Choosing Frequencies in Heterodynes

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Summary

In the last two decades much has been published about high dynamic range receiver front ends. Also oscillators and their long term and short term stability (phase noise) got attention.
With [Manassewitsch]'s publication in the 70's we gained insight in the output frequencies of mixers: Not only the mirror but also other frequency products could interfere. However, he did not give a straight forward method for the designer. One subject became clear: the local oscillator (LO) frequency must be the intermediate frequency (IF) ***over*** *the radio frequency (RF) for the best performance.*
Since computers are at hand of every ham, some of them tried to investigate this subject of undesirable frequencies at the IF-port. However, simulation programs cannot be tested. The programmer should prove the program during development using sophisticated programming techniques in a right programming language.
The next step is to formulate guide lines for the front end designer from the results of such a proved program.

The most important conclusion is that the IF should not be chosen on .... 1/4, 1/3, 1/2, (2/3), 1, 3/2, 2, 3, 4, ... times the RF.

A well designed band pass filter with a band width of no more than 15% of the tuning frequency should be established as well.
A general coverage receiver (or transmitter) should be equipped with at least two (first) IF-filters at ***different*** *frequencies.*

Preface

Since the 30's there is hardly progress in the science of heterodyne receivers. New technologies in the last decades and the change in costs led to new designs: 65 years ago electronic components were expensive and labour was cheap. Nowadays it is the other way around. Moreover the power of components (or better: devices) gained from tubes to integrated circuits.

One of the most effective methods to compensate the poor performance of mixers in front ends is to use a well tuned narrow band pre-selector circuit. In many old receivers, equipped with tubes, one will find many tuned circuits with big high-Q coils and tuning condensers. This is proved to be effective with receivers as the EK07 from Rhode und Schwarz with an outstanding overall performance. Be aware that the best tube mixer is always worse than a simple solid state mixer. Such pre-selectors however are labour-intensive (expensive nowadays), big and sensitive to vibrations. The front end designs of the last decades suffer from narrow band pre-selectors, but they will be equipped with high IP3 double balanced mixers and, if well designed, low phase noise oscillators.
The only problem that is not solved until now is the sensitivity of receivers (and the emission of transmitters) at undesired frequencies because of other shortcomings of mixers. This problem arose when the narrow band tuning circuits were left out. They are replaced by sub-octave filters or band pass filters with some 100kHz band width.
This phenomenon is different from intermodulation. In contrast with [Manassewitsch] a.o., who speak about an 'intermodulation chart', I think that word 'intermodulation' counts for signals on one and the same port: the RF-port of the mixer. The sensitivity of a receiver for undesired frequencies I am talking about here, comes into being by the LO-frequency and the RF, which are sent to *different* ports. As we will see below, a double balanced mixer with good third order intermodulation figures (eg. SRA-1H) does not perform better in this field as a mixer with moderate third order intermodulation figures (eg. SBL-1).

What is the problem?

Mixers, at least double balanced mixers, excite a great number of signals at different frequencies with different amplitudes at the IF-port. In general these are:

$n.f_{LO} - m.f_{RF}$, and
$n.f_{LO} + m.f_{RF}$ in which n and m are cardinals.

If the LO-frequency is over the RF, the desired frequency is $f_{LO} - f_{RF}$, so n and m are 1. $f_{LO} + f_{RF}$ is the mirror. But what about the other signals?
With eg. an IF of 10300 kHz in a receiver for 80m (3500 – 3800 kHz in Europe), one find the receiver sensible at 3550 kHz (-90 dB: $3.f_{LO} - 9.f_{RF}$) and at 3570 kHz (-84 dB: $2.f_{LO} - 5.f_{RF}$), if the receiver has been tuned at 3770 kHz. (One could take a much worse IF!)
Transmitting at 3510 kHz, a signal of -80 dB appears at 3730 kHz being $4.f_{LO} - 5.f_{IF}$. This is the case with a simple SBL-1 mixer with signal strengths of -10 dBm at the RF-port and the prescribed +7 dBm at the LO-port.
-10 dBm is a large signal, but in front ends with IP3 figures of +40 dBm or even +50 dBm this is a reasonable input signal when the station is on a ship or in a multi station contest.

If the SBL-1 should be replaced with a high level mixer like the SRA-1H with the prescribed LO-level of +17 dBm and also -10dBm at the RF-port, the undesired outputs at the IF-port are about the same! Be aware that these figures are found with an ideal pre-selector band pass filter with square edges at 3500 and 3800 kHz. If the ideal square pre-selector band pass were 500 kHz wide (from 3400 – 3900 kHz) then two other signals popped up at 3480 kHz (-86 dB: $7.f_{RF}$ - $1.f_{LO}$) and at 3430 kHz (*-60dB*: $3.f_{RF}$) with a receiver and another -91dB signal ($7.f_{LO}$ - $9.f_{IF}$) during transmission.
As shown, there is no way to filter out these undesired frequencies! *The only way is to choose a different IF!*
The question is: how do you do this for a multi band transceiver? Together with the 'intermodulation' charts of Manassewitsch or whoever, the number of calculations that should be executed are so many that two years separation with pencil and paper would not satisfy.

The solution

These kind of problems can only be solved with the aid of a computer if the problem can be described in formal statements. A computer is a stupid formal thing that can calculate and represent results very fast, but the description of the problem should be established in a program, written in a rigid programming language with a reliable compiler running with a proved operating system on reliable hardware. So, some conservatism is advisable.
Another point is that these kind of programs *cannot be tested*: this program should simulate a mixer. Simulations cannot be tested on eg. validity, correctness and completeness: in the examples above you can recalculate the frequencies, but is the list complete? Are there no other combinations of frequencies that interfere? Should there not pop up a wrong calculated signal that should not be there? I investigated a number of programs that try to tackle this mixer problem. They were not error-free. The one crashed with certain input, the other represented only a (small) part of the list, a third one listed wrong frequencies and/or levels or no levels at all.
As a programmer at the Philips Research Lab, I learned scientific programming methodologies. For my program I chose Pascal as programming language, an old release of TorboPascal (5.0) as compiler and run TP under DOS 5.2 on a well behaving 386 with co-processor. Moreover I only used the by Wirth well defined Pascal statements. The graphical TP-statements for the graphical interface came much later.
I started programming in the summer of 1988 and finished two months later a first version. This program presented tables. From these tables I collected the results in overviews with a word processor. I had stuck the WP-overview-tables at the wall in my shack and decided to stop the project for some time because I did not know how to proceed.

The discovery

Some morning in the autumn of 1988, I opened the curtains of my shack and with the bright rays from the low positioned sun I saw moire-like patterns on the wall with the overview tables. These patterns disappeared as soon as I came closer. Fascinating! Walking to and throw like a painter I emphasised the patterns carefully with a pencil. Eventually I could recognize the patterns at such a distance that I could read the figures in the tables. To make a long story short, I redesigned the overview-tables and discovered the statement:

The IF should not be on ..... 1/4, 1/3, 1/2, (3/2), 1, 3/2, 2, 3, 4 .... times the RF.

This counts for receivers and for transmitters. Is it that simple?

The scepticism

I had my doubts. Nobody should have discovered this simple law before? I spoke with old radio designers at the Philips Research Lab, I investigated block diagrams and frequency plans of all professional receivers I could find in the lab's library: Rohde und Schwarz, Siemens, Marcony, Paye, Philips, Collins, name it. I could not find any lead. Should no developer of all these excellent receivers have been aware of this simple law? The receivers at hand behaved as predicted by my program. I bought me a second hand Rohde und Schwarz EK07 for $ 400. This outstanding 65 kg weighing receiver with tubes from the early 60's, behaved as calculated with my program! I wrote an article on the subject in 'Electron', the Dutch ham radio monthly of the VERON. No response. Later I phoned with [Rudersdorfer] who had no idea of what I was talking about and even abdicated to read this article!
Eventually I kept the law for myself.
By the way: Rereading [Manassewitsch] during the writing of this article and reinvestigating the 'Intermodulation product chart' in figure 2-6. (a) on page 52, a reprint from [EDN], I saw that 'my law' is correct. Only if one *knows* the law already, one can verify it with this chart. I could not *find* the law from this chart.

The answer

Many years later I designed a graphical interface to my program as a finger exercise for a spectrum analyzer. Of course the results presented by the graphics are the same as those presented by the tables, but people to whom I showed the new user interface, started to believe my statements, but I still read articles in professional and ham radio magazines in which the authors show ignorance on the subject: Last weeks I reread some articles in the German CQ DL, the British RadCom and the American QEX and QST and saw again how people go to great lengths to get the best out of devices building front ends. These people deserve to know of my experiences. I made an English version of my program, wrote this article and here I am.

Findings with the graphical interface

The first version of my program (with the table output) did not give any dynamic information. The graphical interface offers the possibility to tune within the frequency band specified. Simulating a receiver, I saw that the unwanted frequency outputs (if any) run *in the same direction* as the tuning frequency. With the transmitter these outputs run in the opposite direction in the frequency domain. This means that unwanted outputs *stay longer in the neighbourhood of the tuning frequency* in receivers. I had no idea of this before.
Another phenomenon that became clear: the 'unsafe' frequency areas enlarge when the band width of the pre-selector band pass filters are enlarged. (Sub-)octave filters do not satisfy at all.
Radio hams should build at least 8-pole band pass filters for each amateur band!

The program

The program is developed for safety first. This includes an old fashioned stable environment like DOS 5.2 on old fashioned hardware like a 40MHz 386 with co-processor. The program even behaves well on a 600 MHz P3 with Windows XP.
The program is self-explainable. However, read the read.me file.
The program offers to calculate the frequency plans of transceivers with a fixed IF, with a tuned (first) IF [the front end as a convertor], VFO's with mixers, and synthesizers.
The band width of (pre selector) filters can be changed.
If you want the program (3 files), mail at info@by-rutgers.nl.

Conclusions

- From the publications of [Manassewitsch] one could learn that the LO-frequency always should be higher than the RF (and the IF). This knowledge is applied in the program.
- A simulation program is scientific hot stuff. Such a program cannot be tested so that reliability, validity, completeness, etc. only can be established with sophisticated programming techniques in rigid languages with reliable compilers running on stable operating systems and well behaving hardware. This includes conservatism: No Delphi or other new systems. Only Pascal, an old stable TP-release running with DOS 5+ on a 386 or so.
- The program 'freqplan.exe' offers the calculation of frequency plans for transceivers, VFO's with mixers and frequency synthesizers as well.
- The planning of frequencies should still be done by the user. A planning for, say, a five band transceiver is too complex to formulate in formal statements. This program only helps to get a better view of the problem by calculating fast and offering a satisfying graphical user interface.
- **The (first) IF should not be chosen on: .... 1/4, 1/3, 1/2, (3/2), 1, 3/2, 2, 3, 4, ... times the RF.**
- A well designed narrow band tuned pre-selector filter masks mixer imperfections.
- For a well performing front end, a well designed pre-selector band pass filter of max. 15% is required. (Sub-)octave filters do not satisfy.
- A general coverage receiver needs at least **two** IF filters at **different** frequencies with small (15%) band pass filters to get a uniform performance over the whole frequency range.
- An IF of 9MHz satisfies for the ham bands: 80, 40, 20, 15 and 10m. However the citizen-band could give troubles on 10m in a crowded environment.
- As soon as the mark bands are added, 9MHz is no longer usable because of at least the 17m-band.

Reference

[Manassewitsch] Frequency Synthesizers, Theory and Design, *Vadim Manassewitsch*, A Wiley-Interscience Publication, JOHN WILEY & SONS, ISBN-13 978-0-471-77263-7

[EDN] EDN Magazine, August 1967

[Rudersdorfer] Ralf Rudersdorfer, Funkempfänger-kompendium' (Johannes-Kepler-Universität Linz) Elektor-Verlag Gmbh, Achen, ISBN 978-3-89576-276-5

The author

Herbert Rutgers was born in 1938 in Amsterdam, studied radio engineering with Philps in the Netherlands, became radio ham in 1958 (PA0SU) and became an electronic engineer at the Technical High School in Rotterdam. He worked at the Philips research Laboratory for some years as an analogue electronic engineer. He switched to computer programming in the late 60's and worked as programmer and system designer at many places within the Philips concern. Studied and taught in the mean while computer science (with the accent on architecture and programming techniques). The last five years of his career he returned to the Research Lab to introduce project management in the research environment, especially software simulation projects. Since 1998 he is retired. He is still active in several social organisations, sings in an even song choir, is active as solo singer, builds excellent HiFi systems, built his complete solid state radio ham equipment already in the late 70's, published about 50 articles on this subject and is sound recording engineer with the 'Concert Zender'.

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