

**APS006 PART 3
APPLICATION NOTE**

**DW1000 Metrics for Estimation
of Non Line Of Sight Operating
Conditions**

Version 1.1

This document is subject to change without notice

Table of Contents

LIST OF FIGURES.....	2
LIST OF TABLES	2
1 INTRODUCTION.....	4
2 EXECUTIVE SUMMARY	5
3 BACKGROUND ON TESTS AND EXPERIMENTAL RESULTS	6
4 DW1000 METRICS	6
5 NON LINE OF SIGHT METRICS	7
5.1 INTRODUCTION	7
5.2 PROBABILITY OF NLOS	7
5.3 UNDETECTED EARLY PATH.....	10
5.3.1 <i>Peak Detection in the Analysis Window.....</i>	<i>11</i>
5.3.2 <i>How to Detect and Count the Number of Peaks in the Window</i>	<i>11</i>
5.3.3 <i>Likelihood of Undetected Early Paths</i>	<i>11</i>
5.3.4 <i>Practical Examples of Undetected Early Paths.....</i>	<i>12</i>
6 CHANNEL IMPULSE RESPONSE AND DYNAMIC RANGE	14
7 CONFIDENCE LEVEL, CL.....	16
8 OPERATING THE DW1000 IN SEVERE NLOS SCENARIOS.....	18
9 GLOSSARY	19
10 REFERENCES	20
11 DOCUMENT HISTORY	21
12 MAJOR CHANGES	21
13 FURTHER INFORMATION	21

List of Figures

FIGURE 1: A TYPICAL ACCUMULATOR FROM THE DW1000 GIVING THE CHANNEL IMPULSE RESPONSE(CIR), SHOWING PEAK PATH(REP: PEAK), FIRST PATH (REP:FP) AND NOISE THRESHOLD (REP: NOISE LEVEL)	6
FIGURE 2: A SIMPLE NLOS SITUATION AND THE ACCUMULATOR THAT RESULTS.....	8
FIGURE 3: SAMPLE ACCUMULATOR FROM A TYPICAL NLOS SCENARIO.....	9
FIGURE 4: SAMPLE ACCUMULATOR FROM A TYPICAL LOS SCENARIO.	9
FIGURE 5: DIAGRAM OF AN ACCUMULATOR WHERE THE ACTUAL FIRST PATH IS MISSED BY THE DW1000	10
FIGURE 6: SAMPLE ACCUMULATOR SHOWING A LOW NUMBER OF PULSES BEFORE THE REPORTED FIRST PATH <i>Luep</i> IS CALCULATED AS 0.14286	12
FIGURE 7: SAMPLE ACCUMULATOR SHOWING A LARGE NUMBER OF PULSES BEFORE THE REPORTED FIRST PATH <i>Luep</i> IS CALCULATED AS 0.42857	12
FIGURE 8: TYPICAL FORM OF AN ACCUMULATOR DISPLAYING THIS EFFECT; MC = 0.965712	14
FIGURE 9: TYPICAL FORM OF AN ACCUMULATOR DISPLAYING THIS EFFECT; MC = 0.994151	15
FIGURE 10: TYPICAL FORM OF AN ACCUMULATOR DISPLAYING THIS EFFECT; MC = 0.996615	15
FIGURE 11: FLOWCHART DESCRIBING THE PROCESSING OF THE ACCUMULATOR AND THE DIAGNOSTIC REGISTERS, TO ARRIVE AT A CONFIDENCE LEVEL FOR THE LAST MEASUREMENT MADE.	17

List of Tables

TABLE 1: LIST OF DW1000 PROVIDED DIAGNOSTICS	6
--	---

TABLE 2 GENERATION OF A FIGURE OF CONFIDENCE CL	16
TABLE 3: TABLE OF REFERENCES	20
TABLE 4: DOCUMENT HISTORY.....	21

1 Introduction

This is one of a library of application notes dealing with the operation, performance and application of Decawave's UWB technology.

This application note is concerned with explaining how Decawave's DW1000 based products provide metrics to allow the estimation of line of sight (LOS) and non line of sight (NLOS) operating conditions.

This application note assumes the reader has some understanding of radio wave propagation and has already read Decawave's application notes APS006 Part 1 [3] and APS006 Part 2 [4]. A basic understanding of the operation of Decawave's DW1000 will also help your understanding.

Further details on Decawave's DW1000 and our other products as well as a library of other application notes are available on www.decawave.com.

2 Executive Summary

Wireless systems will operate in line of sight (LOS) and in non line of sight (NLOS) situations. Where data transfer is the objective, operation in NLOS situations may only result in signal level attenuation, but not loss of data. However, for Ultra-Wideband where distance measurement is the objective, operation in NLOS situations can result in an error in the distance measured.

In general for good line of sight channels the normal operation of the DW1000 suffices. The DW1000 assigns a timestamp to the relevant incoming pulse. This timestamp, is made available through a register in the register set of the device. This timestamp can be used by the software to determine range.

In non line of sight situations the end user system can use the additional capabilities of the DW1000 to assign a level of confidence to the assigned timestamp. This can be achieved by using additional registers provided in the register set of the device. Furthermore post processing of the accumulator in the DW1000 can allow identification of a falsely detected first path, where it may have been incorrectly identified by the device due to NLOS effects. Details relating to these techniques are discussed in later sections of this document.

Inherent in the techniques described above is an assumption that the direct or first path is received by the DW1000. In situations where non line of sight conditions are particularly severe and a large percentage of packets received by the DW1000 do not include the first path, then other approaches may be required. A brief overview of options for these scenarios is presented later in this document.

3 Background on Tests and Experimental Results

A range of laboratory tests and real world application implementations, have been used by Decawave to gather results. These have been used to analyse the operation of the DW1000 in a number of LOS and NLOS scenarios.

The DW1000 offers metrics in the form of registers, detailed in the section titled DW1000 Metrics, below. Output from these metrics have been assessed against the different laboratory and real world results. The value of these metrics and their usage in determining a LOS or NLOS use case is discussed in the following sections.

4 DW1000 Metrics

Some of the DW1000 metrics offered by the chip and referenced in later discussions in this document are outlined in Table 1 and shown in Figure 1.

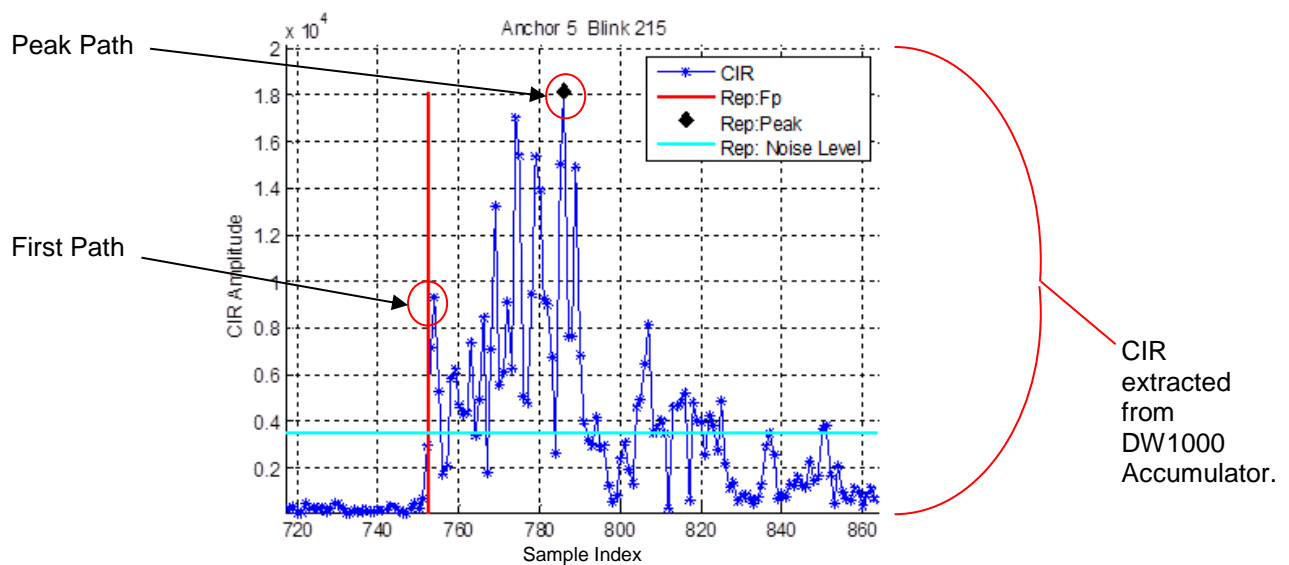


Figure 1: A typical accumulator from the DW1000 giving the Channel Impulse Response(CIR), showing Peak Path(Rep: Peak), First Path (Rep:Fp) and Noise Threshold (Rep: Noise Level)

Table 1: List of DW1000 provided diagnostics

Terms used in this document	Description	DW1000 User Manual Reference [2]
<i>pathPosition</i>	Position of the detected first path, in the Channel Impulse Response (CIR)	Register file: 0x15 FP_INDEX
<i>fpAmpl1, fpAmpl2, fpAmpl3</i>	First, second and third amplitudes around the first path	Register file: 0x15 FP_AMPL1, FP_AMPL2, FP_AMPL3
<i>peakPathIndex</i>	Index of the peak ray in the CIR	Register file: 0x2E – Leading Edge Detection Interface LDE_PPINDX
<i>pkAmp</i>	Amplitude of the peak path	Register file: 0x2E – Leading Edge Detection Interface LDE_PPAMPL
<i>C[]</i>	Array of the complex CIR	Register file: 0x25 – Accumulator CIR memory

Noise Threshold	Standard Noise Deviation x NTM	Register 12:00 for STD_NOISE Register 2E:0806 for NTM
-----------------	--------------------------------	--

5 Non Line of Sight Metrics

5.1 Introduction

We would like to find a definite answer to whether the measurement made was made in a NLOS situation. However, what is achievable, is to assign a figure of merit or a probability that the measurement was made in a NLOS situation.

5.2 Probability of NLOS

Figure 2 below shows a simple NLOS scenario where the transmitted signal from Node 1 has an obstruction in its path. A single reflection is also shown in the top part of the figure. A sketch of the accumulator captured from a DW1000 in this type of scenario is shown in the lower part of the diagram.

Fig: A NLOS with single reflection

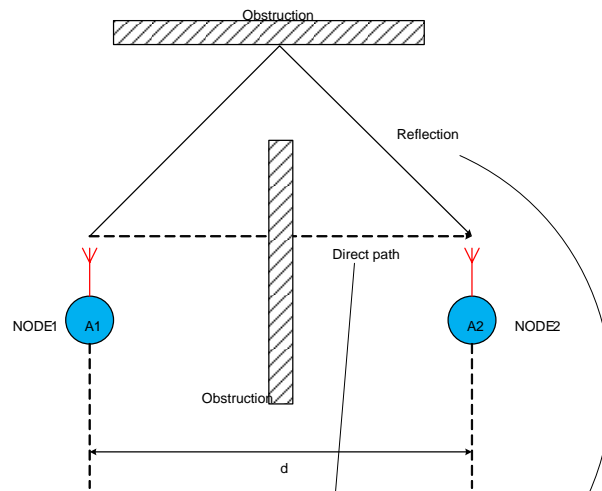


Fig: B NLOS with single reflection in DW1000 Accumulator

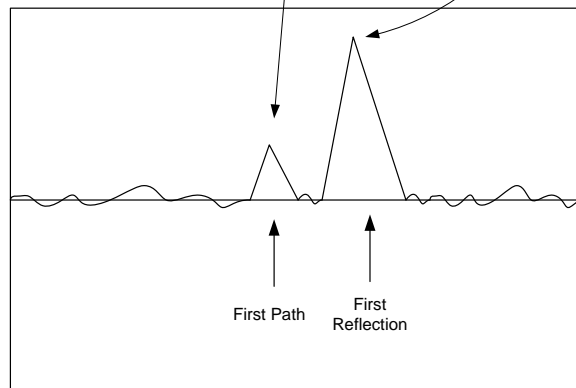


Fig: A. Shows a diagram of a transmitter and receiver where the direct line of sight has an obstruction in its path. A single reflection is also shown.

Fig: B. This shows the samples accumulated in the DW1000 accumulator. The first path corresponds with the direct path while the first reflection corresponds with the reflection shown in figure A.

Figure 2: A simple NLOS situation and the accumulator that results.

The accumulator sketch in the lower part of Figure 2 gives a reasonable presentation of what the accumulator will look like in this scenario. Indeed when reflections occur we find that we get a characteristic pattern in the accumulator. Figure 3 shows an accumulator from a typical NLOS scenario. Its similarity with the lower part of Figure 2 can be seen where the first path has lower amplitude than the peak path which occurs later in the accumulator. The key difference with the sketched accumulator in the lower part of Figure 2 being that there are multiple peaks corresponding to multiple reflections.

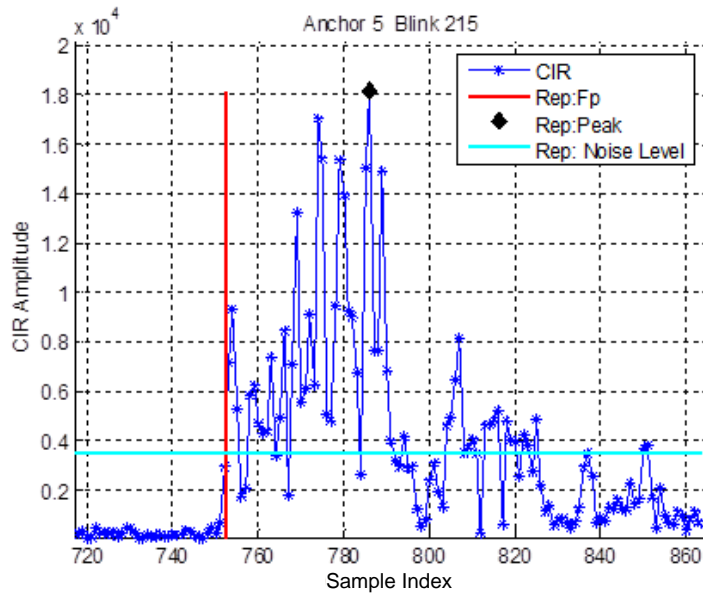


Figure 3: Sample accumulator from a typical NLOS scenario.

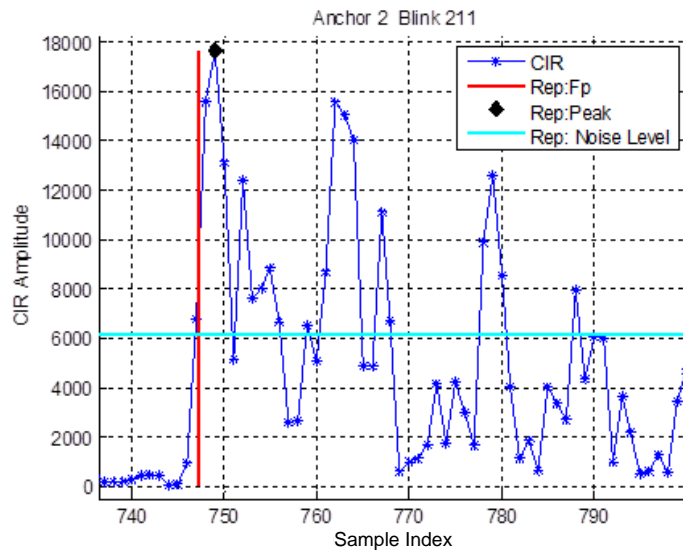


Figure 4: Sample accumulator from a typical LOS scenario.

For reference the diagram in Figure 4 gives a sample accumulator for a LOS scenario. Here you can see that the first path and the peak path are much closer than in the NLOS case.

By comparing the first path position in the accumulator to the peak path position in the accumulator we can come up with a metric to allow us to determine the likelihood that this is a NLOS measurement. If we call this metric *prNlos* and the difference in these two path positions as the magnitude of *IDiff*, we can say:

$$IDiff = | \text{first path position} - \text{peak path position} |$$

Then by processing the figure for *IDiff* obtained in the following manner we can assign a figure of merit to the probability that the scenario was NLOS.

```

If (IDiff <= 3.3)
    prNlos = 0.0;
else if ( (IDiff < 6.0) && (IDiff > 3.3) )
    prNlos = 0.39178*IDiff - 1.31719;
else
    prNlos = 1.0;
end
    
```

The numerical constants as shown in the pseudo code above, are derived empirically based on a range of laboratory and real world testing carried out by Decawave.

Please note that while this section has used the accumulator to describe the scenario that the DW1000 is operating in, the metric can be obtained without extracting the accumulator from the DW1000.

5.3 Undetected Early Path

Should the first path be heavily attenuated, it is possible for a reflection to be identified as the first path by the DW1000. Figure 5 shows a scenario where the first path has been incorrectly identified. The actual first path can be seen below the noise threshold, to the left of Figure 5.

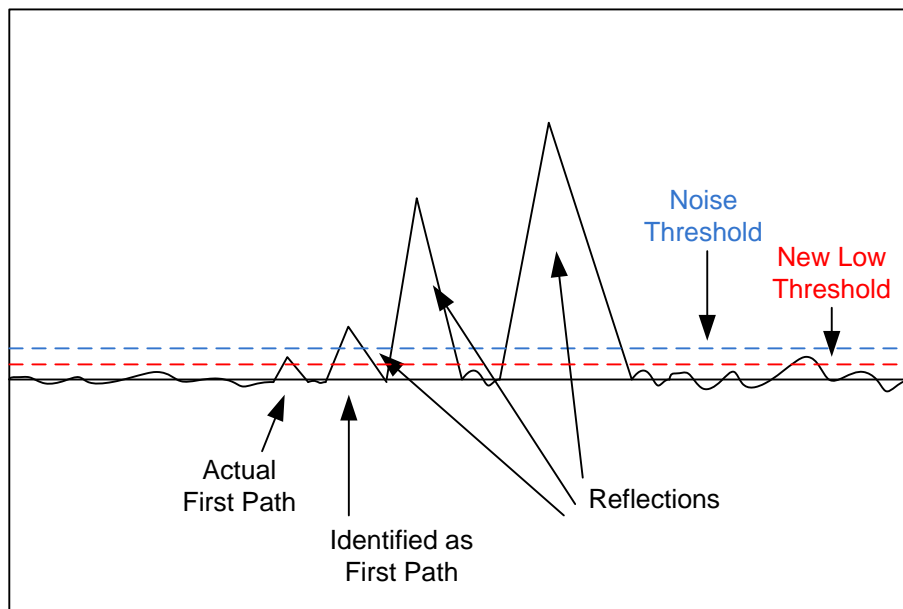


Figure 5: Diagram of an accumulator where the actual first path is missed by the DW1000

If it is possible to detect that peaks occur before the identified first path then we can determine the likelihood that we have an undetected first path. This would reduce our confidence in the DW1000's identification of the first path.

The following steps allow us to determine the number of peaks that have occurred in the accumulator before the DW1000's identification of the first path. Please note, that to complete this process the accumulator, or a section of it, must first be extracted from the DW1000.

1. Calculate a new low threshold by taking 0.6 times the reported noise threshold from the diagnostics. This new threshold is shown in red in Figure 5. Get existing noise threshold as the multiplication of STD_NOISE from Register 12:00 and NTM from Register 2E:0806.

2. From the integer part of the first path position, pathPosition, form an analysis window of 16 samples back tracked from that index.
3. Detect all possible peaks in the analysis window, as described in 5.3.1 and 5.3.2.
4. Find the number of peaks that have an amplitude above the new low noise threshold that was calculated in step 1.
5. Calculate the likelihood value for undetected early paths, as described in 5.3.3.

5.3.1 Peak Detection in the Analysis Window

To determine the number of peaks in the newly formed analysis window we take the difference of consecutive values. We identify a peak when these differences change from positive to negative.

So if;

$d(n)$ is the difference between the value at index $n-1$ and the value at index n and
 $d(n+1)$ is the difference between the value at index n and $n+1$
 then if $d(n)$ is positive and $d(n+1)$ is negative we have identified a peak.

5.3.2 How to Detect and Count the Number of Peaks in the Window

The pseudo code that follows shows how to detect the number of peaks ($iPeak$) in the newly formed analysis window and also how to store the index location of these peaks in the array $peakPosition[]$.

```

peakPosition = [];
iPeak      = 0;
for n = 0 : 13
  if ((d(n)) >0) && d(n+1) <0)
    peakPosition(iPeak) = n;
    iPeak = iPeak + 1;
  end
end
end

```

5.3.3 Likelihood of Undetected Early Paths

Once we have determined the number of peaks that occur before the identified first path we can assess the likelihood that we have undetected first paths. If we call this parameter $Luep$ then the likelihood can be given as:

$$Luep = \frac{\text{Number of peaks above the new low threshold}}{\text{Maximum possible peaks in the analysis window}}$$

To find the maximum possible peaks in the analysis window we take the length of the analysis window subtract one and divide by two. i.e.

$$\text{Maximum possible peaks in the analysis window} = (\text{Length of the analysis Window} - 1) / 2$$

'1' is taken from the length of the analysis window because the number of differences is one less than the length of the analysis window. We divide the result by 2 because a positive transition followed by a negative transition is required to identify a peak.

5.3.4 Practical Examples of Undetected Early Paths

Figure 6 and Figure 7 show practical examples of accumulators where peaks exist in the window prior to the reported first path. Figure 6 shows the situation where there are a low number of peaks prior to the reported first path. The $Luep$ calculated in this scenario is low with $Luep = 0.14286$. A low figure for $Luep$ increases our confidence in the reported first path. However, depending on your application and evaluation of results you may decide that any peaks occurring before the reported first path confirms a NLOS scenario.

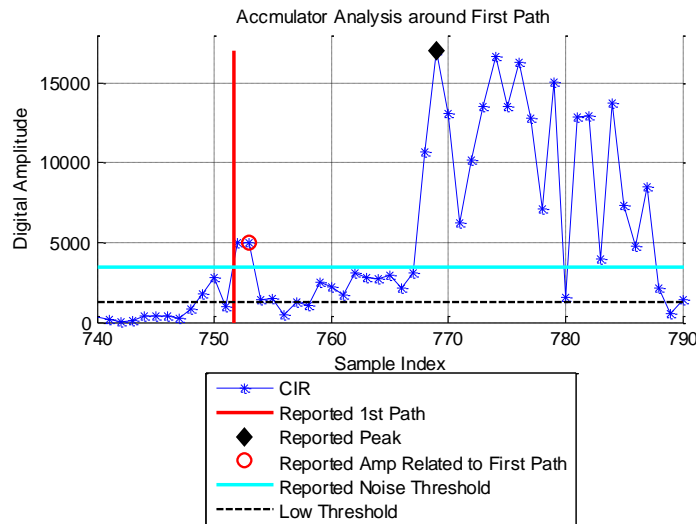


Figure 6: Sample accumulator showing a low number of pulses before the reported first path
 $Luep$ is calculated as **0.14286**

Figure 7 shows the situation where there are a larger number of peaks prior to the reported first path. The $Luep$ calculated in this scenario is higher with $Luep = 0.42857$. A high figure for $Luep$ decreases our confidence in the reported first path.

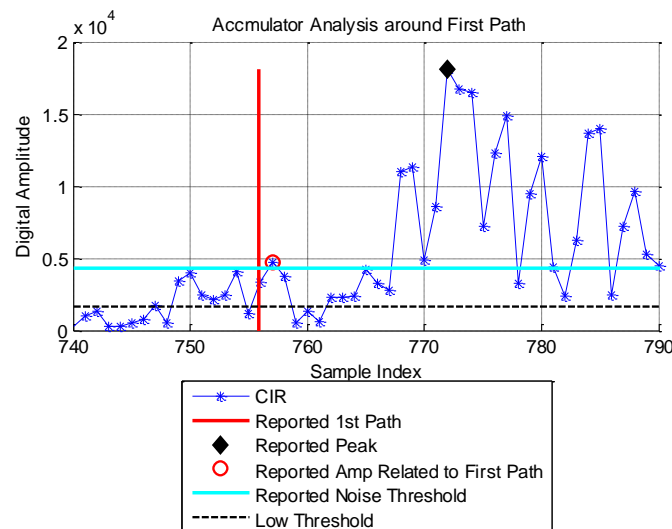


Figure 7: Sample accumulator showing a large number of pulses before the reported first path
 $Luep$ is calculated as **0.42857**

6 Channel Impulse Response and Dynamic Range

The accumulator growth rate is limited by the number of pulses in a symbol (16 or 64). At high signal levels this leads to a distortion which makes it difficult to distinguish between different high power rays. This manifests as high power rays appearing to "saturate" the accumulator.

We can detect the occurrence of this "saturation" if we create a metric M_c given as:

$$M_c = \frac{fpAmpl}{pkAmpl}$$

Where $fpAmpl = \max\{fpAmpl1, fpAmpl2, fpAmpl3\}$

$fpAmpl1, fpAmpl2, fpAmpl3$ are the first, second and third amplitudes around the first path, and max determines the maximum value.

If M_c is greater than 0.9 then we can conclude that this effect has occurred.

If it has occurred, then it is likely that there is a LOS path between the two DW1000 nodes. Other metrics may indicate that there is a NLOS path. The value of the metric, M_c , is that it can be used to overrule a figure for prNlos of greater than zero and conclude at a system level that the first path index is correct.

The three figures that follow, Figure 8, Figure 9, and Figure 10 are extracted from accumulators obtained from practical experiments. They give typical examples of the occurrence of this effect. Each figure includes details of the metric M_c for that instance.

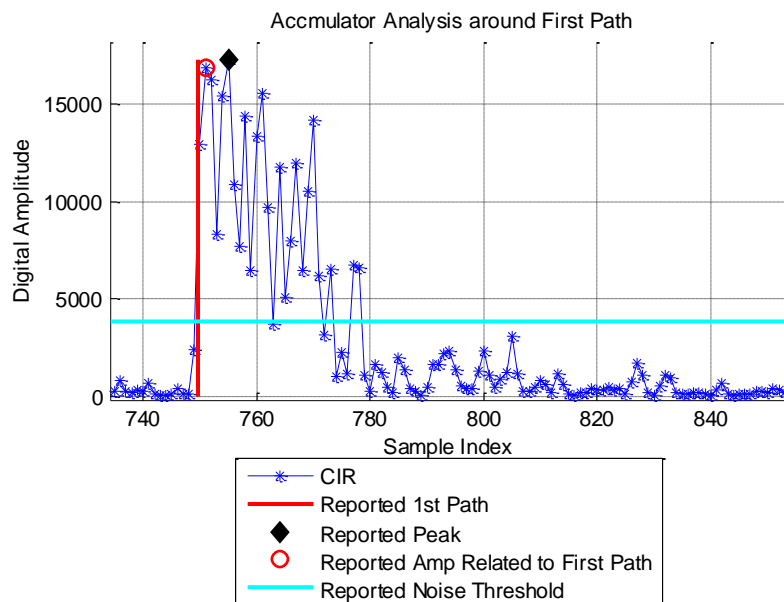


Figure 8: Typical form of an Accumulator displaying this effect; $M_c = 0.965712$

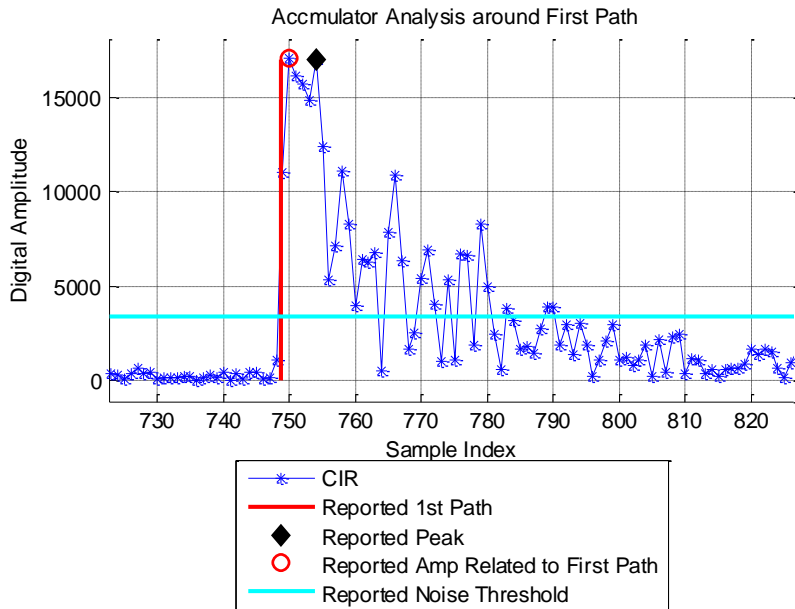


Figure 9: Typical form of an Accumulator displaying this effect; $Mc = 0.994151$

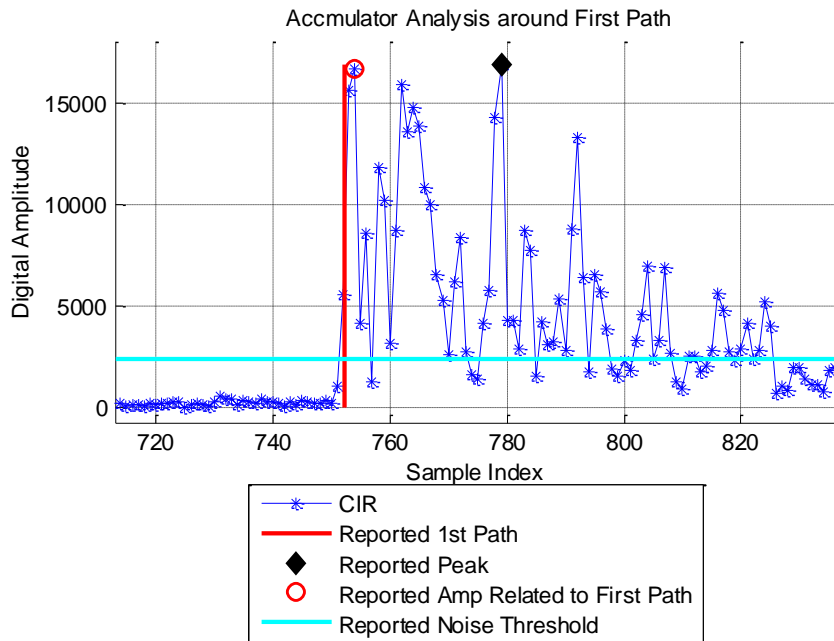


Figure 10: Typical form of an Accumulator displaying this effect; $Mc = 0.996615$

Please note that while this section has used the accumulator to describe the scenario that the DW1000 is operating in, the metric can be obtained without extracting the accumulator from the DW1000. Instead, values of the registers listed in Table 1 can be used.

7 Confidence Level, CL

Our objective has been to assign a figure of merit or a probability that a measurement was made in a LOS or a NLOS situation. This probability figure translates to a level of confidence in the last time stamp or the last measurement made by the device. We will call this figure of merit the confidence level.

The confidence level indicator, CL, takes on values between 0 and 1 where a '1' indicates that the measurement or time stamp is completely trustworthy and a '0' suggests that it is not trustworthy.

The decision list for the assignment of a confidence level CL is:

- The confidence level, CL is 0 regardless of the figure for the other metrics, If there is an occurrence of an undetected first path, earlier than the detected first path, i.e. $L_{uep} > 0$
- CL is 1 if $M_c \geq 0.9$ or if all metrics are 0. If PrNLOS is 0 then M_c doesn't matter.
- The CL value is $(1 - PrNLOS)$ if the $M_c < 0.9$.

These decisions are presented in tabular format in Table 2.

Table 2 Generation of a figure of Confidence CL

<i>L_{uep}</i>	<i>M_c</i>	<i>PrNLOS</i>	Confidence Level, CL
> 0	x	x	0
0	x	0	1
0	< 0.9	> 0	1- PrNLOS
0	≥ 0.9	x	1

Note: x represents Don't Care or doesn't matter.

Figure 11 presents a flowchart describing the processing of the accumulator and the diagnostic registers, to arrive at a confidence level for the last measurement made.

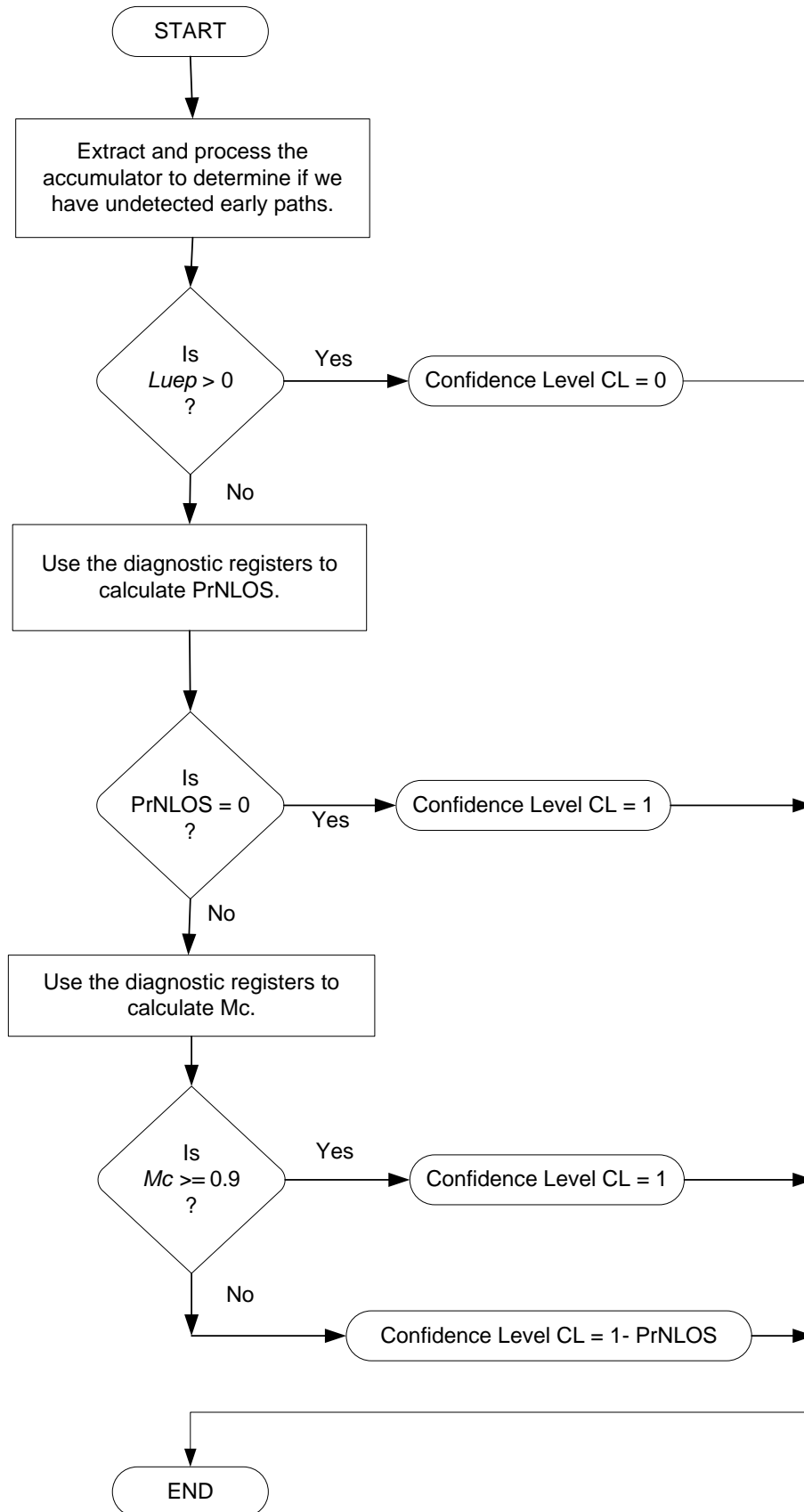


Figure 11: Flowchart describing the processing of the accumulator and the diagnostic registers, to arrive at a confidence level for the last measurement made.

8 Operating the DW1000 in Severe NLOS Scenarios.

All the discussion to this stage of the document has assumed that the DW1000 has received the direct path of communication from the transmitting DW1000. It may have been attenuated when passing through some material but it has been captured in the DW1000, even if only at a very low level. However, should you find that your application of the DW1000 gives rise to mixed periods of LOS, NLOS and severe NLOS operation, then some method of predictive estimation may be required to improve the location accuracy of your system.

Particle filters are one approach to getting greater location accuracy in these situations. Particle filters are a form of Bayesian filter. They adopt a probabilistic approach and take account of the history of the location of the object being located. Initial estimates are calculated based on limited knowledge of the object's location. The estimates contain details of location and velocity. The likelihood that each estimate is the correct location is calculated and the locations with the highest likelihood are retained. This process is then iterated through to track the movement of the object being located.

A brief idea on the algorithm required for the implementation of a particle filter in a location system is given below:

- Start with a large set of random guesses of the DW1000 nodes location.
 - The guesses are known as particles.
 - Each of the particles contains location and velocity.
- For each DW1000 device update
 - Update and randomly dither the particles based on the new information creating many new particles from each old one.
 - Compute the likelihood of each particle.
 - Resample the particles based on their likelihood
 - Remove unlikely particles.
 - Save the likely ones for re-use.
 - We end up with a cloud of particles clustered around the likely DW1000 device location.
 - The location estimate can be based on the most likely particle, the weighted mean, etc.

A large amount of documentation exists in the literature and on the internet. Some excellent introductory reference videos can be found here [5, 6].

9 Glossary

Acronym	Full Name	Explanation
CIR	Channel Impulse Response	The impulse received at the receiving node and displayed in the DW1000 accumulator.
LOS	Line of Sight	An RF clear line of sight [3] exists between the transmitting node antenna and the receiving node antenna
NLOS	Non Line of Sight	No RF clear line of sight [3] exists between the transmitting node antenna and the receiving node antenna.
prNLOS	Probability of NLOS	Gives a metric that describes the likelihood that the last measurement was made in a NLOS scenario.
Luep	Likelihood of undetected first paths.	Gives a metric that describes the likelihood that we have undetected first paths.
<i>Mc</i>	<i>Mc</i>	Detect the occurrence of "saturation".
CL	Confidence Level	This gives a level of confidence in the last time stamp or the last measurement made by the device. We call this figure of merit the confidence level.

10 References

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

Table 3: Table of References

Ref	Author	Date	Version	Title
[1]	Decawave		Current	DW1000 Data Sheet
[2]	Decawave		Current	DW1000 User Manual
[3]	Decawave		Current	APS0006 Part 1: Channel Effects on Communications Range and Time Stamp Accuracy in DW1000 Based Systems.
[4]	Decawave		Current	APS0006 Part 2: Non Line of Sight Operation and Optimizations to Improve Performance in DW1000 Based Systems
[5]	You Tube	17th Dec 2013	N/A	Particle Filters Explained https://www.youtube.com/watch?v=sz7cJuMgKFg
[6]	You Tube	16th Sept 2014	N/A	Particle Filter for Robot Localization https://www.youtube.com/watch?v=sK4bzB8vV1w

11 Document History

Table 4: Document History

Revision	Date	Description
1.0	23/12/16	Initial release
1.1	08/08/18	Updates for new logo and template.

12 Major Changes

v1.0

Page	Change Description
All	Initial external release

v1.1

Page	Change Description
All	New logo
22	New section for “Further Information”
22	New revision 1.1 and addition to Revision table for Document History.

13 FURTHER INFORMATION

Decawave develops semiconductors solutions, software, modules, reference designs - that enable real-time, ultra-accurate, ultra-reliable local area micro-location services. Decawave’s technology enables an entirely new class of easy to implement, highly secure, intelligent location functionality and services for IoT and smart consumer products and applications.

For further information on this or any other Decawave product, please refer to our website www.decawave.com.