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MK5 Time of Flight Application Note

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Prepared for:	Cohda Wireless Pty Ltd.
Prepared by:	Wade Farrell
Authorised By:	Fabien Cure
Distribution:	External

Cohda Wireless Pty Ltd
82-84 Melbourne Street
North Adelaide, SA 5006
Australia

P +61 8 8364 4719
F +61 8 8364 4597

www.cohdawireless.com

Change Log

Version	Date	Comments
1.0	20 Apr 2016	Initial Version
1.1	16 May 2016	Correction made to cyclic delay diversity register number

Table of Contents

1 Time of Flight

This application note explains how the MK5 can be used for time of flight (ToF) measurements. Time of flight is the measurement of the time taken for the RF signals to traverse the air between two communicating radios. As such it is useful in ranging applications where the distance between the two communicating radios is desired to be known.

Section 2 explains the time of flight parameters that the MK5 provides with details on how they are accessed and their performance. Section 3 provides an example of using the time of flight measurements for ranging.

2 ToF Parameters

2.1 Ack/CTS Response Delay

Time of flight measurements between two radios rely on two way communications with known latency between two frames. The easiest known delays are

- Ack response following a unicast reception
- CTS response following an RTS reception

Both of these responses have a known delay of SIFS = 32us. So it is possible to simply use unicast transmissions to obtain a time of flight measurement or to use RTS/CTS in combination with the unicast transmission to get an additional measurement. Figure 1 shows the logical frame transfers for unicast with RTS/CTS. In addition, Figure 2 provides a basic timing diagram showing the inter-frame spacing between the transfers. Note, for unicast transfers only, the RTS and CTS frames are omitted.

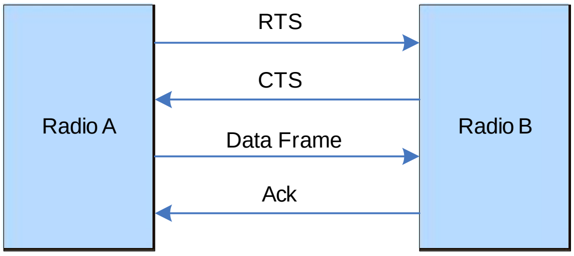

Figure 1 – Two Radios showing RTS/CTS logical frame transfers

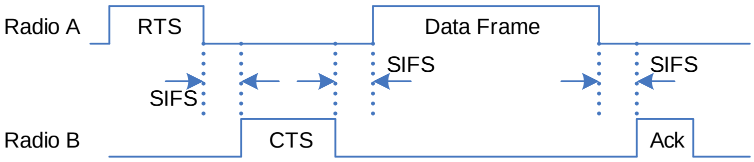

Figure 2 – RTS/CTS Basic Timing Diagram

The MK5 provides these measurements as part of LLC API [1]. The Tx event data, tMKxTxEventData contains the AckResponseDelay and CTSResponseDelay parameters. Both of these are in VDSP clock timer ticks (timer runs at 300MHz). So they should have a value of 9600 if there is no additional time of flight latency present. Any values greater than 9600 represent the time of flight measurements. Note, these measurements are round-trip measurements. They consist of the path delay of the data frame transmission combined with the path delay of the ack frame transmission. Relating the time of flight measurements to the distance between the two radios, a factor 2 is present in the calculation.

```
typedef struct MKxTxEventData
{
  /// Transmit status (transmitted/retired), @ref eMKxStatus
  int16_t TxStatus;
  /// 802.11 MAC sequence number of the transmitted frame
  uint16_t MACSequenceNumber;
  /// The TSF when the packet was transmitted or retired
  tMKxTSF TxTime;
  /// Delay (VDSP ticks) between end of Tx Data frame and start of Rx Ack frame
```

```
  /// Note VDSP Clock runs at 300MHz
  uint32_t AckResponseDelay;
  /// Delay (VDSP ticks) between end of Tx RTS frame and start of Rx CTS frame
  /// Note VDSP Clock runs at 300MHz
  uint32_t CTSResponseDelay;
  /// Time (us) between the arrival of the packet at the MAC and its Tx
  uint32_t MACDwellTime;
  /// Number of retries
  uint16_t NumRetries;
  /// Destination address of the transmitted frame
  uint8_t DestAddress[6];
} __attribute__((__packed__)) tMKxTxEventData;
```

2.2 Debug Access

Any application that would require time of flight measurements would use the LLC API to access the AckResponseDelay and CTSResponseDelay parameters. However there are additional debug methods to access this information outside of the API.

Using the debug command “llc raw 54” will return the acknowledgement response delay.

```
root@MK5:~# llc raw 54
Type: 54 (0x36)
Subtype: 3 (0x3)
Data:
00  0x00000000          0 <- CTSResponseDelay (RadioA)
01  0x00000000          0 <- CTStoDataDelay   (RadioA)
02  0x00002580       9600 <- AckResponseDelay (RadioA)
03  0x00000000          0 <- CTSResponseDelay (RadioB)
04  0x00000000          0 <- CTStoDataDelay   (RadioB)
05  0x00000000          0 <- AckResponseDelay (RadioB)
```

The “llc raw 54” command includes the CTS to Data frame delay which is only available on the radio that transmits the CTS and receives the data frame (Radio B of Figure 1).

It is also possible to access the CTSResponseDelay and the AckResponseDelay via the cw-llc tcpdump command.

```
root@MK5:~# tcpdump -s 0 -w /tmp/tcpdump_cw_llc.pcap -i cw-llc
```

The pcap file generated can then be loaded into the wireshark running on the SDK (the SDK version of wireshark includes the cw-llc packet dissectors). The AckResponseDelay and CTSResponseDelay parameters are present in the MKXIF_TXEVENT packets.

2.3 Disabling Cyclic Delay Diversity

The MK5 by default uses transmit cyclic delay diversity (CDD) when transmitting on both antennas concurrently. CDD is used in order to minimise any beam forming that can occur if transmitting the same signal on two antennas. The MK5 has a default offset of 4 x 10MHz samples for the antenna 2 signal path. It is essential to disable CDD when time of flight measurements are required and if dual antenna transmissions are used. To disable the following command needs to be used:

```
root@MK5:~# llc reg w 0 53 0
```

To reinstate the CDD to use 4x10MHz samples (= 16x40MHz samples)

```
root@MK5:~# llc reg w 0 53 16
```

Note all of the registers for bank 0 can be accessed by the read command

```
root@MK5:~# llc reg r 0
```

2.4 Performance

Due to internal chipset limitations, the accuracy of Ack and CTS response delays are imperfect. The following plots show histograms of measured combined Ack and CTS response delays. Note the Ack and CTS response delays were not averaged in any way. The test configuration used in these measurements is shown in Figure 3. This configuration is used in order to minimise any multi-paths which can affect the results, as described further in Section 2.5.

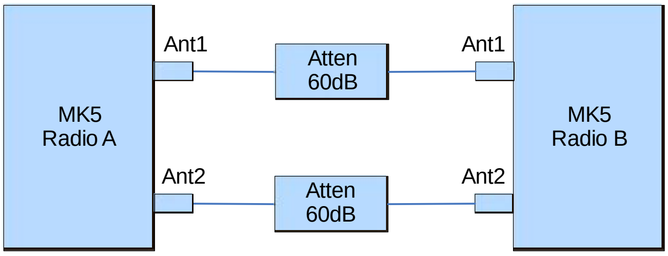

Figure 3 – Two Radio Test Configuration

The distribution of the dual antenna is slightly better due to the radio having two measurements to determine the response delays. Note the cyclic delay diversity was disabled, as discussed in Section 2.3, otherwise the antenna 2 measurements would have been shifted. As mentioned in Section 2.1, these measurements are round-trip delays and as such when converting to distance a factor of 2 is used. The end result is that an error of 0.01us results in a distance error of 1.499m. So if the error is +/-0.04us, then the distance error is +/- 5.996m. Averaging can vastly improve these accuracies, as shown in the example provided in Section 3.

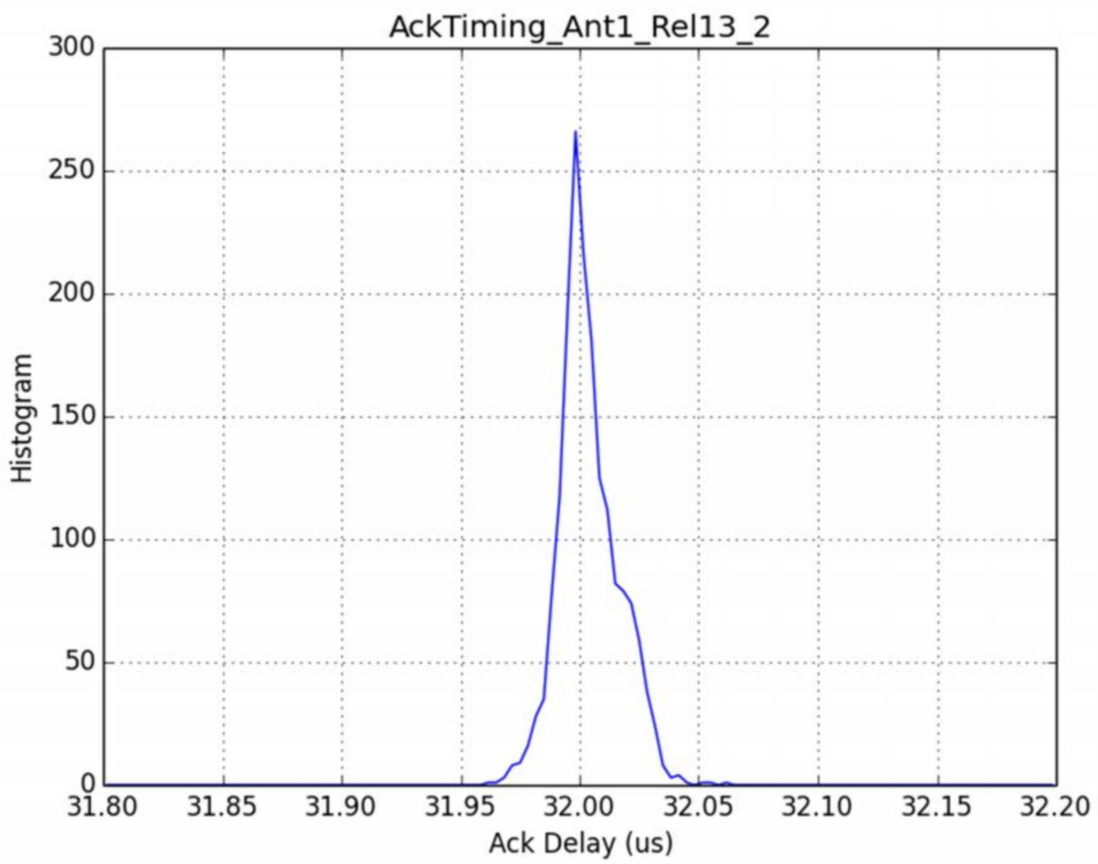

Figure 4 – Ack/CTS Response Delay Histogram, Single Antenna, Release 13.2

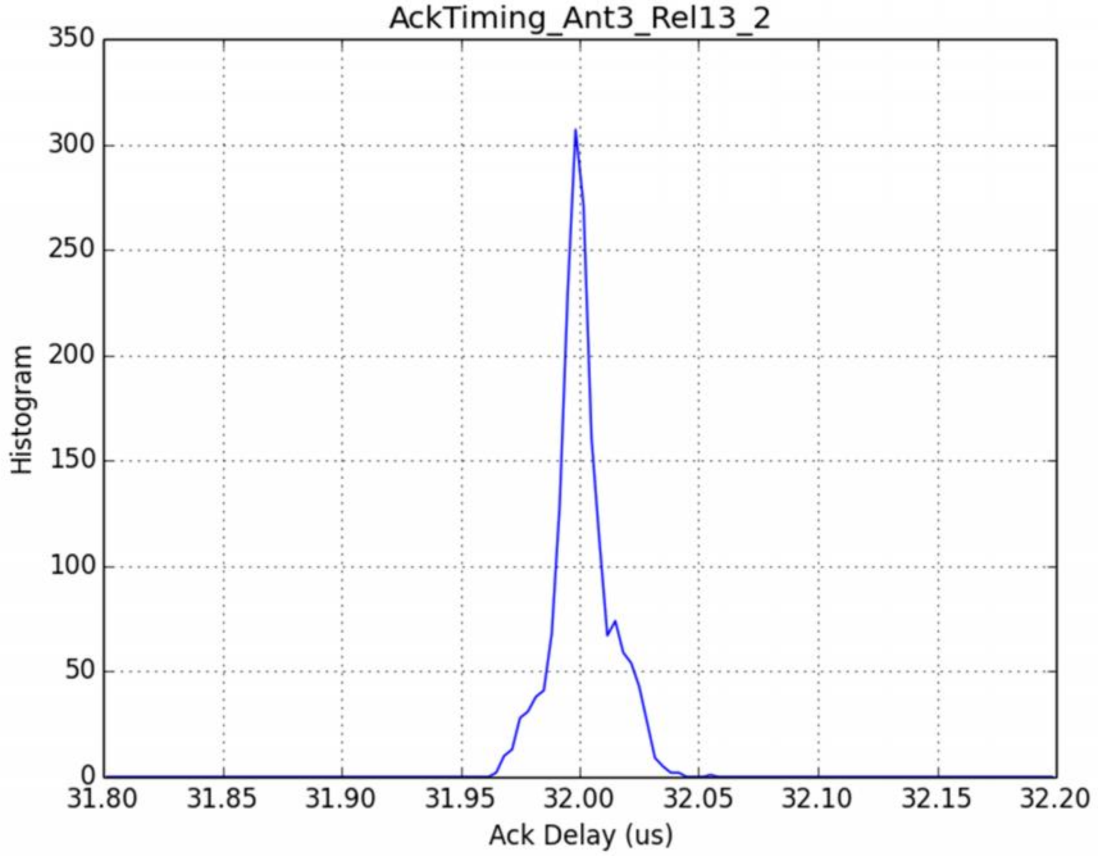

Figure 5 – Ack/CTS Response Delay Histogram, Dual Antenna, Release 13.2

2.5 Multi-path

It is important to be aware that the MK5s usually operate in multi-path environments and that the multi-paths can cause errors in the response delay measurements. If a delayed path has greater strength than the line of sight component then it is possible that the start of frame determination will be delayed. Thus it is important to utilise filtering or modelling techniques to counteract the effect of multi-path in time of flight measurements.

3 Ranging Example

A simple test was performed involving two vehicles; one stationary and one travelling. The travelling vehicle moved along a single stretch of road away from and then towards the stationary vehicle. The road, highlighted in Figure 6, represents a predominantly line-of-sight environment. Both radios were configured with dual antennas and transmit cyclic delay diversity was disabled. A transmit rate of 5 pkt/sec was used and a simple sliding window average of 2 seconds combined with an outlier filter was used for the time of flight determination. The extra filter is required, in order to combat the combined error in the response delay distributions, shown in Figure 4 and Figure 5, and any multi-path effects.

Figure 6 – Test drive region

Figure 7 shows the GPS range versus the averaged ToF measurements across the complete test run. The plot clearly shows the vehicle moving away and then travelling back towards the stationary vehicle. At around 800 metres, the radio link fails as the link becomes non line-of-sight, but resumes soon after turning. The plot also shows that the averaged ToF measurements track the GPS range reasonably well.

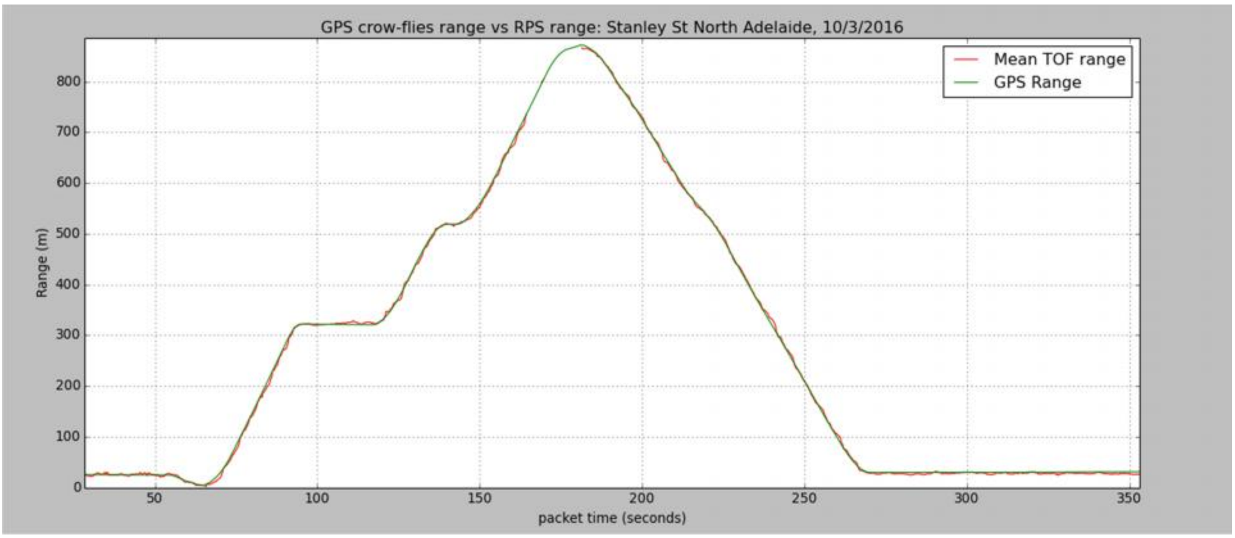

Figure 7 – GPS Range vs Averaged Time of Flight Measurement

Figure 8 shows a zoomed-in portion of the GPS vs averaged ToF measurements, covering a period for when the travelling vehicle was stationary.

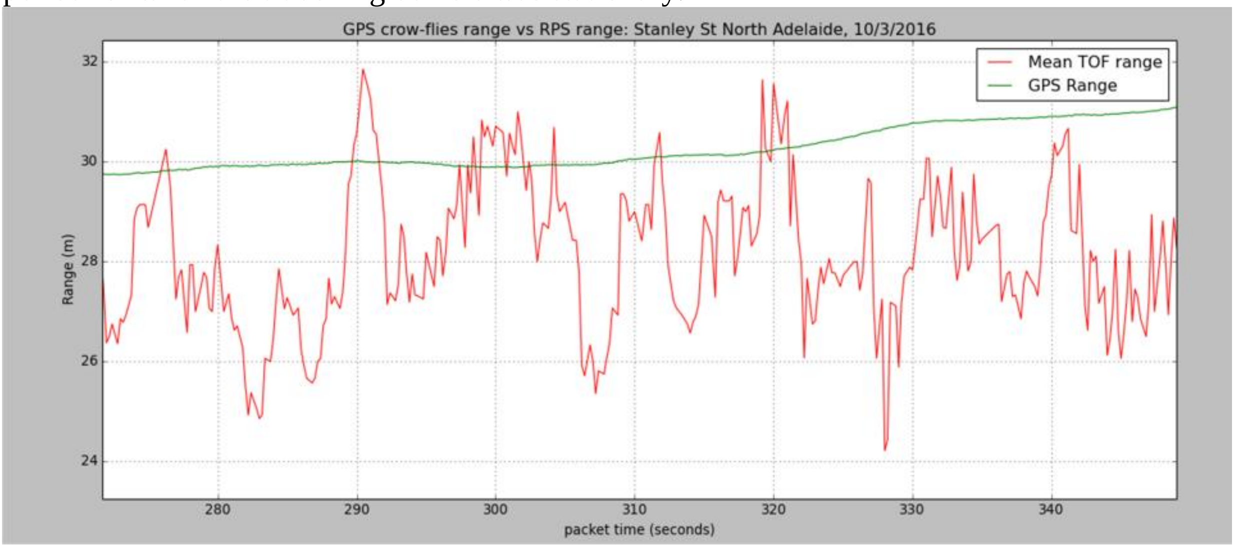

Figure 8 – GPS Range vs Averaged Time of Flight, Zoomed-in stationary portion

Figure 9 shows the error in the averaged ToF measurements vs the range as determined by the GPS position.

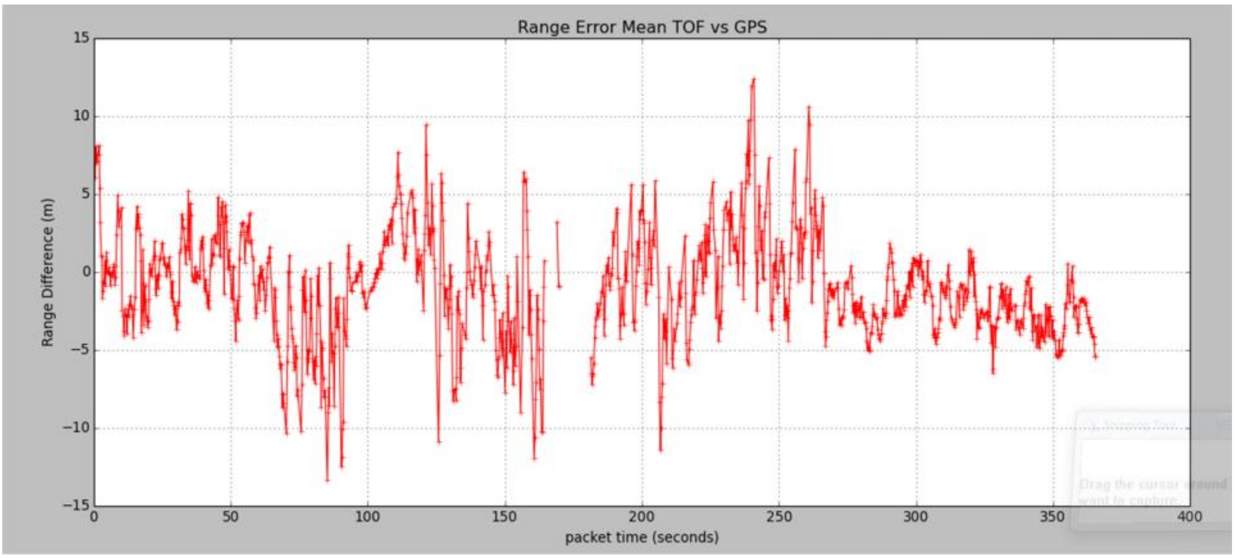

Figure 9 – Range difference between Averaged Time of Flight and GPS

This example shows that the MK5, when combined with relatively simple post-processing techniques, can achieve good, suitable ranging performance.

4 References

[1] CohdaMobility MKx Radio LLCremote API Specification, CWD-MKx-0208-MKxAPISpecification.pdf