Highly Efficient Feed-Forward Amplifier using a Class-F Doherty Amplifier

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***Abstract* — A new feed-forward amplifier configuration is proposed that uses a Doherty amplifier with Class-F operation as the main amplifier. Due to the new configuration, the enhanced main amplifier operates well with less output back-off and achieves high efficiency under Class-F operation compared with Class-B amplifier(non Doherty amplifier). A 2-GHz band 1-W class feed-forward amplifier is investigated. A back-off improvement of 3dB is experimentally achieved compared with a conventional feed-forward amplifier for the same intermodulation distortion level. The efficiency of the main amplifier is also improved from 33% to 52% when third-order intermodulation distortion of feed-forward amplifier is -50dB. The proposed technique can effectively reduce the power consumption of the power amplifiers for cellular base stations.**

I. INTRODUCTION

The continued surge in the popularity of mobile phones means that the number of base stations must also be increased. In many cases, new third-generation system equipment is added to base stations for the second-generation system (Personal Digital Cellular system: PDC). To improve the cost-effectiveness of the base stations, it is essential to reduce the power consumption of their power amplifiers.

Low power consumption must be accompanied by extremely low intermodulation distortion, less than -60dB for the digital cellular system. For this reason, the PDC base stations use feed-forward amplifiers. Even though such amplifiers have been refined over many years, we feel that their designs can be improved upon.

The Doherty configuration [1,2] is known to offer improved power amplifier efficiency, especially at low input-power levels. This paper extends the Doherty amplifier to support Class-F operation and so achieve higher efficiency. This new amplifier is used as the main amplifier of a feed-forward power amplifier [3]. Tests conducted on a 2-GHz 1-W class amplifier confirm the significant efficiency improvement.

II. EFFICIENCY OF FEED-FORWARD AMPLIFIER

The output power P_{out} of feed-forward amplifier can be written as

$$P_{out} = \frac{P_{out\,M}}{L} + \frac{P_{out\,A}}{C_A} \qquad (1)$$

where P_{out_M} is the outpout power of the main amplifier, P_{out_A} is that of the error amplifier, L is the insertion loss from the output terminal of the main amplifier to that of the feed-forward amplifier, and C_A is the coupling factor from the output of the error amplifier to the output of the feed-forward amplifier. The efficiency η_T of the feed-forward amplifier can be expressed as follows:

$$\eta_T = \frac{P_{out}}{P_{DC_M} + P_{DC_A}} \qquad (2)$$

whrere P_{DC_M} and P_{DC_A} are the power consumption of the main amplifier and the error amplifier, respectively. The drain efficiency η_{dM} of the main amplifier and the drain efficiency η_{dA} of the error amplifier are defined as follows:

$$\eta_{dM} = \frac{P_{out\,M}}{P_{DC_M}} \qquad (3)$$

$$\eta_{dA} = \frac{P_{out\,A}}{P_{DC_A}} \qquad (4)$$

From these equations, η_T is given by

$$\eta_T = \frac{1}{L}\frac{\eta_{dM}}{1+\dfrac{P_{out_A}}{P_{out_M}}\dfrac{\eta_{dM}}{\eta_{dA}}} + \frac{1}{C_A}\frac{\eta_{dA}}{1+\dfrac{P_{out_M}}{P_{out_A}}\dfrac{\eta_{dA}}{\eta_{dM}}} \qquad (5)$$

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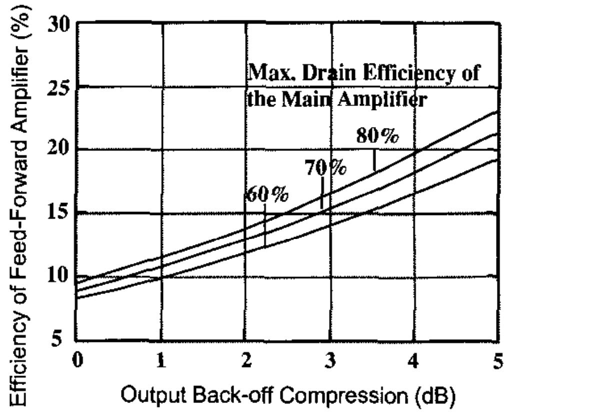

Fig.1 Estimated Efficiency of feed-forward amplifier using Class-B main amplifier, and Class-A error amplifier.

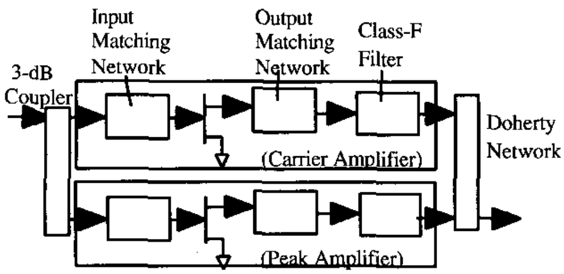

Fig.2 Basic configuration of the proposed amplifier.

The drain efficiencies η_{dM} and η_{dA} can be expressed in terms of the maximum drain efficiency and output back-off as

$$\eta_{dM} = \frac{\eta_{dMmax}}{\sqrt{10^{\frac{B_M}{10}}}}, \quad \text{Class-B} \tag{6}$$

$$\eta_{dA} = \frac{\eta_{dAmax}}{10^{\frac{B_A}{10}}}, \quad \text{Class-A} \tag{7}$$

where η_{dMmax} is the maximum drain efficiency of main amplifier, η_{dAmax} is that of error amplifier, B_M is output back-off of main amplifier, and B_A is that of error amplifier. The efficiency of the feed-forward amplifier, η_T, can be calculated from equations (5)-(7) using the output back-off and maximum drain efficiency.

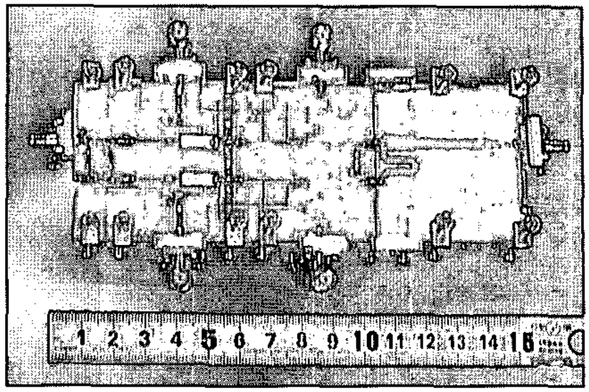

Fig. 3 Photograph of the developed Class-F Doherty amplifier (the enhanced main amplifier).

Figure 1 shows an example of estimated efficiency of the feed-forward amplifier. Output back-off in Fig. 1 is the value relative to the existing feed-forward amplifier in cellular base stations.

When output back-off is reduced by 3dB, the efficiency increases from 9% to 15% at the main amplifier efficiency of 70%. From this estimation, it is found that output back-off reduction and main amplifier efficiency greatly influence the efficiency of the feed-forward amplifier.

One method of reducing the output back-off is to use the predistortion technique [4], but this requires an automatic control mechanism and complicates the feed-forward configuration. In order to minimize the output back-off while also minimizing the size and complexity, we examined the use of the *Doherty amplifier* configuration.

III. DOHERTY AMPLIFIER IN CLASS-F OPEARTION

To improve the efficiency of the Doherty amplifier, we apply Class-F operation. Figure 2 shows the basic configuration of the Class-F Doherty amplifier. Figure 3 shows a photograph of a Class-F Doherty amplifier that offers 1-W output power in the 2-GHz band. The input matching network design frequency is 2.14GHz while the output matching network has design frequencies of 2.14GHz and 4.28GHz. The Class-F filter allows the open condition for the fundamental frequency component, while forcing the short condition for the second harmonic. The Doherty network is made of a 1/4-wavelength transmission line [2].

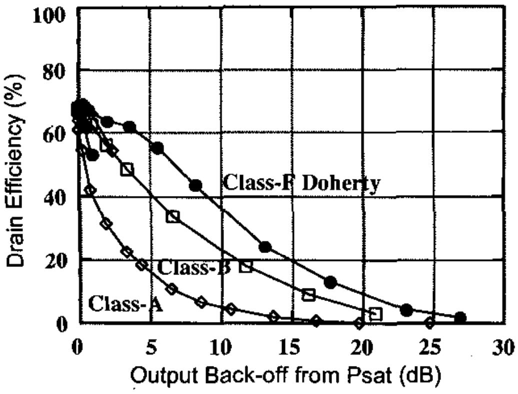

Fig.4 Drain efficiency on the proposed Class-F Doherty amplifier, Class-A, and Class-B amplifiers.

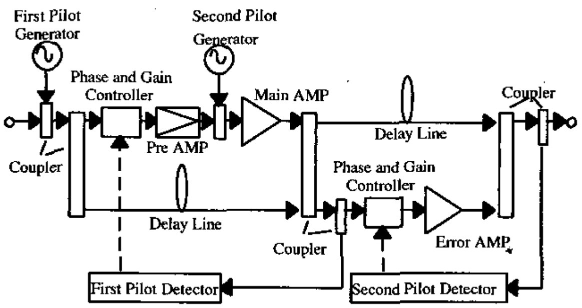

Fig.5 The configuration of Self-Adjusting Feed-Forward Amplifier (SAFF).

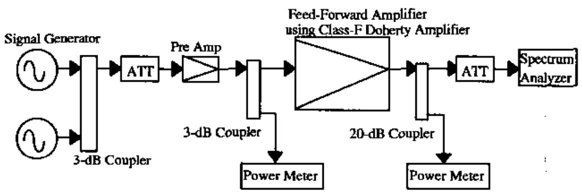

Fig.6 Test system for the proposed amplifier.

Figure 4 shows the drain efficiency of the developed Class-F Doherty amplifier in a comparison to Class-A and Class-B amplifiers. At 5-dB output back-off, the Class-F Doherty amplifier offers 20% higher drain efficiency than the Class-B amplifier.

IV. FEED-FORWARD AMPLIFIER TRIALS

Figure 5 shows a feed-forward amplifier configuration that uses two pilot signals to control the phase and gain [3]. The main amplifier is a Class-F Doherty amplifier.

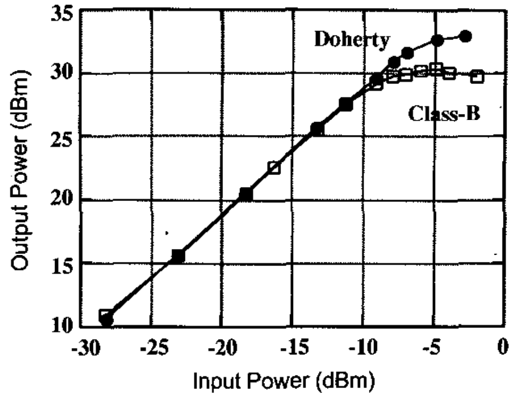

Fig.7 Output power performance of the proposed and the Class-B feed-forward amplifiers.

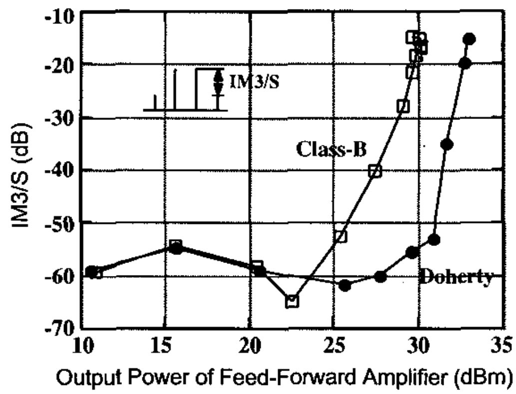

Fig.8 Third-order intermodulation distortion performance of the Doherty and Class-B ampifiers.

Figure 6 shows the test system. Two-tone CW signals were input to the feed-forward amplifier. Figure 7 shows the output power performance of the feed-forward amplifier. The Class-F Doherty amplifier increased the output power about 3dB compared to a Class-B main amplifier. Although most main amplifiers are either Class-A or Class-AB type, this paper considered only the Class-B type to better demonstrate the increase in efficiency possible.

Figure 8 shows the third-order intermodulation distortion performance of the feed-forward amplifier. The Class-F Doherty amplifier holds the distortion to less than –50dB at output powers under 31dBm, and achieves 35dB distortion reduction at 30dBm output power. This is because the Doherty amplifier extended the output power by as shown in the Fig. 7.

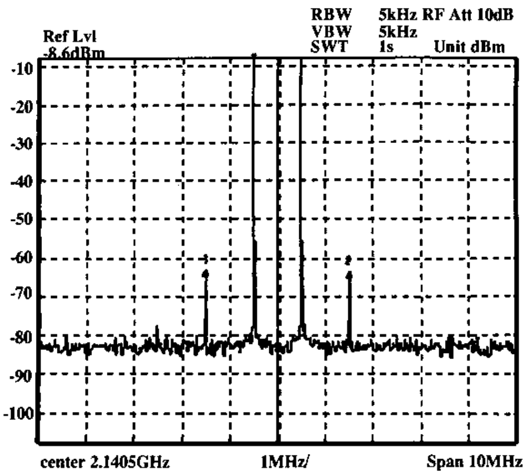

Fig.9 Spectrum of the feed-forward amplifier output signal using the Class-F Doherty main amplifier in output power at 30dBm.

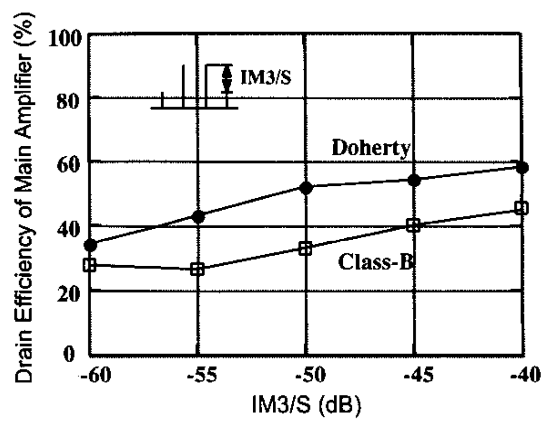

Fig.10 Improvement in drain efficiency of main amplifier with the proposed feed-forward amplifier.

Figure 9 shows the spectrum of the output signal of feed-forward amplifier that use the Class-F Doherty amplifier (output power at 30dBm). Figure 10 shows the drain efficiency performance of the main amplifier. At third-order intermodulaion distortion levels under –50dB, the drain efficiency of the Class-F Doherty amplifier is more than 50%. The improvement is due to the output back-off reduction made possible by the Class-F Doherty amplifier.

According to Fig. 1, 3-dB decrease in output back-off improves the feed-forward amplifier efficiency by 15% when the maximum drain efficiency is 70%.

V. CONCLUSION

A new highly efficient feed-forward amplifier configuration for mobile radio base station has been proposed. An efficiency model of feed-forward amplifiers, showed that efficient feed-forward amplification is possible by increasing the output back-off reduction and the efficiency of the main amplifier. A Doherty amplifier with Class-F operation was developed that achieves both goals. A fabricated 2-GHz band 1-W class Class-F Doherty amplifier was shown to reduce output back-off by 3dB.

At the third-order intermodulation distortion level of –50dB, the drain efficiency of the Doherty amplifier was 52%, which is much higher than 33% efficiency of the Class-B amplifier. The efficiency of the proposed feed-forward amplifier is estimated to be about 15%.

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REFERENCES

[1] W. H. Doherty, "A new high efficiency power amplifier for modulated waves", *Proceeding of the IRE*, vol.24, no.9, pp.1163-1182, 1936.

[2] R. J. McMorrow, D. M. Upton, and P. R. Maloney, "The microwave Doherty amplifier", in *1994 IEEE MTT-S Digest*, no.TH3E-7, pp.1653-1656, 1994.

[3] S. Narahashi, and T. Nojima, "Extremely low-distortion multi-carrier amplifier ---Self-adjusting feed-forward (SAFF) amplifier---", in *IEEE ICC'91, Conf., Rec.*, pp.46.5.1-46.5.6, 1991.

[4] K.Horiguchi, M.Nakayama, Y.Sakai, K.Yotani, H.Senda, Y.Ikeda, T.Takagi, and O.Ishida, "A efficiency bias condition optimized feedforward power amplifier with a series diode linearizer", *IEICE Trans. on Electron*, vol.E86-C, no.12, pp.1973-1980, Dec. 2002.