Architecture of High-Efficiency Digitally-Controlled Class-E Power Amplifier

Jiani Ye, Zachary Nosker, Kazuyuki Wakabayashi, Takuya Yagi, Nobukazu Takai, Kiichi Niitsu, Keisuke Kato, Takao Ootsuki, Haruo Kobayashi, Osamu Yamamoto*, Isao Akiyama*

Gunma University (Japan), *Gigatec Inc.

2011 IEEJ Analog VLSI Workshop
Bali, Indonesia
3 November 2011
Research Background

Realization of High Efficiency in Wireless Communication Systems

Amplitude modulation through digital control
Power amplifier can be implemented in fine CMOS
Class-E Amplifier Architecture

- High efficiency
  - Uses Zero Voltage Switching (ZVS)
- Can be controlled via digital input
Basic Class-E Amplifier Schematic
Digital Control of Output Voltage

Input Signals
Phase: PM
Amplitude: \( d_1, d_2, d_3, d_4, \ldots \)
When all inputs are HI, Total Width = $W_1 + W_2 + W_3 + W_4$

$(W_1 + W_2 + W_3 + W_4) / L$
Binary-Weighted Transistor Size Example

\[ \frac{W}{L} \]
\[ \frac{2W}{L} \]
\[ \frac{4W}{L} \]
\[ \frac{8W}{L} \]

PM
\(d_1\)
\(d_2\)
\(d_3\)
\(d_4\)

\[ V_{DD} \]
\[ L_f \]
\[ C \]
\[ C_1 \]
\[ L \]
\[ R \]

\(v_{OUT}\)

\((W + 2W + 0 + 8W)/L\)

\[ \frac{11W}{L} \]
Effect of Total Width on Output Voltage

\[ V_{OUT} \]

\[ V_{IN} \]

\[ 2\text{GHz} \]

\[ 3V \]

\[ 0 \]

\[ t \]

\[ V_{in} \]

\[ V_{s} \]

\[ V_{dd} \]

\[ V_{out} \]

\[ Lf \]

\[ C \]

\[ L \]

\[ R \]

\[ \text{Note: } N \text{ is the transistor multiplication factor} \]

\[ W_{total} = NW \]
Simulation: Effect of N on $V_{OUT}$

Output voltage nearly constant

Output voltage increases linearly
Output Voltage Modulation Investigation

• Large transistor (N>300)
  – Typical class-e amplifier
    • Output voltage constant
    • Transistor acts nearly like an ideal switch

• Small transistor (N<300)
  – Output voltage increases linearly with N
    • Can be exploited to implement digital control

Why does the transistor size affect the output voltage?
MOS Transistor Drain Current Characteristic

\[ I_D = \mu C_{ox} \frac{W}{L} \left( (V_{GS} - V_{tn}) V_{DS} - \frac{V_{DS}^2}{2} \right) \]

\[ I_D = \frac{\mu C_{ox} W}{2L} (V_{GS} - V_{tn})^2 \]

(W increases \(\Rightarrow I_D\) increases)

Saturation Region

\(V_{DS(sat)} = V_{eff}\)

\(I_D \approx \mu C_{ox} \frac{W}{L} (V_{GS} - V_{tn}) V_{DS}\)

Drain current saturates

With a small \(W\), the drain current tends to saturate

Does not saturate

Kobayashi Lab
Relation Between MOS Current and Total W

N increases \(\Rightarrow\) Drain current increases
Foundations for Digital Control

Note: not operating with ZVS
Not a true class-e amplifier

Linear relationship between $V_{OUT}$ and N

Transistor Multiplication Factor “N”
Output Power and Efficiency

- Output power increases linearly with N
- Losses increase linearly with N
- Output power nearly constant
Controlling Input Duty Ratio

Duty Ratio

\[ \text{Duty Ratio} = \frac{\Delta t}{T} \]

PWM Signal

Input \( V_{IN} \)

Duty Ratio BIG

Duty Ratio small

\( V_{IN} \)

\( V_{OUT} \)

\( V \)

\( Lf \)

\( C \)

\( L \)

\( R \)

\( V_{OUT} \)

2GHz

\( V1 = 0 \)

\( V2 = 3V \)

\( N = 100 \)

\( L = 400n \)

\( W = 8u \)

Kobayashi Lab
Proposed Amplitude Modulation Scheme

Adjusting number of “on” transistors and duty cycle

Control output voltage → Maximize efficiency
Phase Control

Pulse Position Modulation (PPM)

Can be realized
Amplitude and Phase Control

Change switch array “N”
Amplitude can be controlled
Phase does not change

Change Duty Cycle
Amplitude changes
Phase changes

\[ \phi = \tan^{-1} \left[ \frac{\cos (2\pi D) - 1}{2\pi (1 - D) + \sin (2\pi D)} \right] + n\pi \]
Class E Power Amplifier model

\[ i = I_m \sin(\omega t + \phi) \]

Small NMOS variable \( R_1 \)
Large NMOS variable \( C_p \)
Proposed Digitally Controlled Amplifier

Choose desired amplitude, phase, efficiency

Choose transistor array size, pulse width and delay

Complicated system

Feasible to implement with modern CMOS
Conclusion

• Described design and analysis of class-E amplifiers for digital control

• Using PWM with PPM for phase control
  – Large output voltage range, high efficiency

• Complicated digital control system
  – Easily implemented in modern CMOS processes
Fin

• Questions?
Questions from the Audience

• Doesn't the small transistor case have very low efficiency?
  – Yes, the efficiency is smaller than a typical class-
    e amplifier, but theoretically the highest achievable
    efficiency is 89%

• Can the small size case be modeled as a resistance?
  – Yes, our data shows that this can be modeled as a
    resistance.
Photos