A Discrete-Amplitude Pulse Width Modulation for a High-Efficiency Linear Power Amplifier

Young-Sang Jeon and Sangwook Nam

A new discrete-amplitude pulse width modulation (DAPWM) scheme for a high-efficiency linear power amplifier is proposed. A radio frequency (RF) input signal is divided into an envelope and a phase modulated carrier. The low-frequency envelope is modulated so that it can be represented by a pulse whose area is proportional to its amplitude. The modulated pulse has at least two different pulse amplitude levels in order that the duty ratios of the pulse are kept large for small input. Then, an RF pulse train is generated by mixing the modulated envelope with the phase modulated carrier. The RF pulse train is amplified by a switching-mode power amplifier, and the original RF input signal is restored by a band pass filter. Because duty ratios of the RF pulse train are kept large in spite of a small input envelope, the DAPWM technique can reduce loss from harmonic components. Furthermore, it reduces filtering efforts required to suppress harmonic components. Simulations show that the overall efficiency of the pulsed power amplifier with DAPWM is about 60.3% for a mobile WiMax signal. This is approximately a 73% increase compared to a pulsed power amplifier with PWM.

Keywords: Power amplifier, switching mode, pulse modulation.

Manuscript received Sept. 25, 2010; revised Dec. 26, 2010; accepted Jan. 13, 2011.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2010-0018879).

Young-Sang Jeon (phone: +82 42 481 5653, email: junys72@kipo.go.kr) is with the IT Examination Bureau, Korea Intellectual Property Office, Daejeon, Rep. of Korea.

Sangwook Nam (email: snam@snu.ac.kr) is with the School of Electrical Engineering and Computer Science, Seoul National University, Seoul, Rep. of Korea.

http://dx.doi.org/10.4218/etrij.11.0110.0560

I. Introduction

M-ary phase shift keying (MPSK), *M*-ary quadrature amplitude modulation (MQAM), and orthogonal frequency division multiplex (OFDM) have recently found wide usage as modulation techniques due to their high spectral efficiencies. These modulation formats, however, have a high peak-to-average power ratio (PAPR). The high-PAPR signal means that a large back-off is required in order to avoid saturation of an output signal during amplification of the input signal. Therefore, the power amplifiers of most modern communication systems have very poor efficiency when they operate at conventional bias modes such as class A and class AB.

Efficiency is one of the most important issues in linear power amplifiers because it has dominant effects on the talk-time of mobile terminals and the performance of the power amplifiers. In applications such as cellular base-stations and satellite repeaters, efficiency also becomes an important issue because use of a high power amplifier involves a very expensive DC power supplier and a large-size thermal radiator. Furthermore, high DC power consumption, due to low efficiency, causes active devices or power amplifiers to have a short lifetime due to the high channel temperature of the active devices.

Various techniques have been proposed and studied to improve the efficiency of linear power amplifiers. Envelope elimination and restoration (EER) is one of the most efficient linear radio frequency (RF) power amplification systems and its efficiency is ideally 100%. However, since a DC-DC converter is required in the EER system, it has a narrow bandwidth and a large size. Furthermore, its efficiency generally decreases as the input signal decreases. An improved EER transmitter architecture (also known as a “pulsed power amplifier”) which does not require a DC-DC converter was proposed [1], [2]. The pulsed power amplifier modulates an input signal into an RF pulse train. The signal is then amplified by a switching-mode power amplifier with 100% efficiency. The original RF input signal is restored by extracting the inband signal component from the amplified RF pulse train. However, an isolator is necessary to maintain good linearity and stability in the pulsed power amplifier. Therefore, the practical pulsed amplifier has some inherent power loss due to dissipation of upconverted harmonic components at the isolator, wherein the harmonic components are generated by pulse width modulation (PWM) and are upconverted by a phase modulated carrier [3].

To improve the efficiency of the pulsed power amplifier, the authors of this paper suggested a power re-use technique [4]. Instead of wasting the upconverted harmonic components in the isolator, the unwanted harmonic components are rectified and returned to the power supply. Since the wasted harmonics are recycled as DC power, the efficiency of the pulsed power amplifier can be improved without degradation of the linearity. However, a wide-bandwidth rectifier is required to maximize the effects of the power re-use.

Another pulse modulation technique for improving the power amplification system is the multilevel pulse technique. However, it has been limited to the fields of audio power amplifiers [5], [6].

In this paper, a new discrete-amplitude pulse width modulation (DAPWM) technique for improving the efficiency of RF-pulsed power amplifiers is proposed. The DAPWM modulates the input envelope so that it can be represented by a pulse whose area is proportional to its amplitude. Unlike pulse-width modulated signal, the discrete-amplitude pulse-width modulated signal has more than two different pulse amplitude levels. They are selected according to the envelope amplitude of the input signal in order that the duty ratios of the pulses remain large despite a small input envelope. The DAPWM generates smaller harmonics than the PWM because duty ratios of the discrete-amplitude pulse-width modulated signal are larger than those of the pulse-width modulated signal. Therefore, the DAPWM technique can improve the efficiency of the pulsed power amplifier by reducing loss from harmonic components. Furthermore, it reduces filtering efforts that are required to suppress the harmonic components because it lowers the generation of harmonic components compared to PWM.

This rest of this paper is as follows. Section II is an overview of the pulsed power amplifier. Its characteristics and problems are presented. Section III describes the concept of the proposed DAPWM technique. Efficiency and harmonic components of the pulsed power amplifier with DAPWM are analyzed in section IV. Section V describes the structure of the pulsed power amplifier with DAPWM. Two exemplary architectures for the pulsed power amplifier with DAPWM are suggested. Section VI presents simulation results for a pulsed power amplifier with DAPWM. Its overall efficiency and linearity are demonstrated. Finally, section VII concludes this paper.

II. Pulsed Power Amplifier

Figure 1(a) shows a schematic of a pulsed power amplifier. An RF input signal is divided into an envelope and phase modulated carrier by a polar modulator. The low-frequency envelope is modulated by a pulse width modulator whose modulation period is T_{sw}. An RF pulse train is generated by mixing the modulated envelope with the phase modulated carrier. In Fig. 1(a), D and ω_c are the duty ratio and RF carrier frequency of the RF pulse train, respectively. The generated RF pulse train is amplified by a switching-mode power amplifier, such as a class D, class E, or class F amplifier, and goes though an isolator. The original signal is restored by filtering the amplified RF pulse train using a high-Q band pass filter. An isolator between the switching-mode power amplifier and the band pass filter is required for linearity, stability, and protection of the active device.

Figure 1(b) shows frequency-domain components of the RF pulse train in Fig. 1(a). The RF pulse train is composed of an inband component and upconverted harmonic components. The harmonic components are generated by the PWM and upconverted by the phase modulated carrier. They are located

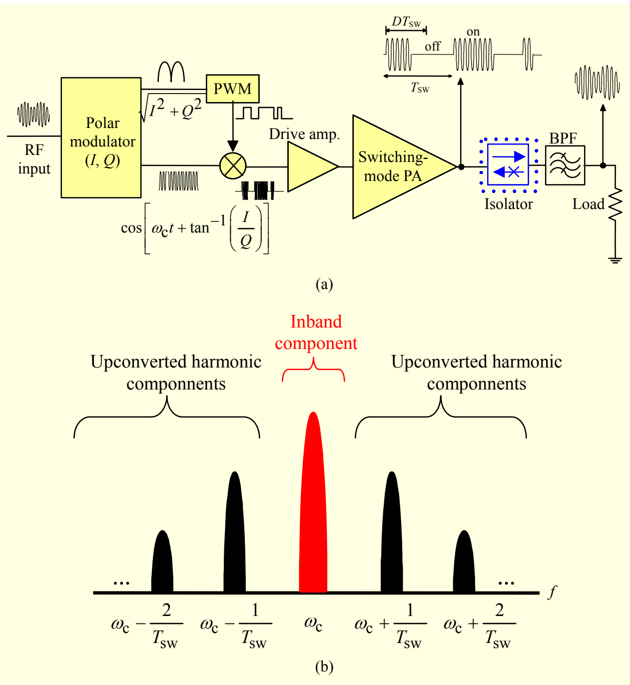

Fig. 1. (a) Schematics of pulsed power amplifier and (b) frequency-domain components of the RF pulse train.

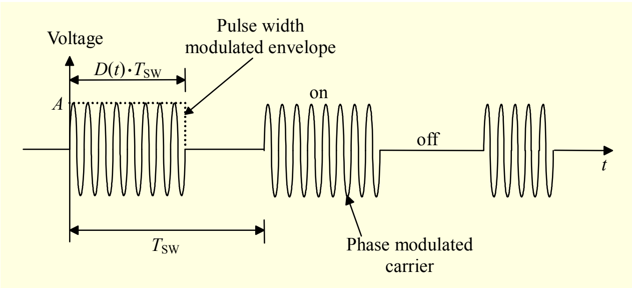

Fig. 2. Time-domain waveform of an RF pulse train at the output of the switching-mode power amplifier.

near to the inband signal.

The inband component goes through the band pass filter, while the upconverted harmonic components are reflected by the band pass filter and enter into the switching-mode power amplifier. Unfortunately, the reflected upconverted harmonics are located very near to the inband signal, and they are larger than the inband component in most cases. It is nearly impossible to adequately terminate them at the switching-mode power amplifier. Thus, the isolator shown in Fig. 1(a) is necessary because the reflected upconverted harmonics can degrade efficiency as well as the linearity without it. Therefore, the efficiency of the practical pulsed power amplifier is not 100% due to the dissipation of upconverted harmonic components at the isolator.

Figure 2 shows a time-domain waveform $v(t)$ of an RF pulse train at the output of the switching-mode power amplifier. The pulse-width modulation period and the amplitude of the RF pulse train are denoted by T_{sw} and A, respectively. The duty ratio of the RF pulse train is $D(t)$. The values of $D(t)$ are between 0 and 1, and is proportional to the amplitudes of the envelope of the RF input signal in Fig. 1(a). If the carrier frequency is ω_c, the waveform is expressed as

$$v(t)=[A\cdot D(t)+\sum_{n=1}^{\infty}\frac{2A}{n\pi}\sin(\pi n\cdot D(t))\cos(\frac{2\pi n}{T_{sw}}t)]\cdot\cos\omega_c t. \tag{1}$$

In (1), $D(t)\cdot\cos\omega_c t$ is the inband component, while the other terms are upconverted harmonic components. Therefore, the efficiency of the pulsed power amplifier with PWM is calculated as

$$\begin{aligned}\eta &= \frac{\text{Inband component power}}{\text{Total power}}\eta_{PA}\\ &= \frac{\frac{1}{2}A^2\cdot D^2(t)}{\frac{1}{2}A^2\cdot D^2(t)+\frac{1}{2}A^2\cdot\sum_{n=1}^{\infty}(\frac{1-\cos(2\pi nD(t))}{n^2\pi^2})}\eta_{PA}\\ &= \frac{D^2(t)}{D(t)}\eta_{PA}=D(t)\eta_{PA},\end{aligned} \tag{2}$$

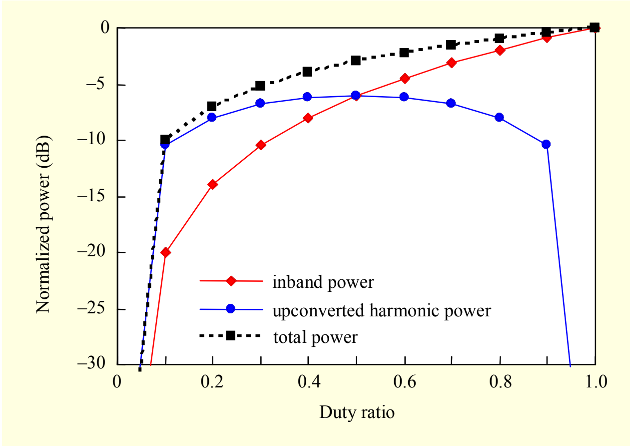

Fig. 3. Comparison of inband power to upconverted harmonic power according to duty ratios of an RF pulse train.

where η_{PA} represents an efficiency of a switching-mode power amplifier whose ideal efficiency is 100%.

Figure 3 shows a comparison of the inband power to the upconverted harmonic power according to duty ratios of an RF pulse train. The maximum output power in the figure is normalized to 0 dB. The upconverted harmonic power is larger than the inband power when the duty ratio is less than 0.5, which corresponds to a 6 dB back-off from maximum power. As the duty ratio decreases, the inband power also decreases. The upconverted harmonic power, however, does not decrease according to the duty ratio. Therefore, most of the power from the RF pulse train is wasted at the isolator when the duty ratio is small, which means the pulsed power amplifier with PWM has low efficiency during low duty ratios.

III. Concept of DAPWM

The main idea of a DAPWM is to maintain large duty ratios in the pulsed power amplifier to improve its efficiency because large duty ratios guarantee high efficiency. The DAPWM modulates an input signal so that it can be represented by the pulse, whose area is proportional to the amplitude of the input signal.

Unlike PWM, both the pulse width and the pulse amplitude can be changed according to the amplitude of the input envelope in DAPWM. A different pulse amplitude level is selected depending on the range of the input signal so that the duty ratio of the pulse can be large for a small input. For example, a low pulse amplitude level is selected for a small input in the DAPWM. Instead, in order to maintain equal pulse areas, the pulse width becomes larger than that of the PWM.

Figure 4 shows the time-domain waveforms of the pulse-width modulated and discrete-amplitude pulse-width modulated signals that correspond to a specific input signal. It

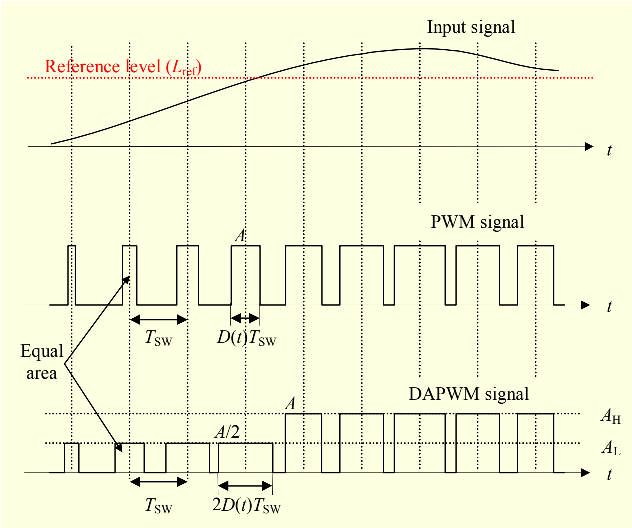

Fig. 4. Time-domain waveforms of pulse-width modulated and discrete-amplitude pulse-width modulated signals according to input signal.

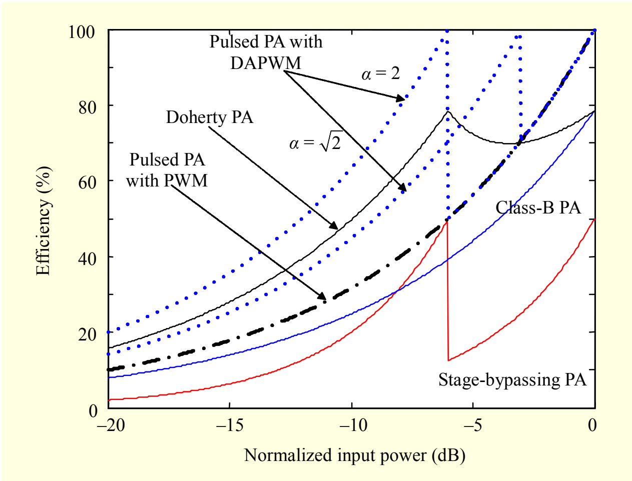

Fig. 5. Ideal instantaneous efficiency of pulsed power amplifier with DAPWM compared to those of other types of high-efficiency power amplifiers.

is assumed that the discrete-amplitude pulse-width modulated signal has two amplitude levels (A_H and A_L), and a reference level L_{ref} is at half of the maximum input signal. When the input signal is higher than the reference level, the discrete-amplitude pulse-width modulated waveform is the same as the pulse-width modulated waveform. On the contrary, when the input signal is below the reference level, the amplitude of the pulses decreases to half of the pulse amplitude of the pulse-width modulated signal. Instead, the duty ratios of the pulses in the DAPWM are increased by double compared to those of the PWM so that the areas of both pulses are equal. Equal pulse areas indicate that the same inband signals are restored when two pulse waveforms go through a band pass filter, because the filter averages the envelopes of the RF pulse trains.

Although both waveforms have equal inband power, the total power of the discrete-amplitude pulse-width modulated signal is smaller than that of the pulse-width modulated signal, as shown in Fig. 4. Therefore, the DAPWM technique can improve the efficiency of the pulsed power amplifier. Considering the harmonic component viewpoint, which is generated by pulse modulation, the discrete-amplitude pulse-width modulated waveform contains fewer harmonic components than the pulse-width modulated waveform. Therefore, the DAPWM technique can reduce the filtering efforts required to suppress the harmonic components.

IV. Characteristics of Pulsed Power Amplifier with DAPWM

The efficiency of the pulsed power amplifier with the DAPWM technique is only higher than that of the PWM technique when the input signal is lower than the reference level. The instantaneous efficiency (η_H) of the pulsed power amplifier with DAPWM when the input signal is higher than the reference level is the same as that of the pulsed power amplifier with PWM. Therefore, according to (2), η_H is equal to $D(t)\cdot\eta_{PA}$. On the other hand, when the input signal is lower than the reference level, the efficiency (η_L) is calculated in the same manner as in (2). Assuming that the discrete-amplitude pulse-width modulated signal has two amplitude levels and a ratio of a high pulse level (A_H) to a low pulse level (A_L) is α, η_L is expressed as

$$\eta_L = \frac{\frac{1}{2}A^2\cdot D^2(t)}{\frac{1}{2}A^2D^2(t)+\frac{1}{2}\cdot(\frac{A}{\alpha})^2\cdot\sum_{n=1}^{\infty}(\frac{1-\cos(2\pi n\cdot\alpha D(t))}{n^2\pi^2})}\eta_{PA}$$
$$= \frac{\alpha D^2(t)}{D(t)}\eta_{PA} = \alpha D(t)\eta_{PA}. \tag{3}$$

In (3), α can be also defined as the ratio of the maximum input envelope to the reference level, according to Fig. 4.

Figure 5 shows the ideal instantaneous efficiency of the pulsed power amplifier with DAPWM compared to other types of high-efficiency power amplifiers. It is assumed that the DAPWM has two pulse amplitude levels, where α is $\sqrt{2}$ or 2. The maximum input power in the figure is normalized to 0 dB.

The efficiency of a pulsed power amplifier with DAPWM does not decrease monotonically as the input signal decreases, unlike the efficiency of the pulsed power amplifier with PWM. In the pulsed power amplifier with DAPWM, the efficiency is abruptly boosted at an input power similar to a stage-bypassing or Doherty power amplifier. The boosting point occurs when the pulse amplitudes change from a high level A_H to a low level A_L. This point corresponds to α-dB backed off from the point of the maximum input power. The ideal peak efficiency of the pulsed power amplifier with DAPWM is 100%.

To maximize the overall efficiency of the proposed power amplifier, α in (3) must be selected considering the envelope distribution of an input signal. The overall efficiency ($\eta_{overall}$) is expressed as

$$\eta_{\text{overall}} = \frac{\int_{-\infty}^{\infty} f(P_{\text{in}}) \cdot P_{\text{out}}(P_{\text{in}}) dP_{\text{in}}}{\int_{-\infty}^{\infty} f(P_{\text{in}}) \cdot P_{\text{DC}}(P_{\text{in}}) dP_{\text{in}}}, \qquad (4)$$

where $f(P_{in})$ is the probability density function (PDF) of the RF input signal. The input, output, and DC power are P_{in}, P_{out}, and P_{DC}, respectively. In high-PAPR systems, the probability that the RF peaks are generated is low. That is, the output power is "low" for a long time and the output power reaches the peak value only for a short time. Thus, the efficiency when the output signal is low is very important for the overall efficiency of a power amplifier in high-PAPR signals. Therefore, the DAPWM technique can significantly improve the overall efficiency of the pulsed power amplifier in high-PAPR systems.

From the viewpoint of the upconverted harmonic components in the pulsed power amplifier, the DAPWM technique can reduce their generation as mentioned in section III. In a pulsed power amplifier, the harmonic components are inherently generated due to the pulse modulation and they are upconverted by a phase modulated carrier. Among the upconverted harmonic components, the upconverted first and second harmonic components are the most important. This is because they are generated very near to the inband component. The upconverted first and second harmonic components are located at $\omega_c \pm 1/T_{sw}$ and $\omega_c \pm 2/T_{sw}$, respectively, as shown in Fig. 1(b). In the pulsed power amplifier with DAPWM, their generation is low compared to the pulsed power amplifier with PWM because the DAPWM technique keeps the duty ratios relatively large with low pulse amplitude.

Figures 6(a) and (b) show the magnitudes of the upconverted first and second harmonic components with respect to the pulsed power amplifiers that have PWM and DAPWM according to the RF input power. It is assumed that the DAPWM has two pulse amplitude levels, and the low pulse level A_L is half of the high pulse level A_H. The maximum input power in the figure is also normalized to 0 dB. The figures show that the DAPWM technique reduces the generation of both upconverted first and second harmonic components, compared to PWM technique. Therefore, the DAPWM technique reduces the burden of the band pass filter in Fig. 1(a), which suppresses harmonic components in the pulsed power amplifier.

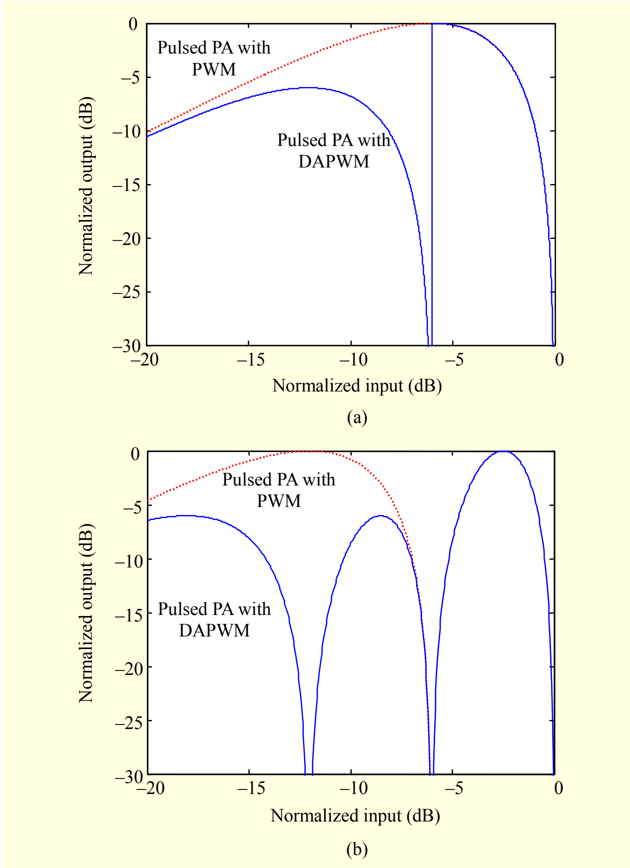

Fig. 6. Magnitudes of upconverted (a) first and (b) second harmonic components of pulsed power amplifiers with PWM and DAPWM according to the RF input power.

V. Structure of Pulsed Power Amplifier with DAPWM

A critical issue for implementing the pulsed power amplifier with the DAPWM technique is generating a discrete-amplitude pulse-width modulated waveform. More than two switching-mode power amplifiers are needed and they must not interfere with the operations of the other amplifiers. Figures 7(a) and (b) show two structures for implementing the pulsed power amplifier with DAPWM that have a pulse amplitude level of two.

One structure is to switch between large and small switching-mode amplifiers according to an input signal level, as shown in Fig. 7(a). The two switching-mode power amplifiers whose sizes are different from each other are connected in parallel, and they do not operate simultaneously. The upper and lower switching-mode power amplifiers have the same structure, except for their power supplies. By using different supplies, V_{DD1} and V_{DD2}, the different sizes of the

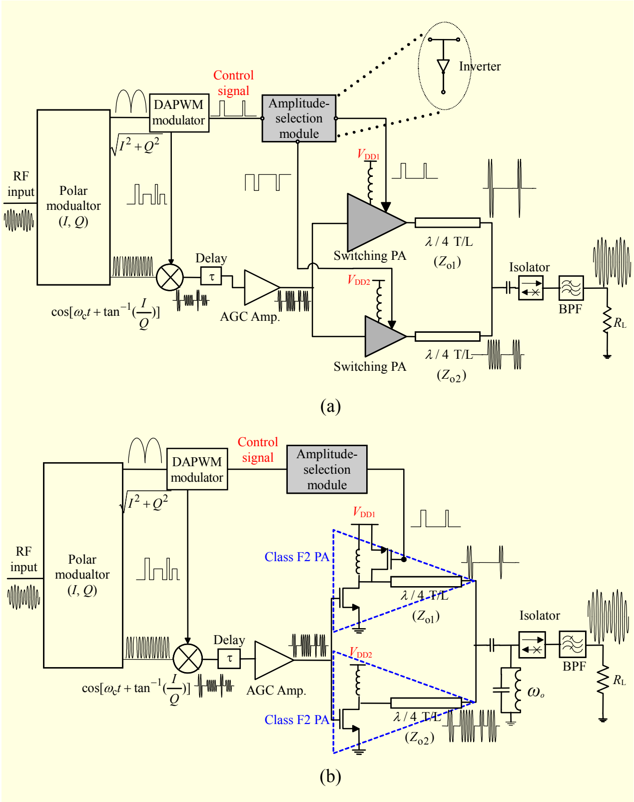

Fig. 7. Structures for implementing pulsed power amplifier with DAPWM using (a) switching between two different-sized power amplifiers and (b) two class-F2 power amplifiers.

power amplifiers can be obtained.

The operation of Fig. 7(a) is as follows. A low-frequency envelope is modulated by a discrete-amplitude pulse-width modulator. An RF pulse train is generated by mixing the discrete-amplitude pulse-width modulated signal with a phase-modulated carrier. The RF pulse train is amplified by an automatic gain controlled amplifier for driving the two switching-mode power amplifiers. Two quarter-wavelength transmission lines, which play the role of an impedance transformer, are located at the ends of each power amplifier in order to stably combine their outputs without affecting their operations.

The control signal generated from the DAPWM modulator selectively turns on or off the large and the small power amplifiers through the amplitude-selection module, depending on the pulse level of the modulated signal. The delay unit is used to achieve synchronization between the DAPWM output signal and the on/off of the one power amplifier. When an input envelope is higher than a reference level, only the large amplifier operates with the small amplifier off. To the contrary, when the input envelope is lower than the reference level, only the small amplifier operates with the large amplifier off. In both cases, in order to avoid loading by the amplifiers in the non-amplifying mode, low impedance must be maintained at the output of the power amplifier when it is off.

The characteristic impedances Z_{o1} and Z_{o2} of the two quarter-wave lines need not be the same. It is preferable, however, to make the two characteristic impedances equal so that the upper and the lower amplification branches will have the same phase transfer function because the output signals of the two branches must be perfectly aligned during branch selection.

Another structure for realizing the pulsed power amplifier with a DAPWM technique is to use two class-F2 power amplifiers, as shown in Fig. 7(b). Two same class-F2 power amplifiers connected in parallel are implemented using nMOS transistors, wherein a parallel LC resonator is shared. A pMOS transistor located at the upper class-F2 power amplifier serves as a switch and is controlled by a control signal. The upper class-F2 power amplifier is enabled or disabled depending on the envelope of the RF input. When an input envelope is higher than the reference level, the two class-F2 power amplifiers operate simultaneously with the pMOS switch off. In this case, the output voltages of the two amplifiers are combined without interfering with the operation of the other branch due to the low output impedances of the nMOS transistors for class-F2 operations. The combined voltage V_{out} at the output terminal is calculated using the superposition of the output voltages of the upper branch and the lower branch as [7]

$$V_{out} = \frac{4}{\pi}\cdot\left(\frac{R_L}{Z_{o1}}V_{DD1} + \frac{R_L}{Z_{o2}}V_{DD2}\right), \tag{5}$$

where Z_{o1} and Z_{o2} represent characteristic impedances of the upper and lower quarter-wavelength transmission lines, respectively; R_L is the load; and V_{DD1} and V_{DD2} are the supply voltages of upper and the lower branches, respectively.

When the input envelope is lower than the reference level, only the lower class-F2 power amplifier operates. In this case, the impedance seen toward the upper class-F power amplifier at the end of the upper transmission line is infinite because the pMOS transistor is turned on by the control signal. Therefore, the upper branch does not interfere with the lower power amplifier.

The structures in Figs. 7(a) and (b) seem to be similar to those of stage-bypassing power amplifiers in which two discrete power amplifiers are selectively used according to the envelope of an input signal in order to improve the efficiency [8], [9]. However, there are no severe mismatch problems in the pulsed power amplifier with DAPWM as there are with the stage-bypassing power amplifier. Because the two power amplifiers have constant-envelope outputs, mismatches must be taken into account at only one operation point. Therefore, the gain and the phase mismatch between the two power amplifiers of Figs. 7(a) and (b) can be easily compensated for by adjusting the duty ratio and using a delay, respectively. If there is a gain mismatch, the duty ratio can be set so that pulse areas are proportional to the envelope of the input signal. This is because the linearity in the DAPWM depends only on the pulse area not the pulse amplitude level. On the other hand, the phase mismatch can be cancelled by adding the delay line to one power amplifier.

The bandpass filters of Figs. 7(a) and (b) eliminate upconverted harmonic components caused by pulse modulation. Therefore, the cut-off frequencies of the band pass filers are between the bandwidth of the inband signal and the pulse modulation frequency. Though the band pass filter with sharp skirt characteristics significantly reduces the upconverted harmonic components, its insertion loss can be increased.

Both structures of Figs. 7(a) and (b) could be extended to more than a three-level amplitude combination which could provide higher efficiency and better suppression of the modulation harmonic products.

VI. Simulation Results of Pulsed Power Amplifier with DAPWM

A pulsed power amplifier with DAPWM with two pulse amplitudes has been simulated for a high-PAPR signal using the Agilent envelope simulator. The simulation is performed assuming that the power amplifier is the ideal switching-mode power amplifier with ideal switches and ideal load networks.

The structure in Fig. 7(a) is selected for the two-level DAPWM. A 802.16e mobile worldwide interoperability for microwave access (WiMax) signal for mobile stations is used as the high-PAPR input signal. The signal has a high PAPR because it uses an OFDM format. Its PAPR is about 10 dB at the 0.001% level of the complementary cumulative distribution function, and its bandwidth is about 8.46 MHz.

When the RF input signal is split into an envelope and a phase modulated carrier, the bandwidth of the envelope becomes larger than that of the RF input [10], [11]. The sampling frequency for the pulse modulation must be at least twice the envelope bandwidth. In this simulation, a 100 MHz pulse modulation frequency, which is about 12 times the RF input signal bandwidth, is used for the DAPWM. When the RF input signal is modulated to the RF pulse train, the resolution of the pulse width is important to linearity performance. Though the high pulse-width resolution reduces quantization noise, it is difficult to practically implement the high pulse-width resolution. Each span of the modulation periods is represented by 200 points regardless of its duty ratio in the simulation. On the other hand, the ideal bandpass filter, whose center frequency and bandwidth are 2.3 GHz and 100 MHz, respectively, is used in order to eliminate the modulation frequency.

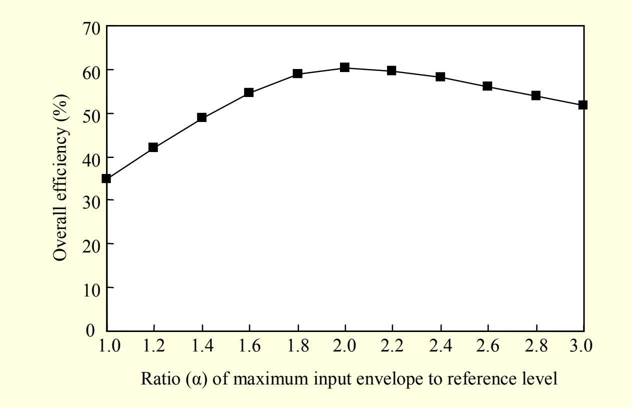

Fig. 8. Simulated overall efficiencies of pulsed power amplifier with DAPWM for various values of α.

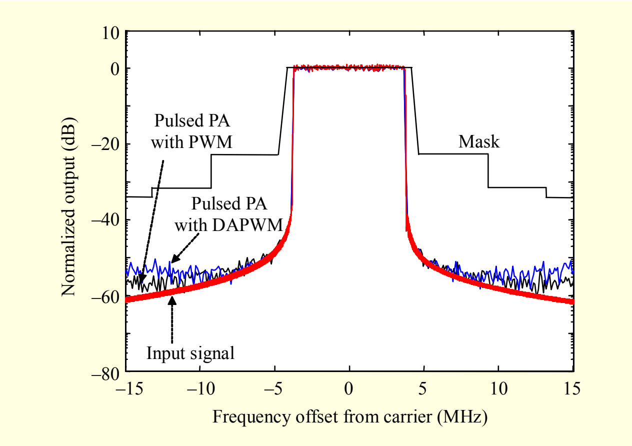

Fig. 9. Simulated inband spectrums of output signals of pulsed power amplifiers with PWM and DAPWM.

The ratio α of a high pulse level A_H to a low pulse level A_L can be selected depending on the envelope distribution of the input signal. Figure 8 shows the simulated overall efficiencies of the pulsed power amplifier with DAPWM according to various values of α when the input is the mobile WiMax signal. The maximum overall efficiency is obtained when the ratio is around 2.

Figure 9 shows the simulated inband spectrums of the output signals of the pulsed power amplifiers with PWM and DAPWM when α is two.

The two spectrums are almost the same as that of the input signal. There is minimal quantization noise in both pulsed power amplifiers. Therefore, the linearity of the two pulsed power amplifiers is quite good at the 100 MHz pulse modulation frequency, which is about 12 times of the inband signal bandwidth. The inband noise in the pulsed power amplifier with DAPWM is severe when the pulse resolution is low. Though the noise can be reduced by increasing the pulse resolution, there is the trade-off relationship between the pulse

Table 1. Comparison between pulsed power amplifiers and conventional high-efficiency power amplifiers for mobile WiMax signal.

	Simulated ideal overall efficiency	Linearity
Pulsed PA with DAPWM	60.3%	Only duty ratios dependant
Pulsed PA with PWM	34.8%	Only duty ratios dependant
Doherty PA	52.3%	Active device dependant

resolution and the complexity of the pulse generation circuit in the DAPWM system.

In practical realization of pulsed power amplifiers, good linearity is maintained because the linearity does not depend on the characteristics of the switching-mode power amplifiers due to the isolators. While the linearity of conventional high-efficiency linear power amplifiers such as stage-bypassing, envelope tracking, and Doherty power amplifiers mainly depend on the characteristics of active devices, the linearity of the pulsed power amplifiers only depends on the on-time duration of the pulses.

On the other hand, the simulated ideal overall efficiency of the pulsed power amplifiers with PWM and DAPWM are about 34.8% and 60.3%, respectively. That is, the DAPWM technique reduces power consumption of the pulsed power amplifier by about 73% compared to the PWM technique for the mobile WiMax signal. Table 1 summarizes comparison between pulsed power amplifiers and various conventional high-efficiency power amplifiers in ideal cases.

Theoretically, the DAPWM technique has very good linearity because linearity depends only on the on-time duration of a pulse. From a practical standpoint, however, there can be nonlinearities associated with various mismatch factors.

Mismatch between an amplitude and a phase of an RF pulse train can occur. Figure 10 shows the simulated error vector magnitude (EVM) versus time mismatch between the modulated envelope path and the RF path in the pulsed power amplifier with DAPWM. The simulation shows that the fine time-alignment resolution must be smaller than 6 ns to satisfy the 802.16e OFDM requirements whose EVM is less than 5.5% for a 16-QAM OFDM signal.

Theoretically, DAPWM has the same EVM as an EER for the amplitude and phase mismatch, provided that the pulse modulation frequency of the DAPWM is sufficiently high. Practically, however, the time mismatch of DAPWM is easy to control compared to that of EER. In EER, the envelope and phase are separately processed and mixed at a switching-mode

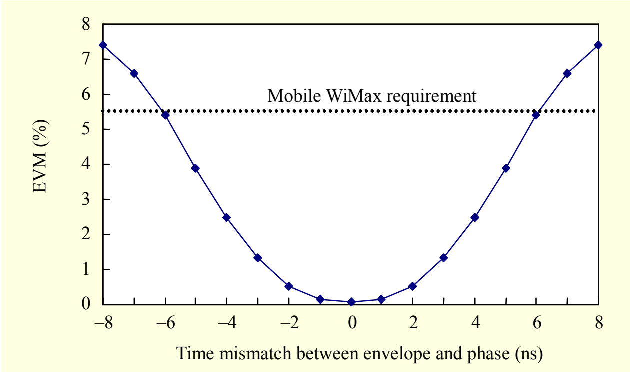

Fig. 10. Simulated EVM versus time mismatch between envelope and phase in pulsed power amplifier with DAPWM.

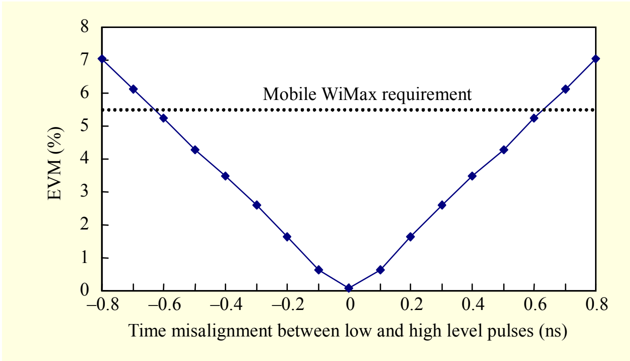

Fig. 11. Simulated EVM versus time misalignment between low (A_L) and the high (A_H) level pulses in pulsed power amplifier with DAPWM.

power amplifier output, and thus there may be different processing time delays for the envelope and the phase. With DAPWM, both the envelope and phase train are mixed in the form of an RF pulse train prior to entering the power amplifier input, and because both the envelope and the phase experience the same time delay when they go through the power amplifier, the time mismatch between the envelope and the phase is not large.

Misalignment errors can occur between the low level (A_L) pulses and the high level (A_H) pulses. Such misalignments happen when the two branches of Fig. 7(a) have different processing times due to the use of different-sized power amplifiers. Figure 11 shows the simulated EVM versus time misalignment between the low and high level pulses in the pulsed power amplifier with DAPWM.

The inaccuracy of α is another factor capable of degrading the linearity of DAPWM because α cannot be exactly 2 in a practical design. Figure 12 shows the simulated EVM versus the inaccuracy of α in a pulsed power amplifier with DAPWM. The inaccuracy of Fig. 12 is defined as the error of the high level (A_H) pulse.

As mentioned above, DAPWM has the effect of suppressing

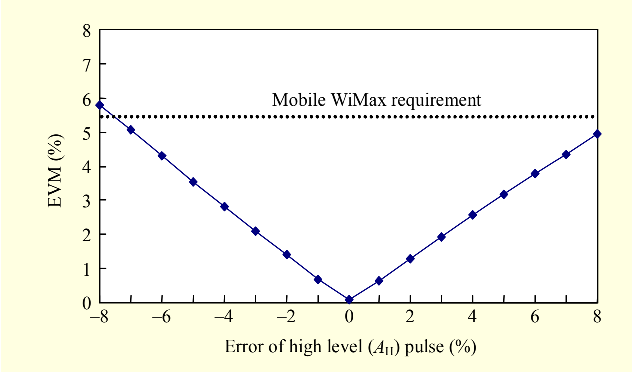

Fig. 12. Simulated EVM versus inaccuracy of α in pulsed power amplifier with DAPWM.

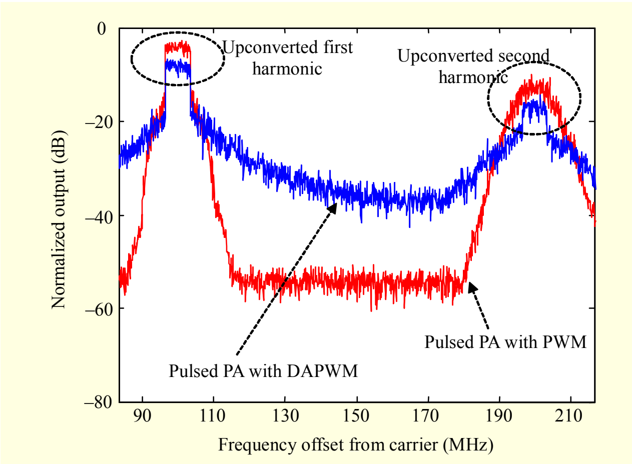

Fig. 13. Upconverted first and second harmonic components of pulsed power amplifiers with DAPWM compared to PWM.

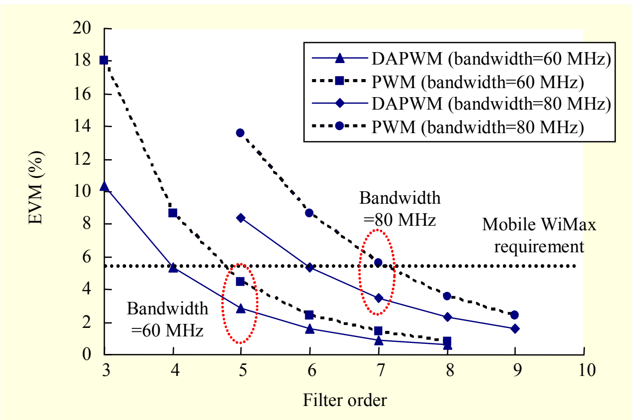

Fig. 14. Simulated EVM versus filter order and bandwidth in the pulsed power amplifier with DAPWM compared to PWM.

upconverted harmonic components. Figure 13 shows the upconverted first and second harmonic component reduction of the DAPWM technique. The proposed DAPWM technique suppresses the generation of the upconverted first and second switching harmonics by 3 dB to 5 dB compared to PWM technique in a pulsed power amplifier. The harmonic component reduction can be more improved as the number of the discrete amplitudes increases because many amplitude levels keep the duty ratios large. However, there is the trade-off relationship between the number of the amplitude levels and the complexity of the amplifier.

Theoretically, there are no nonlinearity problems for the pulsed power amplifier with DAPWM if the upconverted harmonic components are perfectly eliminated because the nonlinearity components exist near the pulse modulation frequency. Therefore, practically, the band pass filter in DAPWM has a great influence on the EVM because the filter plays the role of eliminating the upconverted harmonic components. The effects of the filter order and bandwidth on the performance of the DAPWM are simulated compared to the PWM. It is assumed that the filter is a butterworth-type band pass filter. Figure 14 shows that DAPWM has better linearity than PWM if they use the same band pass filter. This means that DAPWM generates fewer harmonic components than PWM. Therefore, the DAPWM technique can reduce filtering efforts required to suppress the upconverted switching harmonics.

VII. Conclusion

A new concept of DAPWM for a high-efficiency linear power amplifier was proposed and applied to a pulsed power amplifier. The DAPWM modulates an input signal so that it can be represented by the pulse whose area is proportional to the amplitude of the input signal. Unlike other pulse modulations, both the pulse width and the pulse amplitudes can be changed. The discrete-amplitude pulse-width modulated pulse has at least two different pulse amplitudes which are selected depending on the amplitude of the input envelope to maintain large duty ratios of the pulse for a small input. The DAPWM technique can reduce the power consumption of the pulsed power amplifier without linearity degradation. Furthermore, it reduces the filtering efforts required to suppress harmonic components generated by pulse modulation. The simulated overall efficiency of the pulsed power amplifier with DAPWM is about 60.3% for a mobile WiMax signal. The upconverted first and second harmonic components are reduced by 3 dB to 5 dB compared to those of pulsed power amplifier with PWM. The proposed pulsed power amplifier with DAPWM could be suitable for a polar transmitter in high-PAPR systems.

For the DAPWM scheme to be useful in practical power amplification systems, further research into the high-speed pulse modulator and high-speed controller should be performed.

References

[1] A. Dupuy et al., “Digital Pulse Width Modulated Microwave Signal Using a High Efficiency Class-E Amplifier,” *Asia-Pacific Microw. Conf.*, 2003, pp. 1809-1812.

[2] Y.X. Wang, “An Improved Kahn Transmitter Architecture Based on Delta-Sigma Modulation,” *IEEE MTT-S Int. Microw. Symp. Dig.*, 2003, pp. 1327-1330.

[3] Y.-S. Jeon, H.-S. Yang, and S.W. Nam, “A Novel High-Efficiency Linear Transmitter Using Injection-Locked Pulsed Oscillator,” *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 4, Apr. 2005, pp. 214-216.

[4] Y.-S. Jeon, H.-S. Yang, and S.W. Nam, “A Power Re-Use Technique for Improved Efficiency of the Pulsed Oscillating Amplifier,” *IEEE Microw. Wireless Compon. Lett.*, vol. 16, no. 10, Oct. 2006, pp. 567-569.

[5] V.M.E. Antunes, V.F. Pires, and J.F.A. Silva, “Digital Multilevel Audio Power Amplifier with a MASH Sigma-Delta Modulator to Reduce Harmonic Distortion,” *IEEE Ind. Electron. Symp.*, vol. 2, 2005, pp. 525-528.

[6] V.M.E. Antunes, V.F. Pires, and J.F.A. Silva, “Narrow Pulse Elimination PWM for Multilevel Digital Audio Power Amplifiers Using Two Cascaded H-Bridges as a Nine-Level Converter,” *IEEE Trans. Power Electron.*, vol. 22, no. 2, Mar. 2007, pp. 425-434.

[7] A. Shirvani, D.K Su, and B.A. Wooley, “A CMOS RF Power Amplifier with Parallel Amplification for Efficient Power Control,” *IEEE J. Solid-State Circuits*, vol. 37, no. 6, June 2002, pp. 684-693.

[8] F.H. Raab et al., “Power Amplifiers and Transmitters for RF and Microwave,” *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 3, Mar. 2002, pp. 814-826.

[9] J. Staudinger, “Applying Switched Gain Stage Concepts to Improve Efficiency and Linearity for Mobile CDMA Power Amplification,” *Microw. J.*, vol. 43, no. 9, Sept. 2000, pp. 152-162.

[10] F.H. Raab, “Intermodulation Distortion in Kahn-Technique Transmitters,” *IEEE Trans. Microw. Theory Tech.*, vol. 44, no. 12, Dec. 1996, pp. 2273-2278.

[11] F. Wang et al., “An Improved Power-Added Efficiency 19-dBm Hybrid Envelope Elimination and Restoration Power Amplifier for 802.11g WLAN Applications,” *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 12, Dec. 2006, pp. 4086-4099.

Young-Sang Jeon received the BS, MS, and PhD from Seoul National University, Seoul, Rep. of Korea, in 1998, 2000, and 2007, respectively, all in electrical engineering. From 2000 to 2001, he was an administrative official with the Ministry of Government Administration and Home Affairs (MOGAHA), Seoul, Rep. of Korea. Since 2001, he has been with the Korean Intellectual Property Office (KIPO), Daejeon, Rep. of Korea, where he is responsible for patent work and national R&D planning regarding wireless communication systems. His research interests include high-efficiency linear power amplifiers and wireless communication systems.

Sangwook Nam received the BS from Seoul National University, Seoul, Rep. of Korea, in 1981, the MS from the Korea Advanced Institute of Science and Technology (KAIST), Seoul, Rep. of Korea, in 1983, and the PhD from the University of Texas at Austin, in 1989, all in electrical engineering. From 1983 to 1986, he was a researcher with the Gold Star Central Research Laboratory, Seoul, Rep. of Korea. Since 1990, he has been a professor with the School of Electrical Engineering and Computer Science, Seoul National University. His research interests include analysis/design of electromagnetic structures, antennas, and microwave active/passive circuits.