Effects of Amplitude, Phase, and Frequency Imperfections on the Performance of a Direct Conversion Receiver (DCR) for Personal Communication Systems

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***Abstract*— Results from a practical study of a direct conversion receiver (DCR) and its subsections, namely, power splitter, branch coupler hybrid, coupled lines band-pass filter, low-pass filter, balanced mixer, and oscillator, are presented. The receiver is designed for the 2-GHz frequency band, with particular reference to personal communications terminals for the digital european cordless telecommunications (DECT) standard. The DCR overall performance, based on measured figures of individual subcircuits, is analyzed with the aid of the "Eesof–Omnisys" simulator. Typical value for the signal-to-noise ratio 12 dBm for 10^{-3} bit-error rate. The receiver can tolerate amplitude and phase mismatches of 3% and 5°, respectively, as well as 1.2-kHz local oscillator drift. The dynamic range is 80 dB. The performance of the DCR fits well with the DECT specification.**

I. Introduction

THE DEMAND for personal communication services is growing fast. The capacity of existing analog networks is reaching its limit with increasingly poor service in major urban centres. The need for more efficient use of the radio spectrum in terms of numbers of users per MHz per km^2, together with the desire to achieve a low cost floor for terminal hardware has resulted in the development of the GSM Pan-European digital cellular system. However, concerns for system capability to satisfy further demand on capacity have prompted the investigation and standardisation of a 1.8GHz version of GSM, DCS 1800. The digital approach achieves increased capacity by virtue of the ability of digital systems to operate in poorer carrier to interference (C/I) environments than analog systems, thus permitting reduction in cell cluster size [1]. Also such beneficial features as encryption frequency hopping and implementation of source and channel coding are made possible, but they complicate terminal hardware design. Personal communication systems like the Digital European Cordless Telecommunication system (DECT) demand very reliable and low cost hand-set receivers. A MMIC or VLSI direct conversion demodulator (DCD) may be employed for the front-end of the hand-set receiver, and an ASIC or DSP circuit for the data processing functions of the receiver, like clock and data recovery.

Direct Conversion Techniques are very topical and many workers [2]–[9] have presented results emphasising the usefulness of the DCR in digital communication systems. The DCD is the simplest type of receiver. The absence of IF stages eliminates completely the image response problem and reduces the number of spurious responses. The effective use of post-detector filtering achieves good selectivity without difficulty. The fact that the carrier is not involved in the demodulation process provides economy of the receiver cost and a DCD is physically more compact than a superheterodyne receiver. These advantages of the DCD make it very attractive in applications such as paging receivers. These existing applications are, however, at frequencies below 450 MHz. More recently results for a 2-GHz DCR have been reported [8], but without hardware details. In this letter, we present results from a practical study of a direct conversion receiver (DCR) and its sub-sections, namely power splitter, branch coupler hybrids, balanced mixers, VCO's and low-pass filters. Second and third-order intermodulation (IM) product tests were carried out for the frequency conversion subcircuits.

All individual components have been simulated, and also have had their properties measured after fabrication. The complete DCR circuit has been simulated using the parameters measured for separate subsections. Results of all simulations and hardware measurements are reported in the next section.

II. Description of Circuits and Results

A GMSK-RF input is applied to the parallel lines coupled BPF and after amplification is fed to the 90° hybrid splitter. The outputs of this stage are driven in phase quadrature to the mixer—local oscillator systems. The frequency of the LO is equal to the nominal carrier frequency, and the mixer outputs at baseband are filtered in the low-pass filter section. After some amplification and hard-limiting, the data are fed to the digital unit for further processing.

Although the conventional way of modelling the phase quadrature property is through the LO path,"Eesof–Omnisys" does not permit a branch line coupler to be connected between the LO and the mixer. Accordingly, we split the incoming RF

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TABLE I
COMPARISON BETWEEN THE PASSIVE DCR SUBCIRCUITS

Circuit	Match (dB)		Isolation (dB)		Insertion Loss/Gain (dB)	
	meas.	sim.	meas.	sim.	meas.	sim.
Coupled Lines Bandpass Filter	-48	-61			-7.1	-2.7
Single Line Bandpass Filter	-18	-61			-0.8	-0.3
Branch Line Hybrid	-30	-35	-25	-35	-3.2	-3.1
Lumped Element $\pi/2$ hybrid	-30	-32	-20	-39	-3.2	-3.3
Power Divider	-26	-25	-21	-26	-3.7	-3.0
Lumped Element Power Divider	-21	-26	-25	-32	-3.3	-3.1
Low-Pass Filter	-18	-20			-0.8	-0.5
MMIC Low-Pass Filter		-17				-0.1

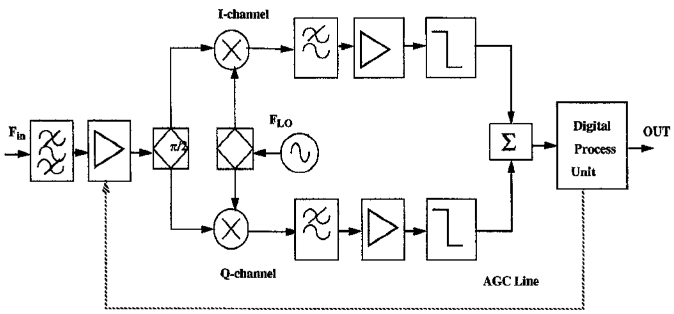

Fig. 1. DCR under test.

signal into two orthogonal modes. Healy[6] uses this topology to analyze his pager. The DCR under test is shown in Fig. 1.

The performance of the direct conversion receiver was tested using the "Eesof–Omnisys" simulator. All the passive subsection data were derived from the measured results of the relevant circuits as shown in Table I. The measured figures for the dual-gate GaAs MESFET mixer were; 1-dB compression point $P1 = 14$ dBm (input power), third-order intercept $P3 = 47$ dBm, when the predictions were 10 and 52 dBm, respectively [7]. A software tool named "ΑΡΓΩ" was developed to analyze and synthesize the DCR subcircuits. Based on the physical dimensions obtained by the programme, S-parameter simulation was performed by "Eesof." All circuits were made on alumina substrate of thickness 0.635 mm. The band-pass filters and the dual-gate GaAs MESFET mixer were realized using thick-film technology and all the rest using thin-film technology.

The simulated signal-to-noise ratio (S/N) level was 9.63 dB for 10^{-3} BER when the dual-gate mesfet mixers were used [7]. This level did not change much, 9.45 dB, for the beam-lead diode mixers. Both figures are well inside the DECT specification. In comparison to the ideal PSK transmission, the receiver needs improvement 8dB in SNR to attain 10^{-3} bit-error rate. The orthogonality of the GMSK causes 3 dB loss [8]. Another 3 dB is lost because of the incoherence of the receiver. The remaining degradation comes from imperfections in the circuitry.

The large signal performance of the receiver depends strongly upon the performance of nonlinear sections such as the mixers and amplifiers. The large signal characterisation of the DCR gave $P3$ dB = 50 dBm and $P2$ dB = 30 dBm when diode mixers were used, and $P3$ dB = 40 dBm and $P2$ dB = 25 dBm when MESFET mixers were in use [7]. However,

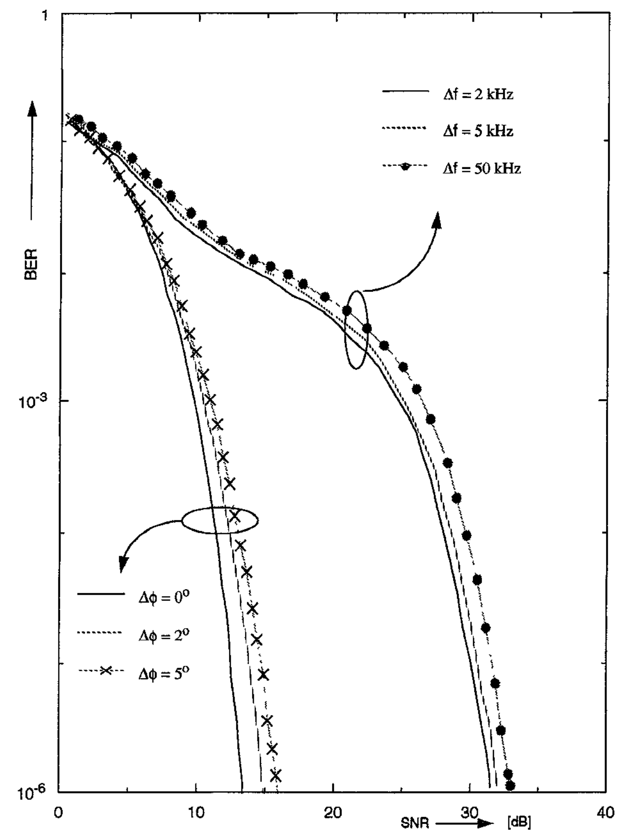

Fig. 2. Phase channel mismatch and local oscillator frequency drift versus output SNR for the GaAs MESFET direct conversion receiver.

no significant changes to the previous figures were observed when alternating the various passive subcircuits.

Although the DCR does not suffer from an image response in the same way as a superheterodyne, the effect of mismatch between the two channels is to induce an image signal whose amplitude depends upon the size of the amplitude and phase errors.

Fig. 2 shows the output SNR versus the phase and frequency imperfections for a DCR using beam-lead Schottky diodes as mixers (diode DCR). Two distinctive categories of SNR can be determined: low SNR when it is less than 12.5 dB and high SNR when its value is between 12.5 dB and 18 dB. Thus two tolerances can be derived; one for low SNR and another for high SNR. The amplitude and phase imbalances were 3.1% and 5.2 for low SNR and 3.4% and 5.8 for high SNR, respectively.

In many cases, when a mismatch occurs in the input circuit of the receiver, there is LO leakage into the signal path. This can happen when the handset user touches its antenna. The hybrid coupler isolates the RF and LO ports by -25 dB and the two gates of the mesfet by -17 dB. When this figure increases the receiver performance decreases dramatically. The receiver cannot tolerate a mismatch of more than -12 dB for low SNR figures. However, this is not a serious disadvantage of the DCR because the frequency conversion circuit is designed to minimize mismatching effects. Also the problem of the LO feedthrough that occurs when the user of the portable unit touches the antenna is impractical. The only interference from the human body in normal operation is its absorbing the vertical electric field component radiated by the antenna [10], resulting in a distortion of the symmetry of the radiation pattern.

Next, the effects of LO frequency stability are investigated. It is very important for the local oscillator to lock to the incoming radio frequency during the 32 synchronization bits of every DECT slot, which makes the use of a synthesized source essential. The performance of the receiver worsens after a few kHz of LO frequency drift as shown in Fig. 2. For low SNR, the frequency tolerance was 1.2 kHz and for high 2.8 kHz.

A possible circuit description equivalent to that of Fig. 1 is a cascaded connection of two port components. The hard-limiter and the digital process unit have been replaced by an attenuator and a gain block. Also, the 90° hybrid is replaced by an attenuator pad. These alterations are necessary due to software limitations in budget analysis. The spurious-free dynamic range (SFDR) is affected by every component in the signal path. Each subsection can be assigned a dynamic range; that is, it will accept a range of signals that can be amplified without distortion or without disappearing into noise, at the high and low ends, respectively. The incoming signal range from -100 dBm to -30 dBm is translated to -60 dBm to 10 dBm for a 16-bit analog to digital converter (ADC), i.e., part of the digital unit represented by an attenuator and a gain block [5].

The direct conversion receiver has, as required, an SFDR of about 90 dB. The range covered is from -20 dBm to -100 dBm for the diode DCR and for -30 dBm to -100 dBm for the GaAs MESFET DCR, while DECT specifies a range from -33 dBm to -96 dBm at least. The marginal behavior of the GaAs DCR at the high end indicates possible limitations when the hand-set receives strong signals. An automatic gain control (AGC) function such that of Fig. 1 would cancel problems of this nature.

III. Conclusion

The direct conversion receiver is a versatile demodulator suitable for transmission schemes used in DECT such as TDMA. It was demonstrated that the DCR fulfils the DECT specification for bit-error rate, dynamic range, and mismatch tolerances. The large signal characterization of the receiver is correlated with the nonlinearities of the relevant subsections and with very satisfactory agreement. The final predicted performance of the DCR, based on measurements of its subsections, indicates that this kind of demodulation has considerable potential for mobile and personal communication systems. The various problems due to imperfections are arguably outweighed by the two main advantages of the DCR over the superheterodyne: the elimination of spurious image responses and its compact size and potentially high degree of integration.

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