Design of Wireless System with Minimum Eb/No and Optimization of Power Consumption

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Abstract

It is very important to design the wireless communication system with the minimum Eb/No and to optimize the power consumption because most of the wireless communication and mobile computing devices basically get the energy from the battery. So, we have to calculate and apply the power consumption and furthermore to develop nice techniques for reducing the power consumption of wireless communication devices. This paper shows the modeling of transmitter and receiver each device part. Also, the analyses the system quality apply to RF power model. But, this paper is only consider free space loss and that has not been analyzed the system performance according to frequency band. In this paper, we consider the effect of signal bandwidth, PAR, symbol rate, modulation level, transmission distance, specific attenuation of frequency band and the signal center frequency on the RF front-end energy consumption and system capacity.

Keywords: *Power model, Energy consumption, Power consumption, Energy per bit*

1. Introduction

Wireless communication and mobile computing device are widely used in everyday. All of these devices are powered by batteries with a limited lifetime. Therefore, capacity of battery and power consumption of device are very important at these devices. Since the advance in battery technology have failed to keep up with increasing current consumption wireless communication and mobile computing device, efficient techniques to reduce the power consumption devices have to developed. The design of technique for low power wireless communication systems constantly attracts a great deal of researchers' attention.

Different approaches of low power wireless communication have been addressed in recent years. These change of the modulation [1]-[3], multi-hop [4], scheduling method [5] etc. These approaches are focused on power consumption at digital parts. However, the wireless communication system consumes more power at RF parts. Therefore, power model of RF parts is required to design of wireless system.

Recently, the RF transceiver power model has been provided [6]. This paper shows the modeling of transmitter and receiver each device part. Also, the analyses the system quality apply to RF power model. But, this paper is only consider free space loss and that has not been analyzed the system performance according to frequency band. In this paper, we consider the effect of signal bandwidth, PAR, symbol rate, modulation level, transmission distance, specific attenuation of frequency band and the signal center frequency on the RF front-end energy consumption and system capacity.

2. Power Consumption Model

2.1. Transceiver Block

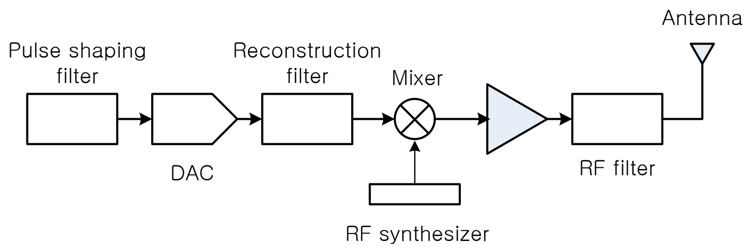

Figure 1. Block Diagram of the Transmitter

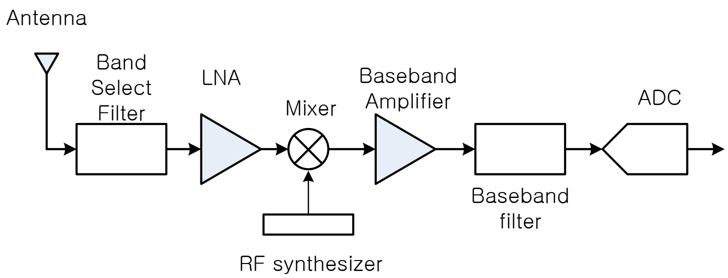

Figure 2. Block Diagram of the Receiver

The wireless transmitter and receiver structure that we have used is described in Figure 1 and Figure 2 [6]. We assume that the transmitter and receiver works in three states : (1) active state when the signal is transmitted, (2) sleep state when there is no signal transmission, and (3) transient state when the transmitter switches from sleep state to active state or active state to sleep state. Therefore the total energy consumption is given by [6]

$$E_{total} = P_{active}T_{active} + P_{sleep}T_{sleep} + P_{transient}T_{transient}. \tag{1}$$

In this paper, we only consider active state power consumption because the power consumption of active mode is dominant. Since transmission energy is delivered by PA [7].

$$\begin{aligned} E_{active} = (&P_{PA} + 2P_{mix} + 2P_{FS} + P_{LNA} \\ &+ P_{filter} + P_{BA} + P_{DAC} + P_{ADC})T_{active} \end{aligned}, \tag{2}$$

where P_{PA}, P_{mix}, P_{FS}, P_{LNA}, P_{filter} and P_{BA} are the power consumption of the PA, mixer, frequency synthesizer, low noise amplifier, filter and baseband amplifier, respectively.

2.2. Power Model

In this section, we present the power models for each of the components in the analog signal chain of a transmitter and receiver. The existing RF power model [6] is used. The power model of DAC can be expressed as a function of PAR (Peak-to-average ratio), SQNR(Signal-to-quantization-noise ratio) signal bandwidth B and resolution.

$$\begin{aligned} P_{DAC} = V_{dd} \cdot I_0 \cdot \Big(2^{SQNR(dB)+PAR(dB)-4.77dB/6.02} - 1\Big) \\ + 0.5 \cdot \frac{SQNR(dB) + PAR(dB) - 4.77dB}{6.02} . \\ \cdot C_p \cdot OSR \cdot B \cdot V_{dd}{}^2 \end{aligned} \tag{3}$$

The power consumption of baseband active analog filter can be estimated as follow [8]

$$P_{filter} = n \cdot kT \cdot Q \cdot f_0 \cdot SNR^2, \tag{4}$$

where n is a proportionality constant depending on the filter topology and the active elements used (op-amp RC, trans-conductance-C, etc.), is the quality factor, is the center frequency(band-pass filter) or corner frequency (low-pass filter), and SNR is the signal-to-noise ratio of the filter.

The power consumption of integer-N PLL frequency synthesizer with multiplication ratio of N can be estimated as follow [6]

$$P_{pll} = b_1 \cdot C_1 \cdot V_{dd}{}^2 \cdot F_{LO} + b_2 \cdot C_2 \cdot V_{dd}{}^2 \cdot F_{ref}\,, \tag{5}$$

where C_1 and C_2 represent the total parasitic capacitance loading of the RF circuits, F_{ref} is the reference frequency and V_{dd} is the supply voltage, which is also assumed to be equivalent to the LO voltage swing.

The power consumption of VCO is given by [6]

$$\begin{aligned} P_{VCO} &= R \cdot I_{pk}{}^2 = C\frac{R}{L}V_{pk}{}^2 = RC^2\omega_c{}^2V_{pk}{}^2 \\ &= \frac{R}{L^2\omega_c{}^2}V_{pk}{}^2 \end{aligned} , \tag{6}$$

where V_{pk} and I_{pk} is the peak voltage and current amplitude inside the tank circuit. For a given series resistance, the efficiency can be increased by increasing the inductance. For an MQAM communication system can be calculated.

$$P_{VCO} = C \cdot \left(\frac{R}{L}\right)^3 \cdot NEF \cdot \frac{k \cdot T}{S_\phi} \cdot \frac{1}{(\Delta\omega)^2}\,, \tag{7}$$

where NEF is the noise excess factor of the active device used in the oscillator, Q is the quality factor of the LC tank, P_{sig} is the ac signal power of the oscillation waveform, and $\Delta\omega$ is the offset frequency from the carrier.

The power model of the mixer is a function of the noise figure NF and the gain K [7].

$$P_{mixer} = k_{mixer} \cdot K / NF. \tag{8}$$

LNA amplifies the received signals with low input referred noise. LNA determines the noise figure of receiver. The power model of LNA is a function of the noise figure NF and the gain A [7].

$$P_{LNA} = k_{LNA} \cdot A / NF \,. \tag{9}$$

The efficiency η of Class A PA is proportional to the RMS(Root mean square) value of the output power [8]

$$\eta = \frac{P_{rms}}{P_{PA}} = \frac{P_{out}}{P_{out\_\max}} \cdot K = \frac{K}{PAR} \,. \tag{10}$$

Therefore,

$$P_{PA} = \frac{P_{rms}}{K} \cdot PAR. \tag{11}$$

The power model of PA is thus given by [6]

$$P_{PA} = \frac{16 \cdot \pi^2 \cdot d^2 \cdot L}{3 G_r G_t \lambda^2 \cdot K} (2^b - 1) \cdot N \cdot \left(Q^{-1} \left(\frac{1}{4} \left(1 - \frac{1}{2^{b/2}} \right)^{-1} SER \right) \right)^2 PAR \,. \tag{12}$$

where G_r and G_t are the transmitter and receiver antenna gain, d is free space propagation at distance(meter). L is the system loss factor not related to propagation, and λ is the carrier wavelength. This equation only considers MQAM. Therefore, for other modulation scheme, the PA model is similar but Q function is different.

Table 1. RF Power Consumption in Transceiver [6]

	Power model function	PAR = 10dB
PA	P (PAR, d, b, SER)	246 mW
Mixer	P (K, NF)	30.3 mW
F.S	P (ω_c , F_{LO} , F_{ref})	67.5 mW
LNA	P (A, NF)	20 mW
ADC	P (PAR, SNR, f)	5.85 mW
DAC	P (PAR, SNR)	2.43 mW
Filter	P (SNR, f)	5 mW
BA	P (B, α_{BA})	5 mW

3. System Capacity

In this section, we study on the effect of channel propagation on the system capacity. We use channel propagation model (ITU-R 676-1) that is dry air and water vapour model. Also, we simulate the system capacity according to frequency band using Shannon capacity formula.

3.1. Specific Attenuation

The specific attenuation due to dry air at ground level (pressure = 1, 013 hPa) and at a temperature of $15^{\circ}C$ is given by the following equation [9],

$$\gamma_{dry} = \{7.19\times10^{-3} + \frac{6.09}{f^2+0.227} + \frac{4.81}{(f-57)^2+1.50}\} f^2 10^{-3} \quad \text{dB/km} \quad \text{for f<57GHz.} \tag{13}$$

Also, the specific attenuation due to water vapor at ground level (pressure = 1, 013 hPa) and at a temperature of $15^{\circ}C$ is given by the following equation,

$$\gamma_{water} = \{0.050 + 0.0021\rho + \frac{3.6}{(f-22.2)^2+8.5} + \frac{10.6}{(f-183.3)^2+9.0} + \frac{8.9}{(f-325.4)^2+26.3}\} f^2 \rho 10^{-4} \quad \text{dB/km} \quad \text{for f<350Ghz,} \tag{14}$$

where f is frequency expressed in GHz, and is the water vapour density expressed g/m^3.

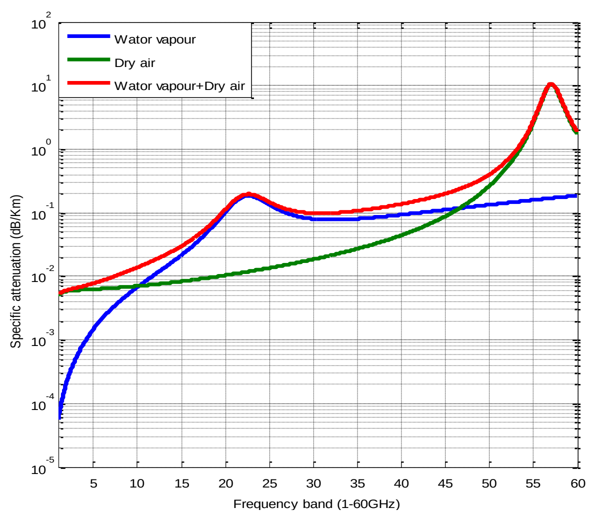

Figure 3. Specific Attenuation-dry Air and Water Vapour Condition (1-60GHz frequency band)

3.2. System Capacity

The system SNR of the receiver is defined as the receiving power over the system noise floor. So, the SNR at the input of the demodulator can be written by [10]

$$SNR_{dem} = \frac{SNR_r}{F} = \frac{P_{out}\cdot G_r \cdot G_t}{PL\cdot F\cdot KTB} \tag{15}$$

where PL is free space loss and F is noise factor. This equation only considers free space loss. So, we add the specific attenuation. Therefore, SNR_{dem} is given by

$$SNR_{dem} = \frac{SNR_r}{F} = \frac{P_{out} \cdot G_r \cdot G_t}{PL \cdot F \cdot KTB \cdot L_{sp}} \quad (16)$$

where L_{sp} is specific attenuation that is dry air and water vapor.

The Shannon capacity is

$$C = B\log_2(SNR + 1) \quad (17)$$

Therefore, the system capacity is given by

$$C = B\log_2(SNR_{dem} + 1) \quad (18)$$

Figure 4 shows the system capacity according to frequency band. In this figure, we can see that the system capacity has been falling sharply in 53 GHz - 60GHz because specific attenuation by dry air. Also, the system capacity is decrease at the high frequency band. Because that the free space loss of high frequency band is higher than low frequency band.

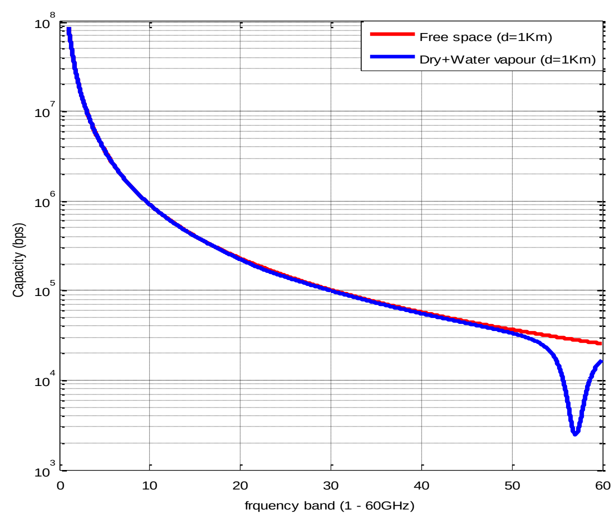

Figure 4. System Capacity using Shannon Capacity Formula (d=1km, Pout=10dBm, Noise factor = 6dB, bandwidth = 1.5GHz, Gr=1, Gt=1)

4. Minimum Eb/No and Optimization of Power Consumption

In this section, we calculate the total power consumption according frequency band and want to find the minimum Eb/No. RF power models in Section 2 are used. Table 2 summarizes the related parameters for the power consumption of PA and ADC. From the power models described in Section 2, we can see that center frequency directly affects the power consumption of ADC, PA and filter. Therefore, we simulate the ADC, PA and filter according the center frequency. Figure 5 shows the power consumption of PA, ADC and filter. The power consumption of ADC and filter is not changed the modulation level. But PA is changed by modulation level. And the power consumption of PA is dominated. In this paper, we only consider active state power consumption. Therefore, the total power consumption is given by

Table 2. PA and ADC Simulation Parameters

	Parameter		Parameter
Bandwidth	20MHz	SER	10^{-4}
Frequency band	1-60GHz	G_r	1
Distance	1Km	G_t	1
Modulation	QPSK, 16QAM	Loss	0.8
Noise Power	-101 dBm	V_{DD}	3 V
Roll-off factor	0.2	L_{min}	0.4 um

$$P_{total} = 2P_{mixer} + 2P_{FS} + P_{LNA} + P_{filter} + P_{BA} + P_{PA} + P_{ADC} + P_{DAC} \tag{19}$$

From the (17), we can define the SNR at the input of the demodulator. So, (18) can be written as

$$SNR_{dem} = 2^{\frac{\varepsilon \cdot R}{B}} - 1 = \frac{P_{out} \cdot G_r \cdot G_t}{KTB \cdot PL \cdot F \cdot L_{sp}} \tag{20}$$

where $\varepsilon \geq 1$ and is a pure number.

So, the out power of the transmitter becomes

$$P_{out} = \frac{KTB \cdot PL \cdot F \cdot L_{sp}}{G_r \cdot G_t} \cdot \left(2^{\frac{\varepsilon \cdot R}{B}} - 1 \right) \tag{21}$$

The total energy is given by

$$E_{tot} = \left(\frac{P_{out}}{\eta} + P_{mixer} + P_{FS} \right) \cdot T_t + P_r \cdot T_r , \tag{22}$$

$$P_r = P_{mixer} + P_{FS} + P_{LNA} + P_{filter} + P_{BA} + P_{ADC} . \tag{23}$$

P_r is receiver power consumption in LNA, BA, mixer, frequency synthesizer and ADC. So, we find that P_r is 132.85mW at 60GHz.

$$P_{tot} = E_{tot} \cdot \frac{1}{T_t + T_r} . \tag{24}$$

Next, the energy per bit becomes

$$E_b = P_{tot} \cdot \frac{1}{R_b} . \tag{25}$$

Therefore, the energy consumption per bit, E_b, is found as

$$E_b = \left[\frac{KTB \cdot PL \cdot F \cdot L_{sp}}{G_r \cdot G_t \cdot \eta} \cdot \left(2^{\frac{\varepsilon \cdot R}{B}} - 1 \right) \cdot T_t + P_r \cdot T_r \right] \cdot \frac{1}{T_t + T_r} \cdot \frac{1}{R_b} . \tag{26}$$

Figure 5 shows the effect of center frequency and modulation level on the system total power consumption. If we further fix the center frequency and compare total power consumption for different modulation level, we can see that higher the modulation level, the higher total power consumption.

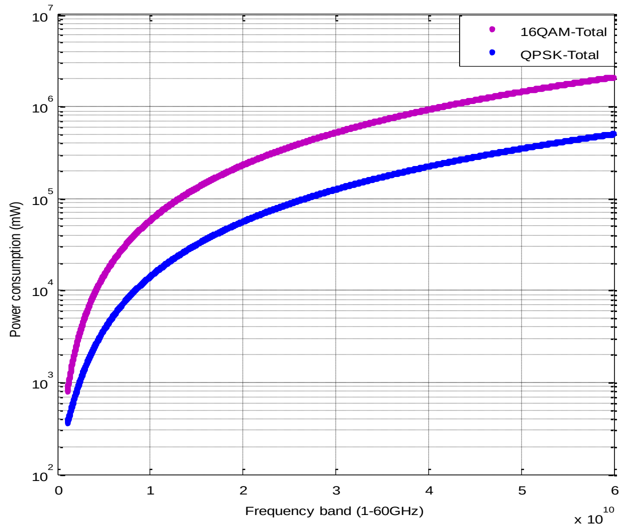

Figure 5. Total System Power Consumption using RF Power Model

Figure 6 shows the effect of bandwidth and R on the energy per bit. At R<5Gbps, the energy per bit is equal bandwidth 1GHz and bandwidth 2GHz. But, energy per bit of bandwidth 1GHz is higher than energy per bit of bandwidth 2GHz at R > 5Gbps. Because this energy per bit increases according to $2^{\frac{\varepsilon \cdot R}{B}}$. Therefore, the energy per bit has very close affinity with the bandwidth.

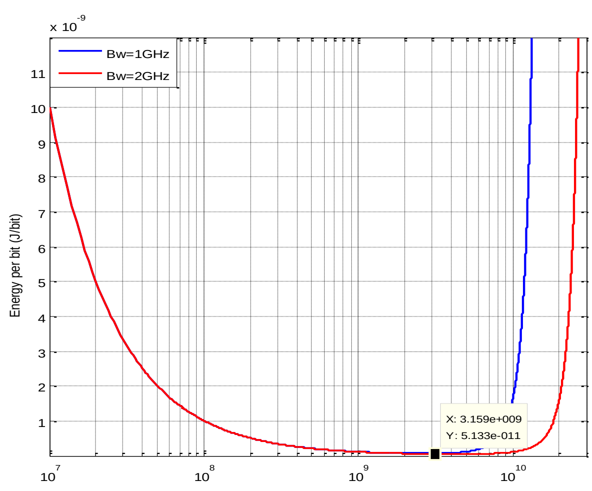

Figure 6. Total System Power Consumption using RF Power Model

5. Conclusions

In this paper, we analyze the system power consumption using the RF power model. RF and analog parts in the mm-wave and EHF frequency domain typically consume more energy compared to the digital parts. So, to design the wireless battery-driven system more power efficiently, we have to investigate the system level energy model for the RF front-end of a wireless transceiver. Also, the effects of the signal bandwidth, PAR, date rate, modulation level, transmission distance, specific attenuation of frequency band, and the signal center frequency on the RF front-end energy consumption and system capacity are considered. Eventually, we analyze the relationship between energy per bit and the data rate with the variation of the system bandwidth so that we can find the minimum Eb/No in the several Gbps data rate.

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