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A study for the efficiency of transmission energy for different high-frequency communication circuits

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Abstract: This paper presents a performance comparison method among the circuits for different high-frequency communication systems using newly proposed figure of merit (FOM). Efficiencies of transmission energy of circuits for optical communications, cellular phone systems, and ubiquitous network systems are compared by the FOM. The FOM expresses the circuit performance among the different communication systems without the influence of the difference of the communication capacity and the device performance. The FOM of the circuits are plotted in the almost equal value without depending on system differences, and the differences indicate the technical evolutions of the systems and circuit designs.

Keywords: High-frequency circuit, transmission efficiency

Classification: Integrated circuits

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1 Introduction

Among high-frequency circuits for different communication systems such as optical communications, cellular phone systems, and ubiquitous network systems, there are no adequate performance indicators about the techniques of the circuit designs. These systems require widely different specifications to the circuits. The communication distance for the optical communication systems is about several hundred kilometers and the data rate is ultra-high-speed of over 10-Gb/s. The circuits of the optical communications provide the performance of high-speed operation while the power consumption of the circuits is over several watts. As for the cellular phone systems, the communication distance is about several hundred meters and data rate is about several Mb/s. The circuits of the cellular phones have a bandwidth of several MHz with operating frequency of several GHz, and low-power-consumption of about several tens milliwatts is required to ensure long battery life. On the contrast, for the ubiquitous network systems such as radio frequency identification (RFID) tags or sensor network systems, the communication distance is very short distance of about ten meters and data rate is about kb/s. The circuits of ubiquitous network systems have a bandwidth of several kHz with operating frequency of several GHz and the circuits are required ultra-low-power consumption of about several microwatts. Comparing these different circuits, these communication systems have trends that the higher data rate circuits consume higher power. Normalization by the power consumption of a circuit over the data rate of the system as a unit of J/bit shows roughly the circuit performance of the efficiency of transmission energy. However, this expresses the circuit performance including the difference of device performance and the difference between the data rate and operating frequency. In this paper, we introduce newly proposed FOM of a circuit performance based on the J/bit for the different communication systems. The FOM presents the efficiency of transmission energy of circuits without concerning of system

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difference, data rate, device performances, and development year.

2 Expression of circuit performance using J/bit

In this session, the circuit performances of transmission efficiency for the various communication systems are indicated by FOM using J/bit as the first step. Figure 1 shows plots of power consumption versus data rate about laser diode (LD) drivers for the high-speed optical systems, up-convertors for the cellular phone systems, and circuits for ubiquitous networks. These data distribute the range from 1 pJ/bit to 1 μJ/bit without the difference among the systems. All systems have the tendency which reduces the J/bit as the year's passes. Theoretical limit for the reduction of the FOM is introduced by the Shannon limit [1]. The communication capability C is expressed using Shannon's formula as follows,

$$C = B_W \log_2 \left(1 + \frac{P_S}{N_0 B_W}\right) \tag{1}$$

where B_w is bandwidth of a signal, P_s is the signal power, and N_o is noise power at unit bandwidth. On the condition that the B_w is infinite, eq. (1) is expressed as follows,

$$C = \frac{P_S}{N_0} \log_2 e \tag{2}$$

Theoretical demanding of energy to transmit 1-bit (Eb) is shown as follows with thermal noise at room temperature,

$$E_b = P_S/C = N_0/\log_2 e = kT/\log_2 e \approx 2.88 \times 10^{-21}\ [J/bit] \tag{3}$$

Eb that comes from Shannon's limit is also shown in Figure 1. The theoretical limit for the J/bit is around 10^{-8} smaller than the actual values of

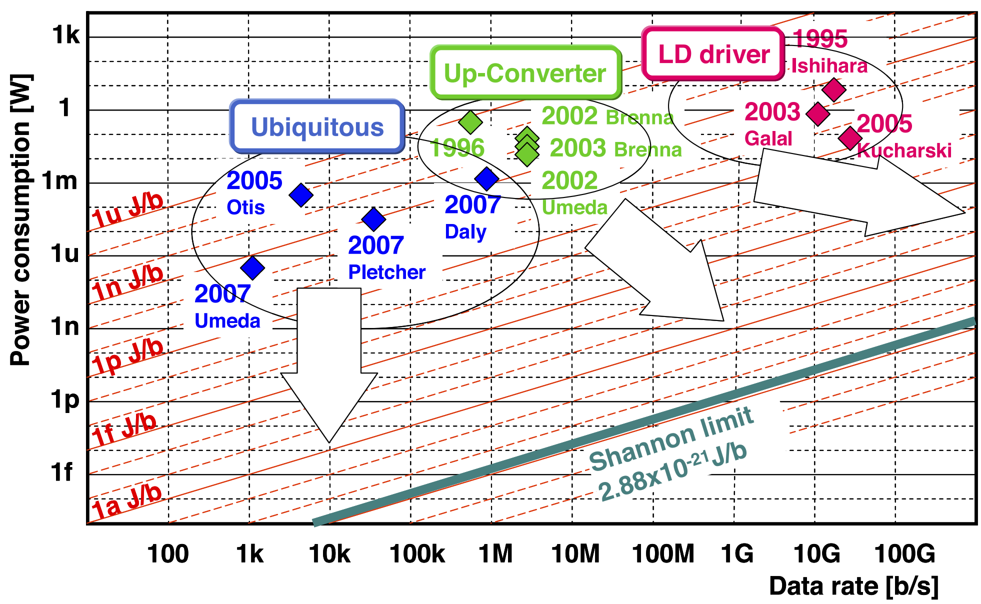

Fig. 1. Circuit performance for LD drivers, up-converters, and circuits for ubiquitous system using indicator of J/bit and theoretical J/bit limit estimated by Shannon formula.

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J/bit, and it means the circuits can further reduce the power consumption. From this result, the FOM of J/bit shows the outline of the circuit performances of transmission efficiency for the various systems. However, this FOM doesn't consider the difference between the data rate and operating frequency, and includes device difference such as gate length of CMOS transistors that improves cut-off frequency of the transistors. To indicate the techniques of high-frequency circuit design, a new FOM that doesn't depend on the difference among the systems is introduced.

3 Proposal of new FOM for circuit performance

In order to express the intrinsic circuit performance, we introduce a new FOM in this session. The proposed FOM is based on the J/bit that is the same as former session but newly two coefficients are introduced. The first coefficient is communication capability coefficient, which complements the difference between bandwidth and operating frequency. The values of the coefficients are widely different among the systems. For example, the data rate of the circuit of high-speed optical system is almost the same as the operate frequency f_{OP}. On the other hand, the data rate of RF front-end circuit is about Mb/s, though the circuit must operate the carrier frequency of over GHz. As for the RF circuits, the performance must be evaluated by the based on the operating frequency because the power consumption of high-frequency circuits depends not on the band width of the data but on the operating frequency or carrier frequency. To complement these differences, we introduce the communication capability coefficient C_f as follows,

$$C_f = \frac{B_w}{f_{OP}}. \tag{4}$$

C_f acts as the bridge between energy efficient per 1-bit transmission and the operation frequency of a circuit. The second coefficient is device performance coefficient C_d, which normalizes the comparison of f_{OP} and the maximum available frequency of the transistor f_{max}. The frequency characteristics of the maximum available gain follows a line of -20 dB/dec. When a circuit is operated at 1/10 frequency of f_{max}, the circuit has theoretically the power gain of 20 dB. This means that the higher f_{max} circuit can obtain the lower power consumption in the same f_{OP} system, and J/bit is reduced only by the improvement of device performance. In order to exclude device performances, we introduce C_d as follows,

$$C_d = \left(\frac{f_{\max}}{f_{OP}}\right)^2 \frac{1}{G_p} \tag{5}$$

where G_p is the actual power gain of a circuit. Eq. (5) means the performance comparison between actual power gain and theoretical power gain. Using these coefficients, we propose new FOM as mentioned below.

$$FOM = C_f \cdot C_d \frac{P}{B_w} = \frac{P}{f_{OP}} \left(\frac{f_{\max}}{f_{OP}}\right)^2 \frac{1}{G_p} \tag{6}$$

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where P is power consumption. This FOM means that circuit performance can be evaluated by the terms of the power consumption, operating frequency, gate length that directly convert to f_{max}, and power gain. Note that this FOM shows the lower value has the better performance. The FOM is useful indicator for circuit evaluation because these terms are almost mentioned in the abstract of a paper.

4 Performance comparison for various circuits

In this session, various high-frequency circuits from different systems are indicated using proposed FOM. Table I shows the performance of the circuits for various systems and development years. Figure 2 shows the FOM versus power consumption for table I. As for the LD driver, the FOM has a tendency of improvement of the performance every year. The reason is that the performance of the LD drivers includes the improvement of the high-frequency characteristics of LD itself. On the other hand, the up-converters have almost same FOM. We think the reason is that the circuit designs of the up-converters are almost same schematics using double balanced mixer. Compared with these circuits, the circuits for the ubiquitous systems show widely different FOM for each circuit. It can consider this is caused by the difference of the circuit components. In the case of Daly et al. in 2007, the RF receiver circuit consists of a low-noise amplifier (LNA) and mixer [10]. The FOM is moderate because this is a same component with general RF circuits. In the case of Pletcher et al. in 2007, the RF receiver circuit consists of only an LNA and excludes a mixer [9]. This is the reason the FOM improves. Compared with these circuits, the FOM of Umeda et al. in 2007 further improves because the RF receiver uses only a rectifier [8]. The trend of the technical evolutions indicates the small power consumption has a better performance. From these results, circuit designer can easily evaluate the techniques of circuit designs using proposed FOM without considering the difference of the systems.

Table I. Performances of circuits for various systems.

	LD driver			Up-Converter			Ubiquitous		
Author	Kucharski[2]	Ishihara[3]	Galal[4]	Umeda[5]	Brenna[6]	Brenna[7]	Umeda[8]	Pletcher[9]	Daly[10]
Affiliation	IBM	NTT	UCLA	Toshiba	ETH	ETH	Toshiba	BWRC	MIT
Year	2005	1995	2003	2002	2002	2003	2007	2007	2007
Power consumption [mW]	70	625	675	49	101.5	68	0.0002	0.065	2.5
Operating freruency [GHz]	20	3.5	10	2	2	2	0.95	1.9	0.9
Gate length [um]	0.13	Si-Bip	0.18	0.25	0.25	0.13	0.13	0.09	0.18
fmax [GHz]	98	40	73	46	46	98	98	140	73
Power Gain [dB]	2.2	13	12	6.7	8.5	12.5	20	30	11.5
FOM [W/Hz]	5.1E-11	1.1E-9	2.6E-10	2.7E-9	3.7E-9	4.5E-9	2.2E-14	1.9E-13	1.3E-9

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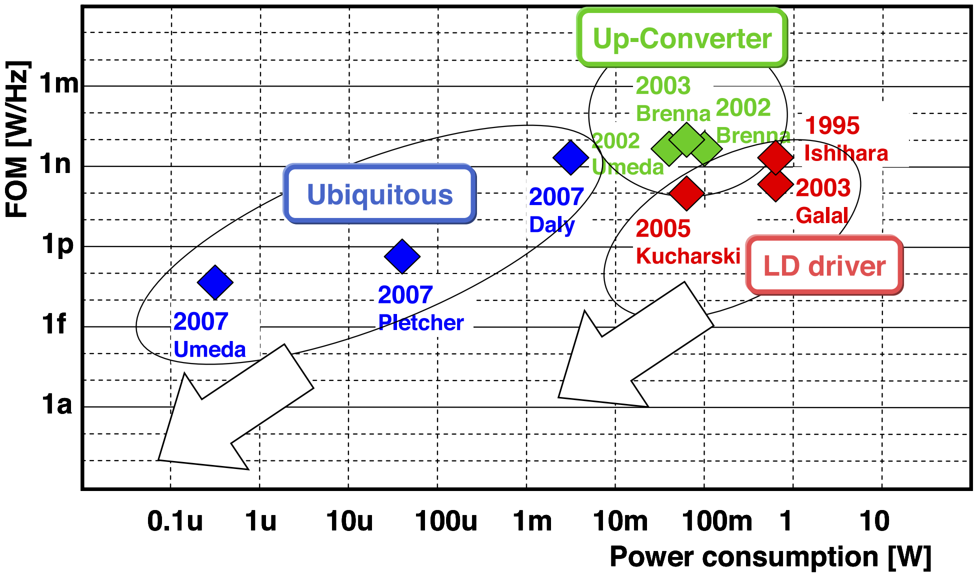

Fig. 2. Circuit performance using proposed FOM.

5 Conclusion

In this paper, we present a performance comparison method of transmission efficiency among the circuits for different high-frequency communication systems using newly proposed FOM. The circuits for optical communications systems, cellular phone systems, and ubiquitous network systems are compared by the FOM. The proposed FOM expresses the circuit performance without the influence of the difference of the communication capacity and the device performance among the different communication systems. Circuit designers can easily evaluate the technical performance of the systems and circuit designs for transmission efficiency using proposed FOM.

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