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Channel Loss Estimation and Test of Ultra-Wideband Propagation from 2 to 10 GHz Application

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Abstract

This paper deals with the channel loss models of ultra-wideband radio wave propagation from 2 to 10 GHz application. IEEE 802.15.4a and Okumura channel loss reference models have been introduced and the estimation methods of channel transmission loss have been discussed with the environments of 2 to 10 GHz short range application. The channel transmission loss was measured in ZigBee circuit with 2 kinds of power, using IEEE 802.15.4a and Okumura channel model to estimate the theoretical channel loss, the theoretical value and the actual measured value were compared and analyzed. The analysis shows that the error between the calculated value and the actual measured value of the IEEE 802.15.4a reference model is small in the ultra-wideband ZigBee channel environment, and the error of the Okumura channel loss model is large. The results show that in the environments of 2 to 10 GHz short range application, IEEE 802.15.4a channel loss model is a high precision reference model for the ultra-wideband channel loss calculation.

Keywords*: channel loss estimation, ultra-wideband, Okumura model, estimation method*

1. Introduction

Since the emergence of Bluetooth, ultra-wideband (UWB) channel of short distance wireless digital communication based on 2GHz~10GHz with the characteristics of low power consumption, miniaturization, it is used more and more widely in the industrial control, household automatic control, toys, portable product. At present, the main standard in PHY layer and MAC layer of UWB communication are IEEE802.15.3a and IEEE 802.15.4a, IEEE 802.15.3a protocol is mainly used in high speed transmission, and IEEE802.15.4a mainly used in low speed transmission. In particular, IEEE 802.15.4a, can also be applied to precise positioning and tracking, such as cargo labels and tracking, the inventory control management based on location, etc. There are some typical technologies, such as ZigBee, Bluetooth, Wirelesses, in UWB channel of short distance wireless digital communication based on 2GHz~10GHz.

But there are many designers who are not clear about how to make the channel loss estimation in the application design. So far, there is little literature on its detailed description; estimating by early mobile communication channel model, brought a large estimation error [1]. IEEE802.15.4a and Okumura (OM) channel loss model are introduced in detail in this paper, the transmission loss estimation method for 2GHz~10GHz UWB channel in the various application environments is explained clearly, and estimation method is tested by the typical ZigBee application circuit, the estimation error is given, the test results show that the IEEE802.15.4a channel loss model in the 2GHz ~ 10GHz UWB applications is a reference model of the error is small.

2. Research Method

2.1. Basic Channel Loss Calculation Models

In narrow band system with the electromagnetic wave propagation channel, the channel loss (PL) is calculated with the following formula:

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$$PL(d) = \frac{E\{P_{RX}(d, f_c)\}}{P_{TX}} \quad (1)$$

PTX and PRX is the power of the transmitter and the receiver antenna, respectively, d is the distance between the transceiver, fc as the central frequency of the transmission signal. E {} is expected value. The size of PL is determined mainly by distance.

In UMB system with the electromagnetic wave propagation channel, the channel loss (PL) is calculated with the following formula:

$$PL(f,d) = E\left\{\int_{f-\frac{f}{2}}^{f+\frac{f}{2}} |H(f,d)|^2 df\right\} \quad (2)$$

Where f is the frequency range of UMB, H(f, d) is the transfer function between antenna connection points for transmitter and receiver, The size of PL is affected by two factors: the distance and the frequency.

In order to simplify the calculation, the channel loss can be written as follows:

$$PL(f,d) = PL(f)PL(d) \quad (3)$$

The frequency factor has the following formula [2]:

$$PL(f) \propto f^{-2k} \quad (4)$$

Where k is the impact index of frequency factor (this expression does not include the frequency factor of the antenna).

For the distance factor (in dB representation), has the following formula:

$$PL(d) = PL_0 - 10n\log_{10}(\frac{d}{d_0}) \quad (5)$$

Where d0 is the reference distance of calculation, the value is 1m; PL0 is the path loss with reference distance, n is the distance attenuation index. The size of the n is determined by the transmission environment, in the visual environment n is among 1 to 2, in the invisible environment n is among 3 to 4, and in the especially poor transmission environment n may reach 4 to 7.

The receiving and transmitting power is given in the above calculation formula, which is the power of transmitting and receiving antenna. Usually the transceiver power refers to the power in the antenna interface point of transmitter and receiver; there is no serious consideration of antenna factors. In the actual communication system, due to difference of the frequency of the system, the environment, the use of different antennas, so the influencing factors of antenna should be considered in the calculation.

For the transmit power [3-8] :

$$p_t(f) = p_{TX-amp}(f)\eta_{TX-ant}(f) \quad (6)$$

According to the calculation formula of the power density of f and d:

$$\hat{p}(f,d) = k_0 \frac{p_t(f)}{4\pi d_0^2}(\frac{d}{d_0})^{-n}(\frac{f}{f_c})^{-2k} \quad (7)$$

and the effective area of the antenna:

$$A_{RX}(f)=\frac{\lambda^2}{4\pi}G_{RX}(f) \quad (8)$$

Assuming the antenna gain is 1, and then the received power is:

$$\begin{aligned}&P_r(f,d)\\&=\{k_0 p_{TX-amp}(f)\eta_{TX-ant}(f)\eta_{RX-ant}(f)\\&\cdot\frac{c_0^2}{(4\pi d_0 f_c)^2}\frac{1}{(\frac{d}{d_0})^2(\frac{f}{f_c})^2}\}\end{aligned} \quad (9)$$

Suppose as follow formula,

$$\begin{aligned}&\frac{P_r(f_c,d_0)}{p_{TX-amp}(f_c)}=PL_0=k_0\frac{c_0^2}{(4\pi d_0 f_c)^2}\\&=PL_0\frac{(4\pi d_0 f_c)^2}{c_0^2}\end{aligned} \quad (10)$$

The transmission gains or channel loss of the system is as follows:

$$\begin{aligned}&PG(f)=\frac{P_r(f)}{p_{TX-amp}(f)}\\&=\frac{1}{2}PL_0\eta_{TX-ant}(f)\eta_{RX-ant}(f)\frac{(\frac{f}{f_c})^{-2(k+1)}}{(\frac{d}{d_0})^n}\end{aligned} \quad (11)$$

Where 1/2 is the attenuation caused by the body close to the antenna in the actual test, taken to fixed value Aant=-3dB.

Considering the random fading characteristics in the transmission path, the random loss parameter S is added in the loss calculation of the distance component.

$$PL(d)=PL_0-10n\log_{10}(\frac{d}{d_0})+S \quad (12)$$

Integrated frequency and distance factors (in dB representation), the total channel loss is:

$$\begin{aligned}&PL(f,d)=\{PL_0+A_{ant}-G_{TX-ant}-G_{RX-ant}\\&-20(k+1)\log_{10}(\frac{f}{f_c})-10n\log(\frac{d}{d_0})+S\}\end{aligned} \quad (13)$$

Where GRX-ant and GTX-ant is the gain of the transmit and receive antennas, respectively.

2.2. Estimation Method Based on IEEE 802. 15. 4a

According to the IEEE 802. 15. 4a channel model-final report, in the UMB system which IEEE 802. 15. 4a protocol is implicated, the measured channel model parameters determine the channel loss calculation parameters in the 2GHz~10GHz frequency range. In various transmission environments, the model parameters are different. These environments include indoor residential environment, indoor office environment, outdoor environment, outdoor open environment and industrial environment. From the "call for applications", we derived a number of environments in which 802.15.4a devices should be operating. This list is not comprehensive, and cannot cover all possible future applications; however, it should be sufficient for the evaluation of the model:

1. Indoor residential environment: these environments are critical for "home networking", linking different appliances, as well as danger (fire, smoke) sensors over a relatively small area. The building structures of residential environments are characterized by small units, with indoor walls of reasonable thickness.
2. Indoor office environment: for office environments, some of the rooms are comparable in size to residential, but other rooms (especially cubicle areas, laboratories, etc.) are considerably larger. Areas with many small offices are typically linked by long corridors. Each of the offices typically contains furniture, bookshelves on the walls, etc., which adds to the attenuation given by the (typically thin) office partitioning.
3. Outdoor environment: While a large number of different outdoor scenarios exist, the current model covers only a suburban-like microcell scenario, with a rather small range.
4. Outdoor open environment: there are few barriers between wide ranges of visualization. Propagation delay is expected to be less than other environments.
5. Industrial environment: it is characterized by a large workshop; there are a large number of metal reflections. These reflections produce severe multipath effects.

The specific channel loss calculation parameters are shown in Table 1.

Table 1. Measurements of IEEE 802.15.4a channel model modifying factor

Transfer Environment	Correction Factor	Los	Nlos	Remarks
indoor residential environment	PL_0/dB	-43.9	-48.7	7～20m,up to 10GHz
	n	1.79	4.58	
	k	1.12±0.12	1.53±0.32	
	S/dB	-2.22	-3.51	
	A_{ant}/dB	-3	-3	
indoor office environment	PL_0/dB	-36.6	-51.4	2～28m, 2 GHz ～10GHz
	n	1.63	3.07	
	k	-3.5	5.3	
	S/dB	-1.9	-3.9	
	A_{ant}/dB	-3	-3	
outdoor environment	PL_0/dB	-43.29	-43.29	5～17m, 3 GHz ～6GHz
	n	1.76	2.5	
	k	-1.6	0.4	
	S/dB	-0.83	-2	
	A_{ant}/dB	-3	-3	
outdoor open environment	PL_0/dB		-48.96	open areas, such as farms, etc.
	n		1.58	
	k			
	S/dB		-3.96	
	A_{ant}/dB		-3	
industrial environment	PL_0/dB	56.7	56.7	2～8m
	n	1.2	2.15	
	k	-5.6	-7.82	
	S/dB	-6	-6	
	A_{ant}/dB	-3	-3	

2.3. Commonly Used Channel Model Estimation Method for OM

In the field of mobile communication, many field intensity prediction models have been established, which are based on the measured data of field intensity in a variety of topographic features, which can be used in different occasions. The OM model provides more complete data, frequency band and wide range of applications, suitable for the applicable to the frequency band below 3GHz.

In ZigBee (2.4GHz) transmission distance estimation can refer to the OM model curve, find out the transmission loss attenuation correction factor hs, the formula is introduced to estimate the actual maximum transmission distance [9, 10].

In order to make the OM model to be convenient for practical engineering application, the corresponding mathematical formula is shown below [11]:

$$PL(f,d) = 69.55 - 13.28\lg(h_t) - a(h_r) + 44.9 - 6.65\lg(h_t)\lg(d) \quad (14)$$

Where a(hr) is the gain correction factor of the effective antenna height h, the unit is dB, the different terrain has different empirical formula [12].

For small and medium sized cities

$$a(h_r) = (1.11g(f) - 0.7)h_r - (1.56\lg(f) - 0.8) \quad (15)$$

For big cities

$$a(h_r) = 8.29(\lg(1.54h_r))^2 - 1.1 f \le 300MHz; \quad a(h_r) = 3.2(\lg(11.75h_r))^2 - 4.97 f \ge 300MHz \quad (16)$$

For the outskirts of the city

$$PL_{suburbs} = PL_{urban} - 2(\lg f/28)^2 - 5.4 \quad (17)$$

For open country

$$PL_{open} = PL_{urban} - 4.78(\lg f)^2 - 18.33\lg f + 40.94 \quad (18)$$

3. Results and Analysis

Based on the CC2430 chip, we designed two different power ZigBee modules to test the channel loss. One module is a small power data transmission module, the other is a module with LNA and PA large power transmission module, the test module uses a gain antenna with 1.8dB. Assuming the antenna height of transmitter and receiver is 3M, the transmission environment is located in the suburbs, flat terrain, and the maximum distance of the two modules is estimated with the use of IEEE802.15.4a channel loss model. Based on the IEEE802.15.4a channel loss model, the calculation formula of the maximum distance under the condition of the receiving sensitivity is derived (the choice of receiving sensitivity is in order to facilitate the practical test).

$$P_{rs} = P_t + A_{ant} + G_t + G_r - PL_0 - s - 10n\log(d_{\max}) - 20(k+1)\log(\frac{f}{5}) \quad (19)$$

Table 2 and 3 show the power parameters and the estimated maximum distance of the two modules. The actual transmission environment is set up for outdoor open terrain.

Table 2. The estimated distance of IEEE 802.15.4a channel small power data transmission modules

transceiver module parameters	CC2430 module output power: P_t=-2dBm, receiving sensitivity: P_{rs}=-80dBm, transmit antenna gain: G_t=1.8dB, receive antenna gain G_r=1.8dB
the model parameters of correction factor	n=1.58, k=0, s=-3.96, A_{ant}=-3dB, PL_0=-48.96dB
d_{max}	106.77m

Table 3. The estimated distance of IEEE 802.15.4a channel high power data transmission modules

transceiver module parameters	CC2430 module output power: P_t=20dBm, receiving sensitivity: P_{rs}=-91dBm, transmit antenna gain: G_t=1.8dB, receive antenna gain G_r=1.8dB
the model parameters of correction factor	n=1.58, k=0, s=-3.96, A_{ant}=-8dB, PL_0=-48.96dB
d_{max}	6318.77m

To estimate the maximum distance can be transmitted of two modules by using OM channel loss model, environment for suburban and open place, there is no shelter in the middle of the transmission line, also send and receive antenna in the same direction, antenna height is about 3m, adjusted to receive the maximum signal strength.

$$P_{rs} = P_t + A_{ant} + G_t + G_r - PL_{suburbs} \tag{20}$$

$$PL_{open} = PL(f, d_{\max}) - 4.78(\lg f)^2 - 18.33\lg f + 40.94 \tag{21}$$

$$PL(f, d_{\max}) = 69.55 - 13.28\lg(h_t) - a(h_r) + 44.9 - 6.65\lg(h_t)\lg(d_{\max}) \tag{22}$$

Set the parameters as:

$$a(h_r) = 3.2(\lg(11.75h_r))^2 - 4.97, \quad f \geq 300MHz \tag{23}$$

Table 4 and 5 show the power parameters and the estimated maximum distance of the two modules.

Table 4. The estimated distance of OM channel small power data transmission modules

transceiver module parameters	CC2430 module output power: P_t=-2dBm, receiving sensitivity: P_{rs}=-80dBm, transmit antenna gain: G_t=1.8dB, receive antenna gain G_r=1.8dB
parameters of OM	f=2.4GHz, h_t=h_r=3m, A_{ant}=-3dB,
d_{max}	176.14m

Table 5. The estimated distance of OM channel high power transmission modules

transceiver module parameters	CC2430 module output power: P_t=20dBm, receiving sensitivity: P_{rs}=-91dBm, transmit antenna gain: G_t=1.8dB, receive antenna gain G_r=1.8dB
parameters of OM	f=2.4GHz, h_t=h_r=3m, A_{ant}=-3dB,
d_{max}	825.75m

According to the calculation result, we measured the maximum transmission distance of the two ZigBee module which is designed based on CC2430, in the environment of outdoor open space, there is no shelter in the middle of the transmission line, also send and receive antenna in the same direction, antennaheight is about 3m, adjusted to receive the maximum signal strength.

Table 6 shows the measurement data of the ZigBee module without LNA and PA. Table 7 shows the measurement data of ZigBee module with LNA and PA.

Table 6. The measured data of ZigBee high power modules without LNA and PA(m)

Order of test	First	Second	Third	Mean
Estimated distance of IEEE	106.77	106.77	106.77	106.77
Estimated distance of OM	176.14	176.14	176.14	176.14
Testing distance	101.00	105.00	110.00	105.33

Table 7.The measured data of ZigBee high power modules with LNA and PA(m)

Order of test	First	Second	Third	Mean
Estimated distance of IEEE	6318.77	6318.77	6318.77	6318.77
Estimated distance of OM	825.75	825.75	825.75	825.75
Testing distance	5950.00	6020.00	5900.00	5956.67

According to the test results, on the conditions of specific environment, the error between the calculated value and the actual measured value of IEEE802. 15 4a model is small, but the error is large in OM channel loss model. So in the analysis of the wireless channel, in the case of fixed frequency, selecting the appropriate channel model can accurately estimate the maximum transmission distance of the application circuit. In engineering applications, in order to ensure the applicability of a single model of the wireless communication, the general engineering requirements test data standard deviation is less than 10db. In the case of the actual environment model, the estimated error is less than 20%, which is a fairly accurate estimate. It can be seen from the calculation results that in the application design of ZigBee, using IEEE 802.15.4a channel model to estimate the loss is appropriate. example of a technical report in [13].

4. Conclusion

IEEE 802.15.4a and Okumura channel loss reference models have been introduced in this paper and the estimation methods of channel transmission loss have been discussed with the environments of 2 to 10 GHz short range application. Focus on the environments of 2 to 10 GHz short range application of UWB, the estimation method of transmission loss under various application environments based on IEEE802.25.4a protocol is explained. The estimation methods of IEEE802.15.4a and OM channel loss model is tested with the use of the typical ZigBee application circuit. The test results show that in the environments of 2 to 10 GHz short range application, IEEE 802.15.4a channel loss model is a high precision reference model for the ultra-wideband channel loss calculation. In the application design of ZigBee, IEEE802.15.4a is also a suitable channel loss estimation model.

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