

## **APS023 APPLICATION NOTE Part 2**

### **DW1000 TX BANDWIDTH AND CHANNEL POWER COMPENSATION**

**Version 1.4**

**This document is subject to change without  
notice**

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# 1 INTRODUCTION

## 1.1 Overview

This application note outlines the method of compensating the bandwidth and output channel power of the RF signal transmitted by the DW1000 for variations experienced at different temperatures. This is important to ensure the link budget is maximised and that the DW1000 device does not infringe on its regulatory requirements e.g. FCC/ETSI.

This document covers the following topics: -

- Why do we need temperature compensation?
- Calibration of TX bandwidth & power at module production test
- How to compensate for TX power & bandwidth during module operation

## 2 WHY DO WE NEED TEMPERATURE COMPENSATION?

### 2.1 Temperature effects on transmit power and bandwidth

The effects of temperature on the bandwidth and power of the transmitted signal are noticeable across the full range of temperatures that the DW1000 is designed to support. The bandwidth and power plots below show results from an IC with measurements taken at every 10°C between -40°C and 90°C. The channel power measurement involves measuring the transmit power over a bandwidth of 500MHz. The DW1000 IC is inside a temperature chamber, and the temperature is set to each of the temperature points. Once the chamber has reached the target temperature, and after a short settling period, the channel power measurement is taken. The resultant graphs are shown in Figure 1 and Figure 2 below.

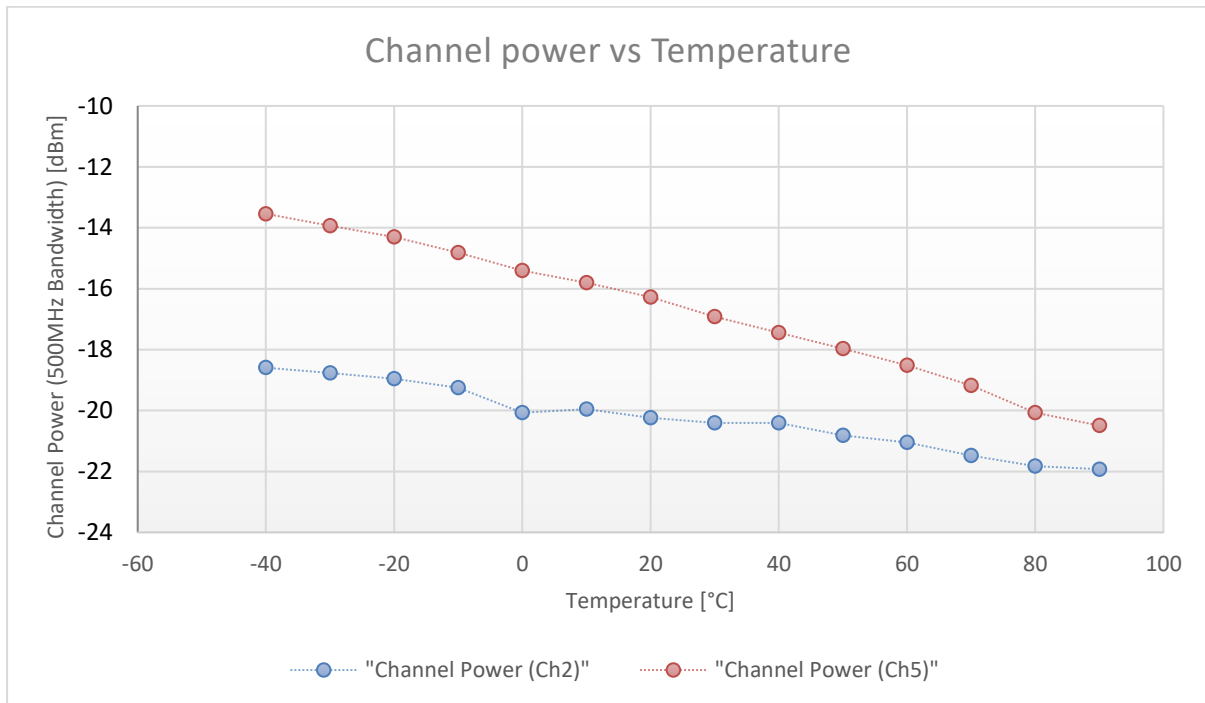
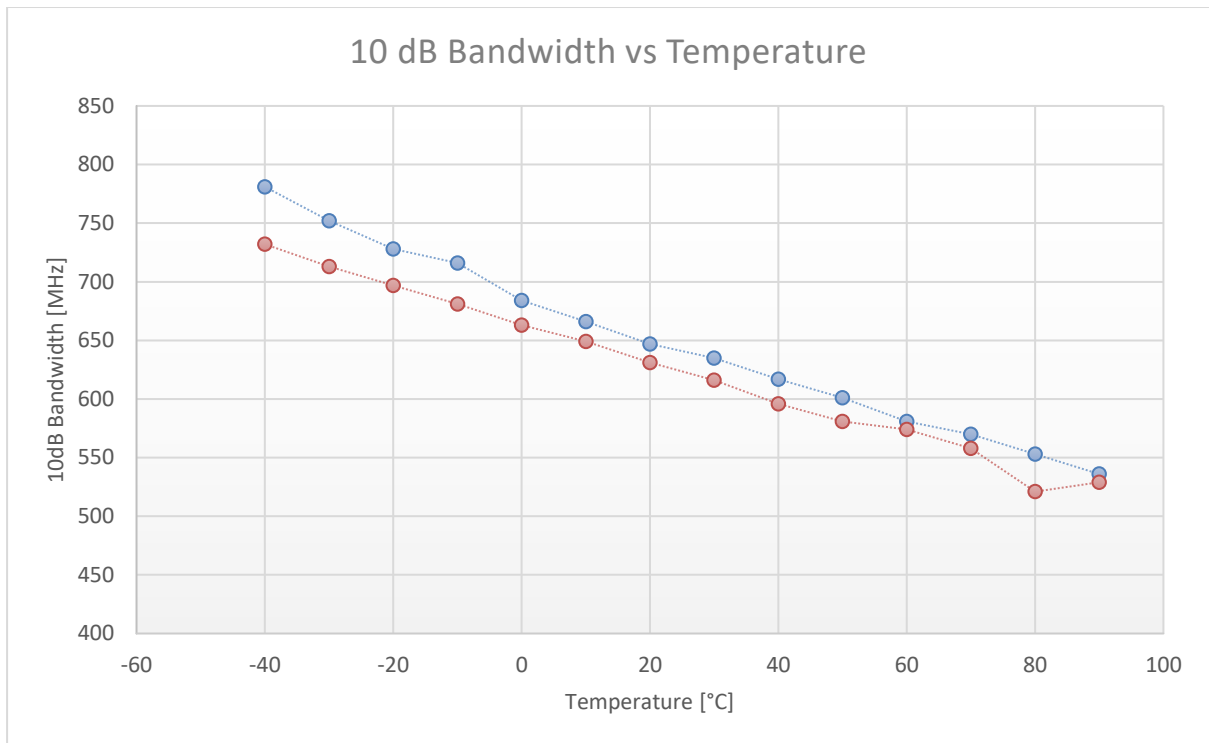


Figure 1: Channel power measured at each temperature (without any compensation)



**Figure 2: Bandwidth measured at each temperature (without any compensation)**

It is evident from Figure 1 and Figure 2 above that both the transmit bandwidth and channel power decrease with increasing temperature. It is also evident that the change is largely linear, and this can be seen across eight DW1000 ICs during testing.

In order to compensate for this, an algorithm must be designed to account for changes in power and bandwidth over temperature. The approach for compensating the bandwidth and the power are different, and are outlined in sections 4 and 5 of this document.

## 3 CALIBRATING TX POWER & BANDWIDTH AT MODULE PRODUCTION TEST

### 3.1 Introduction

During module production testing (a module is a product which integrates DW1000 IC, RF peripherals, antenna, and optionally a microcontroller etc. on a single PCB e.g. DWM1001), the transmit channel power and bandwidth should be adjusted to meet the products specification [2]. Usually this means setting the transmit power to the maximum allowed by regional regulations (typically -41.3 dBm / MHz) and also setting the transmit spectrum bandwidth. DW1000 allows both the transmit power and bandwidth to be adjusted via register settings. Normally a spectrum analyser is required for these measurements. For the testing carried out to provide the data for this application note, a Rohde & Schwarz FSUP Spectrum Analyser was used and thus, the instructions for measurement are focused on this equipment. Other analysers can be used with similar settings to take the same measurements. The following paragraphs describe a method to adjust and set the TX power and bandwidth during production testing. Once the correct register values are found these are usually stored in DW1000's OTP or in some other on board non-volatile memory (NVM) e.g. microcontroller flash memory.

### 3.2 Spectrum Analyser setup

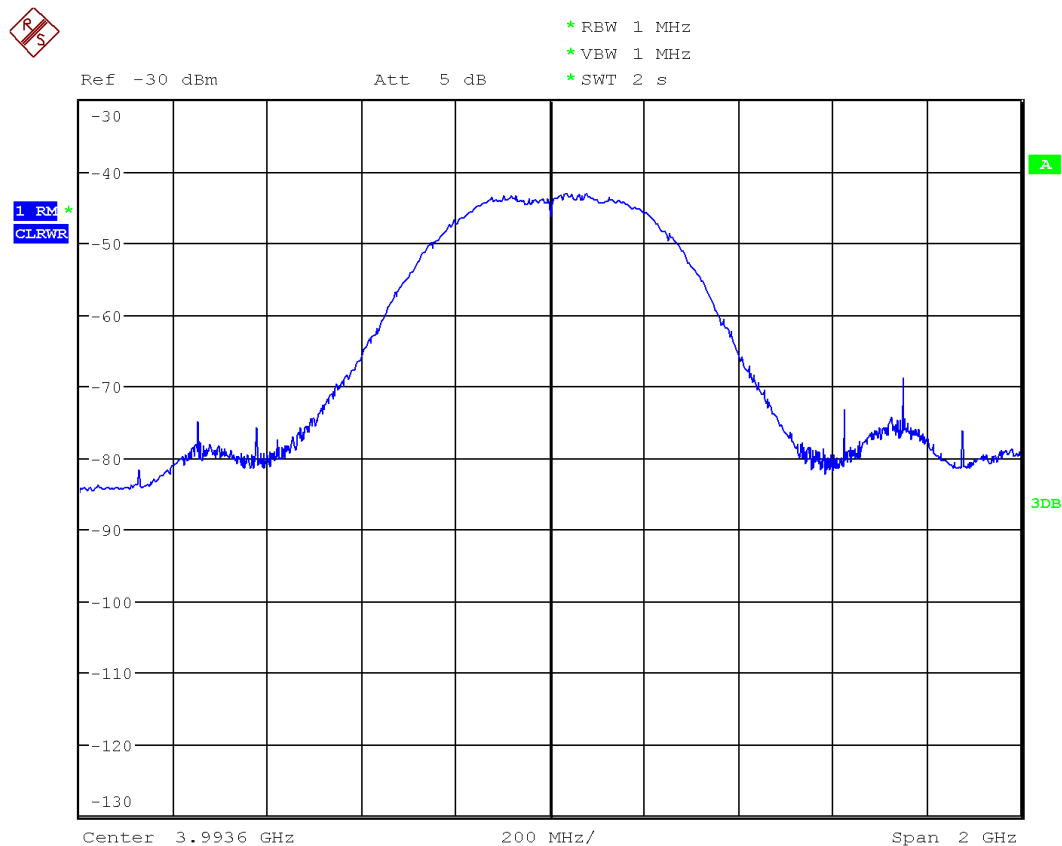
The RF interface of the DW1000 is connected to the RF INPUT port of the analyser. In order to bring up a spectrum to analyse, the DW1000 API function call `dwt_configcontinuousframemode()` can be used to continually transmit frames. The DW1000 API can be downloaded from [3].

The spectrum analyser settings were as follows:

Setting	Value
Centre Frequency	3993.6 MHz (Channel 2) 6489.6 MHz (Channel 5)
Frequency Span	2 GHz
Resolution Bandwidth	1 MHz
Video Bandwidth	1 MHz
Reference Level	-30 dBm
Sweep points	2001
Sweep time	2 seconds

The flow of DW1000 API calls to bring up continuous frame mode in the DW1000 device is outlined in the continuous frame mode example in the DW1000 API, under the examples/ex04b\_cont\_frame directory.

If the spectrum analyser is set up correctly and continuous frame mode has been activated on the DW1000, a spectrum should be visible on the screen of the analyser. An example of this can be seen in Figure 3 below.



**Figure 3: Spectrum Analyser displaying spectrum from DW1000 in continuous frame mode**

On the spectrum analyser measure the 10 dB channel bandwidth. On the FSUP, the NdB Down Bandwidth measurement function is used to measure the 10dB Bandwidth of the spectrum (MKR key → N DB DOWN softkey).

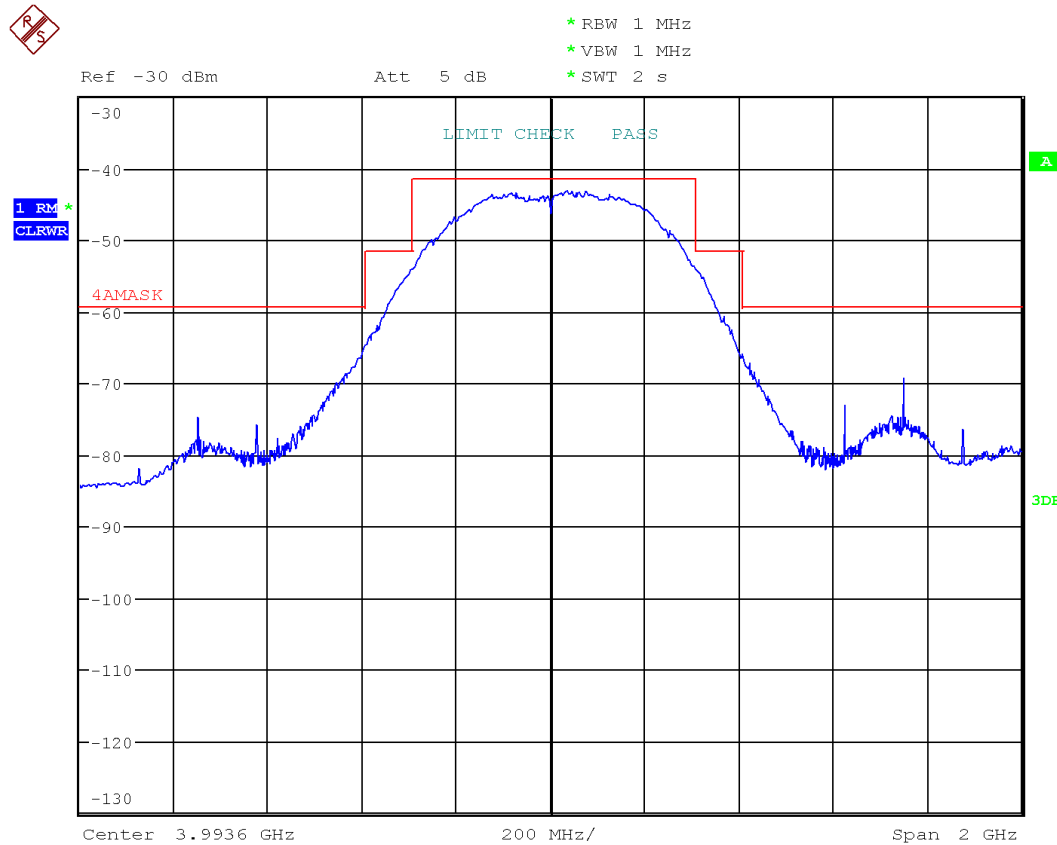
Most spectrum analysers will also have a channel power measurement. Set the channel bandwidth to the required bandwidth, usually 500 MHz.

These two measurements are common throughout the test procedure.

### 3.3 Using a spectrum mask

In order to ensure that the required maximum spectrum bandwidth and power level are programmed during production calibration, a spectrum mask stored in the spectrum analyser is often used. In this document, we use a mask based in the IEEE 802.15.4 HRP UWB PHY spectrum mask for convenience. See Figure 4.

In order to check that the spectrum does not violate the spectrum mask on the FSUP, first the mask must be input (LINES key → NEW softkey) and then limit-checking should be enabled on this new line (LINES key → press ENTER when desired mask is highlighted). A new line on the analyser screen will appear, which is the *Spectrum Mask*. If the spectrum violates the mask, the string "LIMIT FAIL" will appear. If the spectrum does not violate the mask, the string "LIMIT PASS" will be displayed. A typical display on the spectrum analyser is shown in Figure 4 below.



**Figure 4: Spectrum Analyser displaying spectrum with regulatory mask overlaid**

It is advisable to check that the spectrum fits the mask after each adjustment of bandwidth or power, as some adjustments can cause the spectrum to fail the mask.

When the module has been calibrated the contents of the following registers need to be stored in DW1000's OTP or some other NVM: -

- 0x1E [Transmit Power Setting] – see section 5.2
- 0x2A:09 [PG count] – see section 4.2
- Temperature at time of measurement. This can be either using the temperature sensor in DW1000 or any other on-board temperature sensor. Note, it is recommended that the same temperature sensor is used when reading temperature during operation. This is discussed further in section 3.5.1.

### 3.4 Calibrating bandwidth and output power during product calibration

In order to find the optimum bandwidth and output power settings, some reference measurements need to be taken. First, the bandwidth and power should be tuned so that the spectrum fits as well as possible into the IEEE 802.15.4a FCC, ETSI regulatory spectrum masks. This requires adjusting the bandwidth using the PG\_DELAY [0x2A:0B] register value and adjusting the power using the TX\_POWER [0x1E] register value.

#### 3.4.1 How to adjust the bandwidth

The PG\_DELAY sets the UWB pulse width and hence the spectrum bandwidth. The lower the delay, the smaller the pulse and thus, the wider the bandwidth. So, increasing the PG\_DELAY value decreases the bandwidth, and vice versa.



### 3.4.2 How to adjust the output power

The TX\_POWER register represents the Digital to Analogue convertor (DA) attenuation and TX mixer gain settings for the RF transmitter. The details of how the 4-octet register are laid out are detailed in the DW1000 User Manual [4] under the Register Descriptions section. Essentially, however, each octet contains a value for DA attenuation (bits 7:5) and TX mixer gain (bits 4:0).

Details on how to adjust the TX\_POWER [0x1E] register are outlined in section 4.4 of [2]. The approach taken here will be to adjust the TX mixer gain first, as this gives the most fine-grain control, and if necessary, to adjust the DA attenuation for larger power adjustments. Experimentally, it was found that having a TX mixer gain value between 4 and 20 gives the best performance, and so the algorithm outlined in this document will keep this value within these limits.

### 3.4.3 Calibrating bandwidth and output power

There are various ways to calibrate the bandwidth and power so as to fully utilise the allowed spectrum mask. This involves increasing or decreasing the PG\_DELAY and TX\_POWER register values until the bandwidth and power settings give a spectrum that occupies the maximum amount of the allowed spectrum mask.

One way to do this is as follows: -

1. Tune the TX\_POWER register until the top of the spectrum is just below the top of the spectrum mask.
2. Next, tune the PG\_DELAY register until the bandwidth of the spectrum is almost touching the sides of the mask.
3. Usually an increase in bandwidth will give rise to a decrease in channel power, causing the spectrum to violate the mask. So, adjust the TX\_POWER register again to come close to the mask.
4. Finally, readjust the PG\_DELAY register to account for any changes to bandwidth from the last adjustment (should be small)
5. Repeat 3 and 4 until the spectrum fills the mask satisfactorily.

Once the spectrum has been optimised, the reference measurements can be carried out. The procedure to do this is outlined in sections 4.2 and 5.2 for transmit bandwidth and power respectively.

## 3.5 Measuring Temperature

### 3.5.1 Measuring temperature during testing and data collection

During the testing carried out to collect the data presented in section 6.2, the DW1000 device under test (DUT) was placed inside a temperature chamber that was used to control the ambient temperature. Once the target temperature was reached for each test point, the DUT was allowed to sit at this temperature for 2 minutes, to give enough of a settling time to ensure the DW1000 is at the target temperature. The temperature chamber maintained this temperature for the duration of the test, to within  $\pm 0.5^{\circ}\text{C}$ . The temperature sensor of the chamber was used to record the temperature at each test point.

### 3.5.2 Measuring temperature during calibration and normal operation

During calibration and normal operation, to measure the temperature, a number of methods can be used depending on the application. The accuracy of the temperature measurement is important; the smallest transmit power variation that can be corrected for is  $\pm 0.5\text{dB}$ . Given that the largest variation in transmit power that is seen over temperature is  $0.065\text{dB}/^{\circ}\text{C}$ , then a variation in temperature of approximately  $\pm 10^{\circ}\text{C}$  can be endured before an adjustment of the transmit power is needed. It is recommended that the accuracy of the temperature sensor be within  $2\text{--}4^{\circ}\text{C}$  of the true temperature.

The DW1000 has a temperature sensor, which can be accessed by reading the least significant byte of the SAR\_READING register [0x2A:03]. This value gives an approximation of the temperature of the IC within the bounds of the required accuracy. To convert this value to a true  $^{\circ}\text{C}$  reading, the following

formula should be used:

$$T_{\text{real}} = 1.14 * (T_{\text{SAR}} - T_{\text{OTP}}) + 23$$

where  $T_{\text{SAR}}$  is the value read from the SAR,  $T_{\text{OTP}}$  is the value saved in OTP at factory (DW IC production test at 23 °C) and  $T_{\text{real}}$  is the actual temperature in °C.

Alternatively, if the host device or processor has its own temperature sensor, this can also be used to measure the temperature of the device during the calibration step. This temperature, whether measured by the DW1000 or another temperature sensor, will be used as the reference temperature.

## 4 BANDWIDTH COMPENSATION DURING OPERATION

### 4.1 Introduction

This section describes how to compensate for TX BW variation due to temperature by using the stored values from the module production testing. In order to compensate for the effects of temperature changes on the bandwidth of the transmitted signal from the DW1000, the PG\_DELAY [0x2A:0B] register setting must be changed from the IC default. This section will discuss how to take the reference measurement necessary for adjusting the bandwidth at differing temperatures, and the algorithm responsible for making this adjustment.

### 4.2 Taking the reference measurement

The reference value that is required for the bandwidth compensation is contained in the PGC\_STATUS [0x2A:09] register. This represents a counter that increments with every pulse generated by the DW1000 IC's internal pulse generator. Intuitively, this count value (referred to as PG\_COUNT) will vary inversely with the PG\_DELAY value – if the delay between pulses increases, the number of pulses within a given timeframe will decrease, and vice versa.

The PG\_DELAY value will not give the same bandwidth at varying temperatures. The PG\_COUNT value, however, will give a stable bandwidth across all temperatures. It is taken as a reference as the DW1000 has a pulse generator auto-calibration procedure; the procedure takes a PG\_COUNT value and calculates the PG\_DELAY value from this. This PG\_DELAY value can then be programmed in to give the desired bandwidth.

To get the reference PG\_COUNT value, first optimise the bandwidth and power as outlined in section 3.4.3 and record the PG\_DELAY setting. Then perform the following register writes to disable sequencing and adjust the clock settings of the DW1000: -

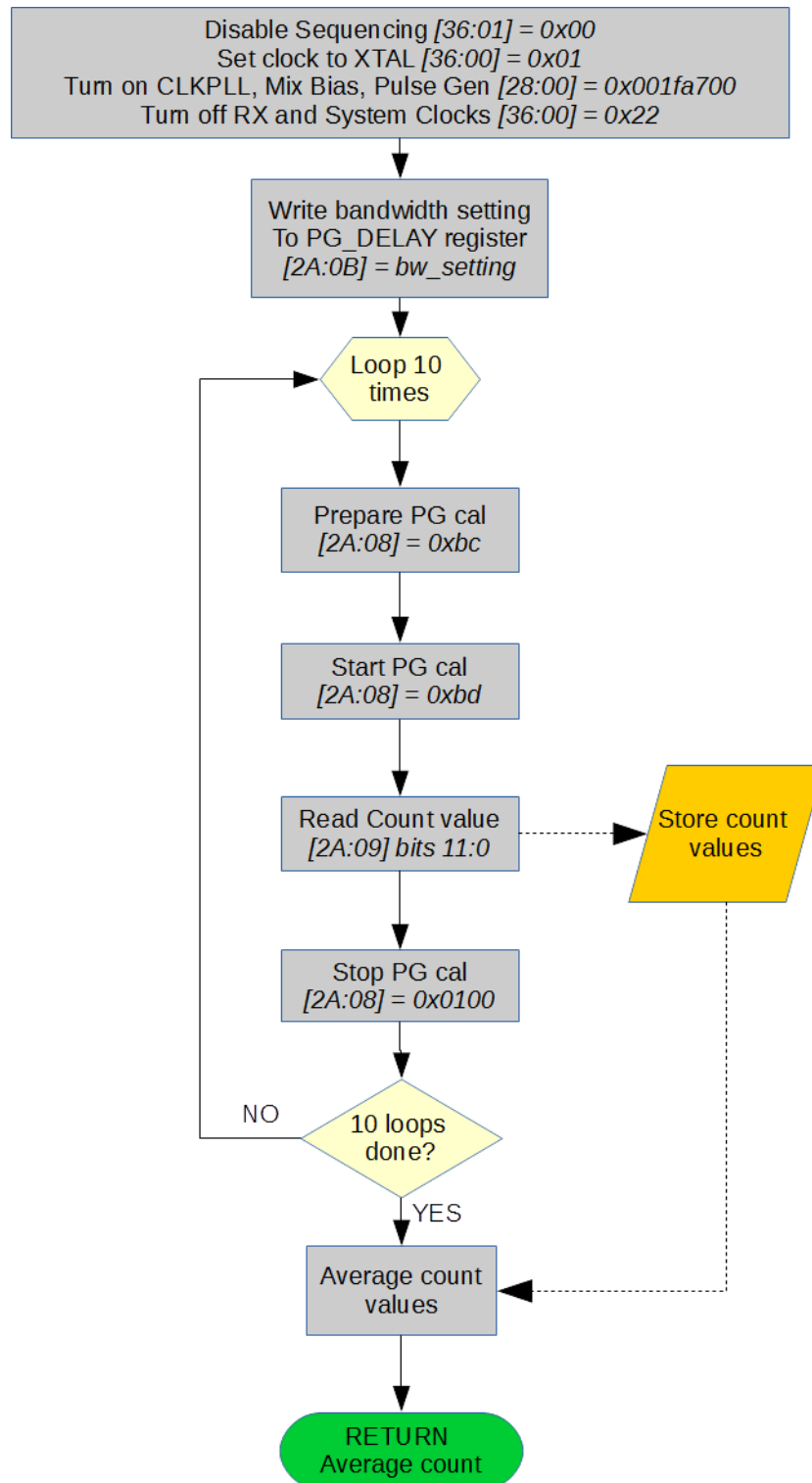
1. Write 0x01 to register 0x36:00
2. Write 0x0000 to register 0x36:04
3. Write 0x001FA700 to register 0x28:00
4. Write 0x22 to register 0x36:00

In order to get a stable value for the PG\_COUNT, the following register read/writes should be performed 10 times and the result averaged: -

1. Write the PG\_DELAY setting from the optimisation step to register 0x2A:0B
2. Write 0xBC to register 0x2A:08
3. Write 0xBD to register 0x2A:08
4. Read the least significant 11-bits from register 0x2A:09; this is the PG\_COUNT value

Repeat these last four steps ten times and average all PG\_COUNT values.

This PG\_COUNT value should be saved in a non-volatile store (e.g. the DW1000 OTP) so that it can be used later during normal operation as the reference value for the compensation algorithm. The steps are outlined visually in Figure 5 below.



**Figure 5: Flowchart detailing the steps to obtain the reference PG\_COUNT value**

This sequence of steps is carried out by the `dwt_calcpgcount()` API call, which returns the PG\_COUNT value. This API function can be used in production test to obtain the PG\_COUNT value for storage into NVM. The API example 09a shows how this API function is used.

### 4.3 Adjusting bandwidth to compensate for effects of temperature

The bandwidth compensation algorithm can be run periodically during normal operation to restore the

desired bandwidth that was achieved during the calibration step, in order to counteract the effects of changing temperature. This will require the reference PG\_COUNT value recorded in section 4.2 above. The compensation algorithm takes the PG\_COUNT as an input and uses it to calculate the PG\_DELAY value that should be programmed into the DW1000 to give the desired bandwidth.

The DW1000 API call `dwt_calcbandwidththtempadj()` carries out this procedure. The algorithm itself is a basic binary search that steps through each bit of the PG\_DELAY value. The steps of the algorithm are:

1. Disable sequencing and setup clocks as in steps 1-4 of the procedure to retrieve the reference PG\_COUNT in section 4.2
2. Set PG\_DELAY to an initial value of 0x80 (bit 7 set)
3. For each bit in the PG\_DELAY value, starting at bit 7:
  - a. Set the current bit in the PG\_DELAY value
  - b. Write this value to register 0x2A:0B
  - c. Write 0xBC to register 0x2A:08
  - d. Write 0xBD to register 0x2A:08
  - e. Wait for ~10us
  - f. Read the PG\_COUNT value from the least significant 11-bits of register 0x2A:09
  - g. Find the absolute difference between this count value and the reference PG\_COUNT value recorded earlier
  - h. If this difference is lower than for previous iterations of this loop, record it and the PG\_DELAY value from step a
  - i. If the PG\_COUNT read in step f is greater than the reference PG\_COUNT, keep the current bit of PG\_DELAY value set
  - j. If the PG\_COUNT read in step f is less than the reference PG\_COUNT, unset the current bit of the PG\_DELAY value
  - k. Move to the next least-significant bit

In short, this algorithm moves through each bit in the PG\_DELAY value and sets the bit, then reads the PG\_COUNT value. If the reference count value is less than the value read back, then the bandwidth is too high, and the PG\_DELAY should be increased (by setting the bit we are currently on). If the reference count is greater than the read PG\_COUNT value, then the bandwidth is too high and the PG\_DELAY should be decreased (by clearing the bit we are currently on). Eventually, the algorithm will converge on a value for PG\_DELAY that gives a count value as close as possible to the reference PG\_COUNT. The algorithm is outlined visually in Figure 6 below.

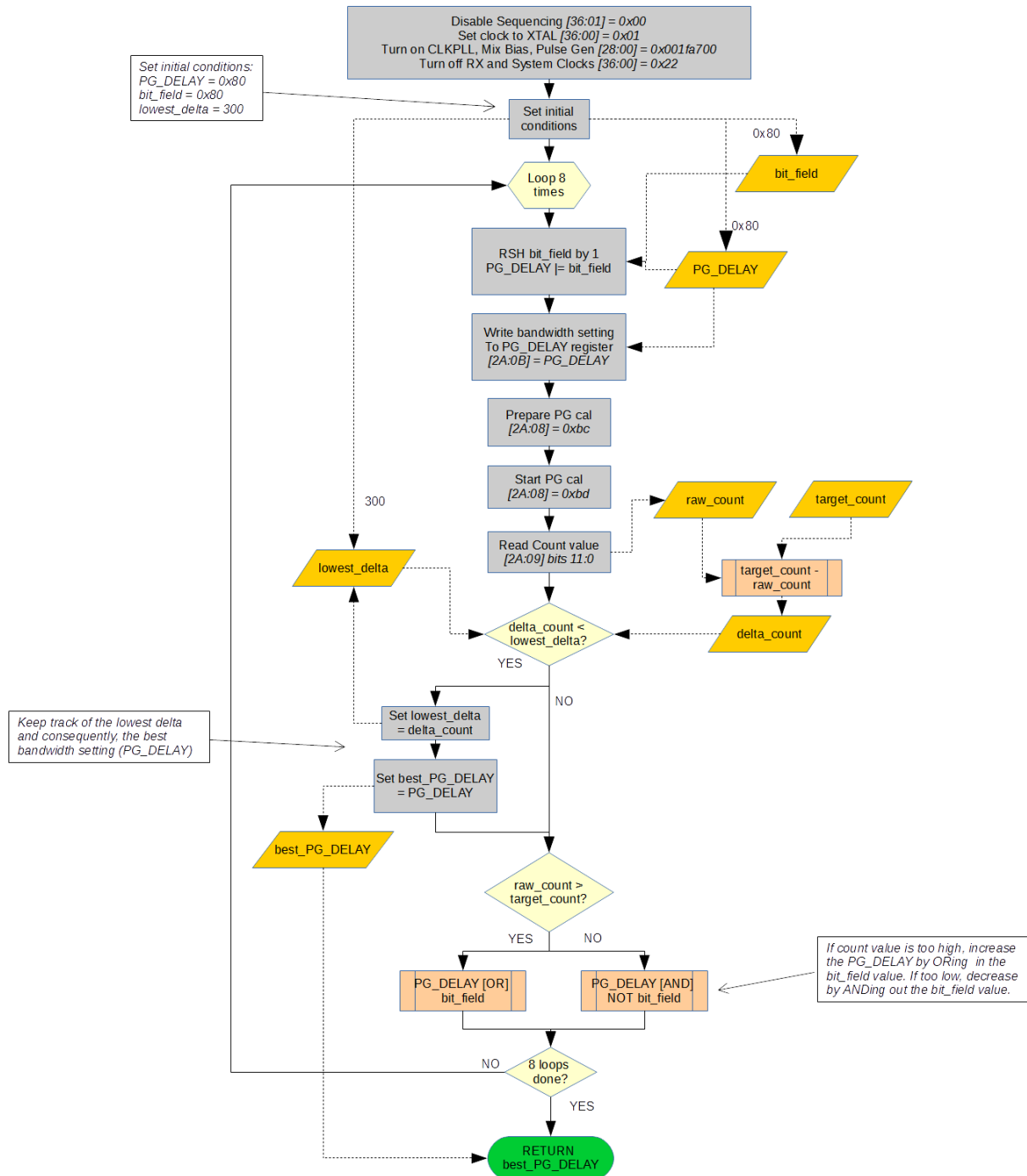


Figure 6: Bandwidth calibration procedure flowchart

This value can now be programmed to register 0x2A:0B, and the resulting bandwidth will be close to the calibrated bandwidth, regardless of the temperature.

The algorithm is implemented in the API function `dwt_calcbandwidthtempadj()`, and the API example 09b shows how this API function is used.

## 5 POWER COMPENSATION

### 5.1 Introduction

This section describes how to compensate for TX output power variation due to temperature by using the stored values from the module production testing and by reading the temperature periodically. In order to compensate for the effects of temperature changes on the power of the transmitted signal from the DW1000, the TX\_POWER [0x1E] register setting must be changed from the IC default. This section will discuss how to take the reference measurement necessary for adjusting the power at differing temperatures, and the algorithm responsible for making this adjustment.

### 5.2 Taking the reference measurement

The reference values that are required are the contents of the TX\_POWER [0x1E] register after the calibration step outlined in section 3.4.3, and the temperature at which the calibration was carried out. This reference temperature should be measured as described in section 3.5.2 above. These reference values will be used as a base for relative adjustments to the output power based on the temperature difference from the reference temperature.

### 5.3 Adjusting output power to compensate for the effects of temperature

The output power compensation algorithm can be run periodically during normal operation to restore the desired output power that was achieved during the calibration step. This will require the reference temperature and TX\_POWER register value recorded in section 5.2 above.

As shown in Figure 1, the relationship between TX channel power and temperature is close to linear. This is confirmed by testing done over a number of DW1000 devices for channels 2 and 5. The relationship is different for channel 2 and channel 5. Using this relationship, and based on the temperature difference, the expected power difference can be calculated.

Using this power difference, the TX\_POWER register can be adjusted to reflect the required difference, thus restoring the output power back to the desired level that was achieved during optimisation.

The linear relationship for channel 2 determines that power changes at 0.035 dB/°C from the reference temperature taken in section 5.2. The same relationship for channel 5 determines a power change of 0.065 dB/°C.

The DW1000 API call `dwt_calcpowertempadj()` implements the compensation algorithm, which is outlined as follows: -

1. Subtract the current temperature from the temperature at which the reference measurements were made.
2. Multiply this temperature difference by the constant calculated from the linear relationship above, according to the channel that the DW1000 is set to. This gives a relative power difference.
3. Using the reference TX\_POWER register value taken after the optimisation step, apply the power difference by changing the DA attenuation and TX mixer gain values

In short, the algorithm calculates the difference in temperature from the reference temperature, and uses this to calculate the expected difference in power according to the linear relationship between channel power and temperature for either channel 2 or channel 5. Then the TX\_POWER register is programmed with the reference TX\_POWER value (taken after power and bandwidth optimisation) adjusted to implement this relative power difference, which will give a channel power close to that seen at the reference temperature.

Section 8 of [2] discusses when the appropriate circumstances in which to perform the adjustment, depending on the use case.

The API example 09b (TX Bandwidth & Power Compensation) shows how this API function is used.

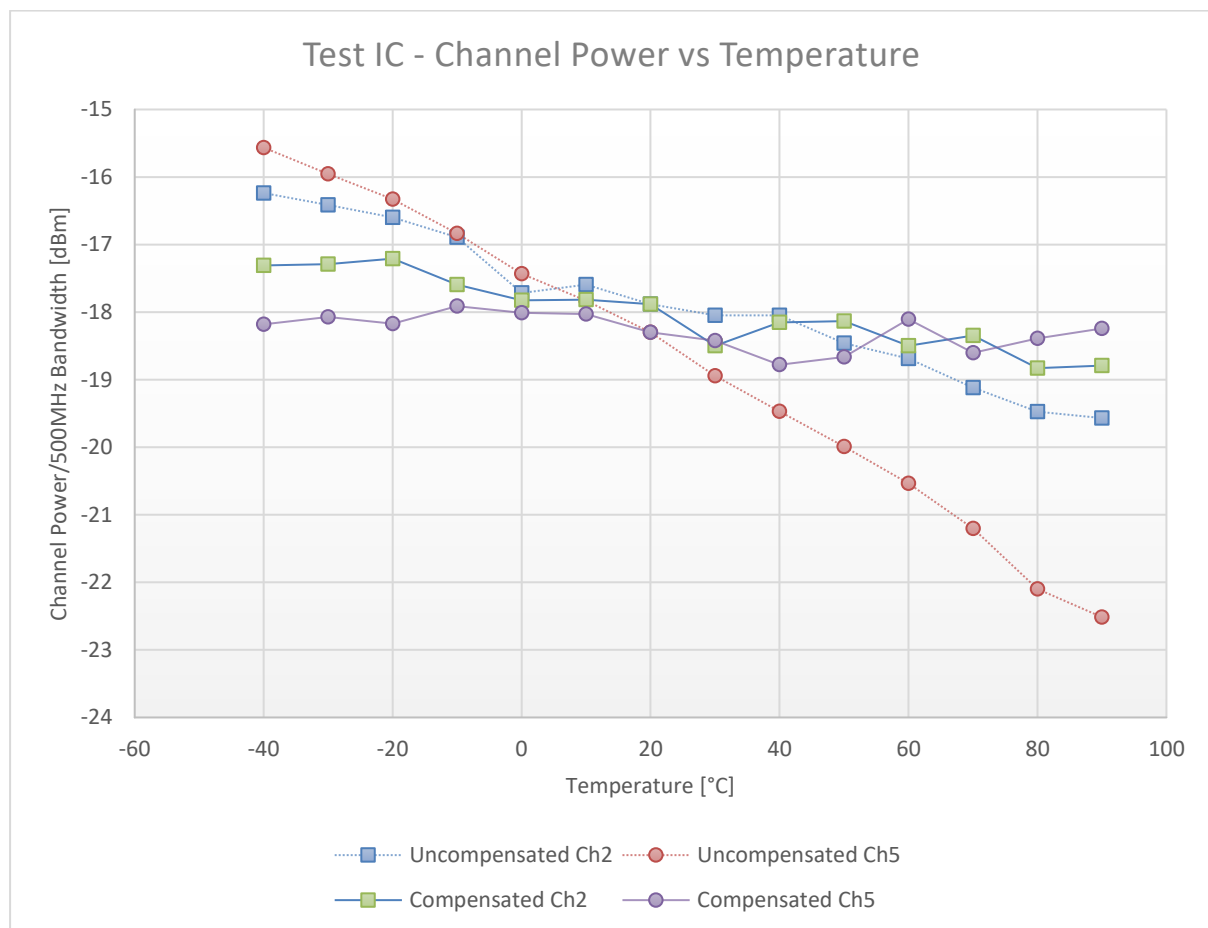
## 6 RESULTS

### 6.1 Overview

To judge the effectiveness of both algorithms, the results of measurements taken using the uncompensated, chip-default TX\_POWER and PG\_DELAY values can be plotted against the same measurements where compensation for the effects of temperature has been made. The measurements described in section 2 are taken at every 10°C from -40°C up to 90°C.

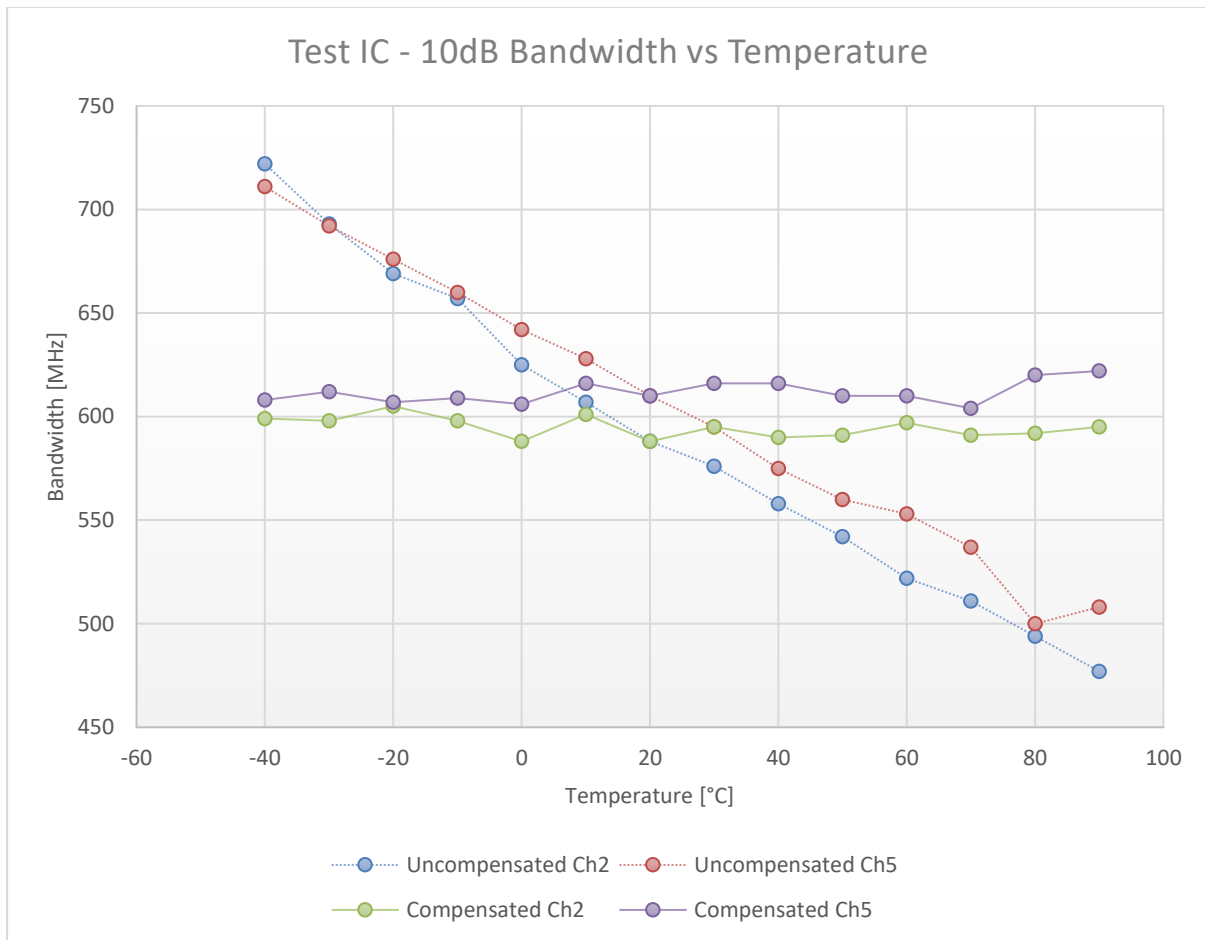
### 6.2 Results data

A sample of results for one DW1000 IC is shown below in Figure 7 and Figure 8. The uncompensated measurements are displayed as dashed lines, and the compensated measurements are displayed with solid lines.



**Figure 7: Channel Power vs Temperature for uncompensated (dashed) and compensated measurements**





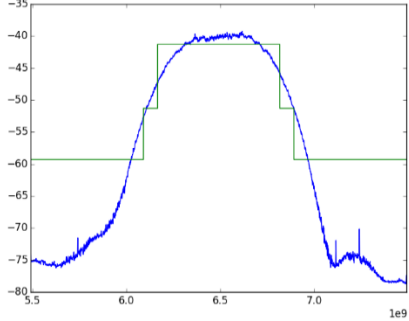
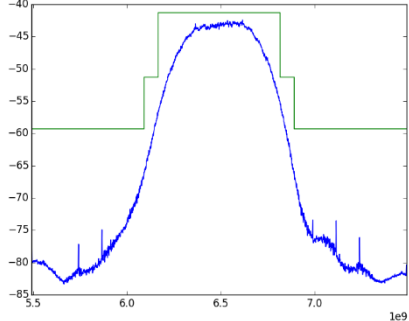
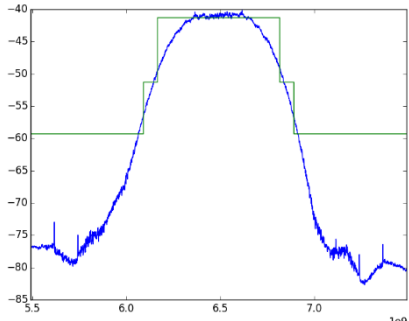
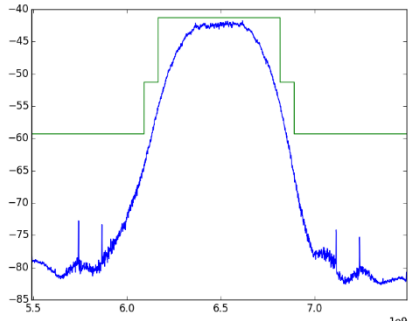
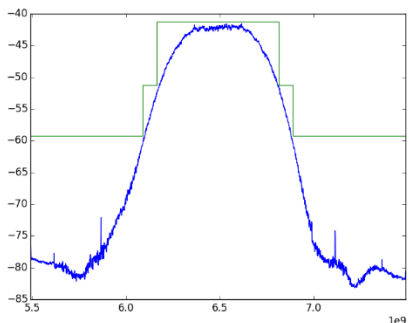
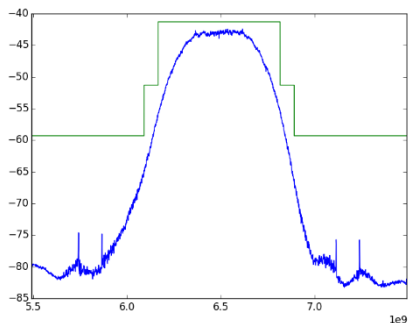
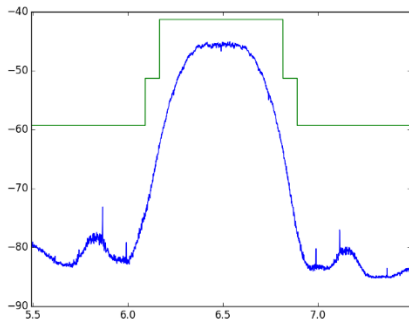
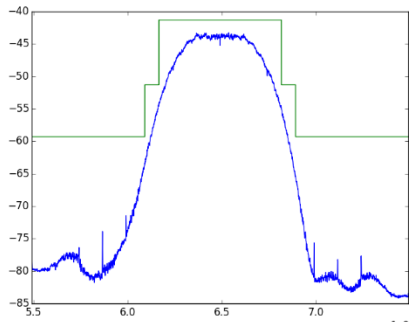
**Figure 8: 10 dB Bandwidth vs Temperature for uncompensated (dashed) and compensated measurements**

As we can see from each graph, the dashed lines show a much larger variation across temperature. After compensation of transmit bandwidth and power, the variation in channel power and 10dB Bandwidth are much lower, and the graphs in Figure 7 and Figure 8 show the solid lines as being much flatter than the dashed ones.

Therefore, we can see that the compensation achieves the goal of keeping the transmit power and bandwidth at approximately the same level regardless of the temperature of the IC.

To view how the spectrum changes across temperature, the following table shows the effect for the uncompensated case and also shows the spectrum after the compensative adjustments have been made. The spectrum is from a DW1000 in continuous frame mode at channel 5, and the IEEE mask is overlaid onto the plot also.

**Table 1: Comparison of spectrum for uncompensated and compensated measurements at selected temperatures**

Temperature	Uncompensated	Compensated
-40°C		
0°C		
20°C		
90°C		

As is evident from Table 1, the spectra transmitted after the compensative adjustments have been made are stable across temperatures, whereas the uncompensated spectra vary drastically between the lower temperature extreme and the higher. The success of the compensation algorithms is borne out across other devices, but the data is not included here for brevity.

## 7 REFERENCES

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

**Table 2: Table of References**

Ref	Author	Date	Version	Title
[1]	Decawave		Current	DW1000 Data Sheet
[2]	Decawave		Current	APS023 Part 1 Application Note: Transmit power calibration and management
[3]	Decawave		Current	Decawave Software downloads page <a href="http://www.decawave.com/support/software">http://www.decawave.com/support/software</a>
[4]	Decawave		Current	DW1000 User Manual

## 8 DOCUMENT HISTORY

**Table 3: Document History**

Revision	Date	Description
1.0	23 <sup>rd</sup> December 2016	Initial release
1.1	7 <sup>th</sup> April 2017	Scheduled update
1.2	13 <sup>th</sup> August 2018	Scheduled update
1.3	9 <sup>th</sup> October 2018	Scheduled update
1.4	15 <sup>th</sup> May 2024	Scheduled update

## 9 MAJOR CHANGES

### Revision 1.0

Page	Change Description
All	Initial release

### Revision 1.1

Page	Change Description
11	Correction of value written to register 0x28:00 from 0x001FA500 to 0x001FA700
12	Update to Figure 5 to reflect register value change
13	Update to Figure 6 to reflect register value change

### Revision 1.2

Page	Change Description
All	Update of revision number from 1.1 to 1.2
All	Update of company logo

### Revision 1.3

Page	Change Description
All	Update of revision number from 1.2 to 1.3
All	Couple of updates (typos, clarifications) following a review and API functions updates. Also updated the temperature conversion formula for converting DW IC units to °C to match the User Manual

**Revision 1.4**

Page	Change Description
All	Modification to footer.

## 10 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](http://www.decawave.com).