Advanced Materials Research Vol. 367 (2012) pp 199-204
Online available since 2011/Oct/24 at www.scientific.net

doi:10.4028/www.scientific.net/AMR.367.199

Analysis of a Weaver, Hartley and Saw- Filter Based, Image Reject Architectures for Radio Receiver Design

F.E. Idachaba[1,a] and H.E. Orovwode[2]

Department of Electrical and Information Engineering,
Covenant University Ota
[1]idachabafe@yahoo.com
+234-803-957-0321

Keywords: Hartley, Weaver, SAW filter, Image reject, Radio receiver

Abstract: This paper presents an analysis of the three popular image reject architectures used in radio receiver design. The SAW-filter based image reject architecture is the simplest to implement and has the lowest power consumption while the weaver is the most complex with the highest power consumption. The Hartley architecture which utilizes half the number of mixers used in the weaver architecture does not consume as much as the weaver architecture but is not as efficient due to the use of the 90^0 phase shifter. The three architectures are optimized for various design specifications. The receiver design with power constraints is better realized using the SAW filter while the receiver with portability as its highest priority is better realized using the weaver architecture. The architecture implemented for any particular radio design is determined by the receiver specification with the highest priority.

Introduction

The rapid growth in communication services has led to the increase in research into radio receiver design with the aim of producing low cost, low power, single chip radios being the driving force. Wireless receivers can be generally divided into two categories according to their architecture. These two categories are the homodyne receivers and the heterodyne receivers. Examples of architecture under these classifications include the direct conversion radio architecture, the superheterodyne architecture and the low IF architecture. This paper provides the technical characteristics of the major radio receiver architectures and will aid in the design of radio receivers. The heterodyne receiver developed by Armstrong during the First World War is the most widely used architecture due to its high selectivity and excellent sensitivity with lower power consumption [1]. In this architecture, the incoming RF signal is frequency translated to a lower frequency known as intermediate frequency (IF). The IF is obtained by mixing the amplified RF signals with the local oscillator signal. The mixer generates two sets of outputs, the sum and the difference components. The difference components are selected (using filters) for receiver design. Translating the RF signal to a much lower IF signal provides a lot of advantages since the Q factor required for the channel select filter is relaxed. Figure 1 shows the block diagram of the super heterodyne receiver architecture. The advantage of the superheterodyne receiver which is due to the translation of the high RF signal to a lower IF signal introduces what is the most significant challenge of the superheterodyne architecture (The image frequency problem). The image frequency is represented by the formula in Equation 1 and in Figure 2.

$$F_{image} = F_{RF} + 2F_{IF} \quad (1)$$

If

$$X_{in}(t) = \cos(\omega_{RF}\, t) + \cos(\omega_{IM}\, t) \quad (2)$$

$$X_{LO}(t) = \cos(\omega_{LO} t) \quad (3)$$

$X_{in}(t)$ is the input signal and the $X_{LO}(t)$ is the Local Oscillator signal fed to the mixer.

The output signal from the mixer by analog multiplication process becomes Equation 4

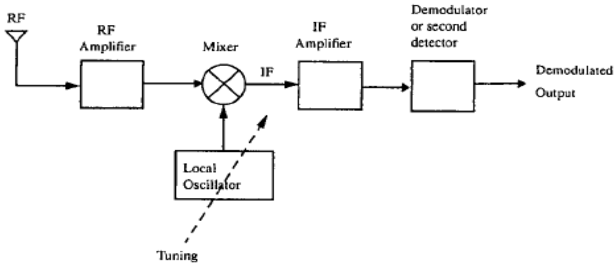

Figure 1 Block diagram of a superheterodyne receiver

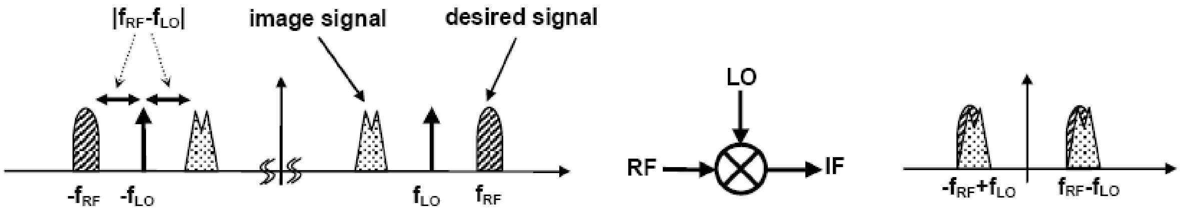

Figure 2 Illustration of the Image frequency problem

$$Y(t) = X_{in}(t) \;.\; X_{LO}(t) \tag{4}$$

The Equation 4 can be resolved mathematically using trigonometric relations to yield Equation 5

$$Y(t) = 0.5\{\cos(\omega_{RF} - \omega_{LO})t + \cos(\omega_{RF} + \omega_{LO})t\} \tag{5}$$

The mixer output consists of both the sum components and difference components as shown in Equation (4).If the output of the mixer is passed through a low pass filter we have the sum components eliminated and both the RF signal and the image frequency signals are then mixed with the LO signal to produce the following down conversion products in Equation 6

$$y(t) = 0.5\{\cos(\omega_{RF} - \omega_{LO})t + \cos(\omega_{IM} - \omega_{LO})t\} \tag{6}$$

The image frequency is represented by Equation 7

$$\omega_{RF} - \omega_{LO} = \omega_{IF} \tag{7}$$

$$\omega_{IM} - \omega_{LO} = (\omega_{RF} + 2\,\omega_{IF}) - \omega L_O \tag{8}$$

where

$$\omega_{IM} = \omega_{RF} + 2\,\omega_{IF} \tag{9}$$

$$\text{But } \omega_{IF} = \omega_{LO} - \omega_{RF} \tag{10}$$

Substitute Equation 10 into Equation 7 yields Equation 11

$$\omega_{IM} - \omega_{LO} = 2\omega_{LO} - \omega_{RF} = \omega_{LO} - \omega_{RF} \tag{11}$$

$$\omega_{IM} - \omega_{LO} = \omega_{LO} - \omega_{RF} \tag{12}$$

but $\omega_{LO} - \omega_{RF} = \omega_{IF}$ thus

$$\omega_{IM} - \omega_{LO} = \omega_{IF} \quad (13)$$

From Equation 13 the image frequency is down converted to the intermediate frequency

$$y(t) = 0.5\{\cos(\omega_{IF})t + \cos(\omega_{IF})t\} \quad (14)$$

Therefore any undesired signal located at the image frequency will be translated to the same IF along the desired RF signals. The image signal which can be much larger than the desired signals due to the fact that the wireless standard may not have the control over signals in order bands can distort the desired signal leading to system failure. Thus it should be eliminated. [2]
More than 80dB of image rejection is required in receivers for proper signal processing. [2][3] External band select filters are used before the low noise amplifiers and these filters provide up to 30dB – 40dB image rejection. [2]

Image Rejection Strategies
The traditional approach for image rejection is to place an image reject filter before the mixer. The high Q factor requirement for the image reject filters makes the SAW filters the conventional choice for this application. The use of the SAW filters imposes restrictions on the receiver design since the LNA must drive 50ohms impedance of the filter. This leads to difficult design trade-off between gain, NF, stability and power dissipation in the amplifier. The use of off chip SAW filter also impedes the development of fully integrated monolithic transceivers. Approaches which enable full monolithic integration of the radio receivers include the Hartley and the weaver architecture. The achievable image rejection ratios of these architectures are limited to 30 – 35dB.[3] The three image-reject architecture listed above will be discussed with a view showing the weakness, strength and suitability of each architecture for radio receivers (transceiver design).

The Hartley Architecture: The Hartley image reject architecture was developed by R. Hartley.[4] It originated from the single side band modulation technique. In this architecture, the RF input is mixed with the quadrature phase of the LO (Sin $W_{LO}t$ and Cos $W_{LO}t$) in two identical mixers as shown in Figure 3.

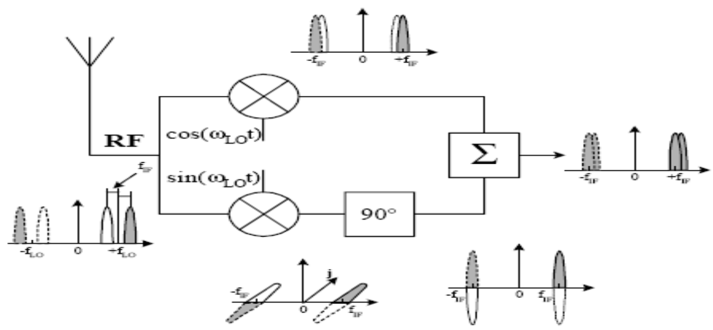

Figure 3 Hartley image reject architecture

The IF from the two mixers has a 90^o phase difference with respect to each other. The output is low pass filtered with one side of the signal being given a 90^o phase shift before both signals are added together to generate the IF output.
The mathematical analysis of the circuit shows that after the low pass filtering, signals at point A (after mixer at the top) and B (after the mixer below) are given represented by Equations 15 and 16.

$$V_A(t) = -0.5\ [\mathrm{Sin}(\omega_o - \omega_1)t + \sin\ [\omega_o - \omega_2]t) \quad (15)$$

$$V_B(t) = 0.5\ (\ \cos\ [(\omega_o - \omega_1)t + \cos\ [\omega_o - \omega_2]t) \quad (16)$$

where,
ω_0 = LO signal, ω_3 = Image, $\omega_1 = R_F$, ω_2 = IF

After the 90^0 phase shift (e.g sin (x) is transformed to –cos(x) the signal at point C becomes (Equation 17)

$$V_C(t) = 0.5 (\cos [(\omega_o - \omega_1)t - \cos [\omega_o - \omega_2]t) \quad (17)$$

The sum of $V_B(t)$ and $V_C(t)$ is the final output signal which is represented by Equation 18

$$V_{OUT}(t) = \cos(\omega_o - \omega_1)t \quad (18)$$

The image part $\cos(\omega_o - \omega_1)t$ and - $\cos(\omega_o - \omega_1)t$ both cancel out producing the desired IF output signal

The major limitation of the Hartley architecture is due to the high accuracy requirement of 90^o phase difference and amplitude balance between the two LO signals. It is hard to construct integrated phase shifters with accuracy better than 1^o and amplitude imbalance better than 0.1% and this leads to additional image filtering or some forms of automatic image filtering [5].

The 90^o phase shifter in the upper branch of the Hartley oscillator also produces amplitude error limiting the achievable image rejection. In theory, the architecture would completely eliminate the image frequency but in practice only a partial image cancellation is possible due to limitations in the current IC processing technologies, I/Q mismatches in mixers, low pass filters and 90^o phase shifters [3][13]. To overcome these problems, the use of the $+45^o$ phase shifter in one path and -45^o phase shifter in the other path is used to replace the single 90^o phase shifter (which is not practical at high frequencies) [3]. A voltage controlled gain is also used to compensate the gain variation from the LO phase shifting network. These modifications can yield image rejection values of up to 35dB [3].

Weaver Architecture: The weaver architecture introduced by D.K. Weaver [6] replaces the 90^o phase shift in the IF path with a second quadrature mixing stage. The architecture uses two- steps down conversion approach. The first mixers down convert the RF signal using the quadrature phases of the LO and then the IF is low pass filtered. The output of the low pass filter are then mixed with the quadrature phases of the second LO, signals. The mixers translate the signals to base band signals and these signals are then added together. The resulting signal contains only the wanted signal. Since this architecture does not use the phase shifter networks (RC- CR) it can achieve greater image rejection under process and temperature variations [6].The weaver architecture requires double copies of mixer compared to the Hartley architecture and as such consumes twice the power [7][8]. The weaver Image reject topology is shown in Figure 4

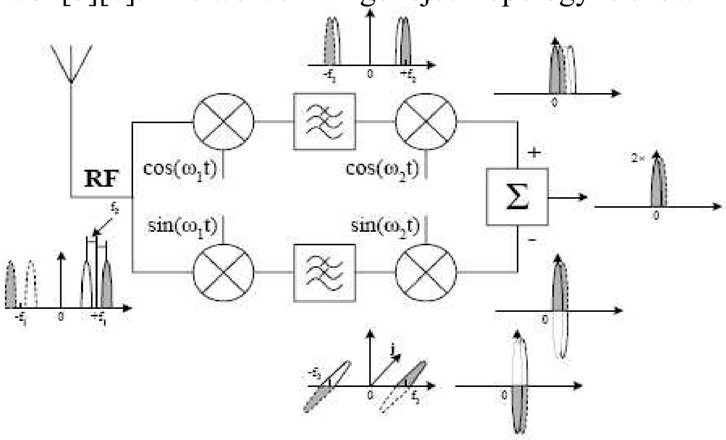

Figure 4 Weaver image reject topology

The use of the second set of mixers introduces the problem of secondary image. the weaver architecture is also sensitive to mismatches in phase and gain of the LO quadrature signals. It suffers from high noise due to use of four mixers [2] and the second set of mixers may need to be preceded with low noise linear amplifiers which leads to more power consumption.

The image problem arises if the second mixer does not translate its RF up to base band i.e IF is not zero. This secondary image will now require additional filtering, increasing the circuit costs. This secondary image problem can be eliminated if the second mixer stages translate to base band. This how ever will introduce similar problems to that faced by the direct conversion receivers which include DC offset problem and the LO leakage problem.
Different techniques have been explored to improve the performance of the weaver architecture [9][10] and image rejection of 40dB and 74mW power consumption has also been achieved [11].

SAW Filter Based IR Architecture: This is the traditional approach for image rejection in superheterodyne receiver. The requirement for filters used in cellular communication include

1. Light weight 2. Small size 3. Low power consumption 4. Low cost 5. Low insertion loss
   6. High gain

The surface acoustic wave (SAW) filters are available as commercial off the shelf chips which can be ordered from manufacturer web stores. These chips are manufactured with typical noise figures varying from 2dB to 4dB with flat pass band and high Q factors. Examples of those chips are those manufactured by murata corp., the impedance of the chips can be designed to 50 ohms. This value is matched easily to the ASIC chips which are designed with 50 Ohms input and output impedance values. The major setback in this architecture is the inability of monolithic integration of the entire receiver block due to the difficulty of integrating the SAW chip together with other receiver components. The second draw back is due to the fact that they can be physically large [1]. The SAW image reject architecture is shown in Figure 5

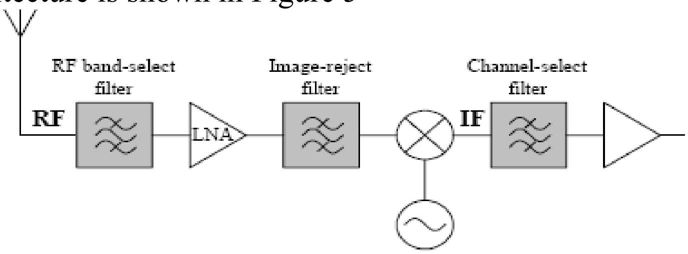

Figure 5 SAW image reject topology

Discussion
The three architectures are compared based on the following benchmarks:

1. Complexity 2. Efficiency (image rejection achievable) 3. Cost 4. Power dissipation
2. Form factor (ease of integration) 5. Drawbacks/limitations

Table 1 Comparison of the Image-Reject Topologies

Benchmark	SAW	WEAVER	HARTLEY
Complexity	Low	High	medium
Efficiency (image rejection)	High	High	Medium
Cost	High	Medium	Medium
Power dissipation	Low	High	Medium
Form factor (space consumption)	High	Medium	Medium
Limitations	(1)50Ω ports required (2)non monolithic transceivers	(1)high power consumption (2)I/Q mismatches in the LO paths (3)Possibility of DC offset and LO leakages problem if IF is non zero (4)secondary image requiring special filters	(1)I/Q mismatches (2) Phase mismatch due to RC-CR 90^0 phase shifter (3)Lower image reflection ratio

The results of the comparison are shown Table 1. From the table, the Weaver architecture is the most complex, it generates better image rejection ratio than the Hartley architecture. It is however faced with the problems of the DC offset, LO leakage and secondary image which requires additional filtering to eliminate. This makes it the architecture with the highest power consumption. The Hartley has lower power consumption than the weaver architecture because it uses half the number of mixers. The use of the 90^o phase shift circuit reduces the efficiency of the architecture and makes more evident the I/Q mismatches in both local oscillator paths. [12]

The SAW architecture has the lowest power consumption but due to the current technology, it can not be fully integrated does not permit the development of a fully integrated receiver. Its other disadvantage is its high cost and requirement of 50 ohms ports

Conclusion

The different architectures have different features which can be optimized for the design of radio receivers. In systems with extreme power constraints, transceivers based on the super heterodyne architecture are better realized using the SAW image reject architecture. For systems with high portability requirement like the mobile phones, the Hartley or the weaver architecture would be more suitable. For low cost infrastructure, the SAW based architecture is the optimum choice due to its low complexity and low power consumption. In conclusion, the image rejects architecture used in design of radio receivers should be determined by a compromise between the different receiver specifications.

References

[1] L.E.Larson, Radio Frequency Integrated Circuit Technology for low power wireless Communication by IEEE personal communication (June 1998)

[2] H.Lee, Monolithic image rejection Methods suitable for GSM receivers. A PhD qualifying examination report, School of Electrical and Computer Engineering, Georgia institute of Tech (April 2001)

[3] N. Yan. On chip image reject techniques for wireless receivers. University of Toronto department of electrical and computer Engineering. (Nov 2001)

[4] R Hartley, Modulation System US patent 1666206 Apr (1928)

[5] D. Pache et al, An improved 3V 2Ghz BiCMOS image reject Mixer IC , IEEE custom Integrated circuits conference, 1995, 95-98.

[6] D.K. Weaver, A third method of generation and detection of single side band signals. Proceedings of IRE vol 44 No 12, 1956, 1703-1705.

[7] B. Razavi, Architecture and circuits for RF CMOS receivers. IEEE customs integrated circuits conference (1998)

[8] Xin He,Fully integrated transceiver design in SOI process, PhD thesis, Department of Electrical and Computer Engineering, Kansas state University Kansas (2004)

[9] T. Okanobu, D. Yamazaki and C. Nishi, A new radio receiver system for personal communication. IEEE Transactions on Consumer Electronics vol 41,No 3, 1995, 795-803.

[10] M Banu et al,A BiCMOS double Low- IF receiver GSM . IEEE customs integrated circuits conference 1997, 521 – 524.

[11] S. Wu and B. Razavi, A 900MHz/1.8GHz CMOS receiver for dual band application IEEE journal of solid state circuits vol 33 no 12, 1998, 2178 -2185.

[12] On the direct conversion receiver. Application note 101735A.Skyworks solutions (July 20th 2001)

[13] Tsung-Yuan Chang and Steven B.Bibyk, Analysis of the improved Hartley image reject receiver by bandpass delta sigma modulator. Analogue Integrated circuits and signal processing. Kluwer Academic publishers (1999)

Advances in Materials and Systems Technologies III
10.4028/www.scientific.net/AMR.367

Analysis of a Weaver, Hartley and Saw-Filter Based, Image Reject Architectures for Radio Receiver Design
10.4028/www.scientific.net/AMR.367.199

DOI References
[1] L.E. Larson, Radio Frequency Integrated Circuit Technology for low power wireless Communication by IEEE personal communication (June 1998).
doi:10.1109/98.683726

[5] D. Pache et al, An improved 3V 2Ghz BiCMOS image reject Mixer IC , IEEE custom Integrated circuits conference, 1995, 95-98.
doi:10.1109/CICC.1995.518144

[6] D.K. Weaver, A third method of generation and detection of single side band signals. Proceedings of IRE vol 44 No 12, 1956, 1703-1705.
doi:10.1109/JRPROC.1956.275061

[7] B. Razavi, Architecture and circuits for RF CMOS receivers. IEEE customs integrated circuits conference (1998).
doi:10.1109/CICC.1998.695005

[9] T. Okanobu, D. Yamazaki and C. Nishi, A new radio receiver system for personal communication. IEEE Transactions on Consumer Electronics vol 41, No 3, 1995, 795-803.
doi:10.1109/30.468082

[10] M Banu et al, A BiCMOS double Low- IF receiver GSM . IEEE customs integrated circuits conference 1997, 521 – 524.
doi:10.1109/CICC.1997.606680

[11] S. Wu and B. Razavi, A 900MHz/1. 8GHz CMOS receiver for dual band application IEEE journal of solid state circuits vol 33 no 12, 1998, 2178 -2185.
doi:10.1109/ISSCC.1998.672400

[13] Tsung-Yuan Chang and Steven B. Bibyk, Analysis of the improved Hartley image reject receiver by bandpass delta sigma modulator. Analogue Integrated circuits and signal processing. Kluwer Academic publishers (1999).
doi:10.1109/MWSCAS.1998.759434