APS006 APPLICATION NOTE

CHANNEL EFFECTS ON COMMUNICATIONS RANGE AND TIME STAMP ACCURACY IN DW1000 BASED SYSTEMS

Version 1.02

This document is subject to change without notice

Table of Contents

List of Figures

List of Tables

1 Introduction

This application note is concerned with how channel characteristics affect the communications range and ranging accuracy of DecaWave's UWB products. There are other effects apart from channel characteristics that affect communications range and these are dealt with in other application notes available on www.decawave.com where you will also find details of DecaWave's other products and support materials.

2 Channel types

2.1 Introduction

When considering a channel between a transmitter and a receiver in a radio scheme one of the most important properties of the channel is whether it is either: -

1. Line of Sight (LOS); or
2. Non Line of Sight (NLOS)

The channel can have many other properties but for the purposes of this note we will concern ourselves with this primary distinction.

Throughout this document, for the purposes of brevity, line-of-sight is abbreviated to LOS and non-line-of-sight is abbreviated to NLOS

LOS channels are discussed in section 3 while NLOS channels are discussed in section 4. Each of these channel types is considered in the context of communications range, range accuracy and how various other factors can influence communications range and time-stamp accuracy.

For a detailed analysis of UWB channels and a comparison between UWB and narrow band channels see [3].

2.2 What do we mean by "Range"

In this note it is important to understand the distinction between the following terms: -

Term	Description	Primarily depends on
Communications range	The range between two DW1000 nodes at which successful communications takes place (as defined by acceptable packet error rate for a given application).	The **total energy** transmitted into the channel by the transmitter and received at the receiver over all paths between the two nodes. If this is above the receiver sensitivity then communications can occur. See sections 3.2 and 4.2 for a discussion on communications range in LOS and NLOS cases.
Direct path detection range	The range between two DW1000 nodes at which the DW1000 can correctly detect and timestamp the direct path signal between the two nodes rather than any multipath	The energy received at the receiver only over the **direct path** between the transmitter and receiver. This energy must be above a dynamically adjusted threshold in order for it to be detected by the DW1000.

These two may or may not be the same depending on the channel and in certain circumstances will definitely not be the same.

The DW1000 operates by deriving the impulse response of the communications channel between the transmitter and receiver for each received frame. It does this by processing the preamble sequence which comes at the start of every IEEE802.15.4-2011 UWB frame.

This allows the IC to: -

- Detect the signal from below the noise floor
- Extract the direct path signal and any multipath signals that follow it.
- Process the impulse response and timestamp the first peak in this response that exceeds a dynamically adjusted detection threshold.

The DW1000 reports the time-stamp of this first peak in the impulse response via registers to which the application software has access. This value can then be used in a variety of different ways to implement location and ranging schemes.

3 LOS operation

3.1 Introduction

An optically clear line of sight between two wireless nodes exists if an imaginary straight line can be drawn between the antennas of the two nodes.

It is important to make the distinction between an optically clear line of sight and clear line of sight from an RF perspective: -

- An optically clear LOS exists when no physical objects obstruct viewing one antenna from the location of the other antenna.
- An RF clear line of sight exists if a defined area around the optical line of sight, known as the Fresnel Zone, is clear of obstacles. See Appendix 2 for further information on this topic.

For communications between DW1000 devices, it is the RF line of sight that is of interest.

3.2 Communications range in LOS channels

The communications range between two DW1000 ICs is determined by: -

1. the signal level that arrives at the receiver and
2. the sensitivity of the receiver

So long as the signal level at the receiver is greater than or equal to the receiver sensitivity then the receiver can detect the signal and communications will take place successfully.

The receive signal level depends on a number of factors as seen by examining Friis' path loss formula: -

$$P_R\ [dBm] = P_T\ [dBm] + G\ [dB] - L[dB] - 20\ \log_{10}(4\pi f_c d / c)$$

Where: -

- P_R is the received signal level;
- P_T is the transmitted power.
- G includes the antenna gains of the transmitting and receiving antennas, as well as any other gain from external amplifiers. In a properly calibrated system, the DW1000 emits sufficient power so that -41.3 dBm / MHz is radiated from the transmitting antenna.
- L includes any PCB, cable, connector and other losses in the system
- c is the speed of light, 299792458 m/s;
- f_c is the center frequency of the channel used, expressed in Hertz;
- d is the distance in meters between the transmitter and receiver.

Provided P_R is greater than the receiver sensitivity, the signal will be correctly received. The difference between the value of P_R and the receiver sensitivity is known as the **Link Margin** and gives an indication of the robustness of communications over the channel. A large link margin means that communications are robust and can handle additional attenuation without causing communications loss and vice versa.

Friis' formula clearly shows that: -

- For a given distance, as the signal frequency increases so does the path loss
- For a given frequency as the distance between transmitter and receiver increases so does the path loss.

So to maximize range: -

- Transmit power needs to be kept at the maximum allowable limit to ensure the maximum energy is transmitted into the channel. These limits are set by regulatory bodies in different parts of the world and for normal UWB operation this is usually -41.3 dBm / MHz.
- Losses due to PCB and antenna effects need to be kept to a minimum (in the case of the antennas in the DecaWave EVK1000 they should be mounted tightly to the EVB1000 boards to prevent impedance mismatch and leakage).It is important that PCB layout guidelines are followed and impedances are correctly matched.
- The lowest channel frequency possible should be used if maximum range is the overriding requirement.

Receiver sensitivity is quoted in the DW1000 datasheet and depends on a number of parameters including the selected channel and the data rate. For longest range the lowest data rate (110 kbps) should be used. See [1] and [2] for further information.

3.3 Ranging accuracy in LOS channels

3.3.1 Overview

In order to determine the distance between two nodes it is necessary to accurately measure the time of flight (TOF) of the radio signal between those two nodes. Knowing the TOF between the two nodes and the speed of the radio signal in free space, it is possible to calculate the distance between the nodes as shown in Figure 1 below.

The precision with which the TOF measurements are made is vital. A TOF measurement precision of 1 ns allows range to be determined to a precision of approx. 30 cm whereas a measurement precision of 100 ps reduces that figure to 3 cm. The DW1000 automatically handles the time-stamping of arriving signals to a precision of better than 20 ps.

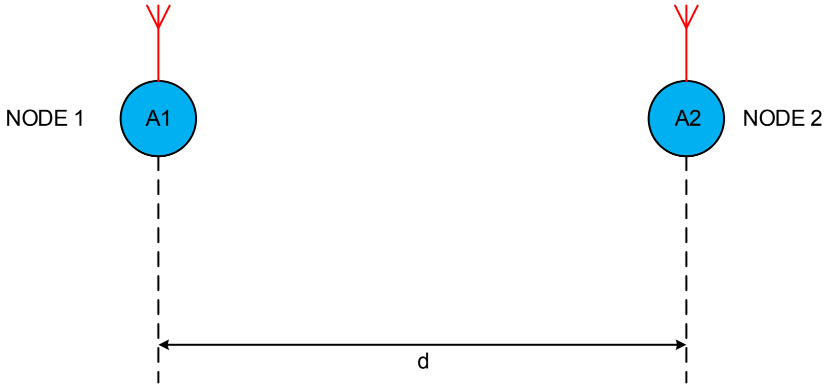

Figure 1: Line of Sight channel

$$d' = c \times TOF$$

Where: -

- TOF is the time of flight between the two nodes
- d is the actual physical distance between the two nodes in meters
- d' is the calculated distance between the two nodes in meters
- c is the speed of light in m/s

Since there are no obstructions in the channel and therefore no NLOS effects, d = d' and the ranging accuracy is determined by the bandwidth of the channel and other factors inside the two nodes. For a more detailed analysis of these internal factors see [4].

In the simplest LOS case where no multipath is present the impulse response as determined by the

DW1000 is a single peak representing the energy in the direct path signal.

There are 3 cases to consider here: -

Table 1: LOS communications & ranging scenarios

Scenario	**Direct path signal**	**Comms?**	**Time-stamp?**	**Correct direct path?**
1	Large Link Margin	Robust	Yes	Yes
2	Small or no Link Margin	Adequate	Yes	Yes
3	Negative Link Margin	None	No	No

1. The first scenario represents correct and normal operation. The two DW1000 nodes attempting to communicate are within range such that the signal transmitted by one node, when it arrives at the other, is above the sensitivity level of the receiver and is correctly received, processed and time-stamped.
2. The second scenario also represents correct and normal operation. Here we are reaching the limit of normal communications but the arriving signal is still at or above the sensitivity of the receiver.
3. In the third scenario no communications is possible between the two DW1000 nodes because either: -

   - they are too far apart in free space, or
   - there are obstacles in the RF path between the two nodes attenuating the signal such that it is below the receiver sensitivity level.

3.4 LOS operation with multipath

3.4.1 Introduction

Multipath refers to a channel in which the direct path between the transmitting node and receiving nodes is not the only signal path that exists. This is usually the case in the real world.

Multipath signals are generally caused by the radio signal reflecting off RF-reflective surfaces. These surfaces may be in any orientation to the transmitting and receiving antennas (above, below, behind, to the side etc.).

Multipath signals caused by a single reflection will be inverted in phase to the original signal and may therefore interfere with the direct path signal at the receiver depending on the relative lengths of the two paths.

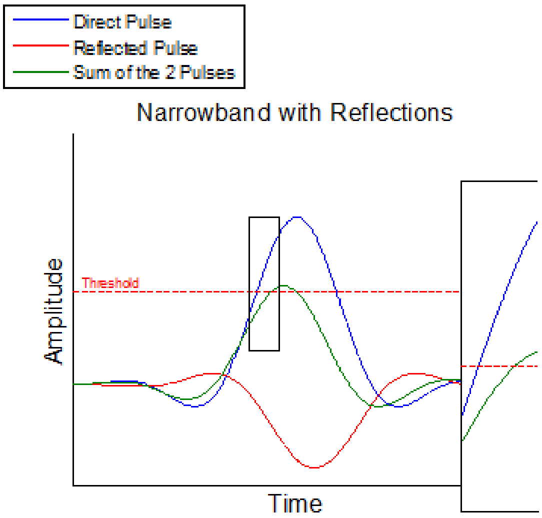

Figure 2: Narrowband signal in the presence of multipath

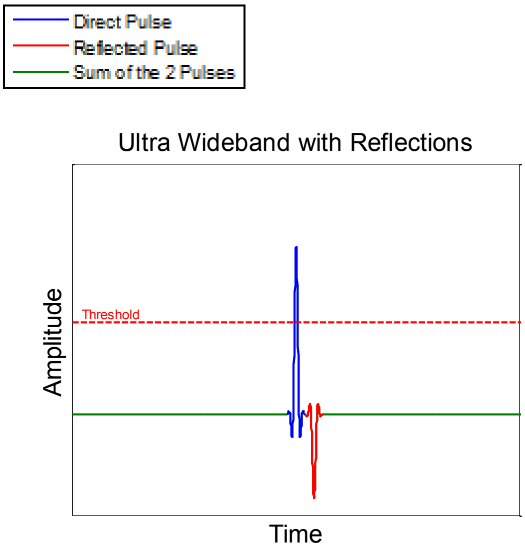

Figure 3: Ultra wideband signal in the presence of multipath

In a narrow-band radio scheme the pulses used are, relatively speaking, very wide. This means that there are a large number of multipaths over which the reflected signal will overlap and interfere with the direct path signal. In an ultra-wideband scheme on the other hand, the pulses are very narrow (2 ns) so there is only a very small group of multipath signals where the path length is within 2 ns of the direct path length and is capable of causing interference at the receiver. Figure 2 & Figure 3 illustrate this concept.

In a LOS channel, multipath signals have less energy than the direct path and they all have a path length between receiver and transmitter that is longer than the direct path. They therefore arrive later in time than the direct path. It is this property that allows us to distinguish the direct path from the later-arriving multipaths and thereby calculate the correct time of flight between the transmitting and receiving nodes.

Because the multipath signals will all have less energy than the LOS direct path by definition (they are longer and therefore suffer greater loss) from the point of view of direct path detection the LOS case with multipath is no different to the LOS case without multipath.

Because the multipaths do not interfere in UWB systems, except in very specific circumstances, the arrival of the signal along each multipath represents additional energy arriving at the receiver compared to the direct path only case. This provides a useful boost in the link margin and increases LOS communications range.

Table 2: LOS scenarios in presence of multipath

Scenario	Direct path signal	Multipath signals	Comment	Comms ?	Time-stamp ?	Correct direct path?
1	Large direct path Link Margin	Large multipath Link Margin	Direct path will be reliably detected	Yes	Yes	Yes
2	Small Link Margin	Small or no multipath Link Margin	Direct path will be reliably detected	Yes	Yes	Yes
3	No Link Margin	Negative Link Margin	Direct path will be reliably	Yes	Yes	Yes

Scenario	Direct path signal	Multipath signals	Comment	Comms ?	Time-stamp ?	Correct direct path?
			detected	🟩	🟩	🟩
4	Negative Link Margin	Negative Link Margin	No communications	None	No	No

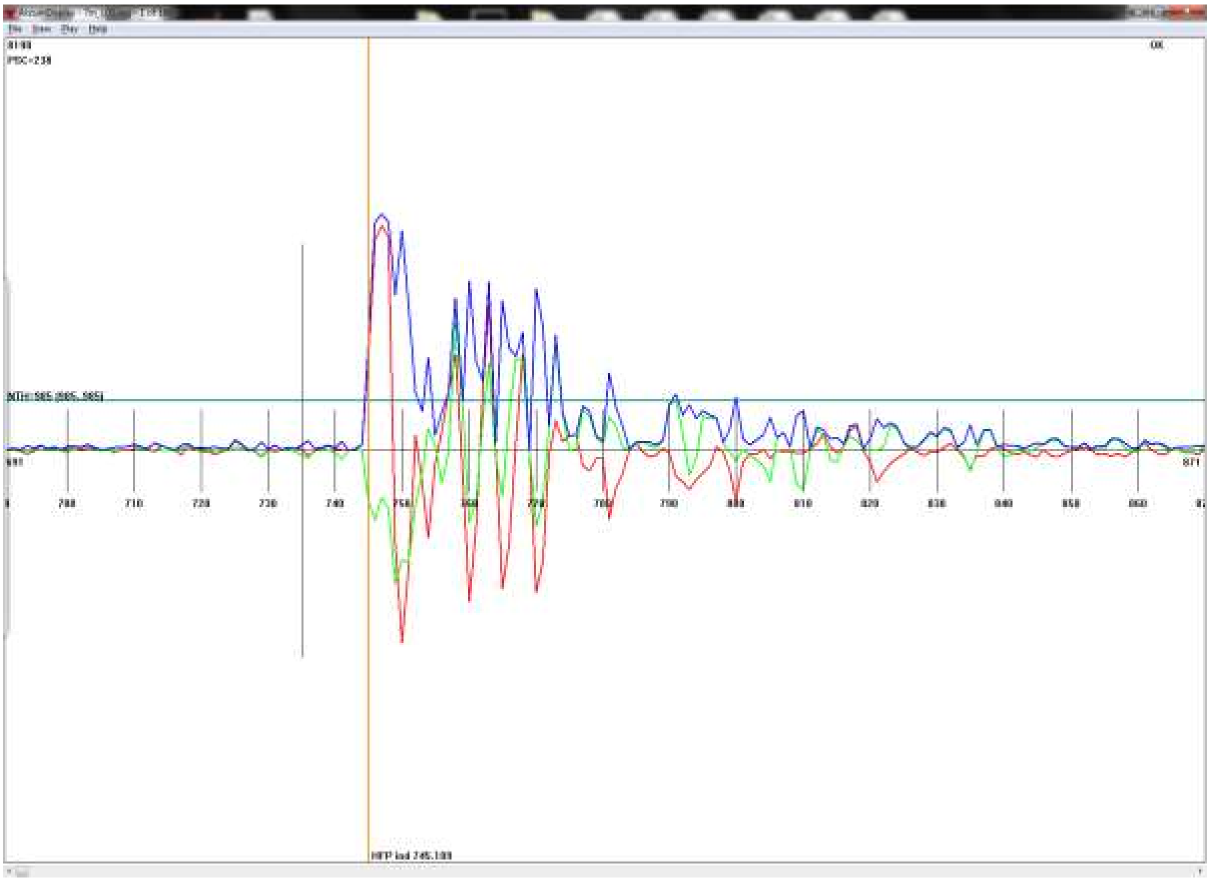

Figure 4: LOS channel with multipath

Figure 4 shows an example of the impulse response of the communications channel in scenario 1 from Table 2. The channel response in the absence of a signal (left hand side of the plot) is uncorrelated noise. In the presence of a signal, the impulse response shows the magnitude of the energy received along the direct path and each of the multipaths that follows it.

The first path is clearly visible and is the strongest signal received. Strong multipath is also present but none of the multipath signals are as strong as the direct path indicating that the direct path is a LOS path.

3.4.2 Multipath due to ground-bounce

In outdoor environments and large open indoor spaces the most common form of multipath is caused by RF reflections from the ground. Figure 5 illustrates the concept. It can be seen that there are an infinite number of such paths between the transmitter and receiver.

The primary concern here is how these multipath components interfere with the direct path (or not) as they both arrive at the receiver. As in 3.4.1 above, the multipath length must be within 1 ns of the direct path length for the multipath signal to interfere with the direct path signal. This is clearly a very specific case and represents the only situation where UWB is subject to fading as a result of multipath. This is obviously influenced by the height of the two nodes above the ground and the distance between the two nodes.

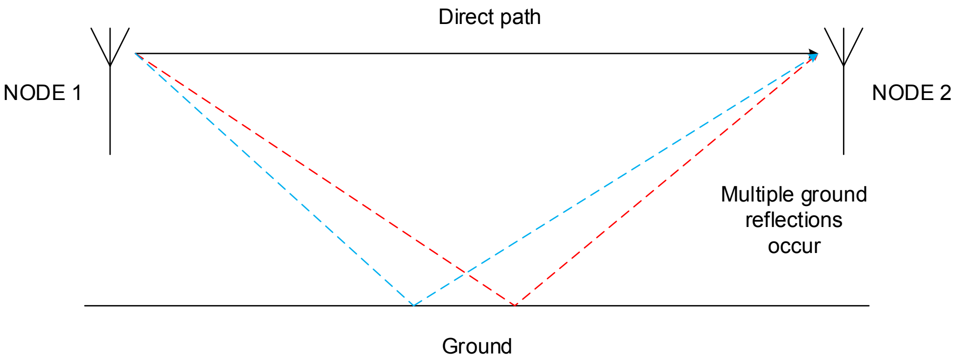

Figure 5: Multipath caused by reflections from the ground

A rough analysis of this scenario can be performed by considering how two sine waves at the channel center frequency might interfere (both constructively and destructively) as the direct and reflected path lengths vary. If we apply this analysis to channel 2 (4 GHz center frequency) and consider two nodes each 1 m above the ground we get the results shown in Figure 6.

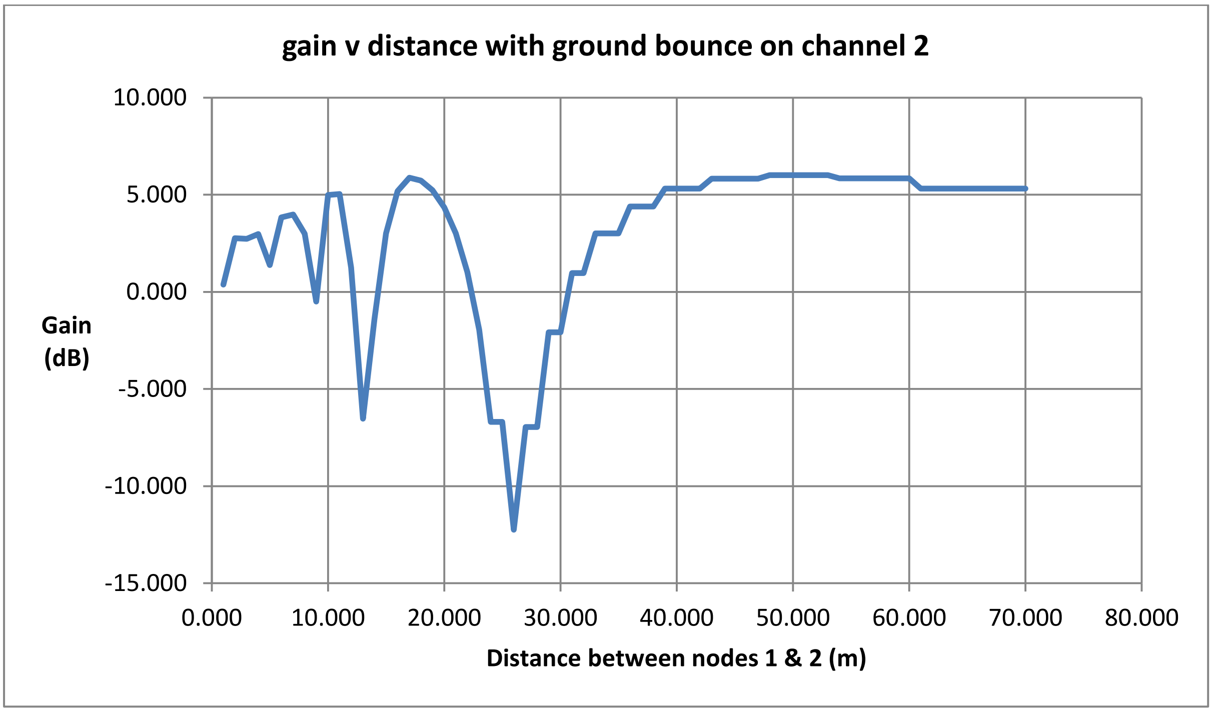

Figure 6: Fading due to ground bounce for two nodes each 1 m above the ground

This shows that there is potential for fading of -12 dB when the two nodes are approximately 26 m apart. This analysis is a gross over-simplification of the real world situation since a UWB transmission is not a single frequency but is spread across 500 MHz so even though some part of that bandwidth may be subject to fading at a particular multipath length, other parts of that bandwidth will not.

3.4.3 Multipath in indoor environments

As the physical environment becomes more cluttered so too does the number of multipaths between the transmitter and the receiver. However the principles in Table 2 hold.

4 NLOS operation

4.1 Introduction

There are three aspects to consider when examining NLOS operation: -

1. Reduction in communications range due to overall signal attenuation
2. Reduction in direct path detection range due to attenuation of the direct path signal
3. Time of Flight errors due to differences in the refractive index of the obstructing material

These concepts can be illustrated in the following diagram: -

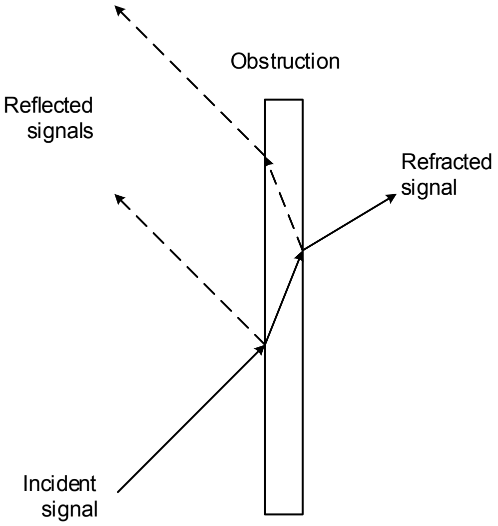

Figure 7: RF propagation through an obstruction

An incident RF signal arriving at an obstruction suffers two effects. A certain portion of the incident energy is reflected back from the obstruction while the remainder passes into the obstruction. A portion of that remainder is absorbed in the material (and leads to heating). Some of the remaining signal may be further reflected from the far edge of the obstruction while the remainder exits the obstruction on the other side.

4.2 Reduction in range due to signal attenuation

The degree to which the signal is reflected or attenuated by any particular obstruction depends on the materials that make up the obstruction, the thickness of the obstruction and the frequency of the incident RF signal.

The attenuation characteristics of different materials are given in Appendix 1.

The signal power at the receiver, as well as being a function of the transmitted power, any antenna gains / losses in the system and the free-space attenuation, as in the LOS case, must now also account for the losses in the material causing the path to be a NLOS path.

If we assume there is no multipath we can represent this as follows: -

$$P_R\,[dBm] = P_T[dBm] + G\,[dB] - L[dB] - 20\,\log_{10}(4\pi f_{c(}d_1{+}d_{2)}\,/\,c) - L_{MATERIAL}[dB]$$

Where all quantites have the same meanings as the LOS case and: -

d_1 = free space distance from transmitter to attenuating material
d_2 = free pace distance from atttenuating material to receiver
$L_{MATERIAL}$ = loss in the attenuating material

In this situation, depending on the losses in the obstructing material, communications range between the two nodes can be severely reduced to the point where the material is impervious to radio signals and communications can no longer take place.

4.3 TOF errors due to refractive index differences

Consider the following scenario. A UWB transmitter is one side of a physical obstruction and the receiver is the other side. The obstruction is such that: -

- it **does not** attenuate the signal sufficiently to prevent it being received by the receiver
- it **does not** permit multipath around it

So, what effect does the introduction of the obstruction have on the time of flight between the transmitter and the receiver when compared to the LOS case?

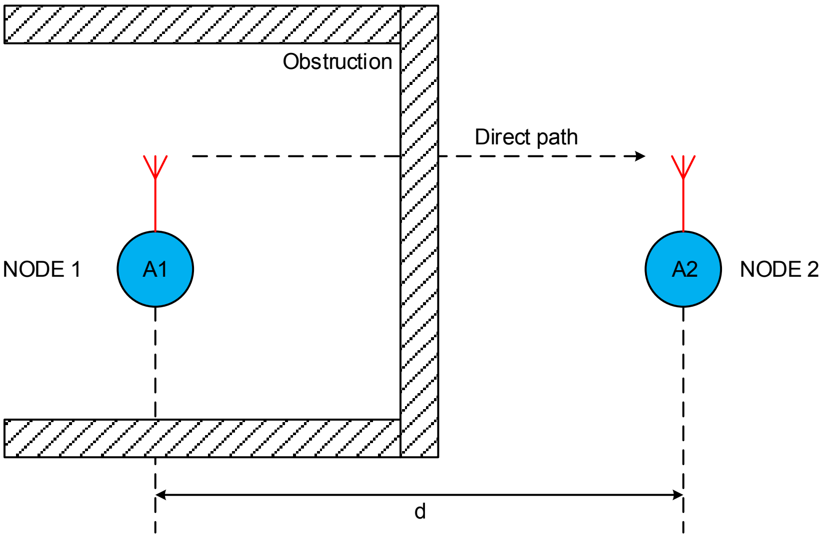

Figure 8: Effect of an obstruction

The fundamental effect is that the speed of propagation of the radio signal is slower through the obstruction than in free space. This means that the message will arrive at the receiver delayed by the increased propagation time through the obstruction as follows: -

$$TOF = \frac{d - w}{c} + \frac{w \times R}{c}$$

$$TOF = \frac{d + w \times (R - 1)}{c}$$

$$d' = TOF \times c = d + w \times (R - 1)$$

Where: -

- TOF is the time of flight between the two nodes
- d is the physical distance between the two nodes in meters
- d' is the calculated distance between the two nodes
- c is the speed of light in m/s in free space and the term c / R represents the reduction in the speed of radio signals though the obstruction

- w is the width of the obstruction
- R is the refractive index of the obstruction

So we can see that the calculated distance has been over stated by a factor which is dependent on the refractive index of the obstruction and tends to zero as the refractive index approaches that of free space: -

$$w \times (R - 1)$$

Assuming the obstruction is fixed and therefore w and R are constant it may be possible to calibrate out the effect of the obstruction in specific use cases such as using UWB for anchor clock synchronization in real-time location schemes.

Different materials have different values of R. Typical values are given in Appendix 1.

The extent of the impact on the time of flight depends on the relative thickness of the obstruction compared to the overall path length.

For example, if the overall path length is 10 m of which 25 cm is made up of an obstruction of refractive index 1.25 then the resulting error in the time of flight is of the order of 200 ps which equates to an error in the measured path length from transmitter to receiver of roughly 6 cm so the reported distance would be 10.06 m rather than 10 m.

4.4 NLOS operation with multipath

4.4.1 Introduction

The presence of multipath in the NLOS case raises interesting scenarios. A typical example is given in Figure 9 below. Here we can see that the direct path between the two nodes is obscured while other unobscured paths are possible because of reflections from nearby surfaces. Figure 8

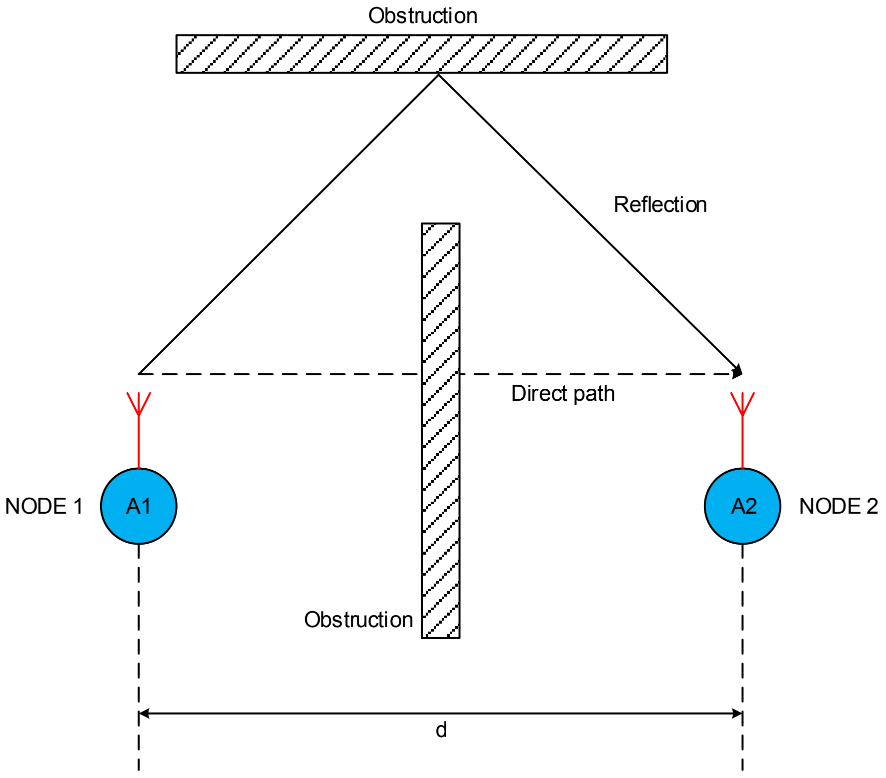

Figure 9: NLOS with muiltipath

The table below lists some typical examples of these scenarios in terms of the direct path and multipath signals arriving at the receiver.

Table 3: Various NLOS scenarios

Scenario	Direct path signal	Multipath signals	Comment	Comms ?	Time-stamp ?	Correct direct path?
1	Large direct path Link Margin	Large multipath Link Margin	This is the same as the LOS case with multipath	Yes	Yes	Yes
2	Reduced direct path Link Margin and direct path above detection threshold	Large multipath Link Margin	Direct path will be reliably detected	Yes	Yes	Yes
3	Reduced direct path Link Margin and direct path below detection threshold	Large multipath Link Margin	First arriving multipath above the detection threshold will be detected as the direct path	Yes	Yes	No
4	Negative direct path Link Margin	Large multipath Link Margin	First arriving multipath above the detection threshold will be detected as the direct path	Yes	Yes	No
5	Negative direct path Link Margin	Small multipath Link Margin	First arriving multipath above the detection threshold will be detected as the direct path	Yes	Yes	No
6	Negative direct path Link Margin	Negative multipath Link Margin for all multipaths	No communications	None	No	No

4.4.2 Analysis

Figure 10 shows a typical channel impulse response of a NLOS channel.

In the example illustrated the direct path amplitude is less than some of the subsequent multipath amplitudes but is above the detection threshold (shown by the horizontal line). This indicates that the first path is not a LOS path but has been attenuated in some way relative to the following multipath components. This example corresponds to scenario 2 in Table 3.

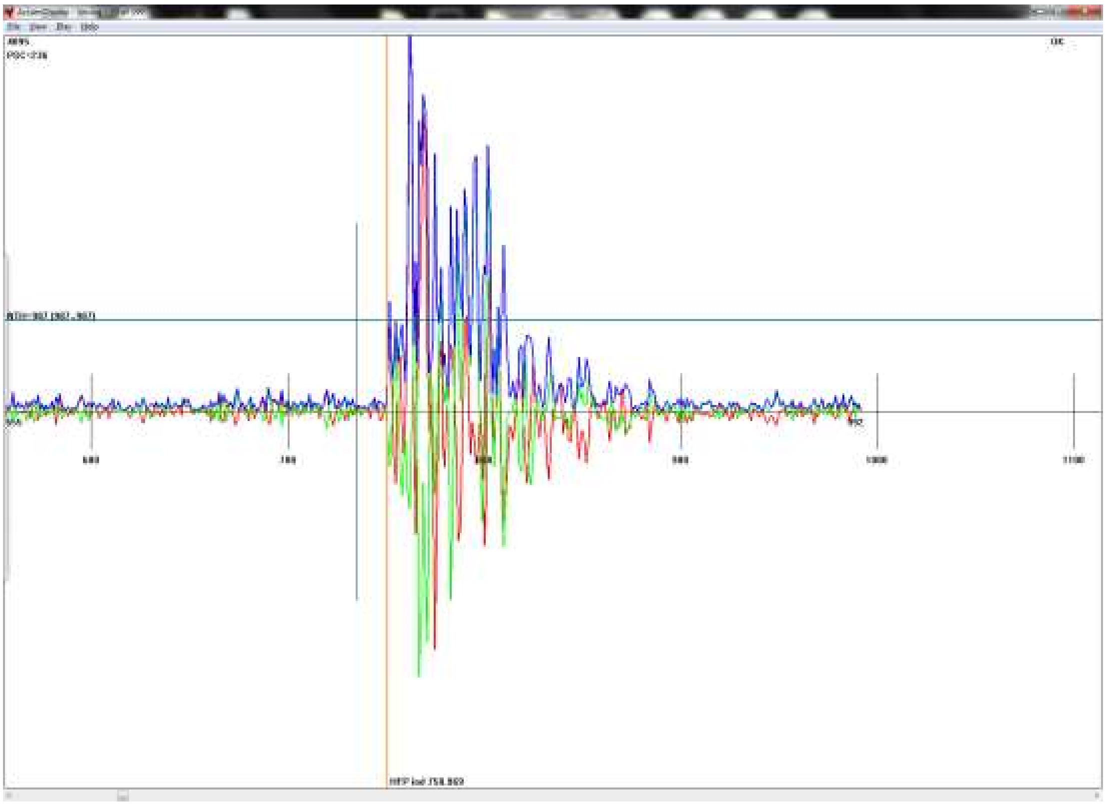

Figure 10: Example channel impulse response of a NLOS channel

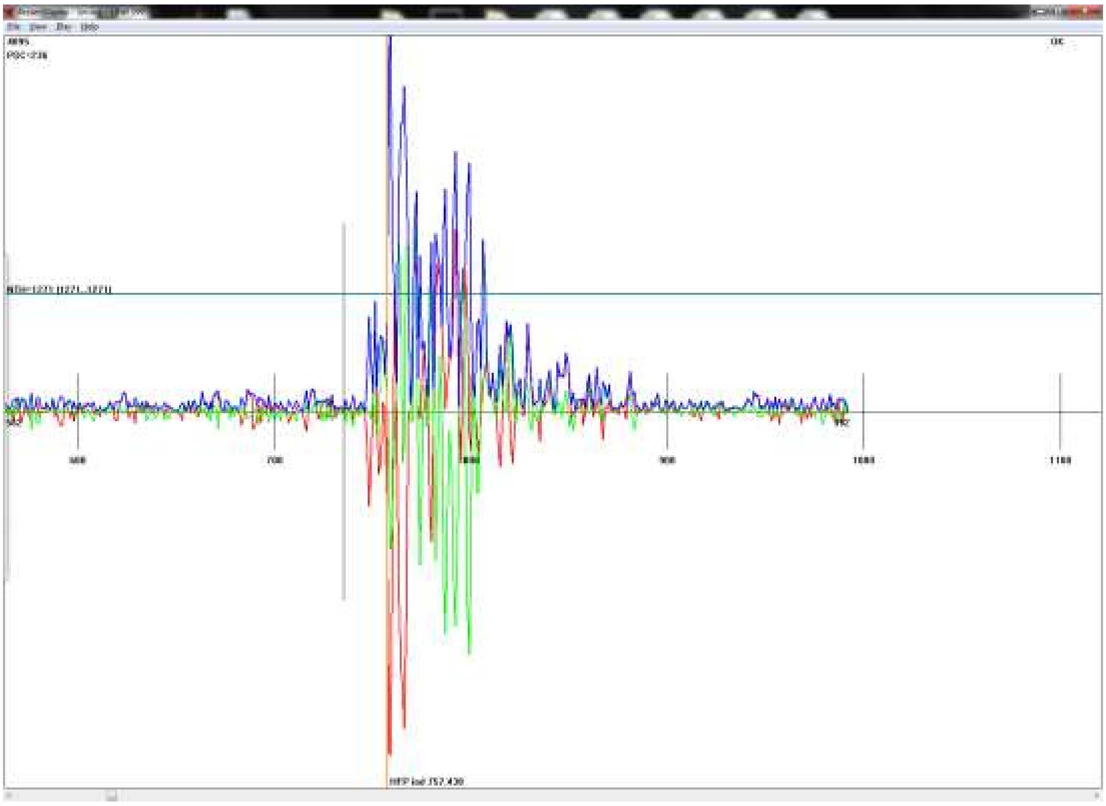

Figure 11: NLOS channel where the first path is not correctly detected

Figure 11 shows an example of scenario 3 above where the direct path is below the detection threshold and a later multipath signal is time-stamped as the direct path. This will lead to an error in the calculated distance between the two nodes the magnitude of which depends on the relative path lengths between the direct path and the reflected path.

4.4.3 Mitigating strategies for operation in NLOS environments

First of all, the need for a mitigating strategy in NLOS conditions depends on the end application. If the end application is a communications application then the consequences of not receiving the direct path are not as severe as in a location based application where the direct path is used as an input to a location determination algorithm.

The mitigating strategies that can be employed in NLOS conditions are essentially three-fold: -

- Optimize hardware & DW1000 configuration settings to maximise the possibility of receiving and detecting the direct path signal.
- Use on-chip DW1000 channel diagnostic information to determine whether the reported time-stamp is the result of a multipath signal or the direct path signal and take appropriate action.
- Use other system and algorithmic knowledge to recognise that the timestamp returned by the DW1000 is in fact a time-stamp of a multipath signal rather than the direct path signal. In this case the calculated distance / location will be incorrect but with knowledge of previous locations, the operating environment and suitable algorithms it may be possible to reject or weight these multipath timestamps.

These three strategies are dealt with in other documentation and support materials available from DecaWave.

5 References

5.1 Listing

Reference is made to the following documents in the course of this Application Note: -

Table 4: Table of References

Ref	Author	Date	Version	Title
[1]	DecaWave		Current	DW1000 Data Sheet
[2]	DecaWave		Current	DW1000 User Manual
[3]	DecaWave		Current	Comparison of Narrowband and Ultra Wideband channels
[4]	DecaWave		Current	APS011 Sources of error in TWR schemes
[5]	NIST	Oct 1997		NISTIR 6055, NIST Construction Automation Program Report No. 3, Electromagnetic Signal Attenuation in Construction Materials

6 About DecaWave

DecaWave is a pioneering fabless semiconductor company whose flagship product, the DW1000, is a complete, single chip CMOS Ultra-Wideband IC based on the IEEE 802.15.4-2011 UWB standard. This device is the first in a family of parts that will operate at data rates of 110 kbps, 850 kbps and 6.8 Mbps.

The resulting silicon has a wide range of standards-based applications for both Real Time Location Systems (RTLS) and Ultra Low Power Wireless Transceivers in areas as diverse as manufacturing, healthcare, lighting, security, transport, inventory & supply chain management.

Further Information

For further information on this or any other DecaWave product contact a sales representative as follows: -

DecaWave Ltd
Adelaide Chambers
Peter Street
Dublin 8
t: +353 1 697 5030
e: sales@decawave.com
w: www.decawave.com

7 Appendix 1: Attenuation characteristics and refractive indices of materials

Table 5: Attenuation characteristics of various materials

Material	Attenuation at 4 GHz	Notes
Brick	-15 dB	89 mm thick brick sample
Brick / Concrete combo	-36 dB	90 mm brick backed by 102mm of plain concrete
Concrete - solid	-23 dB	102 mm thick sample
Concrete - solid	-46 dB	203 mm thick sample
Concrete - solid	-73 dB	306 mm thick sample
Masonry block	-15 dB	203 mm thick sample
Masonry block	-24 dB	406 mm thick sample
Masonry block	-34 dB	610 mm thick sample
Dry Wall	0 dB	6 mm sample
Dry Wall	0 dB	13 mm sample
Dry Wall	-0.1 dB	16 mm sample
Glass	-1.3 dB	6 mm sample
Glass	-0.1 dB	13 mm sample
Glass	-0.8 dB	19 mm sample
Human body	15 – 30 dB	Depending on body mass index and incident angle of the incoming signal
Plywood	0 dB	6 mm sample
Plywood	0 dB	13 mm sample
Plywood	-0.3 dB	19 mm sample
Plywood	-1.5 dB	22 mm sample

Table 6: Refractive indices of various materials

Material	Dielectric Constant	Refractive Index	Notes
Concrete - solid	7.5	2.73	
Concrete - hollow	3	1.73	
Dry Wall	2	1.41	
Human body	51	7.14	
Plywood	2	1.41	
Water	80	8.94	At 4 GHz

8 Appendix 2: Fresnel Zone

The Fresnel Zone is defined as follows: -

$$R = \frac{1}{2} \times \sqrt{(\lambda \times D)}$$

Where: -

- R = radius of the first Fresnel zone
- λ = wavelength of the radio signal
- D = distance between sites

When at least 80% of the first Fresnel Zone is clear of obstacles, propagation loss is equivalent to that of free space.

So, in an ultra-wideband context, for two nodes 10 m apart, the Fresnel zones for the channels supported by the DW1000 are as follows: -

Table 7: First Fresnel zones for DW1000 channels at a distance of 10 m

Channel	Channel Center Frequency MHz	Band MHz	Fresnel Zone radius Bottom of band cm	Fresnel Zone radius Top of band cm
1	3494.4	3244.8 – 3744	48.1	44.8
2	3993.6	3774 – 4243.2	44.6	42.0
3	4492.8	4243.2 – 4742.4	42.0	39.8
4	3993.6	3328 – 4659.2	47.5	40.1
5	6489.6	6240 – 6739.2	34.7	33.4
7	6489.6	5980.3 – 6998.9	35.4	32.7

So, for example, to ensure no NLOS effects in Channel 2 then the path between the antennas must be completely unobstructed for a radius of 44.6 cm around the straight-line optical path between the antennas.