

Link Budget

2/1/06

Received Power

When ignore other loss:

$$P_r = \left(\frac{\lambda}{4\pi r} \right)^2 P_t G_t G_r$$

$$P_r (dB) = 20 \log \left(\frac{\lambda}{4\pi r} \right) + P_t + G_t + G_r$$

When consider other loss L_o :

$$P_r (dB) = 20 \log \left(\frac{\lambda}{4\pi r} \right) + P_t + G_t + G_r - L_o$$

where P_t is the transmitted power, G_t and G_r are for transmitting power gain and receiving power gain respectively.

Free Space Path Loss

$$L_p = \left(\frac{4\pi r}{\lambda} \right)^2$$

$$L_p (dB) = -20 \log \left(\frac{\lambda}{4\pi r} \right)$$

Receiver noise

The average noise power generated internally to the receiver is:

$$P_{n,int} = k T_e B_w$$

$$P_{n,int} (dB) = 10 \log (k T_e B_w)$$

where

$$k = 1.38 \times 10^{-23} \text{ J/}^\circ\text{K}$$

B_w =bandwidth, and

T_e =effective noise temperature of the device and is given as:

$$T_e = T_0 (N_f - 1)$$

where $T_0 = 290^\circ \text{K}$

N_f : noise figure of the receiver.

Thermal noise N_0 at room temperature (290°):

$$N_0 = 10\log(1.38 \times 10^{-23} \times 290 \times 10^3) = -174\text{dBm/Hz}$$

Since in general $N_f \gg 1$,

$$P_{n,\text{int}}(\text{dB}) = N_0 + N_f$$

This is also known as noise floor of the receiver.

The overall average noise power generated to the receiver is:

$$P_n(\text{dB}) = 10\log(kTB_w)$$

where

$$T = T_e + T_{\text{ant}} + T_{\text{fl}}$$

T_{ant} is the temperature of the antenna and the T_{fl} is the feed line loss.

The receiver signal to noise ratio (SNR)

$$SNR = \frac{P_r}{P_n} = \left(\frac{\lambda}{4\pi r} \right)^2 \frac{P_t G_t G_r}{L_o kTB_w}$$

$$SNR(\text{dB}) = 20\log\left(\frac{\lambda}{4\pi r} \right) + P_t + G_t + G_r - L_o - P_n(\text{dB})$$

Assuming following parameters:

- Symbol rate: 13.0/19.5 MHz
- Bits per symbol: 11.5/16.5
- Code rate: 0.8/0.8
- Center frequency $F_c=4.8$ GHz
- Pulse Tx power $P_t=0.5/-1.3$ dBm
- Antenna gain $G_t= G_r=0$ dBi
- Implementation loss(I)= $3.0/3.0$ dG
- Rx noise figure $N_f=7$ dB
- Minimum $E_b/N_0(S)=5.4/4.5$ dB
- Range= $15.8/12$ m

Raw bit rate R= Bits per symbol× Symbol rate=11.5×13.0=149.5 or 16.5×19.5=321.8

Throughput=Raw Bit Rate × Code Rate=149.5×0.8=119.6 or 321.8×0.8=257.4

Average thermal noise power per bit (in table 1 $N=N_0+10\log(R_b)$)

$$N_1 = N_0 + 10\log(R_1) = -174 + 10\log(149.5 \times 10^6) = -92.3dBm \text{ (in table 1 } -93.2dBm)$$

$$N_2 = N_0 + 10\log(R_2) = -174 + 10\log(321.8 \times 10^6) = -88.9dBm \text{ (in table 1 } -89.8dBm)$$

Average noise power per bit

$$P_n = N + N_f = -92.3 + 7 = -85.3 / -81.9 dBm \text{ (in table 1 } -86.2dBm/-82.9dBm)$$

Path loss L_1 = $20\log(4\pi r_0/\lambda) = 20\log(4\pi F_c/C) = 46.1dB$ (in table 1 46.0dB)

Path loss L_2 = $20\log(d) = 24.0/21.6dB$ (in table 1 20.0/12.0dB)

Rx Power: $P_r = P_t - L_1 - L_2$

$$P_{r1} = P_{t1} - L_1 - L_{2_1} = 0.5 - 46.07 - 23.97 = -69.5dBm$$

$$P_{r1} = P_{t2} - L_1 - L_{2_2} = -1.3 - 46.07 - 21.58 = -69.0dBm$$

Link Margin: $M = P_r - P_n - S - I$

$$M_1 = P_{r1} - P_{n1} - S_1 - I = -69.54 + 85.25 - 5.4 - 3 = 7.3dB$$

$$M_2 = P_{r2} - P_{n2} - S_2 - I = -68.95 + 81.92 - 4.5 - 3 = 5.5dB$$

Two ways to calculate receiver sensitivity:

1. Follow the paper: Minimal signal strength required (receiver sensitivity)

$$S_{\min_1} = P_{r1} - M_1 = -69.5 - 7.3 = -76.8dBm \text{ (in table 1 } -77.8dBm)$$

$$S_{\min_2} = P_{r2} - M_2 = -68.9 - 5.5 = -74.4dBm \text{ (in table 1 } -75.4dBm)$$

2. Follow the definition: Minimal bit energy required for specified E_b/N_t

$$(E_b)_{\min_1} = N_0 + N_f + (E_b/N_t)_1 = -174 + 7 + 5.4 = -161.6dBm/Hz$$

$$(E_b)_{\min_2} = N_0 + N_f + (E_b/N_t)_2 = -174 + 7 + 4.5 = -162.5dBm/Hz$$

Minimal signal strength required (receiver sensitivity)

$$S_{\min_1} = (E_b)_{\min_1} + 10\log R_1 + I = -161.6 + 10\log(149.5 \times 10^6) + 3 = -76.8dBm$$

(in table 1 -77.8dBm)

$$S_{\min_2} = (E_b)_{\min_2} + 10\log R_2 + I = -162.5 + 10\log(321.8 \times 10^6) + 3 = -74.4dBm$$

(in table 1 -75.4dBm)

Below is the corrected table 1.

Table I
Link Budge from IEEE 802.15a Proposal

Parameter	>110Mbps	>200Mbps	Unit
Throughput (R_b)	119.6	257.4	Mbps
Center frequency F_c	4.8	4.8	GHz
Path loss at 1 meter ($L_1=20\log(4\pi F_c/C)$)	46.1	46.1	dB
Path loss at d meters ($L_2=20\log(R)$)	24.0	21.6	dB
Rx Power ($P_r=P_t-L_1-L_2$)	-69.5	-69.0	dBm
Average thermal noise power per bit ($N=-174+10\log(R)$)	-92.3	-88.9	dBm
Rx Noise Figure (N_f)	7.0	7.0	dB
Average noise power per bit ($P_n=N+N_f$)	-85.3	-81.9	dBm
Minimum E_b/N_0 (S)	5.4	4.5	dB
Implementation loss (I)	3.0	3.0	dB
Symbol rate	13.0	19.5	MHz
Bits per symbol	11.5	16.5	
Raw bit rate	149.5	321.8	Mbps
Code rate	0.8	0.8	
Pulse Tx power (P_t)	0.5	-1.3	dBm
Link margin ($M=P_r-P_n-S-I$)	7.8	5.5	dB
Min. Rx sensitivity (P_r-M)	-76.8	-74.4	dBm
Range	15.8	12	m

(Note: yellow: defined value; green, original correct value; red, corrected value)