Development of High Efficiency Amplifier for Cellular Base Stations

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Demand for wireless communications by cellular phones and other wireless communication means is increasing dramatically; data traffic in 2015 is expected to be 10 times that in 2008. To meet such increasing demand, many telecommunication carriers are planning to replace their second-generation systems with third- or future-generation systems. One major problem to be resolved before upgrading the current systems is how to minimize the power increase associated with high data rate and system bandwidth broadening. In such circumstances we have developed a new technology that can dramatically reduce the power consumption of high power amplifiers, which comprise the majority of power consumed at cellular phone base stations. We successfully incorporated this technology into trial products of remote radio heads for base station use. These trial products achieved the industry's highest level of power efficiency.

Keywords: wireless, cellular, amplifier, envelop tracking, efficiency

1. Introduction

The popularity of cellular phones and other wireless communication means is growing rapidly. The number of cellular phone subscribers in Japan exceeded 100 million in 2007, which suggests many Japanese people currently use two or more cellular phones. The introduction of flat-rate data communication and other user-beneficial services has fostered the steady increase of data communication traffic by cellular phones. According to a demand forecast, worldwide demand for data communication traffic in 2015 will reach 10 times the level seen in 2008 (1).

In response to the increasing demand for communication traffic, cellular phone operators are planning to replace their second-generation cellular systems with third-generation or its successor.

One major problem associated with upgrading current cellular system to next-generation system is an increase in power consumption of the equipment caused by increasing data rate and broadening bandwidth. Cellular phone operators consume most of the power to operate base stations, switchboards and other communication equipment. Their power consumption accounts for some 10% of that consumed in the communications sector.

Taking these situations into account, we have developed a new technology to radically improve the efficiency of high-power amplifiers that consume most of the power required by cellular phone base stations. Using this technology, we manufactured high-power amplifiers and installed them in a remote radio head (RRH) for use in a cellular phone base station. The manufactured remote radio head achieved the highest level of efficiency in the industry. This paper discusses the details of the new technology.

2. Technology for Improving High-Power Amplifier Efficiency

Studies to improve power amplifier efficiency date far back to the time of AM broadcasting, but with wireless communication equipment, typified by cellular phones, now growing in popularity at an unprecedented pace, these studies have rapidly moved into the spotlight. In the early stages, researchers in these studies emphasized amplifier operation at a point near the saturation region, to achieve the highest possible efficiency while compensating for the distortion resulting from such operation. For this purpose, researchers introduced various linearization techniques, such as analog pre-distortion, feed forward and digital pre-distortion (DPD).

In recent studies, researchers have focused on improving the amplifier circuit itself, so as to further enhance amplifier efficiency. As a result, Doherty amplifier and other classic, yet new, techniques have been put into practice (2).

We introduced the Envelope Tracking (ET) technique as the new technology because it was expected to improve the efficiency of power amplifiers, enable broader bandwidth, and facilitate the manufacture and adjustment of power amplifiers more easily than Doherty amplifiers, which is currently mainstream in this field.

We also used the GaN-HEMT (gallium nitride high electron mobility transistor) in place of the currently popular Si-LDMOS (silicon laterally diffused metal oxide semiconductor) , in order to further improve efficiency.

Though the above two techniques were expected to dramatically improve the efficiency of power amplifiers, they would also affect the linearity and increase the distortion of the amplifiers. To eliminate such adverse effects, we developed a new DPD system as the third technique most adaptable to the above two techniques. CFR (crest factor reduction) is the fourth technique we incorporated into the new technology to further improve power amplifier efficiency. The CFR suppresses the crest of the RF (radio frequency) input signal for amplifiers, so as to enable their operation in high efficiency region. Combination of these four leading edge techniques achieved the highest level of efficiency in the industry (**Fig. 1**). These four techniques are detailed in the following sections.

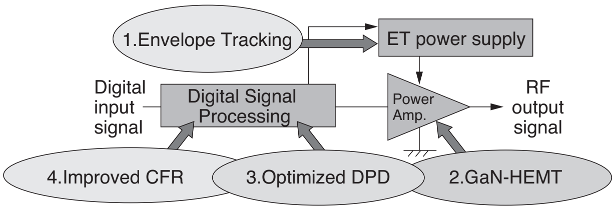


Fig. 1. Efficiency improvement of high-power amplifier

2-1 ET: Envelope Tracking

The ET was first described by Bell Laboratories in 1937 as a technique for improving power amplifier efficiency. For a conventional power amplifier, a constant high voltage is applied to the high-frequency high-power transistor so as to prevent distortion of the output signals even if their amplitude is maximized (**left of Fig. 2**). However, in the WCDMA (wideband code division multiplexing access) and OFDM (orthogonal frequency division multiplexing) systems, which are widely applied in new cellular phones and other communication networks, the modulated signal amplitude fluctuates largely with time. A large amount of electricity is therefore wasted when input signal amplitude is small.

According to the ET, the supply voltage to the transistor is controlled in response to input signal amplitude, so as to save a large amount of electricity that would be wasted in a conventional power amplifier (**right of Fig. 2**). Until recently, it has been difficult to design a power supply system (ET power supply unit) that can accurately respond to input signal amplitude fluctuation. However, the combination of a recently improved fast semiconductor and advanced digital signal processing technology has made it possible to put the ET into practical use.

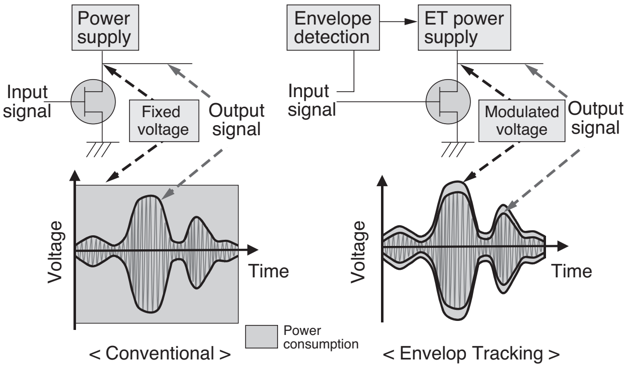


Fig. 2. Envelop tracking

2-2 GaN-HEMT

Owing to its excellent high-frequency and high-voltage operation characteristics, Si-LDMOS has mainly been used as a high-frequency high-power transistor for conventional power amplifiers for cellular phone base stations. Meanwhile, the use of GaAs or GaN, a compound semiconductor, further improves the high-speed high-frequency operation of the equipment. Sumitomo Electric Device Innovations, Inc. has commercialized GaN-HEMT for the first time in the world. In addition to its excellent high-speed, high-frequency characteristics, this product has a high-voltage operation characteristic, making it ideal for improving power amplifier efficiency.

Table 1 compares the physical properties of GaN with those of conventionally used semiconductors (3). Since GaN has a higher breakdown voltage than Si, it can operate at higher voltages and improve power amplifier efficiency.

GaN also has high electron mobility and saturation velocity, making it suitable for high-efficiency, high-power operations.

Table 1. Physical properties of hi-frequency transistor materials

Material	Breakdown Voltage (MV/cm)	Thermal Conductance (W/cm/K)	Mobility (cm^2/Vs)	Saturation Velocity ($\times 10^7$cm/s)
Si	0.3	1.5	1,300	1.0
GaAs	0.4	0.5	6,000	1.3
GaN	3.0	1.5	1,500	2.7

2-3 DPD: Digital Pre-Distortion

Although using the GaN-HEMT as a high-frequency high-power transistor and operating it by ET will dramatically improve power amplifier efficiency, it will substantially affect amplifier linearity and increase the distortion. Since distortion lowers telecommunications quality and broadens the frequency spectrum of RF, the allowable deterioration limit is strictly controlled by the applicable laws and standards.

In recent years, DPD techniques are frequently used to compensate for signal distortion in power amplifiers. In a DPD technique, the input part of the amplifier is equipped with a distortion compensation circuit called a pre-distorter. To enable a pre-distorter to thoroughly compensate the signal distortion in an amplifier, it is necessary to accurately estimate the amplifier's distortion characteristic. For this purpose, a statistical method is used in which the response of output signal amplitude and phase to the amplitude of signals fed into an amplifier is measured for use in developing the amplifier's distortion property model. The pre-distorter is an inverse model to the distortion property model of the amplifier, and preliminarily distorts the input signals in the direction opposite that of the amplifier, thereby finally obtaining distortionless amplifier output signals (**Fig. 3**).

The newly developed power amplifiers consisting of

GaN-HEMT and ET have a distortion property more complex than that of conventional amplifiers. To efficiently compensate for such complex distortion property, we developed a new distortion property model and model estimation algorithm for the new amplifiers. In this way, we succeeded in minimizing the distortion to a level that cannot be achieved by conventional techniques.

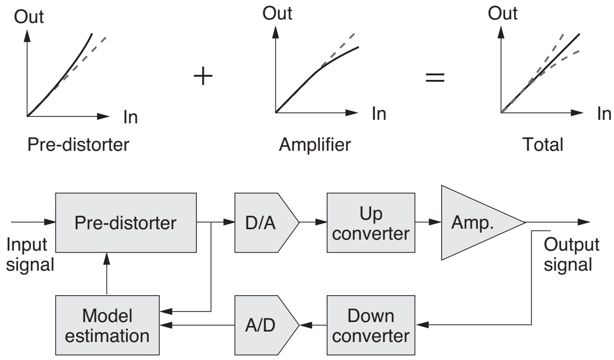


Fig. 3. Digital Pre-Distortion

2-4 CFR: Crest Factor Reduction

In WCDMA, OFDM, and other modulation architectures that are used in modern cellular phone systems, a large PAPR (peak-to-average power ratio) is the main factor in lowering the efficiency of power amplifiers. Reducing PAPR is also effective for improving ET power amplifier efficiency.

Simply reducing the peak of a signal will produce heavy distortion. To prevent distortion of a signal even when PAPR is reduced, Noise Shaving, Peak Windowing and various other CFR techniques have been developed (**Fig. 4**). In addition to these techniques, we have also developed a new CFR technique that is ideal for cellular phone systems. This new technique can reduce signal distortion at a PAPR to below conventional levels.

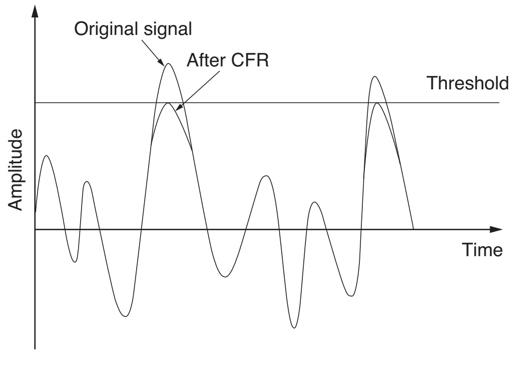


Fig. 4. Crest Factor Reduction (CFR)

3. Specifications of Trial Product

We have developed a high-power amplifier by integrating the above-discussed efficiency-improvement techniques and schemes, and have manufactured a unit as RRH (remote radio head) for cellular phone system. The equipment specifications are shown in **Table 2**; a photograph of a trial product is shown in **Photo 1**.

Table 2. Specifications of manufactured RRH

RF output port	Tx/Rx × 1
Transmission band	2110 - 2170MHz
Reception band	1920 - 1980MHz
Average output power	>40W
Application	3G & 3G-LTE
RF bandwidth	20MHz
BBU interface	CPRI (2.4576Gbps)
Input voltage	-39 ~ -60V
Waterproof level	IPX4

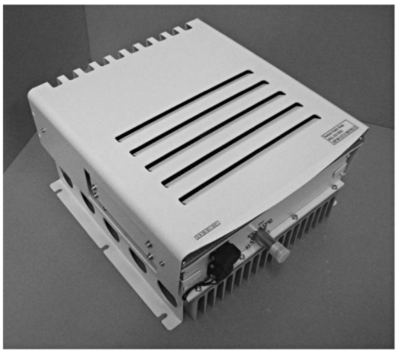


Photo 1. Manufactured RRH

3-1 RRH: Remote Radio Head

For a conventional cellular phone base station, only a antenna is installed in a high place, whereas the base station containing a high-power amplifier is located distantly from the antenna, such as inside a building or in a simply constructed station house. In some installations, high-frequency signals are transmitted a distance of 50 m or more between the antenna and base station. Coaxial cables are used to transmit high-frequency signals, yet the transmission loss becomes larger with the length of the cables. Use of larger diameter cables, to reduce such loss, deteriorates wiring flexibility and requires installation of cable-support frames.

The number of base stations with a new design scheme has increased recently. The high-frequency signal transmitter/receiver is separated as an independent unit from the base station and is located beneath the antenna. Signals are transmitted between this unit and the base station via a fiber-optic communication channel. This type of

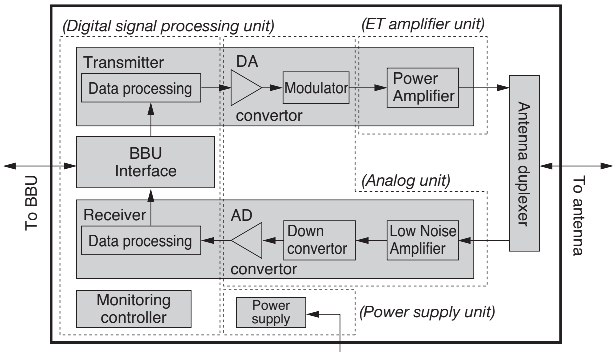


Fig. 5. Block diagram of RRH

wireless transmitter/receiver unit is called an RRH, which consists of a transmitter comprising a high-power amplifier, a receiver that receives and amplifies radio waves sent from cellular phones, a duplexer for transmitter and receiver, a base station interface, a monitoring controller and a power supply unit. A block diagram of an RRH is shown in **Fig. 5**. The following sections detail the functions of each unit represented by the circuit boards enclosed by broken lines in **Fig. 5**.

3-2 Functions of each unit

(1) ET amplifier unit

The ET amplifier unit consists of a GaN-HEMT amplifier, subunit an ET power supply unit that controls the power-supply voltage to be applied to the GaN-HEMT amplifier subunit, and a driver amplifier. An example of the efficiency characteristic of the manufactured GaN-HEMT amplifier subunit is shown in **Fig. 6**. The advantage of an ET amplifier is that it can maintain high efficiencies over a wide output power range by controlling the power-supply voltage. It shows that the manufactured amplifier maintained an efficiency of 50% or higher over an output power range of 9 dB.

(2) Digital signal processing unit

The digital processing unit mainly processes signals for DPD, and CFR for improving power amplifier efficiency, but it also has a digital up converter, a digital down converter, a base station interface and a monitoring controller.

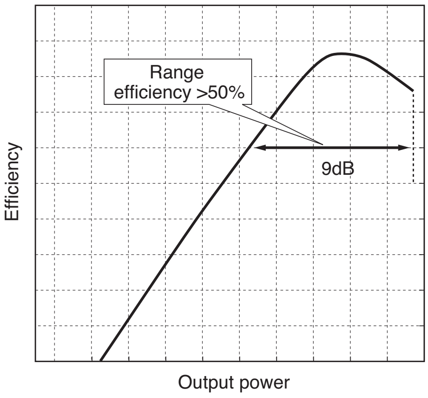


Fig. 6. Measured ET amplifier efficiency

The digital up converter develops along a frequency axis the wireless signals of each channel transmitted from the base station on a time-division basis. The digital down converter is responsible for time-division multiplexing each channel wireless signal received by an analog unit. The base station interface converts these wireless signals to CPRI (Common Public Radio Interface) format, in order to maintain communications with the baseband unit of the base station. Since most of these functions have been implemented in FPGA (field programmable gate array), this digital signal processor unit can be used for 3G (third-generation), 3G-LTE (third-generation long time evolution) or any other practical system by changing the firmware.

(3) Analog unit

The analog unit consists of a transmitter part and a receiver part. The transmitter part includes a high-speed DA converter, a quadrature modulator etc. so as to realize the data transmitting functions of the RRH. This unit converts transmit data generated by a digital signal processing unit to wireless signals.

The receiver part is provided with a low-noise amplifier to be connected to the antenna duplexer. When the unit receives signals, it amplifies these signals to a level sufficient for conversion to intermediate frequencies. The unit then performs signal sampling with a high-speed AD converter, so that the signals can be processed by a digital signal processing unit as incoming data.

(4) Power supply unit

The input power voltage for the manufactured RRH is -48VDC, which is common for RRHs. The main function of the power unit is to transform this input voltage to secondary voltages necessary for powering the devices with isolation. This power supply unit is also equipped with a surge absorber to protect them from lightening impulses and other electrical surges.

(5) Enclosure

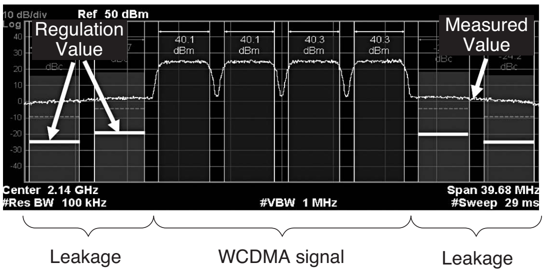
RRH is usually housed in an aluminum die-cast enclosure to facilitate outdoor installation and ensure sufficient heat dissipation. For a small number of manufactured RRHs, we made the enclosures by attaching an aluminum sheet metal box to heat sink available on the market. Owing to the use of waterproof connectors and the construction of watertight enclosures, the RRHs meet the IPX4 requirements of IEC Standards. The manufactured RRHs are maintenance-free because they do not contain cooling fans, which are essential for inefficient power amplifiers. With volume of 15.8 l and weight of 12.4 kg, each finished RRH is very compact and lightweight.

4. Evaluation Results

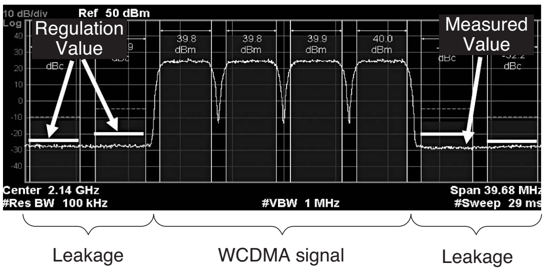
The following sections describe the evaluation results for the manufactured RRHs, particularly their applicability to third-generation or newer cellular phone systems: 3G (with WCDMA modulation) and 3G-LTE (with OFDM modulation). The new RRHs are applicable to various systems by changing the firmware implemented in the digital signal processing unit.

4-1 Applicability to 3G system

In the 3G system, a maximum of 4-channel WCDMA signals with a bandwidth of 5 MHz are transmitted. **Figure 7** shows the frequency spectrum obtained when 4-channel WCDMA signals with a center frequency of 2140 MHz were transmitted from one of the manufactured RRHs. Symbol (a) indicates the transmit frequency spectrum before application of the DPD. As this spectrum shows, a high ACLR (adjacent channel leakage ratio) caused by signal distortion was observed. In contrast, application of the newly developed DPD reduced the ACLR remarkably, to below the criteria of the applicable standard (4), as shown by spectrum (b). The RF output power level of the RRH was 46.1 W and its total power consumption was 164.6 W, meaning that its power efficiency was 28.0%. These powers were measured when all devices, including the signal receiving system, were fully loaded.



(a) without DPD



(b) with DPD

Fig. 7. RF output spectrum for 3G

4-2 Applicability to 3G-LTE system

Applicability of the new RRHs to the 3G-LTE system was also evaluated under the same conditions as those used for the 3G system. **Figure 8** shows the frequency spectrum of output signals that was obtained when 2-channel OFDM signals of 10 MHz bandwidth were transmitted. This figure shows that introduction of the new DPD technique reduced ACLR to below the criteria of the applicable standard (5).

For the 3G-LTE system, the applicable standard controls signal distortion more severely than for the 3G system, because the former uses a 64QAM (Quadrature Amplitude Modulation) architecture for the primary data modulation. The transmission speed of this architecture is higher than that used in the latter. In practice, the standard requires severe EVM (error vector magnitude). EVM is defined as the difference in amplitude and phase of an output signal that is demodulated by an ideal receiver from the theoretically determined amplitude and phase. **Photo 2** shows a constellation: a map that plots the amplitude and phase of transmitted signals that are demodulated by a measuring instrument in one plane; 64 signals corresponding to 64QAM can be identified clearly, demonstrating that the new RRHs can also clear the EVM criteria of the applicable standard (5).

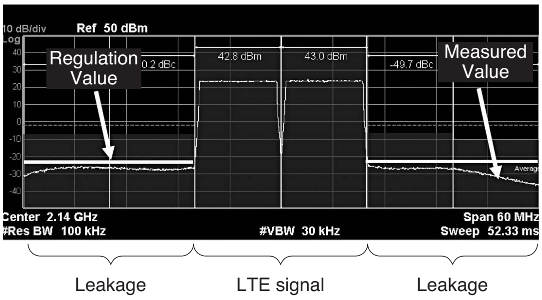


Fig. 8. RF output spectrum for 3G-LTE

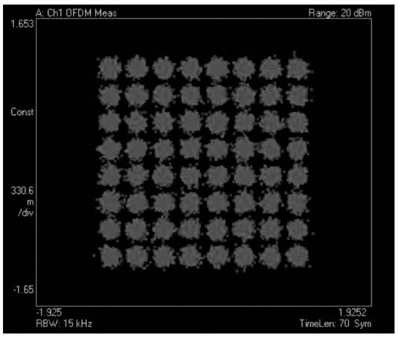


Photo 2. Constellation for 3G-LTE

The RF output power level of the RRH was 44.9 W and its total power consumption was 161.8 W, meaning that its power efficiency was 27.8%. As discussed above, the RRHs applied to the 3G-LTE system demonstrated the same high level of efficiency as for the 3G system.

5. Conclusions

We have developed a technology that can improve the efficiency of high-power amplifiers used in cellular phone base stations and other wireless stations. Using this technology, we manufactured power amplifiers of increased efficiency and installed them in RRHs. The RRHs achieved an overall efficiency of up to 28%, the highest level in the industry. These RRHs have been verified as suitable for practical use.

Our future task is to further refine this technology while expediting the development and commercialization of new products that will fully meet various customer needs in the field.

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