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A Software Defined Radio Receiver Test-bed

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Abstract-This paper identifies the issues that are important in the design of a SDR receiver. Receiver architectures are first discussed, and the conclusion drawn that the conventional superheterodyne structure is most appropriate for a SDR receiver. Issues associated with image rejection, and receiver linearity are discussed. The design of a sweepable preselect filter is discussed in detail. Design considerations for a practical SDR test-bed are presented.

I. INTRODUCTION

Paper analysis [1], [2] of the Software Defined Radio (SDR) concept indicates that there are major obstacles to the hardware implementation of a true SDR receiver. In order to assess the issues that the paper study has revealed, it was decided to construct a hardware demonstrator.

The concerns raised by the paper study are as follows:

- The receiver amplifiers will need to be highly linear to preserve the integrity of digital modulation schemes, and also to prevent out of band blocker signals from producing in band interference¹.
- Rejection of image signals will need to be considered, as a true SDR will need to have a front end exposed to a several octaves of RF signals. If the receiver is to cope with the major European air interface standards, then it

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¹ An ideal SDR will be required to have a wide bandwidth front-end. A wide bandwidth will allow blocking signals, which are further away in frequency from the wanted channel, to appear at the receiver input. Because they are far away from the wanted signal, they are permitted, by blocking specifications, to have a higher power level. Receiver non-linearities, can cause these blockers to generate third order products which appear "inband".

should be capable of receiving signals extending from about 900MHz, up to about 5,600MHz.

There are other important hardware issues less directly connected with the receiver design, such as antennas and duplexers. This paper will concentrate solely on receiver design issues.

II. RECEIVER ARCHITECTURE

The primary distinction between receivers, is the number of stages taken to down convert a signal to baseband. Direct conversion takes one down-conversion. Superheterodyne receivers employ two or more. In general, complexity increases with the number of down-conversions. Sections A and B set out to briefly examine the alternative architectures. It will be shown that the simplicity of direct conversion is bought at considerable cost. This cost makes direct conversion architecture inappropriate for a SDR receiver.

A. Direct Conversion

A direct conversion receiver is shown in Fig. 1

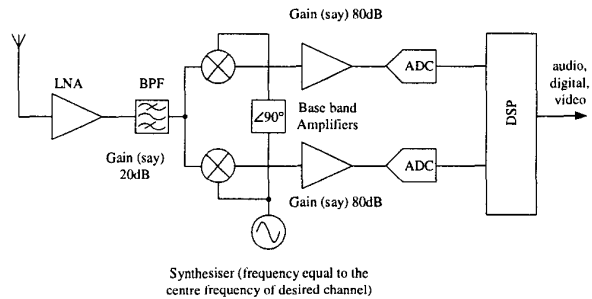


Fig. 1 Direct conversion receiver

This receiver consists of a LNA which provides modest RF gain at a low noise figure. The output signal from the LNA is filtered in a pre-select filter, and down converted in a complex (I, Q) mixer. The majority of the gain, and AGC (Automatic Gain Control) is provided in a high gain, baseband amplifier.

Advantages:

- Low Complexity.
- Suitable for integrated circuit realization.
- Simple filtering requirements.
- Image signal suppression is easier (compared to multiple conversion architecture).

Disadvantages:

- A local oscillator is required, in which the two output signals are accurately in phase quadrature and amplitude balance, over a wide frequency range.
- The mixer needs to operate over a wide frequency band.
- Local oscillator leakage through the mixer and LNA will be radiated from the antenna, and reflected back into the receiver from that antenna. The reflected signal will vary with the physical environment in which the antenna is placed. This “time varying” DC offset caused by “self-mixing” is a problem.
- Most of the signal gain to occurs in one frequency band creating the possibility of instability.
- $1/f$ noise is a major problem.
- 2nd order distortion product mix down “in band”.

B. Multiple Conversion - Superheterodyne

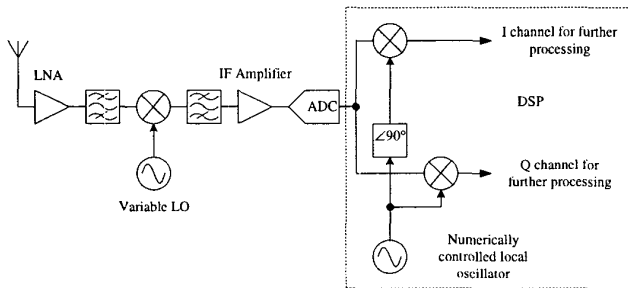


Fig. 2 Multiple conversion superheterodyne stage.

A superheterodyne receiver is shown in Fig. 2.

Advantages:

- Gain is distributed over several amplifiers operating in different frequency bands.
- Conversion from a real to a complex signal is done at one fixed frequency, and therefore a phase quadrature, amplitude balanced, local oscillator, is only required at a single frequency.

Disadvantages:

- The complexity is high.
- Several local oscillator signals are required.
- Specialized IF filters will be required. This makes it impossible to achieve single chip realization of a superheterodyne receiver. In addition, coming off and onto a chip at 50Ω impedance, required by most specialist filters, could cause problems with IC design

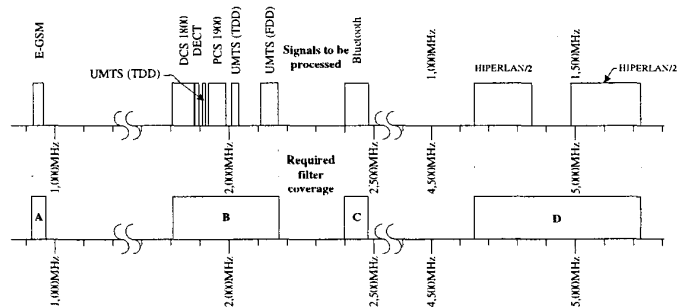
where impedance levels tend to be of the order of hundreds of Ohms.

Although the multiple conversion stage of Fig. 2 only shows 2 explicit down-conversions (one in the RF hardware and one in the DSP (Digital Signal Processing)), further conversions can be done in the DSP via the processes of “decimation” and/or “sub-sampling”.

The receiver architecture illustrated in Fig. 2 represents the best choice for a SDR receiver design, given that the three principal disadvantages of direct conversion are practically insurmountable with current technology. With this architecture, one conversion is done in RF hardware, and all of the others are done in DSP.

III. FILTER FUNCTIONS WITHIN A RECEIVER

In any radio receiver that employs superheterodyne architecture, filters are required to perform three functions. First, filters are employed to allow the image signal to be separated from the wanted signal. This function is performed at the first opportunity in the receiver chain. Second, they should band limit the signal to the frequency of interest. This function is often referred to as “channelisation” and is achieved, for preference, in base band area of the receiver. Third, filters should prevent nearby, but out of band “blocker” signals generating sufficient “in band” power to interfere with the wanted signal. It should be noted that if the receiver amplifier were perfectly linear, then it would not be possible for out of band signals to generate inband products, and a filter to prevent this would not be required. In practice, some non-linearity exists in all amplifiers and mixers that make up the receiver chain. This means that some degree of channelisation needs to occur at a fairly early stage in the amplifier - mixer chain.



IV. IMAGE FILTERING

Fig. 3 Frequency of operation of an SDR image reject filter.

The frequency range of wanted signals for the SDR receiver test-bed could be represented graphically, as shown in the top line of Fig. 3.

The bottom line of Fig. 3 shows the frequency coverage required of the image reject filters. It can be seen that if 4 filters are provided to pre-select the wanted signal, then only 2 of those filters need to be able to be swept. TABLE 1 summarizes this information.

TABLE 1

BANDWIDTH, CENTER FREQUENCY AND SWEEPING RANGE REQUIRED OF SDR PRESELECT FILTER

Filter	Filter Bandwidth (MHz)*	Lower end of coverage	Upper end of coverage	Sweep from	Sweep to	Effective centre frequency	Sweep as a percentage of centre frequency
A	50	935	960	fixed	fixed	947.5	0.0
B	100	1805	2170	1855	2120	1987.5	13.3
C	125	2400	2483.5	fixed	fixed	2441.8	0.0
D	300	5150	5725	5300	5575	5437.5	5.1

*Minimum set at approximately 5% of centre frequency

One possible arrangement for the variable preselect filters is shown in Fig. 4. It can be seen that a constant bandwidth filter is proposed (100MHz in the case of the lower frequency filters, and 300MHz in the case of the HIPERLAN/2 filters). "Filter B" will be stepped 4 steps to cover the UMTS, DCS1800, and DECT band, and "Filter D" in 3 steps to cover the HIPERLAN/2 band. This paper will now review possible techniques for realizing this filter.

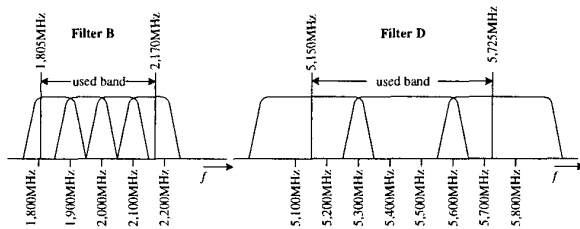


Fig. 4 Filter coverage required for the UMTS, DCS1800, and DECT band and for the HIPERLAN/2 band

V. SWITCH TUNEABLE IMAGE REJECT FILTERS

The image filter is operating at RF frequencies, and hence the options for the design of a flexible preselect filter must be limited to realization as, either a "distributed component" design, or as a MMIC (Monolithic Microwave Integrated Circuit).

There have been number of variable MMIC filter designs reported in the literature. In particular, a design reported in [3] by Katzin. This filter would have been ideal for our application. It unfortunately never progressed past the

prototype stage, due to problems with insufficient dynamic range [4].

There are several classic types of distributed component microwave filters. Most of these filter architectures were developed in the late 50s early 60s (see [5]). If we restrict consideration to those filters, which could conceivably be realized in microstrip, or similar, technology, then we are left with the geometries illustrated in Fig. 5.

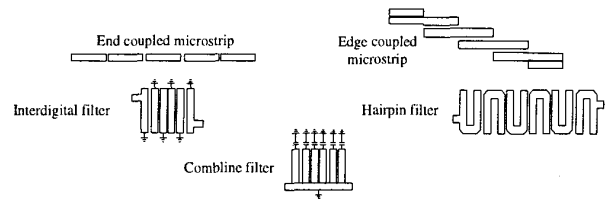


Fig. 5 Classical microstrip types

All of these filter architectures are designed for a fixed center frequency, fixed bandwidth application. The question remains as to how they might be electronically tuned. A number of suggestions are listed below.

- Varactor diode tuning at some strategic point on the filter structure.
- Constructing the filter on a substrate, whose dielectric constant could be electrically varied.
- Switching parts of the transmission line so that the physical characteristics of the filter structure could be varied.

Varactor diode tuning has been investigated with combline filters [6]. Filter designs are reported in which the center frequency can be swept from 3,200MHz to 4,800MHz with a bandwidth of about 200MHz. Reported insertion loss for such filter is of the order of 5dB. It is believed that this filter will exhibit distortion problems because of the frequency control is achieved through non-linear, varactor diodes².

It would be possible to sweep the filter characteristic by sweeping the dielectric constant of the substrate. As the electrical length of a transmission line is inversely proportional to the square root of the effective dielectric constant, this will cause the center frequency of the filter to vary. The substrate would allow the dielectric constant to change, in response to variation in an electrical bias. Such a substrate material has been developed by a (UK) research laboratory. This technology has been subsequently sold on to a third party, and its future is uncertain.

² Based on UoB experience with tunable patch antennas. This may not be such a problem with the much more complex resonant structure of a filter.

Switching the component parts of a filter, in and out of circuit, using MEMS (Micro-Electro Mechanical Structures) switches seems to offer a solution to this problem [7]. The use of MEMS switches will mean that the filter is composed entirely of linear components, and therefore dynamic range of the filter will not be an issue. One major problem with electrically switching a filter is to preserve the filter geometry as the center frequency is translated, whilst at the same time keeping the switching arrangement simple. Structures, such as edge coupled lines, or inter-digitated filters, have geometric problems as line lengths are changed, by switching.

At the time of writing, the simplest arrangement for altering the filter characteristic is the modified hairpin structure (see [8], [9]) shown in Fig. 6. This filter has a coupled line, which loads the top of the hairpin and forms part of the filter resonator. Interstage transformer action is brought about by edge coupling of the “U shaped” structure. Tuning of this filter can be achieved by changing the length of the top loading coupled line as is also shown in Fig. 6.

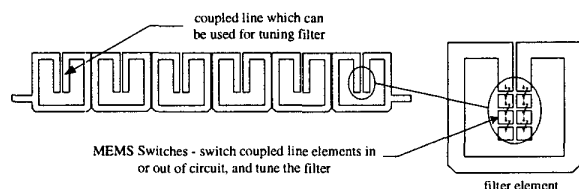


Fig. 6 Switchable modified Hairpin line filter

VI. DEVICE CONSIDERATIONS

Device manufacturers are slowly making available devices, which are suitable for application in SDRs. Amplifying devices are available, which combine a high TOI with a reasonably good noise figure, and wide bandwidth. Analogue to Digital Converters (ADC) are available which combine high resolution, with high sampling rates, and high analogue bandwidth. The improved performance of all devices is usually achieved at the expense of increased DC power consumption.

The linearity of mixers tends to be a bottleneck in the design of a receiver chain with a good TOI performance. There are some high TOI mixers becoming available, but unfortunately the RF bandwidth, over which they are useful, tends to be severely limited. This is not important if the mixer is to be used as a second mixer, but it is a problem if the device is to be used as the first mixer. The University of Bristol, as part of its involvement in the European TRUST project, is studying the design of low distortion mixers.

To measure the practical performance of an SDR receiver as well as confront the practical design challenges associated with such a system, it was decided to design and construct a SDR receiver test-bed. This receiver design was conceived as a “multi mode”, “multi-band”, receiver. In other words, you have to know in advance what signals the receiver is intended to process. The test bed was to be constructed in modular form. It was felt that as time progressed, various technological advancements, such as a linear mixer and electronically tunable pre-selection filters, could be incorporated into the receiver. In this way it was felt that the receiver could evolve towards a true SDR receiver.

A block diagram of the receiver is shown in Fig. 7. The receiver has been designed to operate with the major European air interface standards (see Fig. 3). A superheterodyne architecture has been chosen with one down-conversion in hardware, and the other in a digital IF strip. The hardware IF frequency is set at 160MHz. This frequency has been chosen for two reasons. Firstly, the IF frequency should be as high as possible to separate the image signal from the wanted signal (the separation is twice the IF frequency). Secondly, “off the shelf” SAW filters are available at this center frequency, with bandwidths of 250kHz, 5MHz and 20MHz. This is useful, because it is important to separate the wide band blockers from the narrow band signals as early in the amplification process as possible. In this way, only the non-linearities in the LNA, and the first mixer, will contribute to producing “in band” interference.

It should be noted that the analogue bandwidth of the ADC should therefore be at least 160MHz and the sample rate should be at least twice the bandwidth of the sampled signal (40MSPS in this case).

It is not straightforward to design microwave circuits whose performance is “flat” over the wide bandwidths demanded by a SDR. Often, some compromise may be necessary.

Feedback is used to extend the bandwidth of the LNA over the required RF band. This band extends from 935MHz to 2483.5MHz.

An active mixer has been chosen to cover a similar band. Initial tests show a conversion gain varying from -4dB to +2dB over this band with an output TOI of a minimum of +20dBm.

It is not possible to obtain mixers and amplifiers covering both the 5GHz band of HIPERLAN/2, and the 2GHz band, and the 900MHz band. For this reason, the HIPERLAN/2 signal is down converted an additional time using a passive high frequency mixer. The first IF for this down-conversion is chosen as the center frequency of the Bluetooth band (about 2442MHz). So the LNA of the low frequency air interface standards, acts as an IF amplifier for the

HIPERLAN signals, and the preselect filter for the Bluetooth standard, acts as an IF filter for the first HIPERLAN IF.

VII. CONCLUSION

Linearity and image filtering have been shown to be key factors in the design of an SDR receiver. Superheterodyne architecture, whilst not offering the neatest solution to design of an SDR receiver, is the only solution possible given the current technology. Distributed filters, with line lengths switched using MEMS, offer a possible way of realizing electrically variable pre select filters. A true SDR receiver could conceivably evolve from a multi-band, multi mode receiver.

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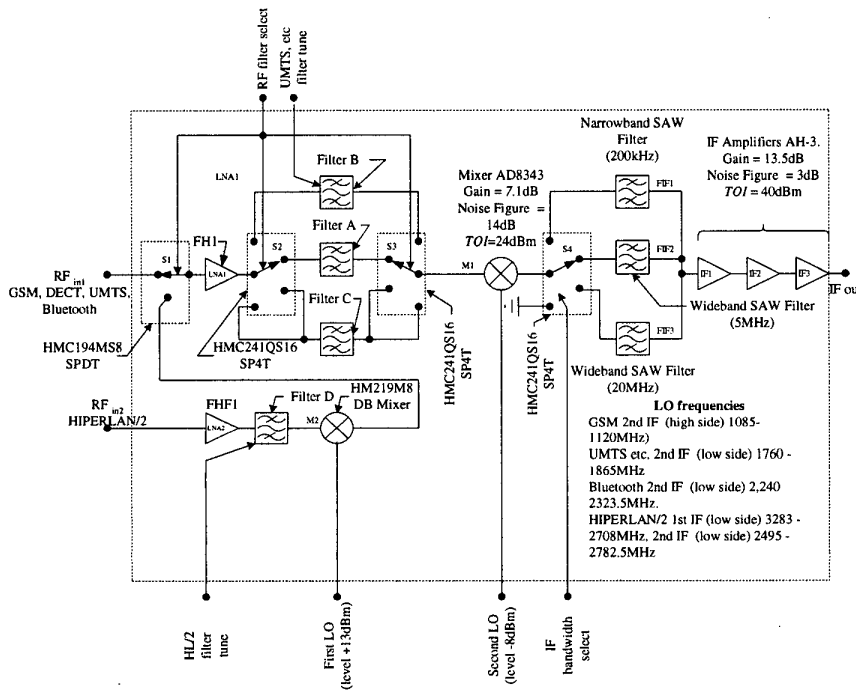


Fig. 7 Receiver block diagram

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