(54) Title: METHOD AND APPARATUS FOR GENERATING A RADIO FREQUENCY SIGNAL
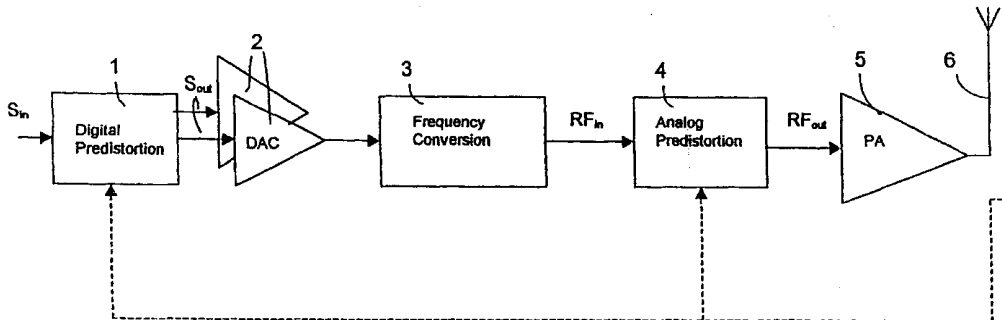
(57) Abstract: The invention relates to linearisation of a radio frequency (RF) power amplifier (5) by predistortion. Digital predistortion is performed (1) on received digitized base-band input signals to compensate for amplifier distortion. The resulting signal is converted to an analog signal via two D/A converters (2), after which analog frequency conversion is performed (3) on the analog signal to achieve a radio frequency (RF) signal. This radio frequency signal is exposed to analog predistortion (4) and thereafter amplified by the power amplifier.

Method and apparatus for generating a radio frequency signal.

TECHNICAL FIELD

The present invention relates to a method and an apparatus for
generating a radio frequency (RF) signal, and more particularly
to linear amplification of radio frequency signals.

BACKGROUND ART

In a radio base station, there is a need for a high power
amplifier in the transmitter section to provide each radio
channel with enough power to reach the outer limits of a cell
covered by a base station.

When using the same amplifier for simultaneous amplification of
several information signals modulated on different carrier waves
or when using linear modulation, such as QAM (Quadrature
Amplitude Modulation), high amplifier linearity is required.
This is because it is essential in this case to maintain all
phase and amplitude positions of the signal components involved
in the amplification. Otherwise inter-modulation will occur
between the signal components and the spectrum of the amplified
signal will broaden. Intermodulation distortion will interfere
with signals on other channels. Examples of systems, wherein
high linearity is required, are those in which several combined
narrow-band signals or wide-band signals such as CDMA need to be
amplified.

RF power amplifiers are inherently non-linear devices since they
generate unwanted intermodulation products, which manifest
themselves as spurious signals in the amplified output signal,
separate and distinct from the input signal. The distortion
introduced by an RF amplifier causes the phase and amplitude of

its amplified output signal to depart from the phase and
amplitude, respectively, of the input signal.

There exist different methods for linearising amplifiers. An
overview and reference list of linearisation methods, including
Back-off of class A, Feedforward, Vector summation, Feedback and
Predistortion Linearisation, is given in "Linearisation of RF
Power Amplifiers" by Mark. A. Briffa, department of Electrical
and Electronic Engineering, Victoria University of Technology,
December 1996, Australia.

Predistortion is a method that modifies the original input
signal to the power amplifier such that it is complementary to
the distortion characteristics of the power amplifier. The
cascaded response of complementary predistortion and amplifier
distortion should therefore result in a linear response.
Typically the complementary predistortion function is based on
the approximation of the amplifier being modelled by a power or
a voltera series (otherwise known as the AM/AM & AM/PM).
However, the complementary predistortion function could also
include higher order effects, such as thermal properties of the
transistor and/or frequency dependent properties due to the bias
and matching circuits. Predistortion can be applied at radioor
Intermediate frequencies, known as analog predistortion, or
applied at baseband, known as digital predistortion.
Additionally, to achieve excellent linearity, adaption of the
predistortion means is needed to circumvent changes due
temperature, component ageing etc.

The predistortion mechanism may be made adaptive by extracting
the error distortion signal component at the output of the RF
amplifier and adjusting the predistortion means in accordance
with the extracted error behaviour of the RF amplifier during
real-time operation, so as to effectively continuously minimize
distortion at the amplifier's output. A good overview of
digital predistortion adaptive means is given in J. K. Cavers,
"Amplifier linearisation by adaptive predistortion", US patent

5,049,832. International patent applications WO 99/45638 and WO 99/45640 provide examples of an analog predistortion adaptive method.

To achieve good results with analog predistortion, careful matching of the complementary predistortion function and amplifier distortion function is required. However, analog elements with excellent matching characteristics are very difficult and expensive to produce. Analog predistortion typically has a limited dynamic (operation) range and is therefore only able to produce limited performance improvements. Analog predistortion, however, can operate over large bandwidths.

On the other hand, adaptive digital predistortion is able to produce, in theory, the excellent matching properties required to achieve significant improvements in linearity. However, because the predistortion occurs at baseband, it needs to be converted to radio frequency before it can be amplified. The frequency conversion, however, takes place in the analog domain, which by its nature destroys the perfect matching capabilities of the digital domain. This results in that also digital predistortion becomes limited in respect of performance and bandwidth compared to analog predistortion.

The frequency dependent properties of the analog frequency conversion process, amplitude ripple and phase ripple, are the basic mechanisms for destroying the digital domain's matching qualities. Both of these quantities are directly linked to the amount of performance improvement that can be obtained. As the amplitude and phase ripple quantities increase, the obtainable linearity performance improvement becomes reduced, regardless of how well matched the complementary function is in the digital domain.

Analog and digital predistortion linearisation are typically implemented as standalone techniques, because of practical

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implementation problems arising from the fact that the two solutions require different architectures for implementation. This is best illustrated in the following two examples. In a normal macro base station, the Power Amplifier (PA) is a module that fits in one part of the rack, sometimes included with the frequency conversion circuits. The digital base band processing circuits physically reside in another part of the rack. These two components are physically separated and the signals are communicated via a coaxial cable. In a mast mounted antenna application, the PA is at the top of the mast and the base band processing part is at the base of the mast. In both examples, the digital baseband processing parts and the PA module are physically separated, which introduces practical implementation problems.

However, there exist some examples of a combined linearisation solution. For example the combination of digital predistortion with feedforward is presented in WO 98/12800. The feedforward architecture requires additional signal paths and two couplers, one to acquire the signal out of the power amplifier (PA) and the other one to subtract the remaining PA distortion. The last coupler inserts a loss. This results in the overall efficiency being degraded, also when combining the two methods. The solution is also quite complicated, requiring a large amount of components, making it difficult to implement.

Another example of combining RF predistortion with Feedforward is described in the technology white paper, Multi-Carrier Power Amplifiers join the Digital Revolution' Yuval Shalom, Fall 1999 issue of Site management and Technology Magazine, Intertec Publishing. It states that the DC-RF efficiency of feedforward amplifiers is limited to around 6-8% because of three factors.

1) Large backoffs due to the large peak to average ratios of multicarrier (wideband) signals. The DC power supplied to the power amplifier is given by P_{DCamp}, and the RF output power from the amplifier is given by P_{RF}.

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2)   Additional hardware such as delay lines and couplers after
      the power amplifier introduce insertion (power) loss. The
      power loss can be defined as a fraction of the total power
      surviving after the loss, typically 0.8 i.e 20% (1 dB) of
      power is lost.

3)   DC power consumed ($P_{DCother}$) by other parts of the feedforward
      system i.e. error amplifiers, control circuitry.

The DC-RF efficiency formula can be approximated for the
combined feedforward and RF predistortion system as

DC-RF efficiency = $0.8 * P_{RF}/(P_{DCother} + P_{dcamp})$

In the case of a predistortion system only, there is no need for
the additional hardware that introduces losses in a feedforward
system. As regards the other parts of the feedforward system,
this reduces complexity and results in the DC-RF efficiency
increasing as shown below by the DC-RF efficiency formula for
predistortion:

DC-RF efficiency = $P_{RF}/P_{Dcamp} > 0.8 * P_{FR}/(P_{DCother} + P_{Dcamp})$

Wide band applications partly have to be designed with
architectures and solutions different from those of the narrow
band solutions because of different problems.

Predistortion is a quasi-closed loop power amplification system,
as opposed to a closed loop system. Closed loop systems are
based on feedback, i.e. cartesian feedback, envelope feedback,
polar feedback.

The advantage of quasi-closed loop systems is that both
narrowband and wideband systems of an order of magnitude of 10's
of MHz can be used. As opposed to this, closed systems are
limited to narrow band signals of an order of magnitude of 100's
of kHz for practical stability reasons, although they can

usually achieve higher levels of linearisation than quasi-closed
loop systems.

In addition to quasi-closed and closed loop systems, feedforward
amplification can be used that can result in both high levels of
linearity and transmittance of wideband signals. As compared to
predistortion methods this requires a rather complicated gain
and phase tracking mechanism to keep the loops in balance and
results in low power efficiency. The feedforward architecture is
currently the most widely used technique for linearising
applications in wideband radio. For wideband radio applications,
predistortion, both analog and digital methods, in general is
characterized by good power efficiency, as compared to the use
of the feedforward methods, although they have lower linearity
performance than feedforward.

Digital predistortion has not been technologically possible to
use for wide band signals earlier with a sufficient performance
because of a relatively slow digital signal processing and
limited precision. The development of faster digital signal
processing by the introduction of e.g. digital circuit
fabrication methods, and advancements in DAC (Digital to Analog
Converter) technology, has, however, remedied this problem.

However, use of digital predistortion techniques in wide band
systems accentuates problems appearing in connection with
upconversion of the base band signal to a radio signal, since
the frequency dependent properties of the analog frequency
conversion process limit performance improvement.

The analog frequency upconversion process is usually assumed to
have the same transfer function regardless of frequency, viz.:

$$Y = f^n(X)$$

wherein Y is the output signal, and is a function of the input
signal X. Typically the frequency conversion circuitry is

designed such that Y is linearly related to X, and this assumption is relevant to narrow band signals. In wideband signal applications, the frequency upconversion process becomes more dependent on frequency:

$$Y = f^n(X, frequency)$$

This frequency dependence destroys perfect digital predistortion matching properties, and therefore limits the amount of linearisation. The dependence on frequency can be reduced, but it becomes expensive, if not impractical, to design over a wide bandwidth with very low amplitude and phase ripple. That is, low enough amplitude and phase ripple allowing digital predistortion to achieve the desired level of linearity. A digital frequency equaliser could be used to negate the frequency upconverter's frequency dependence. However, there will always exist some residual frequency dependence that limits the amount of linearisation, and it will also increase the complexity of the solution.

It is an object of the invention to provide an improved linearisation method by using digital predistortion in both wide band and narrow band applications, that will overcome the frequency conversion problems in connection with digital predistortion.

SUMMARY OF THE INVENTION

The method of the invention for linearisation of a radio frequency (RF) power amplifier by predistortion, comprises the steps of receiving a digitized base-band input signal, to be amplified by said RF power amplifier,
performing digital predistortion of the signals to compensate for amplifier distortion,
converting the signal to an analog signal via two D/A converters,
performing analog frequency conversion to achieve a radio

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frequency (RF) signal,

performing analog predistortion of the RF signal,

amplifying the analog predistorted signal by said RF power amplifier.

The power amplifier of the invention is characterized by means for performing the above steps of the invention. Alternatively, the digitally predistorted signal could be converted to a low digital intermediate frequency in the method and the power amplifier of the invention, whereafter the signal can be converted to an analog signal by using only one D/A converter. Both of these solutions can also be used in such another architecture of the invention, wherein the received base-band input signal can be split into two signals of 90° phase difference, whereafter the rest of the steps of the method of the invention is performed for each of the signals.

In all embodiments of the invention, the predistortion can be made adaptive to further improve the performance and/or circumvent changes due to temperature, component ageing etc.

Furthermore, the invention can be used in connection with different architectures described later.

The invention has several advantages as compared to prior predistortion solutions. By solving the upconversion problems caused by the digital predistortion process by splitting the performance requirements between digital and analog predistortion, improved linearity is achieved compared to digital predistortion alone. The solution of the invention also gives a higher efficiency compared to feedforward linearisation techniques, especially for wide band systems.

The invention also has the advantage of reduced requirements on frequency conversion parts since the linearisation performance now partly is handled by the analog predistortion means. This results in a cheaper frequency conversion solution.

The physical separation of the digital base-band processing parts and the PA module in prior art solutions exemplified above was one of the problems to overcome so that a combination of analog and digital predistortion would be possible.

One of the merits of the invention also lies in the fact that the overall performance improvement can be enhanced by splitting it between digital predistortion and analog predistortion. For example, if the basic amplifier gives a performance of -30dBc and 30dB improvement is required, an overall performance of the linearisation of -60dBc is needed. Then digital predistortion could obtain an improvement of 20 dB and the analog predistortion one of 10dB. This makes a total linearisation solution possible, which is very difficult practically or impossible to achieve with digital or analog predistortion alone. For digital predistortion to achieve this alone would require stringent design requirements on the frequency upconverter resulting in either an impossible design requirement or a very expensive solution. For analog predistortion to achieve this alone would require excellent matching of the complementary predistortion function and amplifier distortion function, and analog parts with excellent matching characteristics are very difficult and expensive to produce.

Another merit of the invention is that it combines the natural strengths of analog and digital predistortion. That is analog predistortion has limited correction capabilities over a large frequency range, whilst digital predistortion has excellent correction capabilities over a narrower frequency range. The combination can therefore yield improved correction capabilities over all frequency ranges when compared to either digital or analog predistortion techniques alone.

The invention will now be described more closely with reference to the appended drawings on which:

Figure 1 is a schematic block diagram illustrating principles of
the invention,

Figure 2 shows a Doherty amplifier architecture according to
prior art,

Figure 3 shows an example of an embodiment of the invention as
implemented in the Doherty architecture,

Figure 4 shows an example of the digital predistortion part of
the invention more in detail,

Figure 5 shows an example of the the analog predistortion part
of the invention more in detail,

Figure 6 shows simulation results of a digital predistortion
method of prior art,

Figure 7 shows simulation results of the method of the
invention.

DETAILED DESCRIPTION

With reference to Fig. 1, a digitized complex baseband input
signal S_{in} is first predistorted, as indicated by block 1, to
produce a complex baseband digital predistorted output signal
S_{out}. More particularly, this is done in a manner to be
complementary with respect to a combination of an analog
predistorter and a power amplifier, discussed further below and
indicated by blocks 4 and 5, respectively. This combination of
an analog predistorter and a power amplifier can be thought of
as forming a linear power amplifier.

The complex baseband digital predistorted signal S_{out} is then
converted to an analog signal by two Digital to Analog
Converters (DAC), indicated at 2. Alternatively, although not
shown in Fig. 1, the baseband digital predistorted signal S_{out}
can be first digitally frequency converted, before being
converted to an analog signal via a single DAC.

The output from the DAC is then frequency converted by frequency
conversion circuits, indicated by block 3, to a radio frequency
signal RF_{in}. The frequency conversion circuits 3 can consist of

mixers, filters, amplifiers etc. arranged in a manner obvious to
a man skilled in the art. The frequency conversion process
introduces frequency dependent amplitude and phase ripple, that
partly destroys the linearisation ability that can be achieved
with digital predistortion alone. The signal RF_{in} containing the
frequency converted digitally predistorted signal, is now
exposed to analog predistortion as indicated by block 4, in a
complementary manner with respect to the power amplifier 5. The
RF predistorted signal, RF_{out}, is then passed through the power
amplifier 5 before being transmitted by an antenna 6.

The digital and analog predistorters 1 and 4, respectively, can
optionally be made adaptive to further improve the linear
performance and/or circumvent changes due to temperature &
ageing etc. The adaption operation, which can be carried out
with methods well known in art, is indicated by dotted lines
ended by an arrow at each one of the blocks 1 and 4 in Fig. 1.

Figure 2 schematically illustrates a so called Doherty
amplifier. The architecture of a Doherty amplifier is e.g.
described in "RF Power Amplifiers for Wireless Communications"
by Steve C. Cripps (ISBN 0-89006-989-1, Artech House, 685 Canton
Street, Norwood MA 02062). According to the basic concept of
this amplifier, two amplifier devices 5, 5' are used in parallel
and the final maximum RF output power is produced by the
combined power of both devices. The Doherty amplifier
constitutes an efficiency enhancement technique as compared to a
one amplifier device technique, but does not introduce any
linearisation improvements. In short, an incoming base band
signal S_{in} is quadrature split, indicated by block 7, into two
signals with 90° phase difference. The two signals are amplified
by the amplifier devices 5, 5', combined as indicated by block
15, and then transmitted by an antenna 6.

With reference to Fig. 3, the performance of the Doherty
amplifier can be improved with respect to linearisation by
introducing therein the solution of the present invention, as

described with reference to Fig. 1. The incoming base band signal S_{in} is first split, indicated by block 7, into a first signal S_{in} being identical to the input signal, and a second signal $S_{in90°}$ being 90 degrees phase shifted. The 90 degree phase shift can be implemented by the so called Hilbert Transform, or according to other methods obvious to a man skilled in the art.

The two signals S_{in} and $S_{in90°}$ are processed in each a path containing the same type of function blocks as in Fig. 1, described earlier, said paths extending in parallel from block 7 to a combiner indicated by block 15. The top path blocks are numbered 1, 2, 3, 4 and 5 as in Fig. 1, whereas the lower path blocks are numbered 1', 2', 3', 4' and 5'. The top path, receiving the original signal, includes the main power amplifier 5, whereas the lower path, receiving the 90 degrees phase shifted signal, includes a peak or auxiliary amplifier 5'.

The output signals from the amplifiers 5 and 5' are combined in the combiner 15 after the signal of the top path having been shifted by 90 degrees. Typically, the combination may be implemented as a quarter wave delay after the main power amplifier 5 output. The combined output signal from the combiner 15 is then transmitted by the antenna 6.

Applying, as described above, the invention on the Doherty architecture improves the linearity of the power amplifiers used, and makes it more suitable for use in both narrow band and wide band radio communication systems.

Figures 4 and 5 illustrate some simple examples of digital and analog predistortion methods that can be used in connection with the invention, assuming in these Figures that the amplifier is memoryless. What is referred to is use of AM/AM (amplitude modulation/amplitude modulation), AM/PM (amplitude modulation/phase modulation) model of amplifier.

If the power amplifier is exposed to memory effects such as

caused by thermal properties of the power transistor and/or
frequency dependent properties due to the bias and matching
circuits, then it is obvious to a man of the art that the
digital and analog predistorters will also require memory to
compensate for these effects. An example of a digital and an
analog predistorter will now be described, that can be used in
connection with the combination of analog and predistortion
methods according to the invention.

Figure 4 illustrates an example of a method for implementing
digital predistortion of the kind referred to by block 1 in Fig.
1. The digital predistorter in this case is assumed to
compensate for the combination of the analog predistorter and
power amplifier with a memoryless non-linearity and is based on
cartesian complex gain predistortion. Other memoryless
predistorter examples could include polar complex gain or full
cartesian mapping, the principles of which are described in US
patent 5,049,832.

In Fig. 4, the complex baseband input digital signal S_{in} of Fig.
1 is received by an address generator 8. The address generator 8
generates an address based on a function of the amplitude of the
signal, this being consistent with the memory non-linearity
assumption of the power amplifier. The address is typically the
amplitude or power of S_{in} and is used to select a complementary
complex gain, S_{corr}, from correction (predistortion) tables 9 for
the digital sample in question. The correction tables 9 contain
the total complementary complex gain of the combination of the
analog predistorter 4 and power amplifier 5, such that the
combination of the complementary gain of the digital
predistorter 1, the analog predistorter 4 and the power
amplifier 5 results in linear gain and phase for all input
signal magnitudes. The complementary complex gain sample, S_{corr},
and the orignal input signal sample, S_{in}, are then processed
by a complex multiplier 10. The output of the complex multiplier
10, S_{out}, is designed to linearise the combination of the analog
predistorter and power amplifier. The signals used in Figure 4

are complex, which is indicated by the number 2 at the signal
paths.

Figure 5 illustrates an example of performing 3rd order analog RF
predistortion of the kind referred to by reference number 4 in
Figure 1. The digitally predistorted signal converted to RF
forms an input RF_{in} to the analog predistorter 4. The RF_{in} signal
is delayed, as indicated by block 11, to ensure that RF signal
and correction signals coincide at multipliers 13, 13'. The
delayed Rf_{in} signal is then split, indicated by block 12, into
two signals with quadrature phase, i.e. there is a 90 degree
phase shift between the two signals.

Both of the quadrature phase signals are then mixed by the
multipliers 13 and 13', respectively, with the correction
(predistortion) signals I_{corr} and Q_{corr}, respectively. These
signals, I_{corr} and Q_{corr}, represent the analog complementary
complex gain of the amplifier. The resulting mixed signals are
then phase combined in a hybrid combiner 14. The output of the
analog predistorter, RF_{out}, is designed to linearise the power
amplifier.

The correction signals, I_{corr} and Q_{corr}, are generated by first
squaring, as indicated by squaring function block 18, the input
signal RF_{in}, then filtering, as indicated by filtering function
block 19, away unwanted harmonics generated by the squaring
function 18, and finally multiplying, as indicated by two blocks
16, the filtered signal from function 19 with two third order
coefficients 17, 17'. The two third order coefficients
approximate the complementary complex gain of the amplifier. It
is obvious to those familiar with the state of the art that
higher order coefficients can be used to achieve better matching
of the complementary gain of the amplifier and that there are
many other examples of analog RF predistorters, some of which
are described in Mark Briffa, "Linearisation of RF Power
Amplifiers", PhD thesis, 1996, department of Electrical and
Electronic Engineering, Victoria University of Technology,

December 1996, Australia and the international patent
applications WO 99/45640 and WO 99/45638.

SIMULATION RESULTS

By solving the frequency conversion problems caused by the
digital predistortion process by splitting the performance
requirements between digital and analog presdistortion in a way
according to the invention, improved linearity is achieved,
compared to digital predistortion alone. The solution of the
invention also gives improved correction capabilities over all
frequency ranges compared to either digital or analog
predistortion techniques alone.

This can be shown through the following simulation results using
a WCDMA signal with a bandwidth of 4.096MHz. Digital
predistortion linearisation only with a given power amplifier is
first assumed with reference to Figure 6.

The adjacent channel performance, or linearity performance, of
the amplifier is defined as the ratio of the power of a signal
to the power of adjacent signal power, on either the lower or
the upper sides. The power is calculated by integrating the
energy over a bandwidth of 4.096 MHz. For the signal this is
shown as the area between the two vertical solid lines, and for
the adjacent signal this is shown as the area between the dotted
vertical lines.

The adjacent channel performance of the given amplifier alone
(shown dotted in Figure 6) is 35.8 dBc and 34.4 dBc for the
lower and upper adjacent channels respectively. Applying perfect
digital predistortion (the ideal complementary function of the
given power amplifier) with 0.6dB peak to peak amplitude ripple
in the frequency converter results in an adjacent channel
performance that (shown solid in Figure 6) is 59.2 dBc and 58.8
dBc for the lower and upper adjacent channels respectively. The
performance of the given power amplifier has been improved by

digital predistortion by 23.4 and 24.4 dB, however limited by
the amplitude ripple in the frequency converter.

In the next set of results, the given amplifier is first
predistorted by a RF analog predistorter. With reference to Fig.
7, the adjacent channel performance (shown dotted in Figure 7)
is 41.1 dBc and 40.6 dBc for the lower and upper adjacent
channels respectively. The analog predistorter has improved the
given power amplifier by 5.3 dB and 5.2 dB. Notice that the
analog predistorter has also improved the higher order
distortions (wider frequency range) of the amplifier in this
example.

Digital predistortion is now applied to the analog predistorter
and the given power amplifier. Perfect digital predistortion
(the ideal complementary function of the analog predistorter and
given power amplifier) with 0.6dB peak to peak amplitude ripple
in the frequency converter results in an adjacent channel
performance (shown solid in Figure 7) of 63.1 dBc and 62.8 dBc
for the lower and upper adjacent channels respectively.
Obviously the performance of the analog predistorter and given
power amplifier has been improved by a further 22 and 22.2 dB
with the addition of digital predistortion.

Notice that the overall performance improvement of digital
predistortion in both examples was 23-24 and 22dB. Given
measurement tolerances these values could be considered very
similar. Digital predistortion has therefore been limited in
performance by the ripple of the frequency upconverter,
regardless of the initial linear performance of the analog
parts. Additionally the overall performance improvement
generated by the combination of analog and digital predistortion
techniques is given by the sum of the individual improvements in
the region where both digital and analog predistortion is
active. This region is shown in Figures 6 and 7. The larger
frequency range over which only analog predistortion is active,
is not shown in Figures 6 and 7. However, the spectral

performance over the larger frequency range is also enhanced but to a lesser extent than that shown in Figures 6 and 7.

CLAIMS

1. A method for linearising a radio frequency power amplifier by
   predistortion, comprising the steps of

a) receiving a digitized base-band input signal, to be amplified
   by said amplifier,

b) performing digital predistortion on the received signal to
   compensate for amplifier distortion,

c) converting by means of two D/A converters the predistorted
   signal to an analog signal,

d) performing analog frequency conversion on the converted
   analog signal,

e) performing analog predistortion on the frequency converted
   signal,

f) amplifying the analog predistorted signal by said amplifier.

2. A method for linearising a radio frequency power amplifier by
   predistortion, comprising the steps of

a) receiving a digitized base-band input signal, to be amplified
   by said amplifier,

b) performing digital predistortion on the received signal to
   compensate for amplifier distortion,

c) converting the digitally predistorted signal to a low
   intermediate frequency,

d) converting the signal to an analog signal via a D/A-
   converter,

e) performing analog frequency conversion to produce a radio
   frequency signal,

f) performing analog predistortion on the radio frequency
   signal,

g) amplifying the analog predistorted signal by said amplifier.

3. A method according to claim 1 or 2, comprising performing the
   step of analog predistortion adaptively by extracting an
   error signal component from the output of the amplifier to be
   used for adjusting the predistorted signal in accordance with
   error behaviour of the amplifier.

4) A method according to any of claims 1 - 3, comprising
performing the step of digital predistortion adaptively by
extracting an error signal component from the output of the
amplifier and adjusting the predistortion signal in
accordance with the error behaviour of the amplifier in
real-time operation.

5) A method according to any of claims 1 - 4, comprising
splitting the received baseband input signal into two signals
having a phase difference of 90o and thereafter performing
the steps of the respective preceding claims.

6) A power amplifier for linear amplification of radio frequency
(RF) signals, comprising
a) means for receiving a base-band input signal,
b) means for performing digital predistortion on the input
signal,
c) means for D/A converting the predistorted signal,
d) means for performing analog frequency conversion to achive
a radio frequency signal,
e) means for performing analog predistortion on the
radio frequency signal,
f) means for performing amplification on the signal of step
e).

7) A power amplifier for linear amplification of radio
frequency (RF) signals, comprising
a) means for receiving a base-band input signal,
b) means for performing digital predistortion on the input
signal,
c) means for converting the digitally predistorted signal to
a low intermediate frequency,
d) means for D/A converting the signal obtained by step c),
e) means for performing analog frequency conversion to
achieve a radio frequency (RF) signal,
f) means for performing analog predistortion.
g) means for performing amplification on the signal of step

f).

8) A power amplifier for linear amplification of radio
   frequency signals, comprising
   a) means for receiving a base-band input signal,
   b) means for splitting the received input signal into two
      signals having 90° phase difference,
   c) first and second path means for receiving each one of the
      two splitted signals obtained in step b), said first and
      second path means each including
      c1) means for digital predistortion of the respective
          signal,
      c2) means for D/A converting the signals obtained by step
          c1),
      c3) means for performing analog frequency conversion on
          the signals obtained by step c2),
      c4) means for performing analog predistortion on the
          signals obtained by step c3),
      c5) means for amplifying the signals obtained in step
          c4),
   d) means for combining the processed signals.

9) A power amplifier for linear amplification of radio
   frequency (RF) signals, comprising
   a) means for receiving a base-band input signal,
   b) means for splitting the received input signal into two
      signals having 90° phase difference,
   c) first and second path means for receiving each one of
      the two splitted signals obtained in step b), said
      first and second path means each including
      c1) means for digital predistortion of the respective
          signal,
      c2) means for converting the digitally predistorted
          signal to a low intermediate frequency,
      c3) means for D/A converting the signal resulting from
          step c2),
      c4) means for performing analog frequency conversion

on the signal resulting from step c3) for
producing a radio frequency signal,

c5) means for performing analog predistortion on the
signal resulting from step c4),
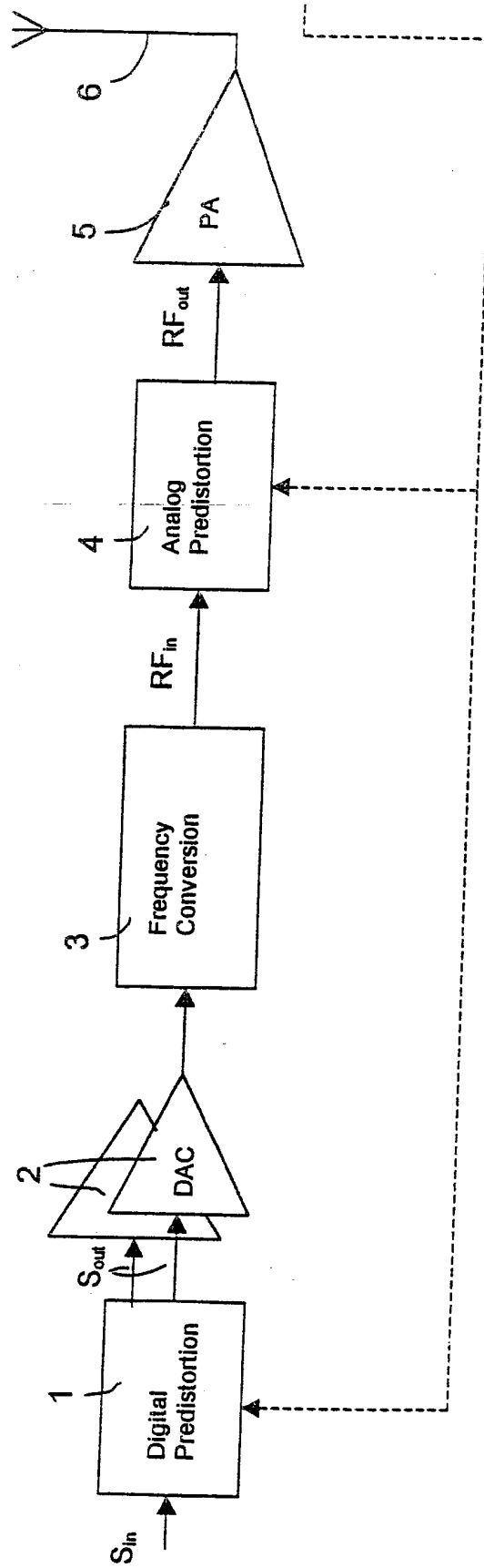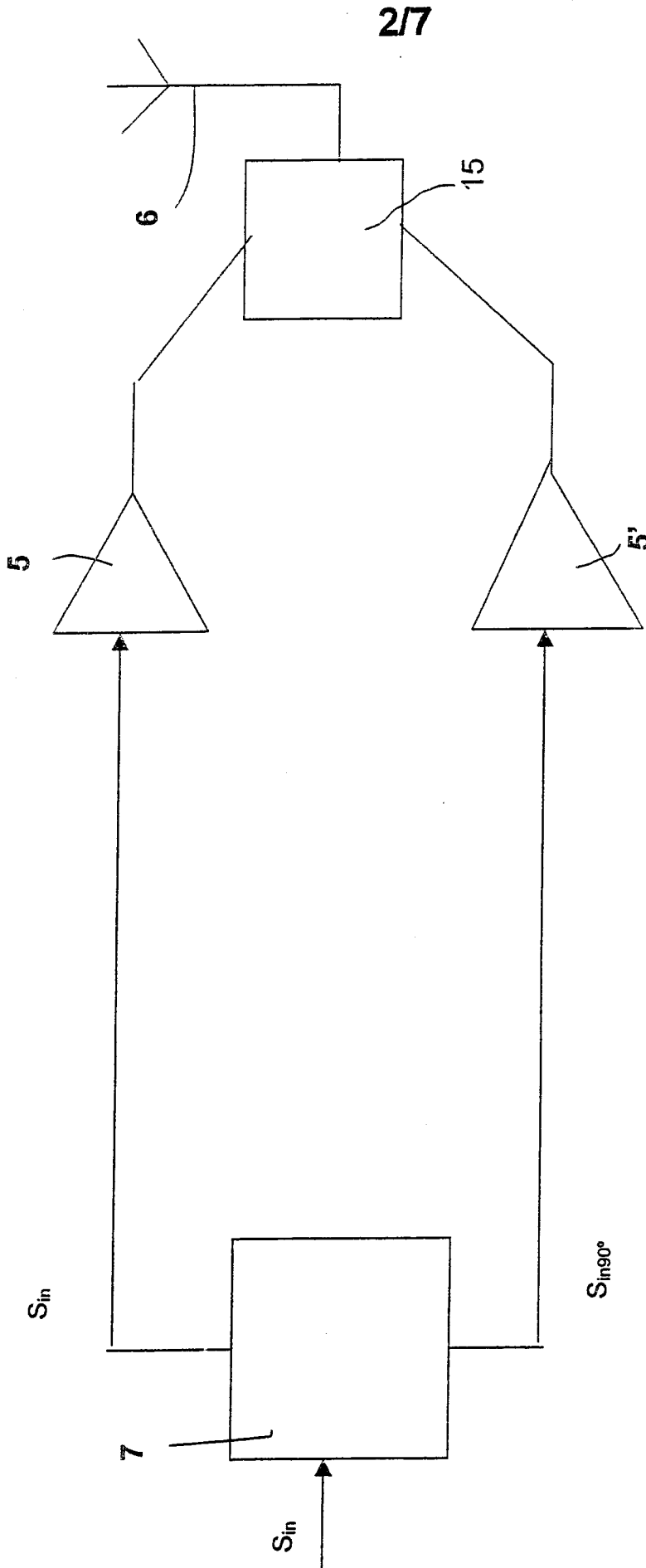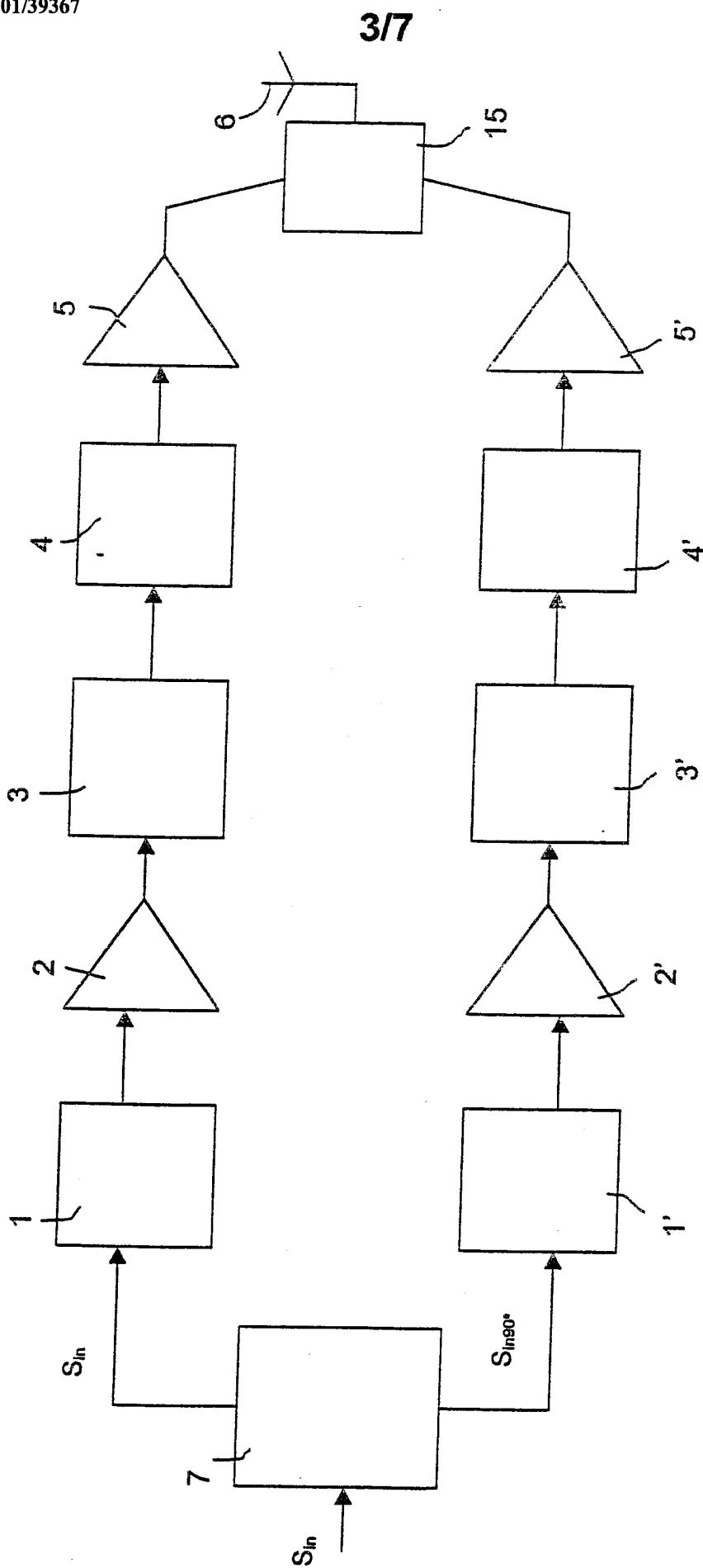
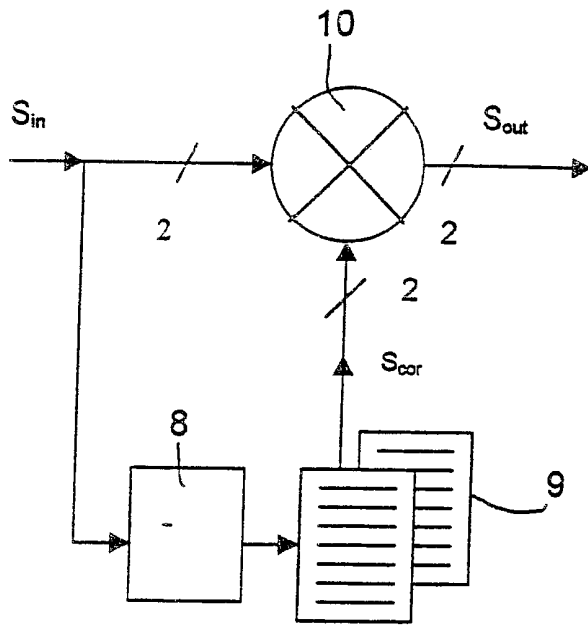d) means for combining the processed signals.

FIG. 1

FIG. 2

FIG. 3

FIG. 4
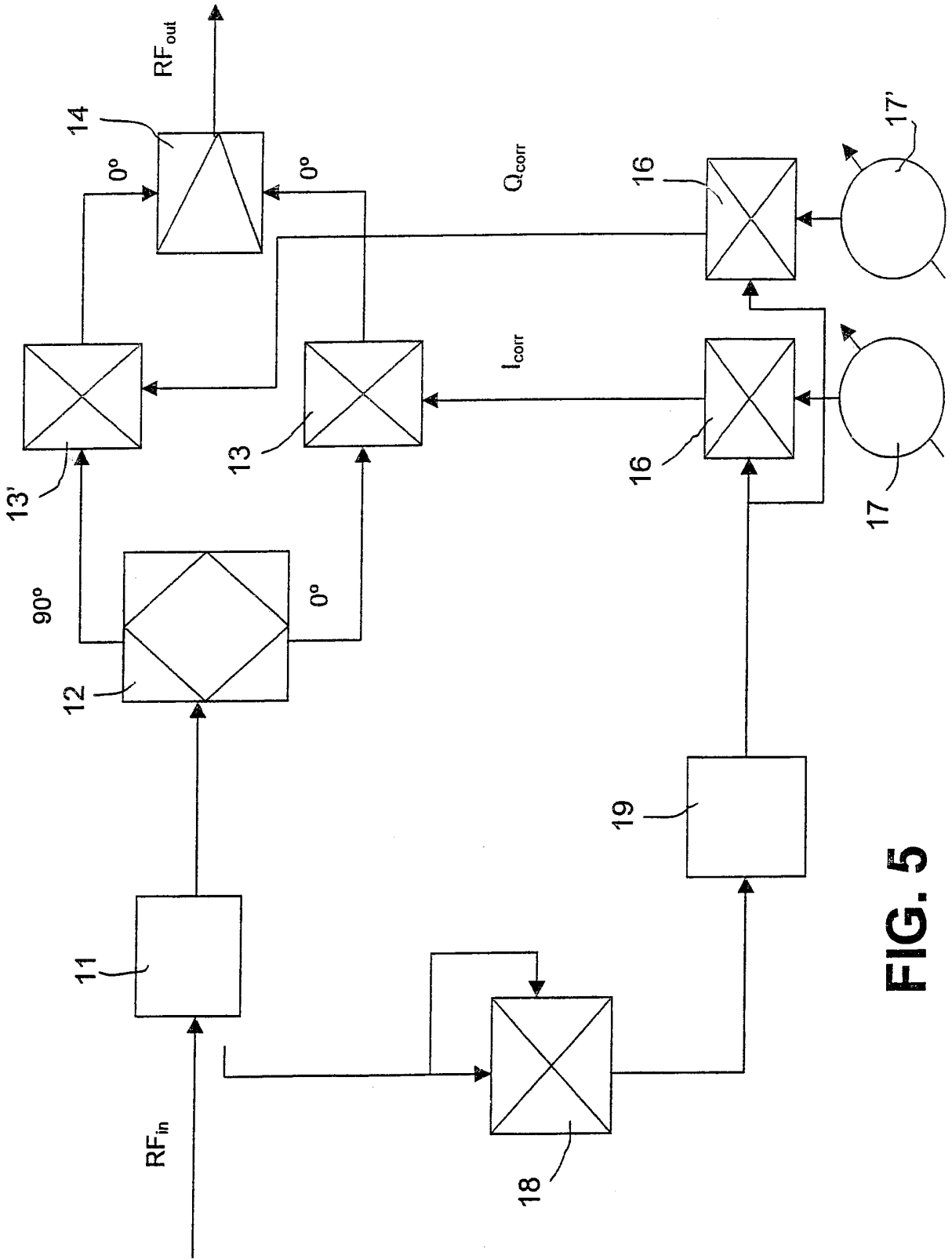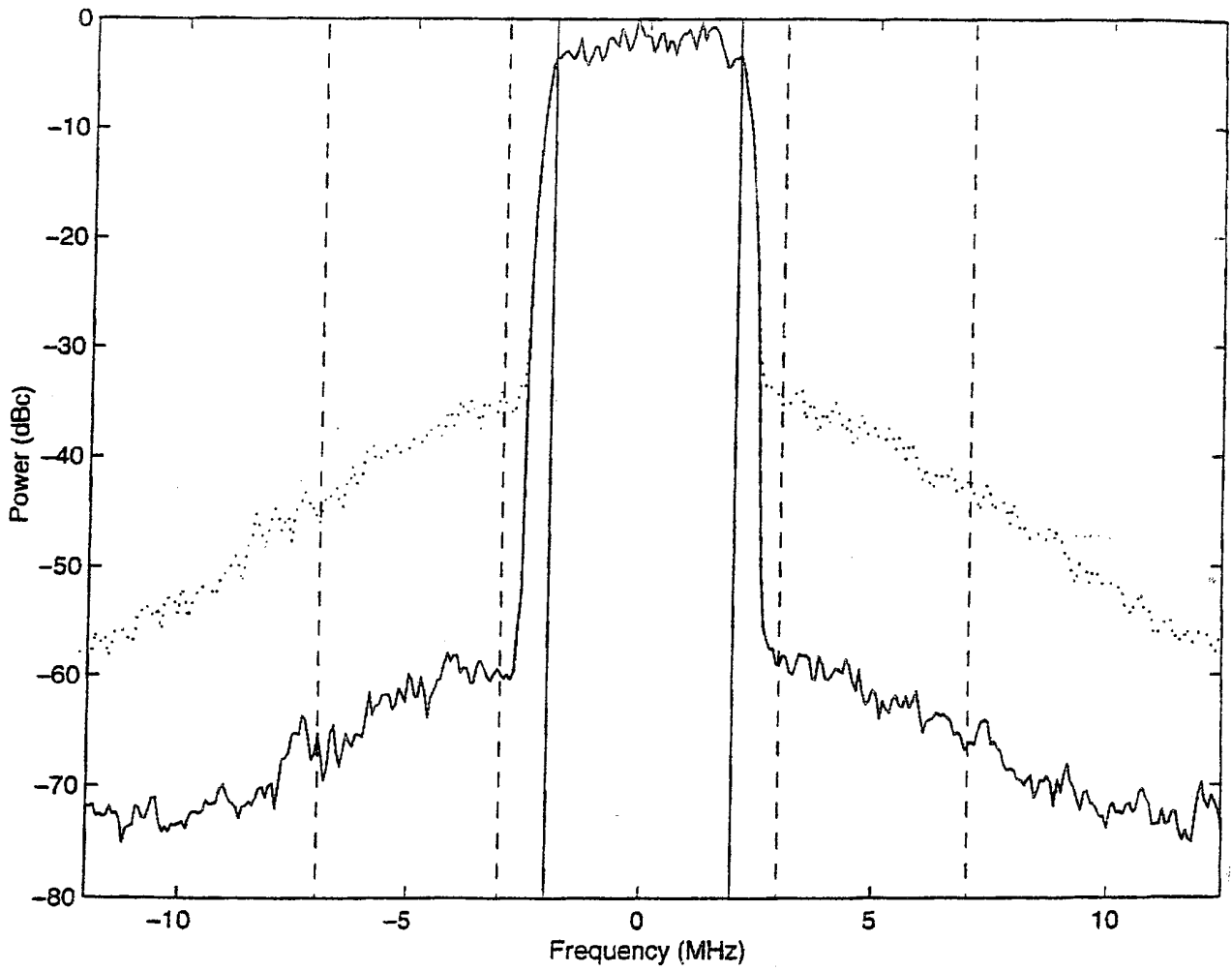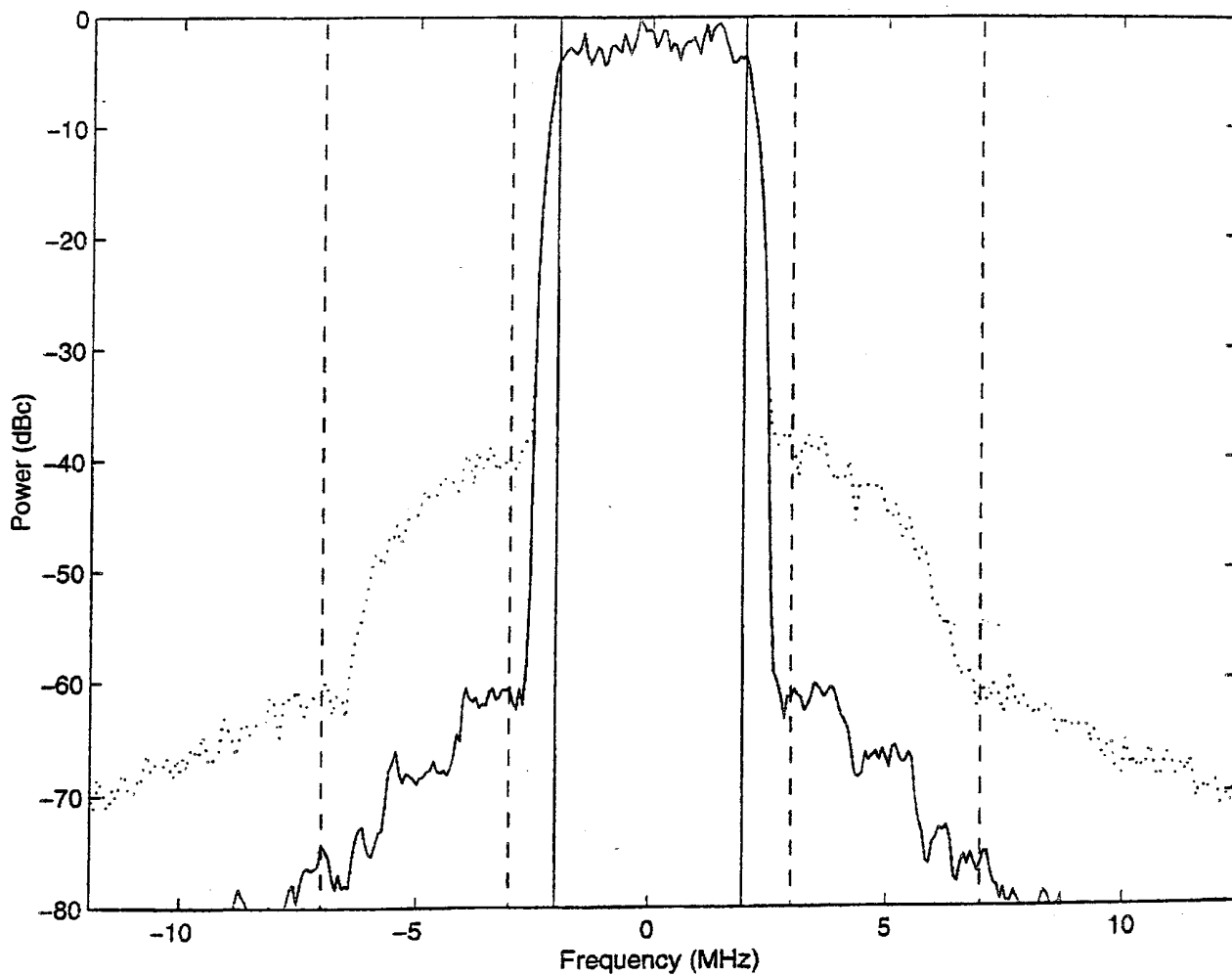
FIG. 5

FIG. 6

FIG. 7

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   H03F1/32

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   H03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 898 338 A (PROCTOR JAMES A ET AL) 27 April 1999 (1999-04-27)	1,3,4,6, 8
Y	the whole document	2,5,7,9
Y	US 4 291 277 A (BOYD ROBERT W ET AL) 22 September 1981 (1981-09-22)	2,5,7,9
A	the whole document	1,3,4,6, 8

☐ Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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Date of the actual completion of the international search	Date of mailing of the international search report
7 March 2001	14/03/2001

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 5898338	A	27-04-1999	EP	0928515 A	14-07-1999
			WO	9812800 A	26-03-1998
			US	5949283 A	07-09-1999
US 4291277	A	22-09-1981	NONE		