working condition for six port receivers is a LO power in the area of the receiver input power which is much less.

In-band dynamic range: When having a strong interferer directly beside the wanted signal or for high order modulation schemes, the receiver has to cope with the resulting dynamic range. For six-port receivers this dynamic range is mainly given by the accuracy of the calibration. First trials have shown a dynamic range of 30 to 40dB [4]. Calibration will also limit the linearity of the receiver. For mixer based receivers the dynamic range is limited by the linearity and a 1dB compression point of -10dBm to +10dBm can be obtained. This results in a dynamic range of about 90 to 100dB for a signal bandwidth of 10MHz.

The influence of out-of-band interferers has to be verified in further simulations.

Self mixing effects: Direct coupling and external reflections lead to a DC offset for direct conversion receiver [3] and six-port receiver. In six-port architectures this topic is inherently handled by the calibration procedure. Direct conversion receivers usually contain some signal processing unit to cope with this effect.

C. *Comparison of Boundary Limitations*

Size: The size of mixer based architectures is mainly given by active components and filters, but no wavelength λ correlated lines are necessary. For IF sampling receivers an additional IF filter is necessary, which is usually large in size and can not be integrated on the chip. The usual setup of a six-port is about ¾ λ in square. For V, W and D band applications it is well possible to integrate the six-port on chip.

Cost: The cost of direct conversion receiver and IF sampling receiver depend very much on the frequency range. Especially for frequencies in the W and D band, mixers become rare and expensive, whereas power detectors are available for higher frequencies. For mm-wave signal generation usually a lower frequency LO is followed by a frequency multiplier, which produces a small LO power. The six-port receiver will have a cost advantage by reduced LO-power requirements. The effort in digital signal processing is actually much higher for six-port receivers; this portion of costs will become negligible in the near future.

D. *Review Receiver Architectures*

Six-port receivers are an interesting alternative to existing mixer based receiver architectures especially in the mm-wave and sub-mm-wave range. In this frequency range we usually do not have to cope with strong neighbor channel interference so the reduced dynamic range will be acceptable.

IV. Six-Port Receiver Architecture

A. *Overview*

The six-port receiver architecture can be separated in an analog and a digital part of the frontend. The analog frontend mixes additively the amplified and bandpass filtered input signal under four different phase conditions. The measured signal power is fed to the ADC after corresponding matching, i.e. low pass filtering to the baseband bandwidth and amplification to match the ADC, which feeds the converted data into an FPGA. The FPGA contains the necessary digital signal processing in order to calculate the complex base band signal.

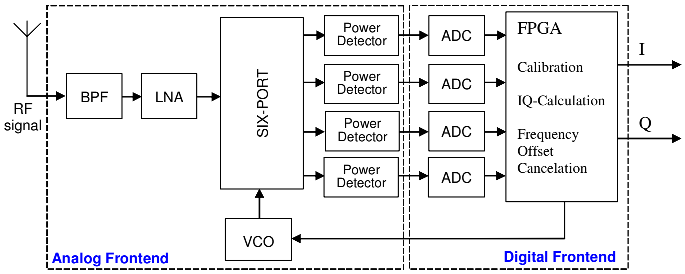

Fig. 9. Six-port receiver architecture

B. *Analog Frontend*

The antenna input signal is band pass filtered and amplified (LNA) in order to limit the noise power and suppress near band interferer. Propagation properties and near range LOS transmission in the upper mm-wave region may allow to dismiss the bandpass filter and LNA.

The antenna signal and the VCO signal, which is set to the reception channel by the digital frontend, are fed into the six-port. The powers of the four independent outputs are measured by power detectors, shown in Fig. 6. The power detector contains the baseband filter and an additional DC amplifier to match the input range of the ADC.

C. *Digital Frontend*

1) *Architecture*

The complex base band signal is calculated by a multiplication of the measured power values with the calibration coefficients c, see equations 4 and 5. The calibration coefficients are determined by solving a linear equation system, generated by sending a known training sequence. Research has shown that the Gaussian elimination method is best suited for hardware implementation.

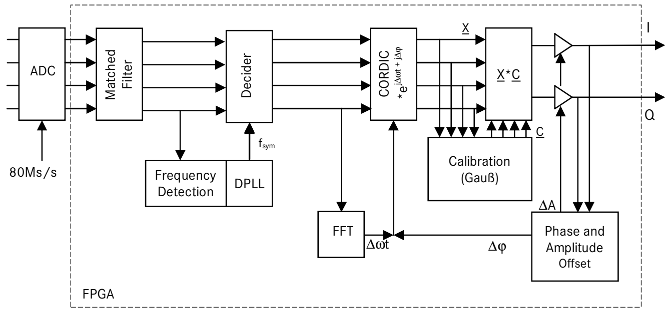

Fig. 10. Digital frontend architecture

An exact calibration is only possible, if the frequency offset between local oscillator and complex baseband signal is eliminated. Further, a calibration is necessary to determine the exact frequency offset, which leads to an iterative calibration procedure.

The calibration by a known symbol sequence forces the symbol detection and matched filtering to be as early as shown in the presented architecture, see Fig. 10.

2) *Frequency Offset Elimination*

A first estimation of the frequency offset is done by a complex FFT analysis of two orthogonal input power streams. The offset estimation allows a rough calibration, which is suited to determine the exact frequency offset by the control loop structure. After recalibration the complex baseband signal can be calculated and subsequently demodulated, see Fig. 11.

A result of a real microwave transmission is shown in Fig. 12. An error free transmission of 10^4 symbols was possible by calibrating, determining the frequency offset and processing the complex base band output signal with the presented architecture.

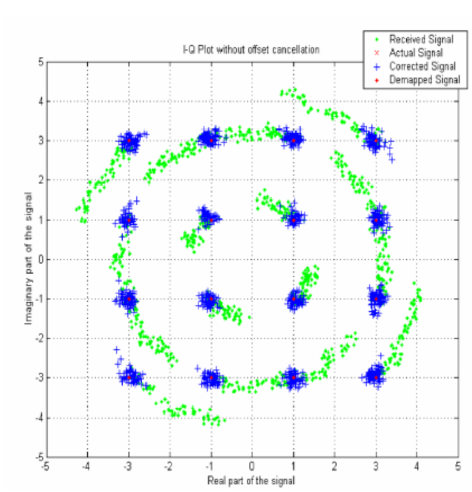

Fig. 11. Calibration and correction of the frequency offset (16-QAM, Δf = 10 kHz, f_{sym} = 10 MHz, SNR = 30 dB)

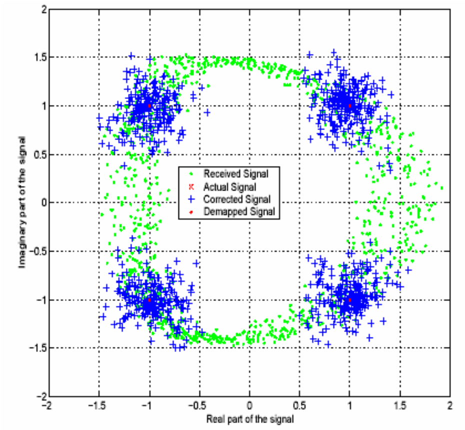

Fig. 12. Real microwave transmission of 10^4 symbols (QAM, f_0 = 24 GHz, Δf = 10 kHz, f_s = 10 MHz)

V. Conclusion

The presented paper reveals the basic theory on six-port receivers. It has been shown that principally five-ports are enough, but the sixth port offers the possibility of realizing a broadband multi-mode/band receiver. The comparison to conventional receiver architectures has shown that the six-port receiver is an interesting alternative to existing mixer based architectures especially in mm- and sub-mm-wave range. A six-port architecture has been implemented for 24 GHz and a digital frontend implementation for a first demonstrator has been shown. First measurements allowed an error free transmission of 10^4 symbols.

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References

[1] B. Gaucher, M. Soyeur, and M. Oprysko, “Silicon Milimeter Wave Integrated Circuits for Wireless Applications”, IBM Research, New York, 20th October, 2004

[2] Hewlett Packard, “The Schottky Diode Mixer”, Application Note 995

[3] H.-J. Jentschel, H. Berndt, U. Pusche, “Direct Conversion Receivers – Expectations and Experiences“, Workshop „RF Front End Architectures“, IEEE MTT-S Internat. Microwave Symposium, June 2000, Boston, Workshop Proc. WMH

[4] J.-U. Jürgensen, D. Krupezevic, M. Ratni, Z. Wang, „Baseband Aspects of a Direct Conversion Receiver Concept using Five-Port Technology“, 2nd Karlsruhe Workshop on Software Radio, Karlsruhe, March 2002 Proc. pp. 63ff

[5] Ji Li, R. G. Bosisio, Ke Wu, “*A Six-Port Direct Digital Millimeter Wave Receiver*”, Digest of IEEE Mtt-Symposium, pp. 1659 – 1662, San Diego, 1994

[6] T. Müller, S. Herter, J.-F. Luy, „Clock Generator Phase Noise in RF Sampling Receivers“, 2nd Karlsruhe Workshop on Software Radio, Karlsruhe, March 2002 Proc. pp.13ff

[7] Rick Poore, “Noise in Ring Topology Mixers”, Agilent EEsof EDA, http://eesof.tm.agilent.com/pdf/ring_mixer_noise_background.pdf

[8] WIGWAM – Wireless Gigabit With Advanced Multimedia Support, www.wigwam-project.de