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送信電力制御による効率劣化の影響

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あらまし ワイヤレスセンターネットワークの長寿命化において送信電力はその重要な1つの方法として考えられる。従来研究においては、消費電力は $O(d^n)$ (ここで d は最大通信距離、n はパス損失係数) で変化すると仮定されてきた。しかし、この仮定は送信効率が常に一定の場合において成り立つものであり、実際には送信効率は変動すると考えられる。そこで本稿では、送信器の最終段であるパワーアンプ、インピーダンス整合回路、アンテナをモデル化し，インピーダンス整合理論ならびに，典型的な A、C 級パワーアンの実回路シミュレーションにより、送信効率の劣化が及ぼす影響を検討した。その結果、送信効率が劣化する場合、送信器の消費電力が $O(d^r)(n/2.8 \leqq r \leqq n/2)$ により変化することを明らかにした。

キーワード ワイヤレスセンサーネットワーク, A 級パワーアンプ, C 級パワーアンプ, 送信電力制御, 効率, インピーダンス整合

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 $O(d^n)$, where d and n denote maximum communication distance and pass loss 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 of $O(d^r)$, where $n/2.8 \leqq r \leqq n/2$ (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 manner and/or by means of simulations. Most of these studies assume that power consumption, p_{TX}, of the RF transmitter and the transmission distance, d, have the relationship, $p_{\mathrm{TX}} = \alpha_{\mathrm{TX}} + \rho_{\mathrm{TX}} \cdot d^n$, where α_{TX} and ρ_{TX} are constant factors and n $(2 \sim 4)$ denotes the path loss factor ([1,2,6,9]). 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 inputted 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 former case, 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 and realistic circuit for class-A and C power amplifiers.The first analysis reveals that the power consumption, p_{PA} of the power amplifier is proportional to the maximum transmission distance, d, to the power of $n/2$, where n denotes the path loss factor. The second analysis shows the value of p_{PA} is proportional to d to the power of $n/2.6$ (resp. $n/2.8$) for class-A (resp. C) power amplifier. Thus the power consumption p_{PA} of the power amplifier is proportional to the maximum transmission distance, d, to the power of n/m, where we call m the degradation factor and it satisfies $m \geqq 2$. 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 EF(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, an antenna power, p_{ant}, and source power, p_{s}, are expressed as follows:

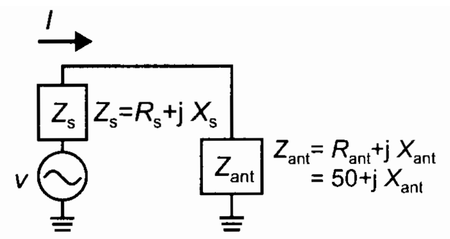

図 1 Matching circuit.

$$\begin{aligned} p_{\mathrm{ant}} &= R_{\mathrm{ant}}|I|^2 = \frac{R_{\mathrm{ant}}|E|^2}{(R_{\mathrm{s}}+R_{\mathrm{ant}})^2+(X_{\mathrm{s}}+X_{\mathrm{ant}})^2}, \\ p_{\mathrm{s}} &= R_{\mathrm{s}}|I|^2 = \frac{R_{\mathrm{s}}|E|^2}{(R_{\mathrm{s}}+R_{\mathrm{ant}})^2+(X_{\mathrm{s}}+X_{\mathrm{ant}})^2}. \end{aligned} \tag{1}$$

p_{ant} becomes the maximum power (and transmits the maximum power from the antenna) if the impedances are matched. In this case, $R_{\mathrm{s}} = R_{\mathrm{ant}}$ 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_{ant} can be controlled by changing the source resistance, R_{s}. When R_{s} is set to aR_{s} ($R_{\mathrm{s}} \to aR_{\mathrm{s}}, a \geq 1$), (1) turns out to the following:

$$\begin{aligned} p_{\mathrm{ant}} &= \frac{R_{\mathrm{ant}}|E|^2}{(aR_{\mathrm{s}}+R_{\mathrm{ant}})^2} = \frac{1}{(1+a)^2}\frac{|E|^2}{R_{\mathrm{ant}}}, \\ p_{\mathrm{s}} &= \frac{aR_{\mathrm{s}}|E|^2}{(aR_{\mathrm{s}}+R_{\mathrm{ant}})^2} = \frac{a}{(1+a)^2}\frac{|E|^2}{R_{\mathrm{ant}}}. \end{aligned} \tag{2}$$

Note that R_{s} can not be reduced, which causes efficiency degradation as follows:

$$\eta = \frac{p_{\mathrm{ant}}}{p_{\mathrm{PA}}} = \frac{p_{\mathrm{ant}}}{p_{\mathrm{ant}} + p_{\mathrm{s}}} = \frac{1}{1+a}. \tag{3}$$

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

$$L = \frac{\lambda^2}{(4\pi)^2 d^n}, \tag{4}$$

where d 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 give as follows:

$$p_{\mathrm{RX}} = k\frac{\lambda^2}{(4\pi)^2 d^n} p_{\mathrm{ant}} = k\frac{\lambda^2}{(4\pi)^2 d^n}\frac{R_{\mathrm{ant}}}{|E|^2} p_{\mathrm{PA}}^2. \tag{5}$$

p_{PA} is eventually as follows:

$$p_{\mathrm{PA}} = \sqrt{\frac{(4\pi)^2|E|^2 p_{\mathrm{RX}}}{k\lambda^2 R_{\mathrm{ant}}}}\, d^{n/2}. \tag{6}$$

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

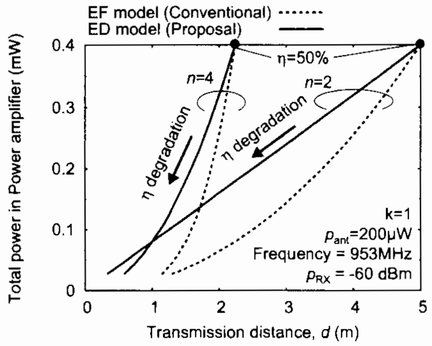

図 2 PA power dependencies on transmission distance in EF and ED models.

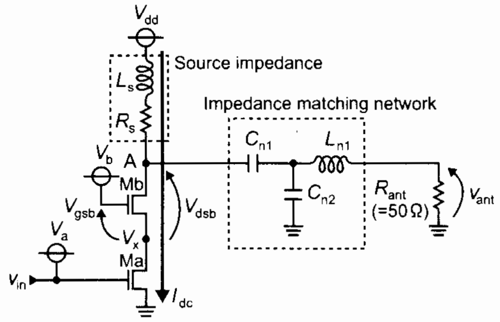

図 3 Cascode power amplifier.

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 cascode 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_a and changing a bias voltage of V_b. By changing, V_b, the source impedance is varied. Besides, a bias current, I_{dc}, is affected by V_b. When V_a is changed, a firing angle in a transistor Ma is varied. In other words, the operating class is varied. If V_a is a threshold voltage of Ma, the amplifier works in the C class. On the other hand, if V_a is larger than the threshold voltage of Ma, 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 enlarged [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_b. When $V_b = V_{dd}$, the maximum antenna power can be obtained, while it is reduced to zero when $V_b = 0$. 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

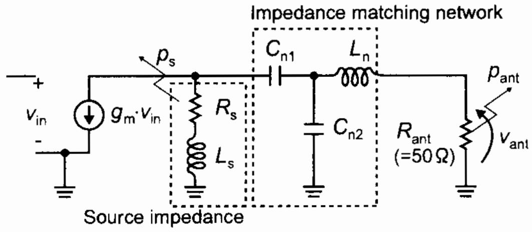

図 4 Small-signal equivalent circuit.

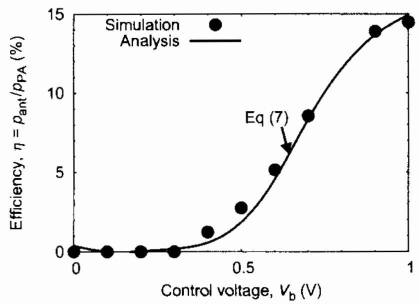

図 5 PA efficiency.

in the actual circuit is given as follows:

$$\eta = \frac{p_{ant}}{P_{dc} + p_s + p_{ant}}, \tag{7}$$

where $P_{dc} = I_{dc}V_{dd}$. 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}; 1V, V_a; 0.6 V, $|v_{in}|$ (amplitude of v_{in}); 0.2 V
- Operating frequency; 953MHz
- Quality factor of L_s; 20

3.1.2 DC power, P_{dc}

An intermediate voltage between Ma and Mb can be obtained by their static characteristics, and fitted as a function of V_b:$V_x = aV_b^2 + b$.

In the figure, the node A is biased to V_{dd} since R_s is much smaller than the impedance of Ma and Mb, and V_{dsb} of Mb is $V_{dd} - V_x$. On the other hand, V_{gsb} of Mb is $V_b - V_x$, which means $V_{dsb} > V_{gsb}$ always holds, and Mb is operated in a saturation region. Hence, I_{dc} is as follows [?]:

$$I_{dc} = \frac{\beta_b}{2}\Big(V_b - V_x - V_t\Big)^{x}\Big\{1 + \lambda(V_{dd} - V_x)\Big\}, \tag{8}$$

where V_t is a threshold voltage of Mb, and β_b is its gain factor.

3.1.3 AC power, p_{ant} and p_s

p_{ant} and p_s are analyzed with a small signal equivalent circuit in Fig. 4. p_{ant} and p_s represent powers consumed by R_{ant} and R_s, respectively, and are functions of a transconductance of Ma, g_{ma}, as follows:

$$g_{ma} = \begin{cases} \beta_a V_x & \text{(Linear region)}, \\ \beta_a(V_a - V_t)(1 + \lambda V_x) & \text{(Saturation region)}. \end{cases} \tag{9}$$

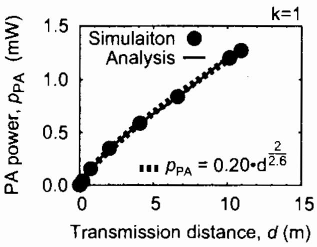

図 6 Transmission distance versus power (n=2).

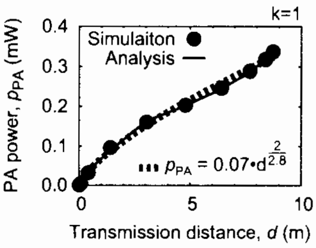

図 7 Transmission distance versus power (n=2).

$v_{\rm ant}$ is obtained as follows:

$$v_{\rm ant} = R_{\rm ant} \cdot \frac{W_{\rm a} - jX_{\rm a}}{P_{\rm a} - jQ_{\rm a}} g_{\rm ma} \cdot v_{\rm in}, \tag{10}$$

where $P_{\rm a}$, $Q_{\rm a}$, $W_{\rm a}$, and $X_{\rm a}$ are constants given by $R_{\rm s}$, $L_{\rm s}$, $C_{\rm n1}$,$C_{\rm n2}$, and $L_{\rm n}$.

Therefore, $p_{\rm ant}$ is as follows:

$$\begin{aligned} p_{\rm ant} &= \frac{|v_{\rm out}|^2}{R_{\rm ant}} = R_{\rm ant} \cdot \frac{W_{\rm a}^2 + X_{\rm a}^2}{P_{\rm a}^2 + Q_{\rm a}^2} \cdot g_{\rm ma}^2 \cdot v_{\rm in}^2 \\ &= \zeta \cdot g_{\rm ma}^2 \cdot v_{\rm in}^2. \end{aligned} \tag{11}$$

$p_{\rm s}$ is also obtained as follows:

$$p_{\rm s} = R_{\rm s} \cdot \frac{W_{\rm s}^2 + X_{\rm s}^2}{P_{\rm s}^2 + Q_{\rm s}^2} \cdot g_{\rm ma}^2 \cdot v_{\rm in}^2 = \xi \cdot g_{\rm ma}^2 \cdot v_{\rm in}^2, \tag{12}$$

where $P_{\rm s}$, $Q_{\rm s}$, $W_{\rm s}$, and $X_{\rm s}$ are constants.

3.1.4 PA efficiency

The PA power is a sum of $p_{\rm ant}$, $p_{\rm s}$, and $P_{\rm dc}$, and thus is expressed as follows:

$$\begin{aligned} p_{\rm PA} &= P_{\rm dc} + p_{\rm s} + p_{\rm ant} \\ &= \frac{\beta_{\rm b}}{2}\Big(V_{\rm b} - V_{\rm x} - V_{\rm t}\Big)^{\chi}\Big\{1 + \lambda(V_{\rm dd} - V_{\rm x})\Big\} \\ &+ \zeta \cdot g_{\rm ma}^2 \cdot v_{\rm in}^2 + \xi \cdot g_{\rm ma}^2 \cdot v_{\rm in}^2. \end{aligned} \tag{13}$$

Figure 5 illustrates the PA efficiency, and it can be seen that the efficiency is degraded as $V_{\rm b}$ is lowered. Figure 6 show the relationship between the PA power and transmission distance that is obtained by (5), (12) and (13). The curve can be fitted to a form of $\rho_{\rm TX} \cdot d^r$ using the least squares method, in which the parameters, $\rho_{\rm TX}$ and r are signified in the figure. The result shows that the PA power consumption is proportional to the transmission distance to the power of $n/2.6$. The degradation factor, m is worse than that in the matching-theorem case because the DC power is added to the PA power.

3.2 Class-C power amplifier

In a Class-C amplifier, the small-signal equivalent circuit is not appropriate and the circuit behavior cannot be analytically solved because $V_{\rm a}$ is biased to a threshold voltage. Thus, a circuit simulation is carried out with Advanced Design System 2004A (Agilent Technologies), from which m is obtained as 2.8. The results are shown in Fig. 7.

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 $P_{\rm TX} = \alpha_{\rm TX} + \rho_{\rm TX} \cdot d^n$, 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 analyzes 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 $P_{\rm TX} = \alpha_{\rm TX} + \rho_{\rm TX} \cdot d^{n/m}$, 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 $R_{\rm rdc}$ by the transmission 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

[1] A. Depedri, A. Zanella, and R. Verdone, "An Energy Efficient Protocol for Wireless Sensor Networks," *Proc. Autonomous Intelligent Networks and Systems (AINS 2003)*, Menlo Park, CA, June/July, 2003.

[2] A. P. Chandrakasan, R. Min, M. Bhardwaj, S. Cho, and A. Wang, "Power Aware Wireless Microsensor Systems," *Keynote Paper 28th European Solid-State Circuits Conference (ESSCIRC)*, Florence, Italy, 2002.

[3] D. D. Wentzloff, B. H. Calhoun, R. Min, A. Wang, N. Ickes, and A. P. Chandrakasan, "Design considerations for next generation wireless power-aware microsensor nodes," *Proc. VLSI Design 2004*, pp. 361-367, 2004.

[4] J. L.Hill and D. E.Culler, "Mica: A wireless platform for deeply embedded networks," *IEEE Micro.*, Vol.22, No.6, pp.12-24, Nov./Dec. 2002.

[5] J. Rabaey, J. Ammer, Jr. da Silva, and D.J. Patel, "PicoRadio : Ad-hoc Wireless Networking of Ubiquitous LowEnergy Sensor/Monitor Nodes," *Proc. IEEE Computer Society Workshop on VLSI(WVLSI)*, Orlando, Florida, April, 2000.

[6] M. Bhardwaj, T. Garnett, A. P. Chandrakasan, "Upper Bounds on the Lifetime of Sensor Networks," *Proc. IEEE ICC 2005*, pp.785–790, June, 2001.

[7] M. Haenggi, "The Impact of Power Amplifier Characteristics on Routing in Random Wireless Networks," *Proc. IEEE GLOBECOM 2003*, San Francisco, CA, Dec. 2003.

[8] M. Haenggi and D. Puccinelli, "Routing in Ad Hoc Networks: A Case for Long Hops," *IEEE Communications Magazine*, Vol. 43, pp. 93-101, Oct. 2005.

[9] O. Younis and S. Fahmy, "Distributed Clustering in Adhoc Sensor Networks: A Hybrid, Energy-Efficient Approac," *Proc. IEEE INFOCOM 2004*, Hong kong, Mar. 2004.

[10] S. Soro and W. Heinzelman, "Prolonging the Lifetime ofWireless Sensor Networks via Unequal Clustering," *Proc. the 19th IEEE international Parallel & Distributed Processing Symposium (IPDPS)*, May, 2005.

[11] B.Razavi,"RF Microelectronics," Prentice Hall, 1998.