

Free Space Path Loss of UWB Communications

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Abstract—Although the Friis' formula is widely used to calculate the free space path loss of narrowband communications, it is considered only single frequency. Therefore, it should be extended to calculate the free space path loss of ultra wideband (UWB) communications by considering the frequency bandwidth. In this paper, the free space path loss of UWB communications is studied. The Friis' formula is extended in the complex frequency transfer function. The ideal and Gaussian filters are used for filtering the specific frequency bandwidth. The UWB free space path loss is derived based on average power and peak power losses. The example results are shown and discussed in the paper.

Key words: Ultra wideband (UWB) communication, free space path loss, Friis' formula.

I. INTRODUCTION

Recently, ultra wideband (UWB) radio technology has become an important topic for microwave communication because its potential is low cost and low power consumption properties [1]-[5]. The Federal Communications Commission (FCC) [6] specified that UWB has a frequency spectrum ranging from 3.1 to 10.6 GHz and a fractional bandwidth greater than 0.20 or occupied bandwidth greater than 500 MHz. The power density of the UWB signal is considered to be noise for other communication systems because its power spectral density is below the part 15 noise limit. Therefore, UWB radio technology can coexist with other RF technologies without interference. Moreover, UWB radio technology can be utilized for commercial, short-range, low power, low cost indoor communication systems such as wireless personal area networks (WPANs) [7].

Friis' free space path loss formula [8] is widely used to calculate the free space path loss for narrow band system. For the UWB system, the free space path loss model based on average power loss is proposed by IEEE 802.15.3a [9]. After that, the complex form of Friis' transmission formula is developed for UWB system [10]-[11]. The closed form expressions of the UWB path loss for the free space channel based on peak power loss are derived [12]-[13]. But these free space path loss models are considered the specific frequency bandwidth by using ideal filter, there are no research about causal filter.

In this paper, the free space path loss of UWB communications is studied. The Friis' formula is extended in the complex frequency transfer function. The ideal and Gaussian filters are used for filtering the specific frequency bandwidth. The UWB free space path loss is derived based on average power and peak power losses.

This paper is organized as follows. Section 2 and 3, the conventional free space path loss and that of UWB communications are presented. The analysis results are illustrated and compared in section 4. Finally, conclusions are discussed in section 5.

II. CONVENTIONAL FREE SPACE PATH LOSS

Friis' free space path loss [8] is widely used to calculate the free space path loss for narrowband communications. It can be written in the dB as

$$PL_f(d) = 20 \log \left(\frac{4\pi f_c d}{c} \right), \quad (1)$$

where $f_c = (f_H + f_L)/2$ is the center frequency, d is the transmitter-receiver (T-R) separation distance, c is the velocity of light, f_L and f_H are the lower and upper frequencies, respectively.

III. FREE SPACE PATH LOSS OF UWB COMMUNICATIONS

For UWB communications, the free space path loss can be defined in the two meanings. The first is based on the average power loss of the signal spectrum in the specific frequency bandwidth. The second is based on the peak power loss of the signal waveform in the specific frequency bandwidth. Conveniently, the ideal filter is used for filtering the specific frequency bandwidth. Unfortunately, the ideal filter is not causal. Therefore, in this paper the Gaussian filter is additionally analyzed and the frequency bandwidth is considered on positive frequency axis.

The Friis' free space path loss is extended in the complex frequency transfer function for considering the frequency bandwidth instead of only single frequency. That is

$$H_f(f, d) = \frac{c}{4\pi f d} e^{-j2\pi f d/c}. \quad (2)$$

The ideal and Gaussian filters are used for filtering the specific frequency bandwidth. The frequency transfer functions of ideal and Gaussian filters are respectively defined as

$$H_i(f) = \begin{cases} 1 & f_L \leq f \leq f_H \\ 0 & \text{elsewhere} \end{cases}, \quad (3)$$

$$H_g(f) = e^{-\pi^2 d_e^2 (f-f_c)^2}, \quad (4)$$

where d_e is the $1/e$ characteristic decay time and has the relation on the reference level l_r that is used to consider the frequency bandwidth. The relation between d_e and l_r is

$$d_e = \frac{2}{\pi f_b} \sqrt{\frac{-l_r}{20 \log(e)}}, \quad (5)$$

where $f_b = f_H - f_L$ is the frequency bandwidth. Here, l_r is set to be -3 and -10 for considering the -3 and -10 dB bandwidths, respectively.

A. Free Space Path Loss Based on Average Power Loss

The free space path loss based on average power loss is considered as the average power loss of the signal spectrum in the specific frequency bandwidth. The ideal and Gaussian filters are considered.

1) *Ideal filter*: The free space path loss based on average power loss by using ideal filter in dB can be evaluated from

$$PL_{a,i}(d) = -10 \log \left[\frac{\int_{f_L}^{f_H} |H_f(f, d)|^2 |H_i(f)|^2 df}{\int_{f_L}^{f_H} |H_i(f)|^2 df} \right]. \quad (6)$$

This equation can be derived in the closed form, that is

$$PL_{a,i}(d) = 20 \log \left[\frac{4\pi f_{a,i} d}{c} \right], \quad (7)$$

where

$$f_{a,i} = \sqrt{f_L f_H}. \quad (8)$$

This free space path loss formula corresponds with that proposed by IEEE 802.15.3a [9].

2) *Gaussian Filter*: The free space path loss based on average power loss by using Gaussian filter in dB can be evaluated from

$$PL_{a,g}(d) = -10 \log \left[\frac{\int_{f_L}^{f_H} |H_f(f, d)|^2 |H_g(f)|^2 df}{\int_{f_L}^{f_H} |H_g(f)|^2 df} \right]. \quad (9)$$

This equation can not be directly derived in the closed form. Therefore, the Gaussian integration formula [14] is used to estimate this equation. The closed form formula obtained from 2- and 3-point Gaussian integration formulas respectively are

$$PL_{a,g,2}(d) = 20 \log \left[\frac{4\pi f_{a,g,2} d}{c} \right], \quad (10)$$

$$PL_{a,g,3}(d) = 20 \log \left[\frac{4\pi f_{a,g,3} d}{c} \right], \quad (11)$$

where

$$f_{a,g,2} = \frac{12f_c^2 - f_b^2}{2\sqrt{36f_c^2 + 3f_b^2}}, \quad (12)$$

$$f_{a,g,3} = \frac{1}{2} \sqrt{\frac{4 + 5e^{-\frac{3}{10}\pi^2 d_e^2 f_b^2}}{\frac{1}{f_c^2} + 25 \frac{20f_c^2 + 3f_b^2}{(20f_c^2 - 3f_b^2)^2} e^{-\frac{2}{10}\pi^2 d_e^2 f_b^2}}}. \quad (13)$$

B. Free Space Path Loss Based on Peak Power Loss

The free space path loss based on peak power loss is considered as the peak power loss of the signal waveform in the specific frequency bandwidth. The ideal and Gaussian filters are considered.

1) *Ideal filter*: The free space path loss based on peak power loss by using ideal filter in dB can be evaluated from

$$PL_{p,i}(d) = -20 \log \left[\frac{\int_{f_L}^{f_H} |H_f(f, d) H_i(f)| df}{\int_{f_L}^{f_H} |H_i(f)| df} \right]. \quad (14)$$

This equation can be derived in the closed form, that is

$$PL_{p,i}(d) = 20 \log \left[\frac{4\pi f_{p,i} d}{c} \right], \quad (15)$$

where

$$f_{p,i} = \frac{f_b}{\ln\left(\frac{f_H}{f_L}\right)}. \quad (16)$$

This free space path loss formula corresponds with that proposed in [12]-[13].

2) *Gaussian Filter*: The free space path loss based on peak power loss by using Gaussian filter in dB can be evaluated from

$$PL_{p,g}(d) = -20 \log \left[\frac{\int_{f_L}^{f_H} |H_f(f, d) H_g(f)| df}{\int_{f_L}^{f_H} |H_g(f)| df} \right]. \quad (17)$$

This equation can not be directly derived in the closed form. Therefore, the Gaussian integration formula [14] is used to estimate this equation. The closed form formula obtained from 2- and 3-point Gaussian integration formulas respectively are

$$PL_{p,g,2}(d) = 20 \log \left[\frac{4\pi f_{p,g,2} d}{c} \right], \quad (18)$$

$$PL_{p,g,3}(d) = 20 \log \left[\frac{4\pi f_{p,g,3} d}{c} \right], \quad (19)$$

where

$$f_{p,g,2} = \frac{12f_c^2 - f_b^2}{12f_c}, \quad (20)$$

$$f_{p,g,3} = \frac{4 + 5e^{-\frac{3}{20}\pi^2 d_e^2 f_b^2}}{\frac{4}{f_c} + \left(\frac{100f_c}{20f_c^2 - 3f_b^2}\right) e^{-\frac{3}{20}\pi^2 d_e^2 f_b^2}}. \quad (21)$$

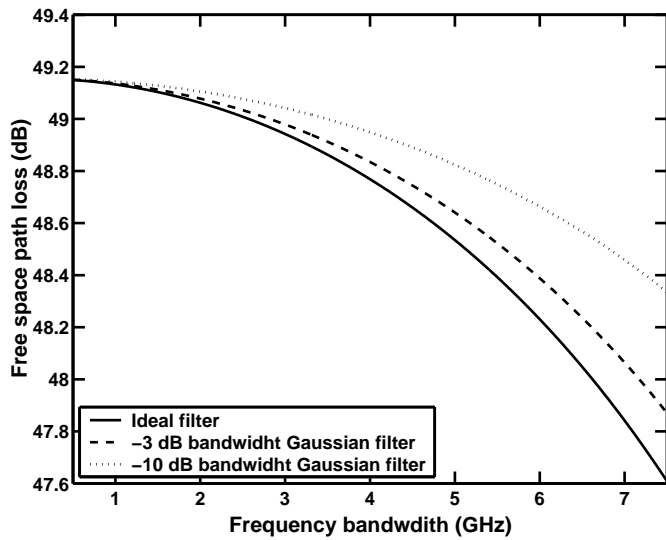


Fig. 1. free space path losses based on average power loss with center frequency is $f_c = 6.85$ GHz and T-R separation distance is $d = 1$ m along frequency bandwidth f_b from 500 MHz to 7.5 GHz.

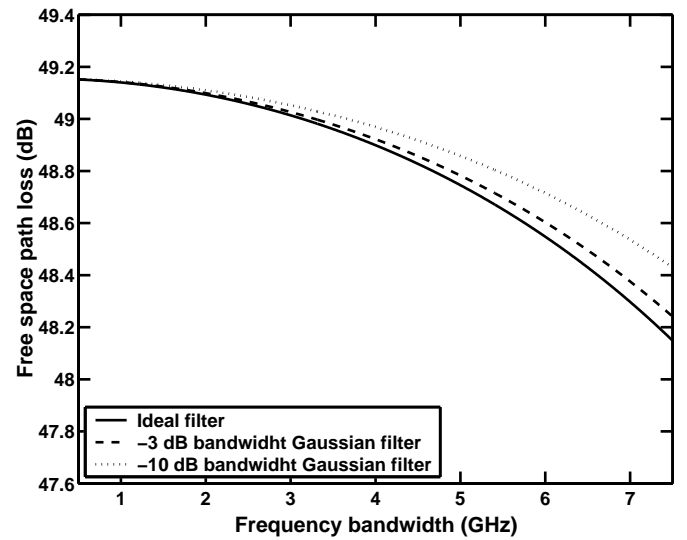


Fig. 2. free space path losses based on peak power loss with center frequency is $f_c = 6.85$ GHz and T-R separation distance is $d = 1$ m along frequency bandwidth f_b from 500 MHz to 7.5 GHz.

IV. ANALYSIS RESULTS

First case, UWB free space path loss is studied by setting the center frequency f_c to be 6.85 GHz. That is the center frequency of UWB bandwidth for communications. The frequency bandwidth f_b is considered from 500 MHz to 7.5 GHz which corresponds with minimum to maximum UWB bandwidth. The T-R separation distance d is set to be 1 m.

Figure 1 and 2 show the free space path losses based on average and peak power loss for the first case, respectively. The ideal and Gaussian filters with $l_r = -3$ and -10 are considered. In this case, the free space path loss obtained from the Friis' formula is constant about 49.16 dB which is almost the same with each UWB free space path loss at the frequency bandwidth about 500 MHz. Each free space path loss is decreased when the frequency bandwidth is wider. The free space path losses based on the average power loss are lower than that based on the peak power loss. The free space path loss with ideal filter is lowest and it is higher when uses the -3 dB and -10 dB bandwidth Gaussian filters, respectively.

Second case, the UWB free space path loss is studied by setting the lower frequency f_L to be 3.1 GHz. That is lowest frequency of UWB bandwidth for communications. The same frequency bandwidth f_b range is considered that from 500 MHz to 7.5 GHz.

The free space path loss obtained from Friis' formula is shown in Fig. 3. Figure 4 and 5 show the free space path losses based on average and peak power loss for the second case, respectively. The ideal and Gaussian filters with $l_r = -3$ and -10 are considered. Each UWB free space path loss at about 500 MHz frequency bandwidth is almost the same that obtained from Friis' formula. In this case each free space path loss is increased when the frequency bandwidth is higher. That is because in this case the center frequency is increased when

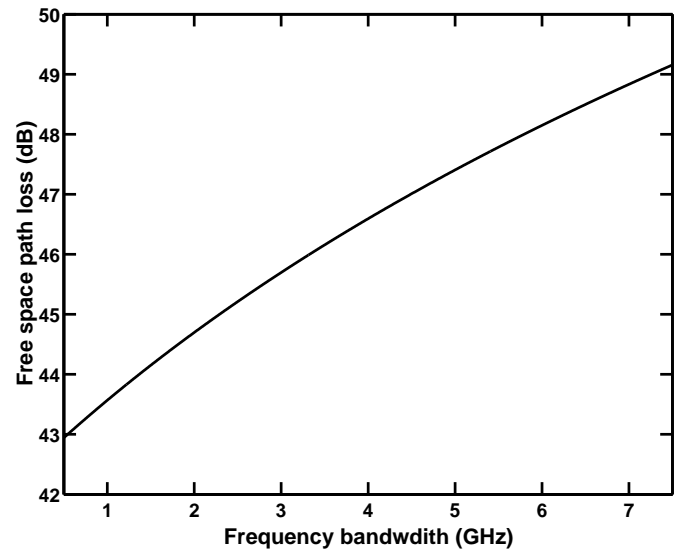


Fig. 3. free space path loss obtained from Friis' formula with lower frequency is $f_L = 3.1$ GHz and T-R separation distance is $d = 1$ m along frequency bandwidth f_b from 500 MHz to 7.5 GHz.

the frequency bandwidth is wider while the lower frequency is constant. The characteristics of the free space path losses based on average power loss respect that based on peak power loss are the same with the first case. That is the free space path losses based on the average power loss are lower than that based on the peak power loss. The free space path loss with ideal filter is lowest and it is higher when uses the -3 dB and -10 dB bandwidth Gaussian filters, respectively.

The free space path loss with Gaussian filter can not be directly derived in the closed form formula. Therefore, the 2- and 3-point Gaussian integration formula [14] are used to estimate the equation. Hence, the accuracy of estimation are

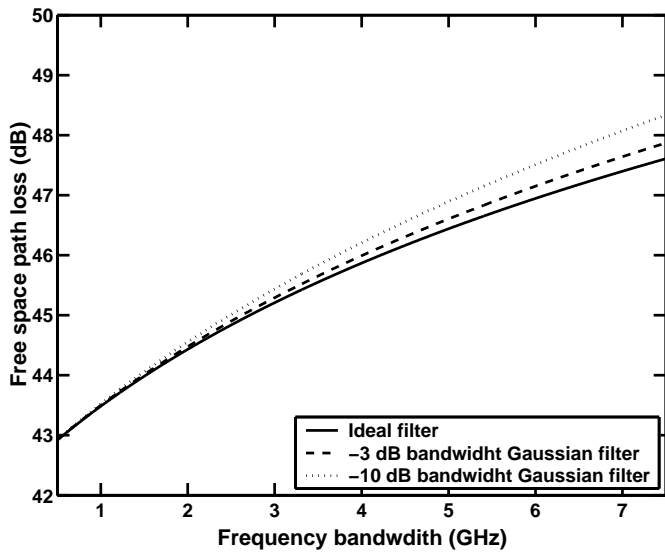


Fig. 4. free space path losses based on average power loss with lower frequency is $f_L = 3.1$ GHz and T-R separation distance is $d = 1$ m along frequency bandwidth f_b from 500 MHz to 7.5 GHz.

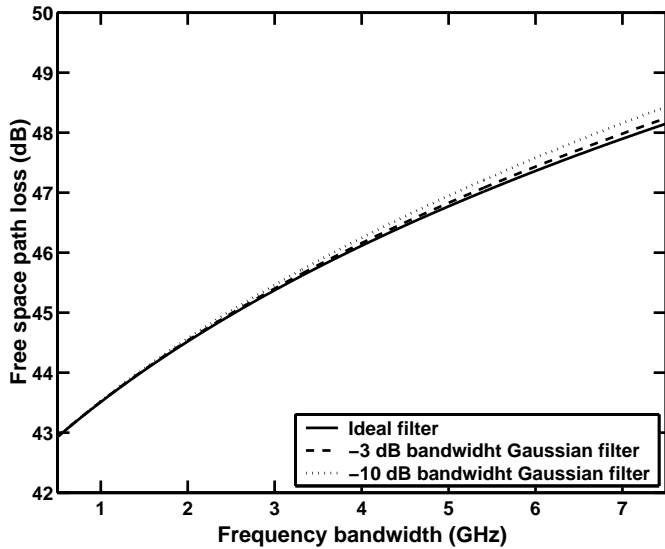


Fig. 5. free space path losses based on peak power loss with lower frequency is $f_L = 3.1$ GHz and T-R separation distance is $d = 1$ m along frequency bandwidth f_b from 500 MHz to 7.5 GHz.

investigated.

Figure 6 shows the free space path losses based on average power loss for the first case. The formula of the -10 dB bandwidth has the error more than that of the -3 dB bandwidth. For the -3 dB bandwidth, the maximum errors of 2- and 3-point Gaussian formula are about 0.08 dB and 0.01 dB, respectively. For the -10 dB bandwidth, the maximum errors of 2- and 3-point Gaussian formula are increased to about 0.51 dB and 0.10 dB, respectively.

The free space path losses based on peak power loss for the first case are shown in Fig. 7. For the -3 dB bandwidth, the maximum errors of 2-point Gaussian formula is about 0.02

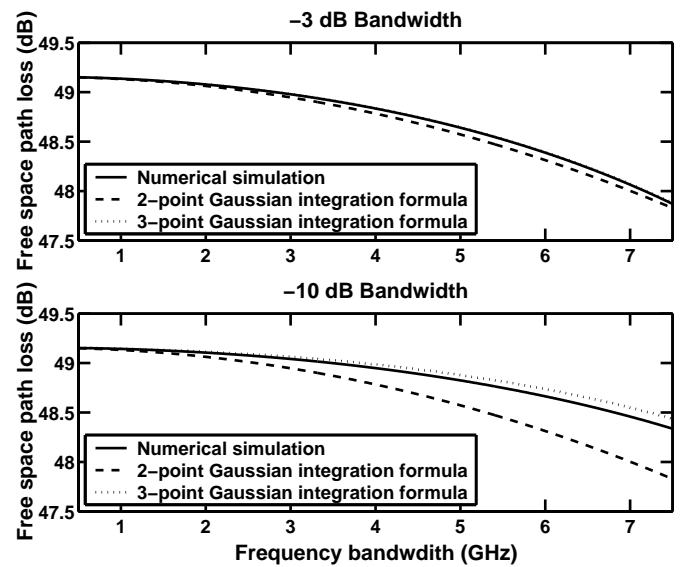


Fig. 6. free space path losses based on average power loss with center frequency is $f_c = 6.85$ GHz and T-R separation distance is $d = 1$ m along frequency bandwidth f_b from 500 MHz to 7.5 GHz.

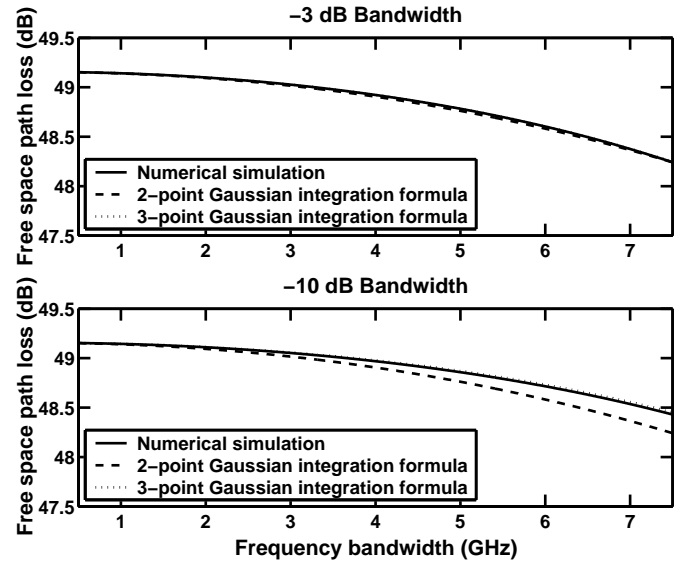


Fig. 7. free space path losses based on peak power loss with center frequency is $f_c = 6.85$ GHz and T-R separation distance is $d = 1$ m along frequency bandwidth f_b from 500 MHz to 7.5 GHz.

dB while that of 3-point Gaussian formula is approached to zero. For the -10 dB bandwidth, the maximum errors of 2- and 3-point Gaussian formula are increased to about 0.19 dB and 0.02 dB, respectively.

Figure 8 shows the free space path losses based on average power loss for the second case. For the -3 dB and -10 dB bandwidth, the maximum errors of 2- and 3-point Gaussian formula are the same with first case. That is about 0.08 dB and 0.01 dB, respectively, for the -3 dB bandwidth and 0.51 dB and 0.10 dB, respectively, for the -10 dB bandwidth.

The free space path losses based on peak power loss for

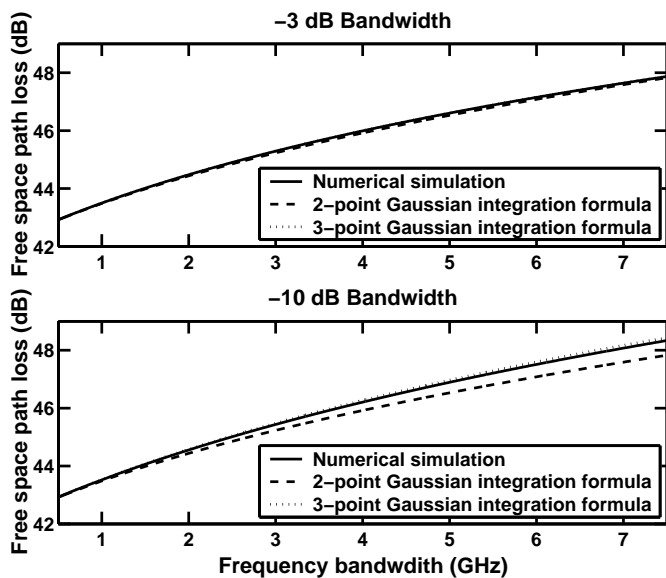


Fig. 8. free space path losses based on average power loss with lower frequency is $f_L = 3.1$ GHz and T-R separation distance is $d = 1$ m along frequency bandwidth f_b from 500 MHz to 7.5 GHz.

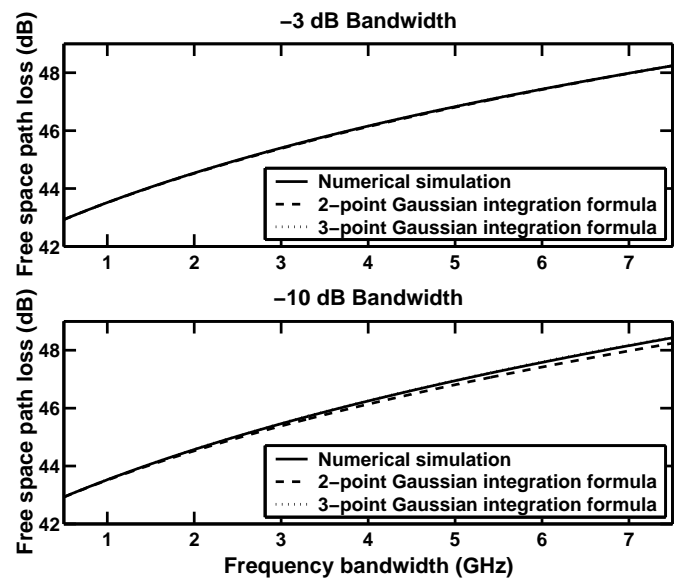


Fig. 9. free space path losses based on peak power loss with lower frequency is $f_L = 3.1$ GHz and T-R separation distance is $d = 1$ m along frequency bandwidth f_b from 500 MHz to 7.5 GHz.

the second case are shown in Fig. 9. For the -3 dB and -10 dB bandwidth, the maximum errors of 2- and 3-point Gaussian formula are the same with rst case.

V. CONCLUSIONS

In this paper, the free space path loss of UWB communications is studied. From the analysis results, the UWB free space path loss at the frequency bandwidth about 500 MHz is almost the same with that obtained from Friis' formula. When the frequency bandwidth is increased, the UWB free space path loss is lower than that obtained from Friis' formula. The free space path loss based on the average power loss is lower than that based on the peak power loss. The free space path loss with ideal l_{ter} is lowest and it is higher when uses the -3 dB and -10 dB bandwidth Gaussian l_{ters} , respectively. For the Gaussian integration formula which is used to estimate the closed form formula of the free space path loss with Gaussian l_{ter} . The 2- and 3-point Gaussian integration formula has very errors which have maximum errors about 0.5 dB, and 0.1 dB, respectively. Therefore, the Gaussian integration formula proposed in this paper can be well used for evaluating the UWB free space path loss.

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