Proposal of Power Saving Techniques for Wireless Terminals Using CAZAC-OFDM Scheme

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Abstract— **A major drawback of Orthogonal Frequency Division Multiplexing (OFDM) signals is extremely high Peak-to-Average Power Ratio (PAPR). Signals with high PAPR lead to a lowering of the energy efficiency of the Power Amplifiers (PAs) and the shortened operation time causes a serious problem in battery-powered wireless terminals. In this paper, we propose a new power saving technique for wireless terminals. It is the combination of a polar modulation technique and Constant Amplitude Zero Auto-Correlation (CAZAC) equalizing technique. Proposed the polar modulation technique for the PA employs a current control by changing the common-gate stage bias in a cascade amplifier circuit. The CAZAC equalization scheme makes the PAPR of M-array Quadrature Amplitude Modulation (M-QAM) OFDM signals into the PAPR of M-QAM single-carrier signals. By using CAZAC-OFDM signal, proposed polar modulation PA exhibits overall efficiency of 40% at Error Vector Magnitude (EVM) of -32dB. Furthermore, a breakthrough technique which transcends barrier of 50% efficiency has been proposed. A prototype of Single Ended Push-Pull amplifier (SEPP AMP) exhibits power gain of 15dB over 100MHz to 1GHz, the maximum efficiency of 65% without polar modulation scheme.**

Keywords-OFDM; CAZAC; polar modulation; SEPP;

I. INTRODUCTION

Orthogonal Frequency Division Multiplex (OFDM) system for high speed and high capacity communications is recently attracting attention in wireless applications, e.g., 3GPP LTE, Wi-Fi and WiMAX. It is well known that one of the most serious drawbacks of the OFDM system is its high peak-to-average power ratio (PAPR), which decreases the energy efficiency of power amplifier (PA) and increases transmitter power consumption. In mobile communications, high PAPR signal negatively affects device battery life.

To overcome the above problem, many techniques are proposed: Partial Transmit Sequence (PTS), Selected Mapping (SLM), etc. [1]. PTS and SLM techniques choose respectively the phase factor and candidate data block to minimize the PAPR of transmission signal, which improves PAPR performance. However, those techniques need side-information in the receiver side, i.e., phase factor and candidate number information, in order to demodulate the received signal correctly, which result in degradation of spectral efficiency, and additional power consumption of DSPs.

On the other approach to overcome the problem, some circuit topology for high-efficiency OFDM power amplifier design have been proposed [2]. Here, a polar modulation PA, or an envelope tracking PA, is the most promising one. In the polar modulation, OFDM signal is separated into phase modulation (PM) component and amplitude modulation (AM) one. The PM component is input to the PA as the quadrature signal with constant amplitude. On the other, the AM component is used as envelope tracking data, which supplies to the PA as drain DC biasing from adaptive output power supply using a DC-DC converter. In general, the efficiency of PAs operating in saturation region is higher than one in linear region. Therefore, the polar modulation PA improves energy efficiency under full-time operation in the saturation region.

In this paper, we propose a new power saving technique for wireless terminals. It is the coupling technique between envelope tracking operation of PAs and CAZAC (Constant Amplitude Zero Auto-Correlation) equalizing. Here, we had reported an original polar modulation PA using a cascade circuit topology [3]. One can control output power by changing common-gate stage biasing in accordance with signal envelope, which improves energy efficiency of PA by full-time operation in saturation region. Since the polar modulation is a simple method of separating into amplitude information and phase information, it can cope with all modulation schemes. We also reported that one CAZAC sequence in cooperation with IFFT signal-process converted the PAPR of the M-QAM OFDM signal into the PAPR of an M-QAM single-carrier signal. Here, this fact was our original discovery [4].

In this paper, this coupling technology has novelty and effectiveness in combining the features of CAZAC-OFDM which is constant amplitude and the characteristics of this PA which is power saving, where a more power-saving system can be created. The coupling technique reduces the PAPR of 5 dB at the 16QAM-OFDM signal while the system imposed no penalties on the BER performances. By using CAZAC-OFDM signal, proposed polar modulation PA exhibits overall efficiency of 40% or more at error vector magnitude (EVM) of -32dB which satisfies the requirement of IEEE 802.11 ac specification [5].

Moreover, a breakthrough technique, which transcends barrier of 50% efficiency has been proposed. As well-known, a Class-B amplifier allows operating at a power efficiency of

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78.5%, while a Class-A amplifier operates at a power efficiency of 50%. The Class-B amplifiers, however, are strongly difficult to achieve high frequency and high linearity operations at the same time.

Our proposal of new circuit topology is certain kind of single ended push-pull amplifier, or SEPP AMP, using a complementary MOSFET technology. The circuit topology is suitable for monolithic circuit configuration and easily applied commercially available process of CMOS foundries. A prototype of the SEPP AMP exhibits power gain of 15dB over 100MHz to 1GHz and the maximum efficiency of 65% with no use of polar modulation scheme.

Up to now we have shown that the polar modulation system is effective with various modulation schemes [3][4]. On the other hand, the contribution of this paper is to demonstrate the achievement of unprecedented power efficiency by combining CAZAC-OFDM which achieved the same PAPR as the single carrier in the world and power-saving polar modulation system.

This paper is organized as follows. Section Ⅱ presents the proposed the operating principle of the coupling technique between envelope tracking operation of PAs and CAZAC. In Section Ⅲ, a performance of proposed system is presented. In Section Ⅳ, the operating principle of further improvement of OFDM-PAs with SEPP and simulation results are given. Finally, Section Ⅴ concludes this paper.

II. PROPOSED SYSTEM

In the proposed system, CAZAC-OFDM and polar modulation are used together to improve energy efficiency. Below, we explain CAZAC-OFDM and polar modulation and propose a system with improved efficiency. A description of OFDM system in section A, CAZAC equalizing technique in section B, and polar modulation technique in section C are shown.

A. OFDM system

In OFDM system, the frequency domain symbol $\boldsymbol{X} = [X_0, X_1, \dots, X_{N-1}]^T$ is modulated by N size inverse Fast Fourier Transform (IFFT). The discrete-time OFDM signal with N subcarriers is represented as

$$x_n = \sum_{k=0}^{N-1} X_k e^{j2\pi kn/N}, \tag{1}$$

where $j = \sqrt{-1}$ and n is discrete time index. On the other hand, receiver acquires frequency domain symbol $\boldsymbol{Y}$ by applying FFT to received signal $\boldsymbol{y}$.

$$\begin{aligned} Y_k &= \sum_{n=0}^{N-1} y_n e^{-j2\pi kn/N} \\ &= \sum_{n=0}^{N-1} (x_n + Noise) e^{-j2\pi kn/N}. \end{aligned} \tag{2}$$

The PAPR of the OFDM signal (1) can be expressed as

$$PAPR = \frac{\max_{0 \le n \le N-1} |x_n|^2}{\mathrm{E}[|x_n|^2]}, \tag{3}$$

where $\mathrm{E}[\cdot]$ is expectation operator. PAPR represents amplitude fluctuation of each symbol. In order to improve the accuracy of PAPR, the OFDM signal x_k is converted to L-times oversampled time domain signal [1].

As shown from (2), the OFDM signal is composed of a plurality of subcarrier signals, which causes an increase in amplitude fluctuation. A high PAPR signal increases the Input Back Off (IBO) at the power amplifier in order to amplify the transmit signal without distortion. In general, increasing in IBO causes decreasing the efficiency of PA.

B. CAZAC equalizing technique

CAZAC sequence is constant amplitude and provides a good cross-correlation property. Therefore, CAZAC sequence is used in wireless communication systems such as channel estimation and time synchronization. The Zadoff-Chu sequence c_k which is one of the CAZAC sequences is represented as

$$c_k = e^{j\pi k^2/N^2}, \tag{4}$$

where $k = 0, 1, \dots, N^2 - 1$ denotes the sequence index. In this paper, CAZAC $N \times N$ matrix $\boldsymbol{M}$ is represented as

$$\boldsymbol{M} = \begin{bmatrix} c_0 & c_1 & \cdots & c_{N-1} \\ c_N & c_{N+1} & \cdots & c_{2N-1} \\ \vdots & \vdots & \ddots & \vdots \\ c_{(N-1)N} & c_{(N-1)N+1} & \cdots & c_{N^2-1} \end{bmatrix}. \tag{5}$$

In CAZAC-OFDM system, multiply the signal with M before the IFFT of the transmitter. frequency domain symbol $\boldsymbol{X}' = [X'_0, X'_1, \dots, X'_{N-1}]^T$ is represented as

$$\boldsymbol{X}' = \boldsymbol{MX}. \tag{6}$$

Therefore, the CAZAC-OFDM time signal x' is represented as

$$\begin{aligned} x'_n &= \sum_{k=0}^{N-1} X'_k e^{\frac{j2\pi kn}{N}} \\ &= N \cdot c_{(N/2-n) \bmod N} \cdot X_{(N/2-n) \bmod N}. \end{aligned} \tag{7}$$

Receiver side can demodulate the original frequency domain symbol with using conjugate $\boldsymbol{M}^H$ [4].

Figure 1 shows PAPR performance of OFDM, CAZAC-OFDM and single carriers with using complementary cumulative distribution function (CCDF). Each signal has 64 subcarriers and oversampling factor $L = 4$. As shown from Figure 1, CAZAC equalization improves PAPR performance about 2.5 dB of PAPR when CCDF value is 10^{-3}. In addition, the PAPR of CAZAC-OFDM and M-QAM signal is same performance, which results from (7).

C. Polar modulation technique

In polar modulation system, AM and PM components are input separately into PA as power voltage and quadrature modulation signal respectively. General polar modulation system supplies AM component into PA by using dc-dc

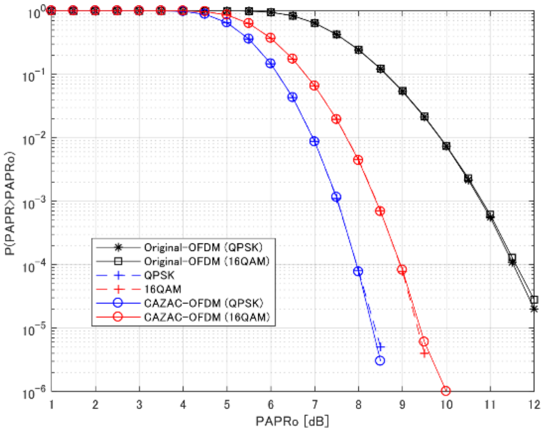

Figure 1. CCDF performance as compared with CAZAC-OFDM, OFDM and single carrier signal.

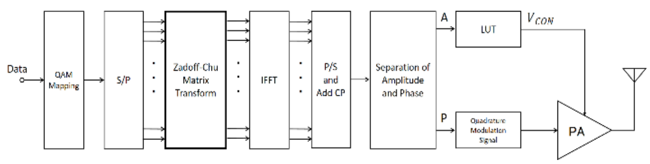

Figure 2. Block diagram of proposed system with polar modulation and CAZAC-OFDM.

converter. However, efficiency of dc-dc converter is around 90%, which affects overall efficiency of transmission system [6]. We have proposed new polar modulation technique without dc-dc converter [3]. In this system, quadrature modulation signal and AM component are input to the common-source and common-gate stage in cascade PA.

Figure 2 shows a block diagram of the proposed system. Mapping data after serial-parallel conversion is applied CAZAC precoding matrix $\boldsymbol{M}$. Secondly, CAZAC-OFDM signal after IFFT is separated into PM and AM component.

Quadrature modulation signal which is composed of PM component of CAZAC-OFDM is input to cascade PA. Lookup table converts AM component to V_{CON} to control envelope of output signal. V_{CON} applies to the common-gate stage in cascade PA.

We suppose OFDM signal in IEEE 802.11 specifications. Therefore, CAZAC-OFDM system must limit bandwidth [4]. In proposed system, we increase the number of data subcarriers and decrease the symbol rate to meet spectrum mask defined IEEE 802.11 specification, which doesn't affect data rate of proposed system.

Prototype cascade PA is shown in Figure 3. In proposed system, the quadrature modulation signal is input to prototype PA as RF_{IN}. On the other hand, proposed system changes the common-gate stage voltage V_{CON} to control envelope of output signal RF_{out}. Figure 4 shows the amplitude and phase shift of output at prototype cascade PA with 10dBm of quadrature modulation signal as input. As shown from Figure 4, changing the common-gate voltage V_{CON} affects the power of output signal RF_{out}. Proposed system controls V_{CON} to linearly amplify the input signal.

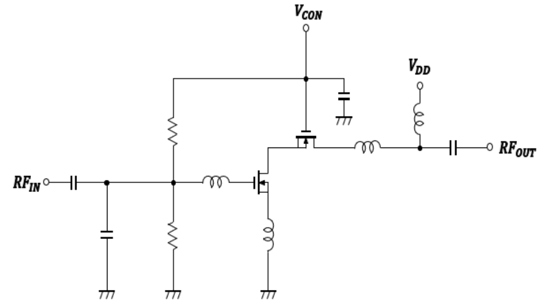

Figure 3. Prototype cascade PA ($\boldsymbol{V_{DD} = 1.8}$V)

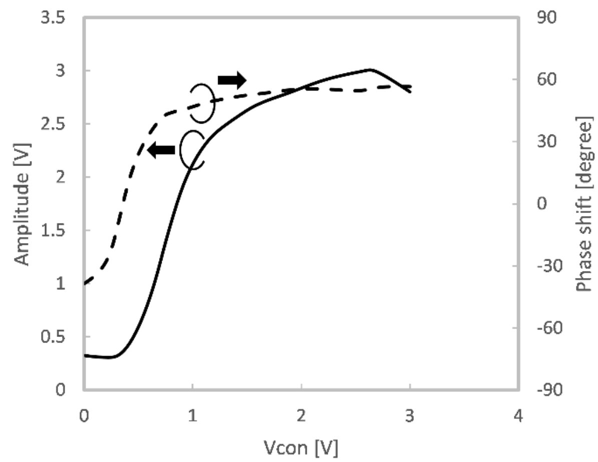

Figure 4. Output power and phase shift curves in cascade PA.

III. PERFORMANCE EVALUATION

We compare conventional OFDM system and proposed system combined CAZAC-OFDM and polar modulation PA. We show the setup of the simulation in section A and the result in section B.

A. Setup

We compare conventional OFDM system and proposed system combined CAZAC-OFDM and polar modulation PA. We have simulated the proposed system by the Advanced Design System 2016.01(ADS) and MATLAB 2014 α. In proposed system, we use MATLAB to generate text files of data set of CAZAC-OFDM IQ signals which are input to polar modulation PA designed by ADS and output signal of PA in ADS is demodulated in MATLAB.We use ADS pallet's OFDM signal source "WLAN IEEE 802.11" in 2.4 GHz and "SpectrumAnalyzerResBW" to measure spectrums.

Table I summarizes the simulation specifications. As carrier frequency, we use 2.4 GHz, which is industrial, scientific and medical (ISM) radio bands. Since we don't evaluate bit error rate performance, we apply no encoding to transmission signal. If the coding rate is 1/2, data rate of proposed system is 24 Mbps in IEEE 802.11g. CAZAC-OFDM system don't have null subcarriers. Therefore, we extend symbol time of CAZAC-OFDM to meet spectral mask in IEEE 802.11.

B. Simulation results

Figure 5 plots simulated Error Vector Magnitude (EVM)

TABLE I. SIMULATION SPECIFICATION

Modulation	OFDM	CAZAC-OFDM
Mapping	16QAM	16QAM
Symbol time	4 usec	5 usec
Guard interval rate	1/4	1/4
Data rate	48 Mbps	48 Mbps
Carrier frequency	2.4 GHz	2.4 GHz
Number of data subcarriers	48	60

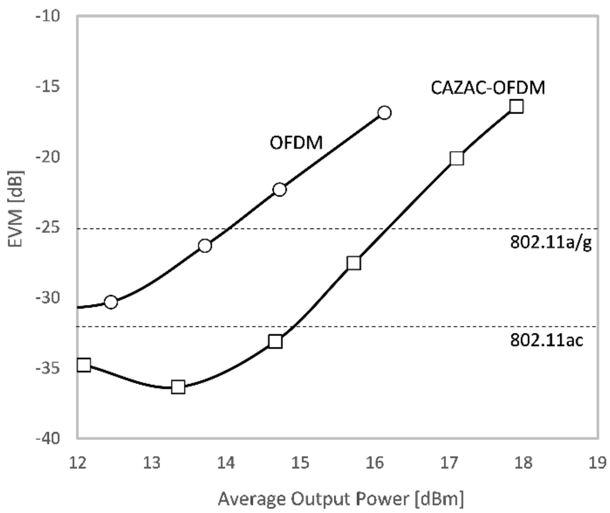

Figure 5. Simulated EVM versus average output power.

versus average output power. EVM represents demodulator performance in wireless communication system. In IEEE 802.11 a/g specifications, EVM of transmitter system must be less than -25 dB. As shown from Figure 5, simulated EVM is deteriorating with increasing average output power, which is caused by non-linear characteristic at polar modulation PA. CAZAC-OFDM system has superiority of about 2 dB in EVM as compared with the conventional OFDM system, which is caused by improving PAPR performance by CAZAC equalization (Figure 1).

The overall efficiency is shown in Figure 6. In the case of -25 dB or less of EVM, the efficiency of OFDM system is about 42 %. On the other hand, the efficiency of CAZAC-OFDM system is about 48 % in IEEE a/g specifications. Moreover, IEEE 802.11 ac specification requires the EVM of transmission signal ≤ 32 dB. The efficiency of proposed system is about 42 % at EVM of -32 dB in IEEE 802.11 ac specification, which is due to improve PAPR performance by CAZAC equalization. Efficiency means drain efficiency in this paper.

Figure 7 shows power spectral density of proposed system with CAZAC-OFDM and OFDM system. CAZAC equalization improves a roughly 5 dB in adjacent channel power ratio (ACPR). To sustain high efficiency at PA, IBO is required to be small. In the case of using high PAPR signal, small IBO causes nonlinear distortion. Since CAZAC equalization improves PAPR performance, ACPR of proposed system is suppressed.

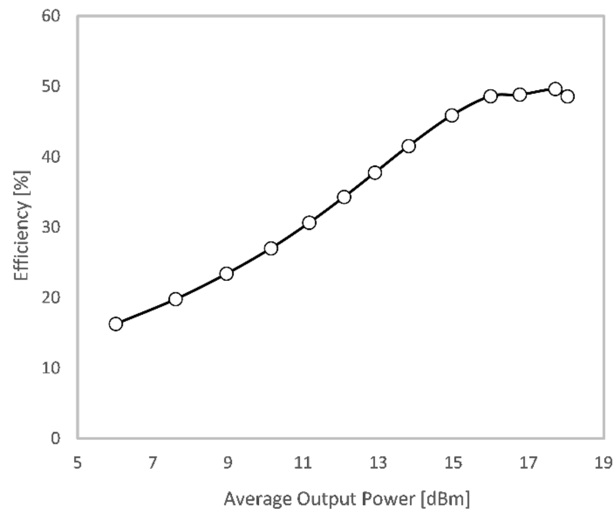

Figure 6. Simulated efficiency of cascade PA

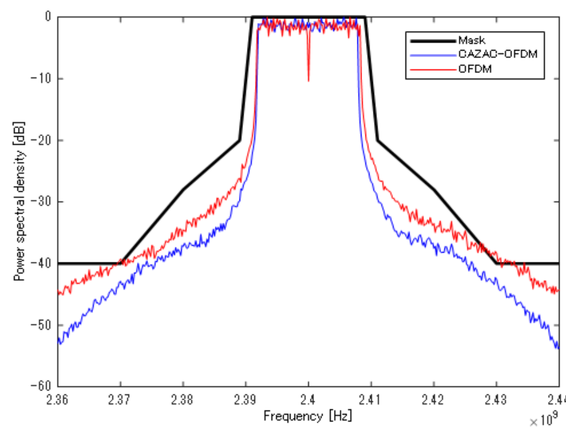

Figure 7. Simulated power spectral density of proposed system.

IV. PROPOSAL OF FURTHER IMPROVEMENT OF OFDM-PAS

In addition to conventional amplifiers, we would like to propose a class B biased wireless amplifier which we could not realize until now. There is still a problem and class B behavior is not realized, but I would like to show a prototype circuit with reference to SEPP. We show the circuit topology in section A, the setup of the simulation in section B and the result in section C.

A. Circuit topology

Since the OFDM exhibit large PAPR and wide bandwidth, the PAs should deliver high efficiency and linearity over wide bandwidth and input dynamic range. Generally, a class-A PA has preferred for good linearity, but lowered efficiency under the condition of small input range. The polar modulation PA mentioned previously, exhibits good efficiency over wide input dynamic range as well as linearity. However, it requires additional signal processing circuits and order-made look-up tables for specific devices.On the other hand, instead of class-A, a PA operated at a deep class-AB or class-B achieves a

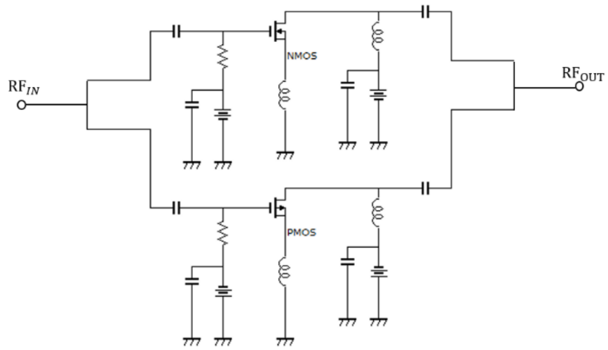

Figure 8. Circuit schematic of a prototype SEPP AMP.

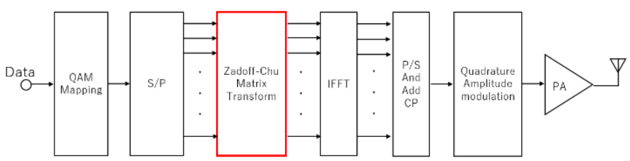

Figure 9. Block diagram of the transmitter with CAZAC-OFDM scheme for the SEPP AMP.

high efficiency in wide input dynamic range, although it has a large gain deviation and degradation of linearity performance. Here, to overcome the problems of class-B PAs, it is considered that push-pull amplifier scheme is one of dominant candidates.

Our proposal is a certain kind of single ended push-pull amplifier, or SEPP AMP, using a complementary MOSFET technology, as in shown in Figure 8. The circuit topology is suitable for monolithic circuit configuration and easily applied commercially available process of CMOS foundries. As shown in Figure 8, the output may be direct-coupled to the load connected through a dc blocking capacitor. Where both positive and negative power supplies are used, the load can be returned to the midpoint (ground) of the power supplies. The NMOS and the PMOS amplify only half the sinusoidal waveform and is cut off during the opposite half. In a deep class-AB or class-B operation, the amplifier has favorable features, i.e., low idle current and small quiescent current. The features provide improved efficiency over wide input dynamic range. Moreover, symmetrical construction of the two sides of the circuit means that even-order harmonics are cancelled, which can reduce distortion and improve linearity

Figure 9 shows the block diagram of transmitter with CAZAC-OFDM scheme for the SEPP AMP.

B. Setup

In ADS, both gate length of the NMOS and the PMOS is 0.18 µm. The transconductance gm of the NMOS and the PMOS is 513mS/mm and 253mS/mm, respectively. Ideal Class B operation requires complimentary devices are used to deliver the power instead of one. Each device conducts for alternate half cycles. To make good complementary pair, the gm of the PMOS must increase to those of the NMOS.

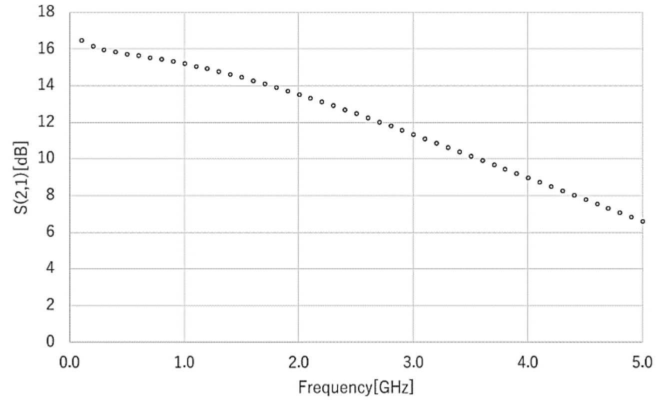

Figure 10. The S21 versus frequency characteristics of the prototype SEPP AMP with no input and output matching circuits.

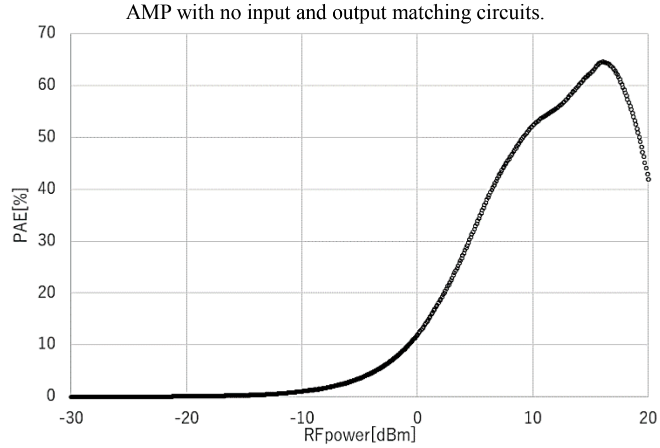

Figure 11. The PAE versus the average output power of the prototype SEPP AMP with no input and output matching circuits.

Since the ratio of the gm of the NMOS and the PMOS is approximately 2: 1, the total gate width of the PMOS is set to twice width of the NMOS. Therefore, the total gate width of NMOS and PMOS is set to 900 µm and 1800 µm, respectively. In the S21 of S parameters, "Simulation-Sparam" is used. In the PAE uses the "P_Probe" of "ads_rflib", subtracts the input power from the output power, divides the DC power and corrects it to a percentage.

C. Simulation results

Figure 10 shows the gain versus frequency characteristics of the prototype SEPP AMP. It exhibits power gain of 15dB over 100MHz to 1GHz. This flat gain performances are from no input and output matching circuits.

Figure 11 shows the efficiency versus the average output power of the SEPP AMP. The maximum efficiency of 65% has been obtained. Higher efficiency is expected if proper band-pass design of input and output matching circuits would be applied.

V. CONCLUSIONS

A new power saving technique for wireless terminals has been proposed. It is the combination of a polar modulation technique and CAZAC equalizing technique.

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The CAZAC equalization scheme makes the PAPR of M-QAM OFDM signals into the PAPR of M-QAM single-carrier signals. By using CAZAC-OFDM signal, proposed polar modulation PA exhibits overall efficiency of 40% at EVM of -32dB. Furthermore, a breakthrough technique which transcends barrier of 50% efficiency has been proposed. A prototype of SEPP AMP exhibits power gain of 15dB over 100MHz to 1GHz and the maximum efficiency of 65% with no use of the polar modulation scheme.

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