The impact of degradation of efficiency by output power control

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Abstract In order to extend available period of wireless sensor networks, transmission power control is regarded as one of the promising schemes. In most of previous research about transmission power control, it is assumed that a transmitter has power consumption of \(O(d^a)\), where \(d\) and \(a\) denote maximum communication distance and power factor. This assumption substantially holds under the condition that the transmitter efficiency is always constant (efficiency-fixed model). In practice, however, the transmitter efficiency can vary with antenna-output power. In this paper, we show a transmitter with its efficiency degradation has power consumption \(O(d^n)\), where \(a/2.8 \leq n \leq n/2\) (efficiency degradation model). To do so, we model the final stage of transmitter including antenna as an integrated circuit of PA (power amplifier), impedance matching circuit and antenna impedance, and then analyze the model in two ways. The first analysis is based on matching theorem. The second analysis treats of a typical and realistic circuit for class-A and C power amplifiers, and also verify the analytical results by circuit simulations.

Key words Wireless sensor network, Class A power amp, Class C power amp, Output power control, Efficiency, Impedance matching
1. Introduction

Recent advances in micro-sensors, integrated circuit and wireless communication technologies enable WSNs (wireless sensor networks) consisting of a number of small nodes to be emerging. One of the most important issues on such a network is to extend available period. Transmission power control enables a transmitting node to reduce its output power of the RF block to a small extent enough to communicate with an intended receiver node. Many researchers have studied the effect of the transmission power control in an analytical manne and/or by means of simulations. Most of these studies assume that power consumption, $p_{RX}$, of the RF transmitter and the transmission distance, $d$, have the relationship, $p_{RX} = a d^x$, where $a$ and $x$ are constant factors and $x$ ($2 \leq x$) denotes the path loss factor ($1, 2, 4, 9$). This assumption substantially holds under the condition that the transmitter efficiency is always constant for any transmission power. In this paper, we discuss the influence of the variation of the transmitter efficiency on the relationship between maximum transmission distance and power consumption of a transmitter in more detail. There are two ways to control the antenna-output power. One is to vary the output impedance of the power amplifier in the final stage of an RF transmitter, and the other is to vary AC power input to the power amplifier. Since discussion of the latter case is deeply related to architecture of RF transmitter and its peripherals, the latter case remains in the future and we address the former case. Therefore, for the purpose of analysis, we analyze the model in two ways. First, we analyze a matching circuit as the model by means of matching theorem. Second, we analyze a typical circuit model for class-A and C power amplifiers. The first analysis reveals that the power consumption, $p_{AX}$, of the power amplifier is proportional to the maximum transmission distance, $d$, to the power of $n/4$, where $n$ denotes the path loss factor. Thus the power consumption $p_{RX}$ of the power amplifier is proportional to the maximum transmission distance, $d$, to the power of $n/2$ (resp. $n/2$) for class-A (resp. C) power amplifier. This reveals that the power consumption $p_{AX}$ of the power amplifier is proportional to the maximum transmission distance, $d$, to the power of $n/2$, where we call $n$ the degradation factor and it satisfies $n \geq 2$. As results, we suggest the power consumption in an RF block for the power control should be modeled by the ED (Efficiency Degradation) model instead of the SE (Efficiency-fixed) model.

2. Fundamental study based on matching theorem

Figure 1 is a simplified schematic of power amplifier. $Z_s$ is a source impedance, and the antenna generally has a 50-ohm impedance. In this figure, as antennas power, $P_{ANT}$, and source power, $P_s$, are expressed as follows:

\[ P_{ANT} = P_{OUT} \frac{R_{IN}}{R_{IN} + X_{IN}} = P_{OUT} \frac{R_{IN} \cdot R_{ANT} + X_{IN} \cdot X_{ANT}}{R_{IN} \cdot R_{ANT} + X_{IN} \cdot X_{ANT}} = P_{OUT} \frac{R_{IN} \cdot R_{ANT} + X_{IN} \cdot X_{ANT}}{R_{IN} \cdot R_{ANT} + X_{IN} \cdot X_{ANT}}. \]  

(1)

$P_{OUT}$ becomes the maximum power and transmits the maximum power from the antenna if the impedances are matched. In this case, $R_{ANT}$ = $R_{IN}$ and the antenna-power efficiency is 50% according to the matching theorem. The reactances in the equations can be canceled thanks to the impedance matching network, which means that $P_{AX}$ can be controlled by changing the source resistance, $R_s$. When $R_s$ is set to $R_s$, $R_s = R_s$, $n \geq 1$, (1) turns out to the following:

\[ P_{AX} = (1 - \frac{R_{AX}}{R_{AX} + R_s}) \cdot \frac{R_{AX} \cdot R_{AX} + X_{AX} \cdot X_{AX}}{R_{AX} \cdot R_{AX} + X_{AX} \cdot X_{AX}}. \]

(2)

Note that $R_s$ can not be reduced, which causes efficiency degradation as follows:

\[ \eta = \frac{P_{AX}}{P_{PA}} = \frac{P_{AX}}{P_{AX} + P_{s}} = 1 + \frac{1}{n}. \]

(3)

A propagation loss in free-space, $L$, is represented as follows:

\[ L = \frac{\lambda^2}{(4\pi d)^2}. \]

(4)

where $\lambda$ is a transmission distance, and $n$ is path loss factor. Hence, a received power in a receiver placed $d$ apart from the transmitter, $p_{RX}$, is given as follows:

\[ p_{RX} = \frac{\lambda^2}{(4\pi d)^2} \cdot P_{AX} = \frac{\lambda^2}{(4\pi d)^2} \cdot \frac{R_{AX}}{R_{AX} + R_s}. \]

(5)

$p_{AX}$ is eventually as follows:

\[ p_{AX} = \left( \frac{(4\pi d)^2}{\lambda^2} \right) \cdot \frac{R_{AX}}{R_{AX} + R_s}. \]

(6)

This equation indicates that a FA power is proportional to the maximum transmission distance, $d$, to the power of $n/2$ instead of $n$. Thus the degradation factor satisfies $n = 2$. Figure 2 compares the conventional ED and proposed ED models, obtained by a simulation. The figure shows that the transmission-power control is no use if $n = 2$. 

\[ \boxed{-14} \]
3. Efficiency analysis in actual circuit

In the previous section, we pointed out that transmission control becomes less effective according to the matching theorem. To make matters worse in an actual circuit, the situation gets more pessimistic.

Figure 3 is called a cascade amplifier that is widely used as a power amplifier. There are two ways to make the transmission-power control: changing a bias voltage of \( V_c \) and changing a bias voltage of \( V_B \). By changing \( V_c \), the source impedance is varied. Besides, a bias current, \( I_B \), is affected by \( V_B \). When \( V_c \) is changed, a firing angle in a transistor \( M_A \) is varied. In other words, the operating class is varied. If \( V_c \) is a threshold voltage of \( M_A \), the amplifier works in the C class. On the other hand, if \( V_c \) is higher than the threshold voltage of \( M_A \), it is called a class-A amplifier. Theoretically, the efficiency of the class C is much better than the class A, however, the antenna power of the class C cannot be evaluated [11]. Thus, the class-A amplifier is widely utilized as a power amplifier.

3.1 Class-A power amplifier

In this subsection, the power efficiency in the class-A amplifier is analytically discussed. The antenna power can be controlled by \( V_c \). When \( V_c = V_{th} \), the maximum antenna power can be obtained, while it is reduced to zero when \( V_c = 0 \). In this manner, the antenna power is controllable, although the efficiency gets worse than the case in the matching theorem because of the bias current. The power efficiency is the actual circuit is given as follows:

\[
\eta = \frac{P_{out}}{P_{in} + P_{loss}},
\]

where \( P_{in} = I_{in} V_{in} \). This is an additional term caused by the bias (compare with (3)). Hereafter, the efficiency is analytically solved.

3.1.1 Circuit condition

The circuit conditions are as follows:
- Circuit simulator: ADS 2004A (Agilent Technologies)
- Device parameter: OKI 0.15-µm SOI-CMOS process
- \( V_{DD} = V_c = 5 \) V, \( V_B = 0.6 \) V, \( |v_{in}| = 0.2 \) V
- Operating frequency: 95 MHz
- Quality factor of \( L_1 \): 20

3.1.2 DC power, \( P_{DC} \)

An intermediate voltage between \( M_A \) and \( M_B \) can be obtained as a function of \( V_c: V_c = \eta |V_c|^2 + b \).

In the figures, the node A is biased to \( V_{dd} \) since \( R_B \) is much smaller than the impedance of \( M_A \) and \( M_B \), and \( V_{dd} \) of \( M_B \) is \( V_{dd} - V_c \). On the other hand, \( V_{dd} \) of \( M_B \) is \( V_c - V_c \), which means \( V_{dd} > V_{dd} \) always holds, and \( M_B \) is operated in a saturation region. Hence, \( I_{dc} \) is as follows:

\[
I_{dc} = \frac{\beta}{2} \left( V_c - V_{dd} \right)^2 \left( 1 + \lambda (V_{dd} - V_c) \right),
\]

where \( V_c \) is a threshold voltage of \( M_B \), and \( \beta \) is its gain factor.

3.1.3 AC power, \( P_{out} \) and \( P_{loss} \)

\( P_{out} \) and \( P_{loss} \) are analyzed with a small signal equivalent circuit in Fig. 4. \( P_{out} \) and \( P_{loss} \) represent power consumed by \( R_{in} \) and \( R_L \), respectively, and are functions of a transconductance of \( M_A \), \( \beta_{in} \), as follows:

\[
\begin{align*}
\eta = & \beta \lambda V_c \\
& \beta \lambda (V_c - V_i (1 + \lambda V_c)) ~ \text{Linear region})
\end{align*}
\]

\[
\begin{align*}
\eta = & \beta \lambda V_c \\
& \beta \lambda (V_c - V_i (1 + \lambda V_c)) ~ \text{(Saturation region)}
\end{align*}
\]
4. Conclusions

In most of the previous studies on the transmission power control, it is assumed that the power consumption of a transmitter is modeled as $P_{TX} = n P_{TX} + p_{TX} d^{-m}$, called EF model in this paper, where $n$ is the path-loss factor. In this paper, impact of degradation of transmitter efficiency on transmission power control is investigated by matching theorem and analyses of a realistic circuit with the aid of circuit simulations. As results, we developed the power consumption model named ED model, which makes a transmitter have power consumption $P_{TX} = n P_{TX} + m P_{TX} d^{-m}$, where $m$ is the degradation factor. Matching theorem revealed that a transmitter has at least $m = 2$, and the analyzes of a realistic circuit showed that the transmitter using A (resp. C) class amplifier has the worse degradation factor $m = 2.6$ (resp. $m = 2.8$). We also showed that the power reduction ratio $R_{DO}$ by the transmitter power control strongly depends on the degradation factor. To conclude, the ED model is more suitable than the EF model for exact studies on the transmission power control.

References