Amplifier Circuit For RF System

Field of the Invention

This invention relates generally to amplifier circuits, and more particularly to amplifier circuits for use in a radio frequency communication system.

Background of the Invention

Conventional feed-forward amplifiers can be generally placed into various categories identified as types I, II, and III, based on the way a desired signal and error signal are distributed through a various amplifiers and couplers comprising a feed-forward loop. A conventional type I feed-forward amplifier achieves a high degree of intermodulation (IM) reduction, typically about 20 dB, but has poor efficiency. Traditional type I feed-forward amplifiers only have an efficiency of about 5% which leads to high operating costs.

Conventional type II feed-forward amplifiers have improved efficiency compared to type I amplifiers, but type II amplifiers have a drawback of limited IM reduction. Also, conventional type II amplifiers reduce system gain, typically about 4 dB. Type III feed-forward amplifiers offer a compromise between efficiency and IM improvement (about 20 dB), but with further reduced system gain of about 7 dB. In addition, due to the complexity of type III feed-forward

amplifiers, it is difficult to control these amplifiers to achieve optimum IM reduction.

Accordingly, there is a need for an improved amplifier circuit that provides improved efficiency, easier control, and IM reduction without undesirably reducing system gain. Further, there is a need for an improved method of controlling feed-forward amplifiers.

Summary of the Invention

One aspect of the invention involves an amplifier circuit for use in a radio frequency system. The circuit is comprised of a first amplifier having a first input receiving a first signal and a first output. A first coupler samples the first input of the first amplifier and a second coupler samples the first output of the first amplifier. A third coupler is responsive to an output of the second coupler and an output of the first coupler. The third coupler produces an error signal which is substantially indicative of the difference between the first input and the first output. A fourth coupler combines the error signal with a second signal to produce a composite signal. The second signal is at least partially correlated with the first signal received by the first input of the first amplifier. A second amplifier is responsive to the composite signal and produces a second output.

A second aspect of the invention concerns a circuit comprised of a first amplifier having a first input and a first output. A second amplifier is responsive to the first output of the first amplifier. The second amplifier has a second input receiving a first signal and also has a second output. A first coupler samples the second input of the second amplifier and a second coupler samples the second output of the second

amplifier. A third coupler responsive to an output of the second coupler and responsive to an output of the first coupler produces an error signal which is substantially indicative of the difference between the second input and the second output. A fourth coupler samples the first output of the first amplifier. A fifth coupler responsive to the fourth coupler and the error signal produces a composite signal. The composite signal is passed to a sixth coupler which is also responsive to the second output of the second amplifier.

A combination of the first two aspects of the invention produces another aspect in which the distortion level of an amplifier and preamplifier is reduced using a feed-forward correction network. A method of reducing errors in the amplifier includes a preamplifier injecting a split signal to parallel amplifiers. A sample of the input and output of one of the parallel amplifiers is compared to generate an error signal. This signal is injected at the input of the second parallel amplifier at such a level as to predistort the second amplifier. The level of this error signal is further set such that when the parallel amplifiers recombine, the error generated from the first of the parallel amplifiers is substantially reduced and the error introduced by the preamplifier is also significantly reduced.

Another aspect of this invention involves a method of controlling the above described amplifier circuits. The method includes the following steps:

(a) taking a plurality of signal strength measurements, each measurement taken at a different frequency within a measured frequency band;

(b) comparing each measurement with a predetermined threshold value;

(c) discarding measurements that exceed the threshold;

(d) selecting a first maximum measured value by picking a highest measured value from the remaining measurements; and

(e) adjusting an amplitude and phase adjustment circuit coupled to an amplifier circuit based on the first maximum measured value.

The invention itself, together with its intended advantages will best be understood by reference to the following detailed description, taken in conjunction with the accompanying drawings.

Brief Description of the Drawings

FIGs. 1-4 are block circuit diagrams of preferred embodiments of amplifier configurations.

FIG. 5 is a flow chart of a preferred embodiment of a method of controlling an amplifier circuit.

FIG. 6 is a block diagram of another preferred embodiment of an amplifier circuit.

FIG. 7 is a more detailed schematic circuit diagram of a particular preferred amplifier circuit.

Detailed Description of the Preferred Embodiments

A preferred embodiment of the invention is shown in FIG. 1. An amplifier **40**, a delay **32**, and couplers **18, 26** and **36** comprise a circuit capable of extracting an error signal generated in an amplifier **22** and re-injecting that error signal at the proper level at a coupler **44**. This allows the error signal to be injected at coupler **44** independent of a component of an input signal **12**.

An amplifier pair of the amplifier 22 and an amplifier 52 as well as a coupler 14 and a coupler 62 form a parallel amplifier network. In this case, coupler 14 and coupler 62 are 90° 3 dB couplers, splitting the power between the amplifiers 22 and 52 and then recombining the outputs of amplifiers 22 and 52 for combined power at an output 64.

In the circuit of Figure 1, a signal 12 is passed through coupler 14 and produces a signal 16 and a signal 45. In the preferred embodiment, these signals 16, 45 are substantially similar in amplitude and have an approximately 90° phase difference. The signal 16 is passed through coupler 18 producing a sample of signal 16 as signal 30 and an input 20 to amplifier 22. The signal 30 passes through the delay 32 to produce a signal 34. The signal 34 then provides a signal comprised of a component of input signal 12. The component of the input signal 12 will hereafter be referred to as the desired signal component. The signal 20 passes through amplifier 22 which produces a composite signal 24 of the desired signal component and an error signal generated in amplifier 22. The error signal generated in amplifier 22 will hereafter be referred to as the first error signal. A coupler 26 supplies a sample of the composite signal 24 as a signal 28. The signal 24 also passes through coupler 26 and a delay 58 to produce a signal 60 which is passed to coupler 62. The signal 60 is comprised of the desired signal component and the first error signal component.

The composite signal 28 is also comprised of the desired signal component and the first error signal component. The delay 32 is set such that the group delay from coupler 18 to coupler 36 through delay 32 is approximately equal to the group delay from coupler 18 to coupler 36 through amplifier 22 and coupler 26. The couplers 18, 26, and 36 and loss

through delay 32 are set such that the desired signal component in signal 34 after it has passed through coupler 36 is substantially similar in amplitude and approximately 180° out of phase from the desired signal component of the composite signal 28 after it has passed through coupler 36. A resultant signal 38 is then generated as the desired signal components are substantially reduced by coupler 36 leaving the first error signal component. This resultant signal 38 is then amplified by amplifier 40 producing a signal 42 which is passed to coupler 44. The signal 45 is delayed through a delay 46 to produce a signal 48 which is also passed to coupler 44.

At this point, coupler 44 combines the signal 48 and the signal 42 to create a signal 50 which is comprised of the desired signal component and the first error signal component. The delay 46 is set such that the group delay from coupler 14 to coupler 44 through delay 46 is approximately equal to the group delay from coupler 14 to coupler 44 through coupler 18, delay 32, coupler 36 and amplifier 40 and such that the phase difference of the two paths is approximately zero. With the rest of the amplifier 100 configured as per the preferred embodiment, this aligns the first error signal component extracted at coupler 36 and passed through amplifier 40 such that feed-forward correction can occur at coupler 62.

The signal 50 is amplified by the amplifier 52 which produces a signal 54. The signal 54 is comprised of the desired signal component, the first error signal component, and an error signal generated in amplifier 52. The error signal generated in amplifier 52 will hereafter be referred to as the second error signal. Signal 54 is input to coupler 62.

In the preferred embodiment, the desired signal component present in signal 20 is substantially similar to the

desired signal component present in signal 50. Also in the preferred embodiment, amplifier 22 and amplifier 52 are the same or substantially similar amplifiers. As such, the first error signal present in signal 24 is substantially similar to the second error signal present in signal 54. When the first error signal component is extracted at coupler 36 and passed through amplifier 40 and amplifier 52, it is approximately 180° out of phase with the second error signal present in signal 54.

The delay 58 is set such that when the desired signal component present in signal 60 passes through coupler 62, the amplitude is substantially similar and the phase is approximately equal with the desired signal component present in signal 54 after it has passed through the coupler 62. With this condition met, the first error signal component present in signal 60 after it has passed through coupler 62 is approximately 180° out of phase with the first error signal component present in signal 54 after it has passed through coupler 62.

In the preferred embodiment, the coupler 44 is set such that the amplitude of the first error signal component present in signal 42 is sufficient to substantially reduce the second error signal present in signal 54 as well as substantially reduce the first error signal component present in signal 60 after it has passed through coupler 62.

One benefit of this configuration is in the ease of construction of the parallel amplifier network. A second benefit is derived from the first error signal being injected at coupler 44 independent of the desired signal component. When controlling the overall amplifier, adjustments made to improve IM performance are substantially isolated from the

power combining of the desired signal components through amplifiers **22** and **52**.

A third benefit from this configuration can be seen when a pre-amplifier **66** is added to the amplifier **100** in FIG. 1. This is shown in FIG. 2 and is a second embodiment of the invention. In most conventional feed-forward amplifiers, output IM performance is limited to the IM performance of amplifier **66**. However by choosing amplifier **66** to have a transfer characteristic that is similar to the transfer characteristic of amplifier **22**, the configuration of amplifier **200** offers an opportunity to correct for the error signal generated in amplifier **66**. This error signal generated in amplifier **66** will hereafter be referred to as the initial error signal. The initial error signal propagates from the output of amplifier **66** through the entire amplifier **20** to a coupler **62**. Since the transfer characteristics of amplifier **22** and amplifier **66** are similar, the error signals generated by these amplifiers will be substantially similar at the output of amplifier **200**. Since this is the case in the preferred embodiment shown in FIG. 2, the component of the first error signal present in signal **50** can be adjusted to a higher level such that it will substantially reduce the initial error signal component present in signal **64**. In this way, the amplifier **200** acts as a postdistortion correction mechanism for amplifier **66**.

An alternative postdistortion correction circuit is shown in FIG. 3. In this circuit **300**, since there is no amplifier **52**, the amount of the first error signal component present in signal **42** injected at coupler **44** is the amount necessary to substantially reduce the first error signal component and the initial error signal component present in signal **64**. The ability of this configuration **300** to correct the initial error signal is dependent on the similarity of the initial error signal and the

first error signal. The closer the transfer functions of these amplifiers 66 and 22, the better the circuit 300 achieves postdistortion correction of amplifier 66.

Another preferred embodiment of the invention is shown in FIG. 4. The amplifier shown, 400, is a feed-forward amplifier providing predistortion correction of amplifier 52, postdistortion correction of amplifier 66, and feed-forward correction of amplifier 22 using an active controller 80. The addition of amplitude and phase adjustment circuits 70 and 83, a power detector 78, a receiver 88, couplers 76 and 84, and controller 80 combine to provide a system that continuously monitors amplifier 400 and makes adjustments to keep amplifier 400 operating approximately near its optimal operating point.

An attenuator 90 is used to set the amplitude of the sampled signal 28 from coupler 26 so that the output of the attenuator 90 is a signal 92 which has a desired signal component with an amplitude substantially similar to the amplitude of the desired signal component contained in signal 72. An attenuation value is typically set such that the amplitude of the desired signal component in signal 92, when passed through a coupler 36, will be approximately in the center of an adjustable amplitude range of the desired signal component contained in signal 72 when it has passed through the amplitude and phase adjustment circuit 70 and through coupler 36. The amplitude of the desired signal component may be adjusted through the amplitude shifter in amplitude and phase adjustment circuit 70. The delay element 32 and phase shifter element contained in the amplitude and phase adjustment circuit 70 set the incoming signals to coupler 36 such that the desired signal components present in signals 72 and 92 are approximately 180° out of phase after passing

through coupler 36. A coupler 76 is used to sample signal 38 and pass samples to the power detector 78. The power detector 78 in conjunction with the controller 80 adjust the amplitude and phase adjustment circuit 70 to minimize what remains of the canceled desired signal components present in signal 38.

An important point in the operation of amplifier 400 is in determining how much of the first error signal component present in signal 42 should be injected into coupler 44. Preferably, there should be sufficient signal present to substantially reduce the second error signal present in signal 54, as well as substantially reduce the first error signal component and the initial error signal component present in signal 64. The amount of the first error signal that is injected is determined by the controller 80 through information gathered from the receiver 88. Using this information, the amplitude and phase adjustment circuit 83 is adjusted for reduction of the error signals present in signal 64.

It should also be understood that the control of this feed-forward system preferably uses a method which is related directly to output distortion. Using such a control method, the preferred embodiment shown in FIG. 4 is easy to configure and is easy to control. A significant advantage of this amplifier 400 is the ability to use a more efficient preamplifier such as amplifier 66. In conventional feed-forward amplifiers, preamplifiers are typically less efficient amplifiers because the linearity of such an amplifier is generally needed to meet the overall linearity requirements of the amplifier 400. In the preferred embodiment, since postdistortion correction of amplifier 66 is configured along with the feed-forward correction of amplifier 22 and the predistortion correction of amplifier 52, the preamplifier 66 can be of a more efficient

class, such as a class AB or class C amplifier, thereby improving the efficiency of the entire amplifier system **400**. With the ability to post-distort correct amplifier **66**, the preamplifier **66** may be any class amplifier except class A since class A amplifiers are not efficient.

To control amplifier **400**, first, a reading is taken for the current settings of the amplitude and phase adjustment circuit **70**. The phase shifter contained in amplitude and phase adjustment circuit **70** is then stepped in value and a new measurement is recorded. This new measurement is compared with the current measurement. If the new measurement is smaller than the current measurement, the phase shifter is left at the new setting and the process repeated. If the new measurement is greater than the current measurement, the phase shifter is returned to its previous setting, the stepping direction is reversed, and a change of direction is noted. The process is repeated until three direction changes have been recorded. The phase shifter contained in the amplitude and phase adjustment circuit **70** is then left at this setting and the amplitude shifter in the amplitude and phase adjustment circuit **70** is adjusted through a similar process. The above process is then repeated for amplitude and phase adjustment circuit **83** using a different measurement of interest. In this way, the amplitude and phase adjustment circuits **70** and **83** are set such that their measurement of interest are substantially reduced.

For amplitude and phase adjustment circuit **70**, the measurement of interest is the power measurement of power detector **78**. For phase and gain adjustment circuit **83**, the measurement, outlined in detail in FIG. 5, is related to the received signal strength indicator (RSSI) of receiver **88**. For the measurement of interest for amplitude and phase

adjustment circuit **83**, the receiver **88** is first stepped, at **502**. Next, at **504**, a received signal strength indicator (RSSI) measurement is taken. At **506**, a comparison is made between the current reading and a previous RSSI reading. If the current reading is greater than the last reading then processing continues back at **502**. However if the current reading is not greater than the last reading then processing proceeds to step **508** where the current reading is stored as a maximum reading hereafter referred to as the new maximum.

Next, at **510** the receiver **88** is stepped again and another RSSI measurement is taken at **512**. At **514**, a comparison is made between the current RSSI reading and the last reading. If the current reading is less than the last reading then processing continues back at **510**. However, if the current reading is not less than the last reading then a comparison is done, at **516**, to determine whether the new maximum is greater than a predetermined threshold value. If so, then the new maximum is discarded at **518**. However, if the new maximum is not greater than the threshold value, then processing continues at **520**. At **520**, a comparison is made between the new maximum against the greatest maximum recorded. If the new maximum is larger than the greatest maximum recorded, then the new maximum is saved at **524** as the greatest maximum. Otherwise, the new maximum is discarded at **522**.

The above processing is continued until the receiver **88** has been stepped across the entire frequency band of interest. In this manner, the preferred method **500** locates the highest local maximum which does not exceed the predetermined threshold value. The controller **80**, based on the greatest measured value which does not exceed the threshold, uses this information to adjust the amplitude and phase adjustment

circuit 83 by attempting to minimize this local maximum RSSI value.

The amplitude and phase adjustment circuits 70 and 83 are periodically adjusted and compared against the maximum value as determined by the method described with reference to Figure 5. In the preferred embodiment, the phase setting and amplitude setting of the amplitude and phase adjustment circuits 70 and 83 is adjusted in an attempt to minimize the measurements of interest.

The amplifier 300 configured as shown in FIG. 3 fixes all values for substantial correction at a desired operating condition. With the addition of a few components, active correction over many operating conditions can be achieved. One such example of this configuration is shown in FIG. 6.

The addition of the amplitude and phase adjustment circuits 70 and 83, the power detector 78, receiver 88, controller 80, and the addition of couplers 76 and 84 comprise a control system for the postdistortion correction amplifier.

This method of controlling a feed-forward amplifier circuit has many benefits. For example, it provides a control method which is directly responsive to the IM present at the output of the amplifier circuit 400 which takes advantage of the postdistortion correction configuration for amplifier 66 and the predistortion correction of amplifier 52. This method also provides a way of separating the distortion from the desired signal without storing large amounts of spectral information. This method also requires very little processing resources and can be applied to both the configuration shown in FIG. 2 and the configuration shown in FIG. 5.

Another example of a particular embodiment is shown in FIG. 7. Further details regarding specific components is available by reference to the Motorola Supercell SC™ 9600 base station and by reference to "Linear Power Amplifier Equipment Description" available from Motorola, Inc., Cellular Publishing Services at 1501 W. Shure Drive, Arlington Heights, Illinois 60004.

Further advantages and modifications of the above described apparatus and method will readily occur to those skilled in the art. The invention, in its broader aspects, is therefore not limited to the specific details, representative apparatus, and illustrative examples shown and described above. Various modifications and variations can be made to the above specification without departing from the scope or spirit of the present invention, and it is intended that the present invention cover all such modifications and variations provided they come within the scope of the following claims and their equivalents.

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Claims

What is claimed is:

1. An amplifier circuit for use in a radio frequency system, said circuit comprising:

a first amplifier having a first input receiving a first signal and a first output;

a first coupler sampling the first input of the first amplifier;

a second coupler sampling the first output of the first amplifier;

a third coupler responsive to an output of the second coupler and responsive to an output of the first coupler, said third coupler producing an error signal which is substantially indicative of the difference between the first input and the first output;

a fourth coupler responsive to the error signal and responsive to a second signal and producing a composite signal, said second signal at least partially correlated with the first signal received by the first input of the first amplifier; and

a second amplifier having a second input that is responsive to the composite signal and having a second output.

2. The circuit of claim 1, wherein said second amplifier has a second input coupled to said fourth coupler.

3. The circuit of claim 1, further comprising a splitter coupled to said first coupler, said splitter producing said first signal and said second signal.

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4. The circuit of claim 3, further comprising a delay circuit responsive to said splitter, said delay circuit receiving an output of said splitter and producing said second signal.

5. The circuit of claim 1, further comprising a fifth coupler responsive to the first output of the first amplifier and the second output of the second amplifier.

6. The circuit of claim 1, further comprising an amplitude and phase adjustment circuit, wherein at least one of said couplers is responsive to said amplitude and phase adjustment circuit.

7. A method of adjusting an amplitude and phase adjustment circuit coupled to a feed-forward amplifier circuit, said method comprising the steps of:

(a) taking a plurality of signal strength measurements, each measurement taken at a different frequency within a measured frequency band in order to determine a local maxima;

(b) comparing the local maxima with a predetermined carrier threshold value;

(c) discarding measurements that exceed the threshold;

(d) selecting a first maximum measured value by picking a highest measured value from the remaining local maxima: and

(e) adjusting the amplitude and phase adjustment circuit based on the first maximum measured value.

8. An amplifier circuit for use in a radio frequency system, said amplifier circuit comprising:

a first amplifier having a first input and a first output,

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a second amplifier responsive to said first output of said first amplifier, said second amplifier having a second input receiving a first signal and a second output;

a first coupler sampling the second input;

a second coupler sampling the second output of the second amplifier;

a third coupler responsive to an output of the second coupler and responsive to an output of the first coupler, said third coupler producing an error signal which is substantially indicative of the difference between the second input and the second output;

a fourth coupler sampling the first output of the first amplifier;

a fifth coupler responsive to said fourth coupler and said error signal and producing a composite signal; and

a sixth coupler responsive to the second output of the second amplifier and responsive to the error signal.

9. The amplifier circuit of claim 8, further comprising a third amplifier responsive to said fifth coupler.

10. A method of reducing errors in an amplifier circuit comprising the steps of:

injecting a split signal from a preamplifier to first and second amplifiers, said first and second amplifiers in a substantially parallel arrangement;

sampling an input and an output of the first amplifier;

generating an error signal by comparing the sample of the input and the sample of the output; and

injecting the error signal at an input of the second amplifier at a level to predistort the second amplifier, the level sufficient to substantially reduce error from the first amplifier and to reduce error from the preamplifier at a combined output of the first and second amplifiers.

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