TIME DOMAIN®

PulsON® Ranging & Communications

Part Three: Two-Way Time-of-Flight (TW-TOF) Ranging

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This is the third in a series of documents that focus on the practical application of Time Domain's Ultra Wideband (UWB) technology, as embodied by the PulsON 400 family of Ranging and Communications Modules (RCM). As of this date the family consists of the P400 and P410. The P400 and P410 units are functionally equivalent and will be referred to in these documents as the RCM. These documents are intended to be used as background technical information by system engineers, programmers, and managers interested in determining how UWB can be used to solve real world problems.

Part One: Scratching the Niche
What is the RCM and why is it needed?

Part Two: UWB Definition & Advantages*
What are the advantages of UWB signaling and how do we optimize performance?

Part Three: Two-Way Time-Of-Flight (TW-TOF) Ranging
How does it work?

Part Four: Tracking Architectures Using Two-Way Time-Of-Flight (TW-TOF) Ranging
Which one is right for you?

*An expanded version of this paper (which discusses radar and other advanced capabilities) is available on the Technology page of the Time Domain website (http://www.timedomain.com/technology.php).

UWB Two-Way Time-of-Flight Ranging

The PulsON Ranging and Communications Module (RCM) computes peer-to-peer distance between radio transceivers using a technique called Two-Way Time-of-Flight (TW-TOF). This technique maximizes accuracy and applicability across a wide range of applications.

The TW-TOF technique is packet-based and involves the following steps:

- The RCM requesting a range (Requester) transmits a long packet of pseudo-randomly encoded pulses (a Request Packet).
- The receiving RCM (the Responder) locks onto the pulse stream, scans around the lock point (determining the time offset between the leading edge of the received waveform and the radio lock point), and demodulates data.
- The Responder, at a precise starting time (picosecond accuracy), transmits a Response Packet that includes the leading edge offset information.
- The Requester locks onto the response pulse stream, likewise measures the leading edge offset, and demodulates response data.
- The Requester then computes the precise time delay from Request Packet transmission and Response Packet reception. This coarse difference time is corrected by subtracting the leading edge offsets. The resulting time difference is measured in picoseconds.
- The antenna delay offsets of each radio are subtracted from the total. These offsets are computed during a calibration step.
- This corrected time-of-flight measurement equals the amount of time it takes a signal to leave the Requester's antenna, arrive at the Responder's antenna and return. Dividing this number by 2 and multiplying by the speed of light yields the distance, in millimeters, between the antennas.

This process is illustrated in **Fig 1**.

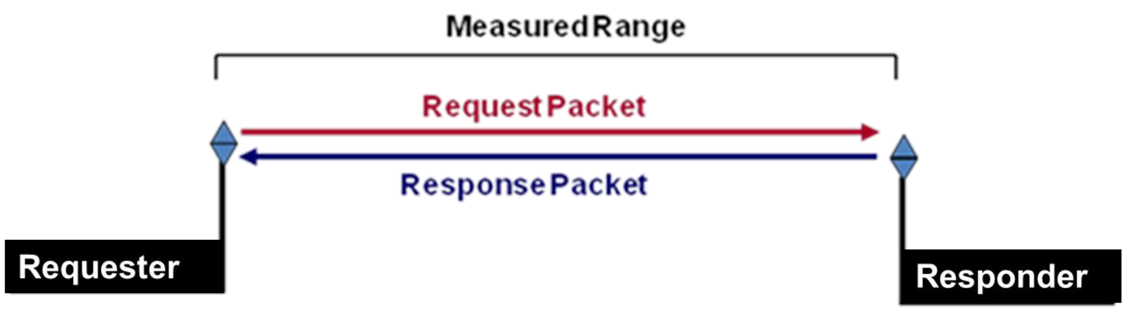


Fig. 1: Packet transmissions required by TW-TOF range measurement

Note that this process is not instantaneous. Because it involves a two-way conversation, it requires a bit of time to complete. This time is variable based on the pulse integration (number of pulses per symbol) chosen by the user. Even so, because of the parallel processing capabilities available in the RCM's custom UWB silicon, the amount of time required is quite small. A single conversation between transceivers provides a complete range measurement. Multiple range measurements are not averaged.

In addition, Time Domain offers a range error estimate, derived from the signature of the leading edge scan. This metric is an estimate of the error of the range measurement based on the shape (slope and height) of the direct path pulse. This unique capability allows the user to derate the measurement if needed.

The RCM automatically performs this complete TW-TOF range conversation at the command of the host. The host simply tells its local RCM to send a range request packet, including the unique identifier of the range target/responder RCM, and the local and remote RCMs do the rest. The result is a distance measurement with high multipath resistance accurate to centimeters.

Although it isn't necessary for a user to understand the precise mechanisms of RCM range conversations, there are a few configuration options and calibration requirements that are best used with a basic understanding of the process. This section will discuss the composition of a packet, the pseudo random code, how leading edges are determined, and how the range measurement is computed.

Packet Transmissions

RCMs communicate by sending a train, or packet, of pulses that may consist of thousands to hundreds of thousands of pulses. These pulses are transmitted at a rate and a phase determined by a pseudo random code. To receive this packet, a responding radio must know the pseudo random code. With this knowledge, the responding radio can acquire or lock onto the transmission using a method quite similar to the acquisition techniques used by Code Division Multiple Access (CDMA) radios. Data is added to the pulses by adding an additional polarity change to the pseudo random code.

The pulses in the packet have been allocated in packet frames for different functions. The frames are illustrated in **Fig. 2.**

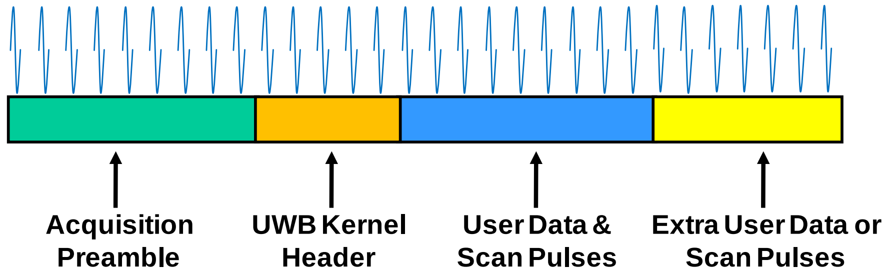


Fig. 2: Allocation of pulses in a notional packet (not to scale)

The first frame is the Acquisition Preamble. These pulses have been encoded to enable the receiver to easily detect, lock, track, and demodulate the packet pulses.

The second frame of pulses is encoded with data that informs the receiver of the contents of the subsequent pulses. These first two blocks represent the system overhead associated with each transmission.

The third frame of pulses represents the data and scan payload. It consists of a train of pulses that the receiver uses to form an image of the received waveform. This image is called a waveform scan and is used by the signal processing to determine the leading edge, or most direct pulse of the incoming signal. While the lockspot can vary from packet to packet, the direct path, or leading edge, is the consistent feature and the measurement of the leading edge offset is mandatory for accurate time of flight measurement in multipath channels.

The train of pulses is also encoded with user data. This allows dual use of the pulses. In other words, the same pulses are used by the requester to both send data to the responder and to allow the responder to generate a waveform scan.

The final block of pulses is automatically appended either for extra user data (i.e., data in excess of carrying capability of the third block) or extra pulses to be used for enhanced waveform scans. The RCM supports up to 1024 user bytes in each packet. The leading edge scan requires a number of pulses equivalent of 136 bytes. Therefore the user can send up to 136 bytes per packet (Request and/or Response) without increasing packet size or transmission time.

Individual pulses have very low power and will not travel very far. All of the transmissions are encoded such that blocks of pulses are integrated to form a single communication “symbol.” A preconfigured number of pulses are summed together for each symbol. A symbol can be a single bit or a single scan measurement. This integration rate is set by the user through the “Pulse Integration Index” (PII) register of the API.

Waveform Scan, Lockspot, and Leading Edge Offset

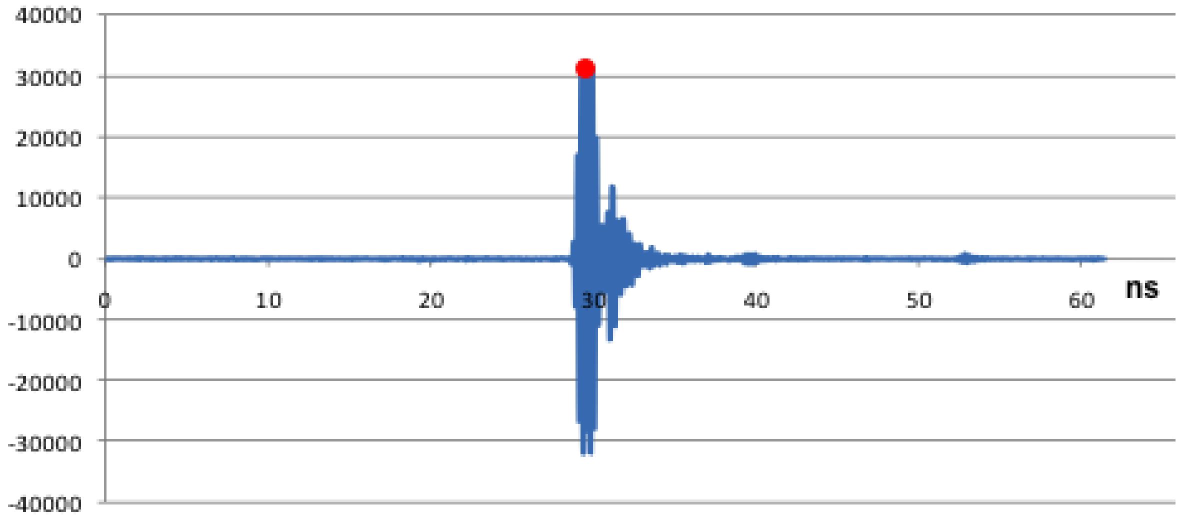
Determination of the leading edge consists of three steps. First, the radio must acquire, or synchronize with, the transmitting radio signal. Optimized pulse encoding allows the acquisition process to quickly find lock onto coherent pulse energy. This coherent pulse energy is most likely a reflection and not the direct path pulse. This point is called the lockspot.

Second, other scanning samplers are used to scan the channel impulse response (CIR) of the link between transmitter and receiver (as measured at the receiving radio). Time Domain refers to this recording as a waveform scan. This direct sequential scan of channel reflectivity is a unique capability of Time Domain’s PulsON transceivers.

Finally, a signal processing algorithm analyzes the waveform scan and finds the first pulse cycles in the scan. Accurate measurement of the Time of Arrival of this initial pulse energy as it rises from the noise, rather than conventional lockspot-to-lockspot measurement, is the critical capability supporting multipath resistance. This first set of cycles represents the most direct RF path between transmitter and receiver. The direct path pulse is always first, and multipath reflections are always late.

The embedded algorithm determines the difference in time between the scan origin (lockspot) and the point at which the first received pulse emerges from the noise. This difference is called the “Leading Edge Offset” and is computed in both the responder and requester radios during a two-way ranging conversation.

To understand this process it is useful to review **Figure 3.**



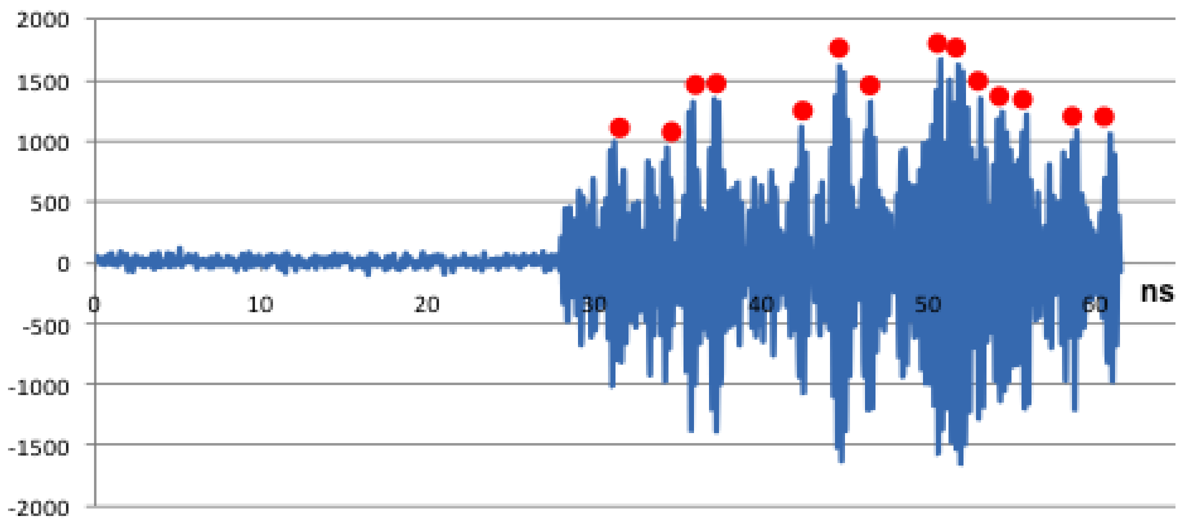


Fig. 3: Received signal in low multipath (outdoors - *top*) and high multipath (indoors, through walls - *bottom*) environments

Signal Acquisition. The radio receiver is designed to acquire the transmitted signal with the strongest received energy. Candidate "lock spots" are indicated on the Figure 3 waveform with a red dot.

Waveform Scan. Once the receiver has locked, a process is initiated to create a waveform scan. This process is analogous to the CIR measurement process used in a laboratory setting. In such settings the waveform scan (or impulse response) would be obtained with measurement system consisting of a UWB transmitter and a sampling scope under the control of a common triggering source. This is illustrated in **Figure 4**.

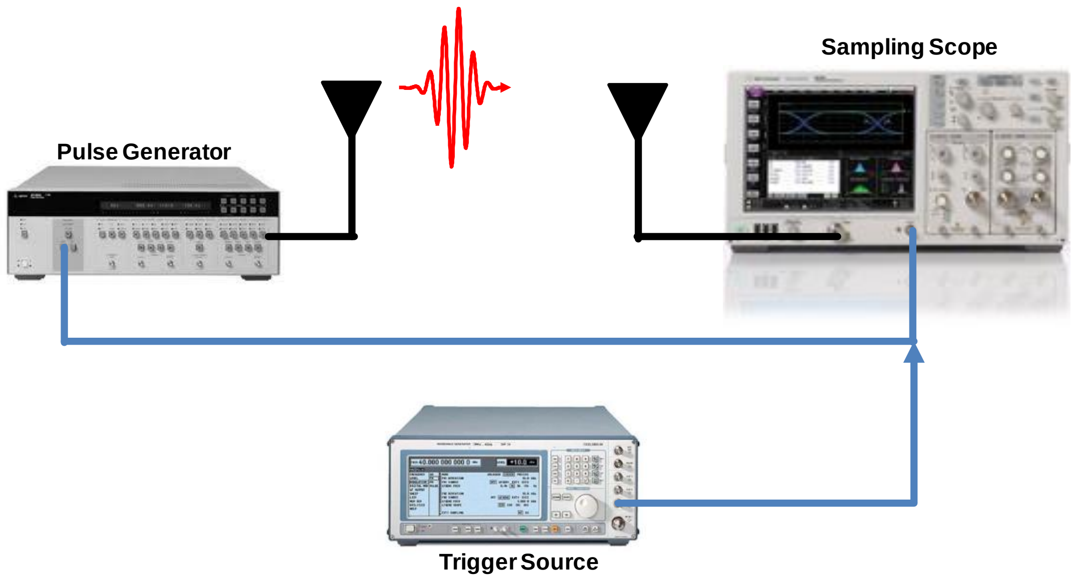


Fig. 4: Typical apparatus for capturing waveforms

However, because the RCM transmissions are coherent, a synchronizing clock is effectively sent from the transmitter to the receiver. This allows the equipment shown above to be replaced with a pair of RCMs, effectively recording the CIR without wires.

This type of sampling is analogous to that of a direct sequential "sampled" oscilloscope. Time Domain's RCM implements direct sequential scanning, with wireless synchronization, on a custom RF analog front end (AFE) chipset.

Computation of Range

At the end of the ranging conversation the requesting radio has 3 critical pieces of information. First, the time delay between transmitted and received packets, measured with respect to the requester's picosecond precision clock, from lockspot to lockspot. Second, the leading edge offset of the request packet as measured by the responder, and third, the leading edge offset of the response packet, as measured by the requester (on the return trip.)

Subtracting the leading edge offsets from the coarse (lockspot-to-lockspot) response time leads to the complete two-way time-of-flight for the direct path conversation. This value is simply divided by 2 and multiplied by the speed of light to yield a range measurement.

One final adjustment must be made. The steps above determine time-of-flight from pulser to sampler. A constant time-of-flight bias is present due to antenna electrical delays. This "Antenna Delay" constant must be determined and subtracted from the overall total to provide a final antenna-to-antenna measurement. The RCM *API Specification* includes separate "Antenna Delay" factors for both the A and B antenna ports. The default Antenna Delay is that of a Broadspec antenna with a 90-degree SMA elbow as delivered in the P400/P410 RCM Development Kits. If longer SMA cables or an alternate antenna is introduced then the Antenna Delay offset should be adjusted to account for this longer time-of-flight.

After proper calibration the final range measurement corresponds to the physical distance from the phase center of the Requester's antenna to the phase center of the Responder's antenna.   This antenna phase center is shown in the following figure.

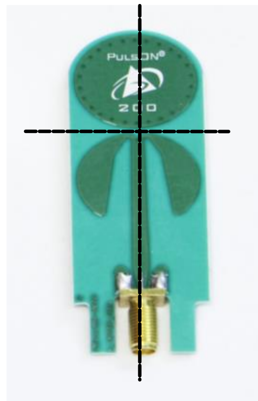


Fig. 5: Crosshairs indicate location of Broadspec antenna phase center

Ranging Update Rate

Time Domain's parallel processing UWB receiver architecture, implemented in silicon, uses multiple correlators to greatly reduce acquisition time and to quickly record and analyze received waveforms. This architecture results in a ranging radio with excellent performance in terms of the three essential criteria: high range measurement rate (up to 25 Hz), long distance (farther than WIFI indoors), and high accuracy (less than 10 cm even in high multipath environments).