TIME DOMAIN®

Time Domain's Ultra Wideband (UWB)

Definition and Advantages

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4955 Corporate Drive, Suite 101, Huntsville, Alabama 35805
Phone: 256.922.9229 Fax: 256.922.0387

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Brief Description of Time Domain's UWB Technology

Ultra Wideband (UWB) is a short duration, pulsed RF technology that achieves the highest possible bandwidth at the lowest possible center frequency. The technology can be used for communications, radar[1], and ranging/location applications.

In contrast with spread spectrum radio technologies that achieve a few 100s of kilohertz (kHz) to 10s of megahertz (MHz) of bandwidth, UWB signals are spread over a few gigahertz (GHz), achieving relative bandwidths of 25-100%.

UWB systems achieve this bandwidth by transmitting an impulse-like waveform. Such waveforms are inherently broadband. In fact, Fourier analysis teaches us that an ideal impulse (i.e., a waveform of a given amplitude and infinitesimally short duration) would provide infinite bandwidth. As a result, transmissions are quite unlike traditional RF modulated sine waves. Instead they resemble a train of pulses. An example of an individual UWB pulse is shown in **Figure 1**.

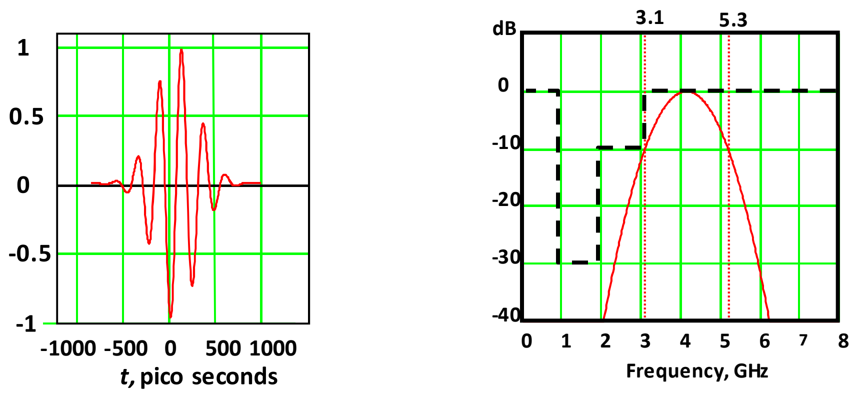

Fig. 1: UWB waveform shown in time domain (at left) and frequency domain (at right)

While most UWB providers use some version of this waveform, there are several different approaches to implementing UWB systems. Some companies transmit waveforms infrequently and use relatively high energy pulses. Others send low energy pulses hundreds of millions of times per second. While a few systems incorporate some level of coherent signal processing, most are non-coherent.

Time Domain relies on low duty cycle transmissions, with coherent signal processing and typical repetition rates of 10 MHz. These UWB transmissions normally consist of a packet of between several thousand and a few hundred thousand coherently transmitted pulses. Because the transmissions are coherent, the signal energy can be spread over multiple pulses, thereby increasing the energy per bit and consequently the signal to noise ratio (SNR).

Independent communications channels are established by pseudo-randomly encoding the phase, position, and/or repetition rate of the pulse train. Data can be added to the transmissions by further modulating either the phase and/or position of the pulses. The pseudo-random code and data are typically applied not to individual pulses but to blocks of many pulses. This approach has been implemented in the PulsON 400 (P400) Ranging and Communications Module (RCM).

Advantages of UWB and the PulsON 400

Most of the advantages of UWB are associated with the amount of RF bandwidth that is achieved. Basically, the more bandwidth a system enjoys the better it performs. Since UWB achieves the highest bandwidth, its performance is maximized. Coherent processing of transmissions offers an additional layer of advantages. Finally, the P400 module has been implemented with several important and useful features.

Key advantages of increased bandwidth: These advantages are due to UWB short pulses (large bandwidths):

- Robust performance in the face of multipath
- The ability to range accurately in the presence of multipath
- Communications with very low RF profiles
- The ability for radars to reject clutter, attain high spatial resolution and discriminate between targets in close proximity to each other.

Key advantages of coherent signal processing. Time Domain is unusual in that we use coherent signal processing to improve performance. Coherent signal processing allows information of any type (ranging, data, or radar[1]) to be spread over multiple pulses. By increasing the degree to which information is spread and then coherently receiving the information, the user can:

- Increase operating range
- Increase SNR
- Increase dynamic range

This improvement comes at the modest cost of reduced update rate.

P400 Implementation advantages. The P400 offers five major implementation advantages.

First, the P400 is an extremely capable and agile timing system. It maintains system clock accuracies of <10ps and distributes this clock wirelessly to other units. This supports coherent operation and thus enables:

- Precise range measurements
- Communications
- Operation as a bi-static and multi-static radar[1]

Second, all of the waveforms used to measure range or produce radar detections are available to the user. This enables the user to optimize system performance in difficult applications.

Third, all of the UWB-specific electronics have been reduced to a chipset. The resultant platforms are small, low cost, and use a minimum amount of power.

Fourth, the system architecture is highly parallel. This results in update rates that are one or two orders of magnitude faster than other RF technologies.

Finally, the P400 has been designed so that it can support ranging, communications, or radar[1]. This approach is ideal for applications such as distributed sensing because it allows the user to simplify and reduce the cost of the overall system. Fused operation also offers higher performance because all functions can be performed ***simultaneously***.

The fundamental limitation of all UWB systems is also associated with bandwidth. First, it is very difficult to build a system that will produce significant transmit powers. For example, a typical UWB system transmits at power levels of only 50 microWatts (uW). A "high power" unit will achieve at most 10mW. Second, regulatory agencies have, in general, limited the transmit power of UWB systems. As a consequence, the operation of UWB systems is limited to short range applications. Coherent signal processing allows range and performance to be significantly extended. For such systems "short-range" generally means operation at tens to hundreds of meters but in some special cases can be extended to tens of kilometers. In contrast, non-coherent systems are limited to operating at ranges of only a few dozen meters.

Stated differently, in order to prevent interference the regulatory agencies have limited transmit power because of the large bandwidths that UWB occupies. However, a 50 uW limit is not very much power. If a user has an "easy" application that doesn't require much range, then they are likely to find the cost and endurance of non-coherent devices very attractive. But if the target application is "difficult" or requires non-trivial operating ranges, then the only option available to the system designer is the use of coherent UWB. Time Domain is one of the few companies focused on coherent UWB and the P400 is the only coherent UWB ranging or radar[1] platform available for integration.

UWB signals are very hard to detect for several reasons. First, they typically do not transmit much power. In most cases they transmit less than 0.00005 watts. Second, because transmissions are pseudo- randomly encoded and modulated, the signal appears noise-like and is spread evenly over approximately 1 to 2 GHz of bandwidth. This translates into a power spectral density of 2.5E-08 W/MHz or 25 nanoWatts/MHz.

This noise-like appearance has two advantages. First, it is unlikely that transmissions will interfere with other UWB or non-UWB devices. Second, these transmissions are very hard for others to detect, especially at distance. Therefore, these transmissions have excellent low probability of intercept/low probability of detection (LPI/LPD) characteristics.

Operating In or Near Buildings – Multipath Resistance

One of the main reasons for selecting a UWB ranging or communications system over a narrow band system is that a UWB system is able to resolve multipath thereby enabling operation in highly cluttered environments. UWB systems can resolve multipath because their transmitted RF pulse has a bandwidth of almost 2 GHz, giving individual pulses a physical length of about 6 inches. Because the pulses are physically small, a UWB system can separate, or resolve, multipath reflections from a main signal by focusing on the first arriving pulse. This is illustrated in **Figure 2.**

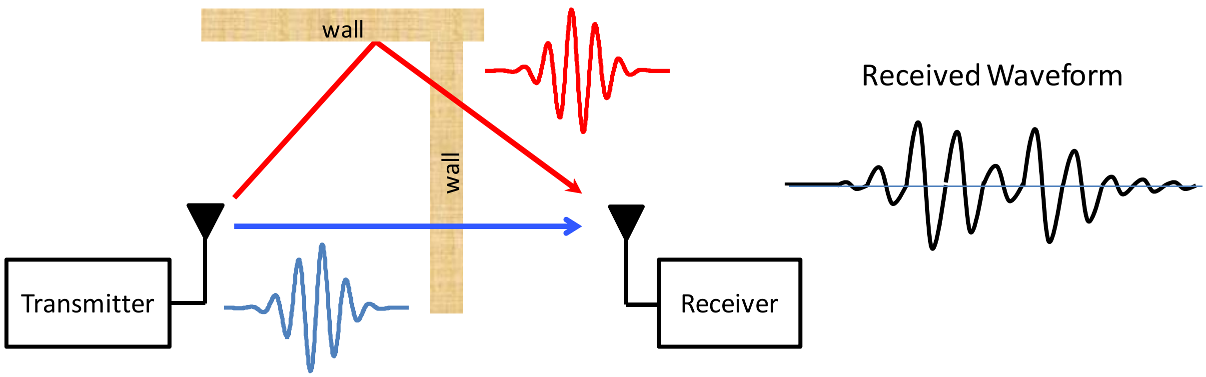

Fig. 2: UWB transmitter and receiver, with transmitted signal (blue), reflected signal (red), and composite received waveform (black)

This figure shows a transmitter and receiver system separated by a wall. In this example, a transmitted pulse can take at least two paths. The pulse may go directly from the transmit antenna to the receive antenna as shown with the blue pulse. Alternatively, the pulse may arrive at the receiver after reflecting from a wall. This is shown with the red pulse. Two items are worth noting. First, the red pulse takes a longer path and therefore arrives at the receiver sometime after the blue pulse. Second, because the red pulse reflects it will be inverted and, depending on the path length difference, may add either constructively or cancel. The resultant received waveform is shown on the right. In contrast (and at the risk of oversimplification), narrowband systems are unable to resolve multipath because their effective pulse lengths are simply too long, in essence overlapping direct and reflected long pulses to the extent that they cannot be effectively differentiated.

The received waveform must be evaluated both from a radio and ranging perspective as well as in contrast to narrowband approaches. To do so, consider the real life waveform illustrated in **Figure 3**.

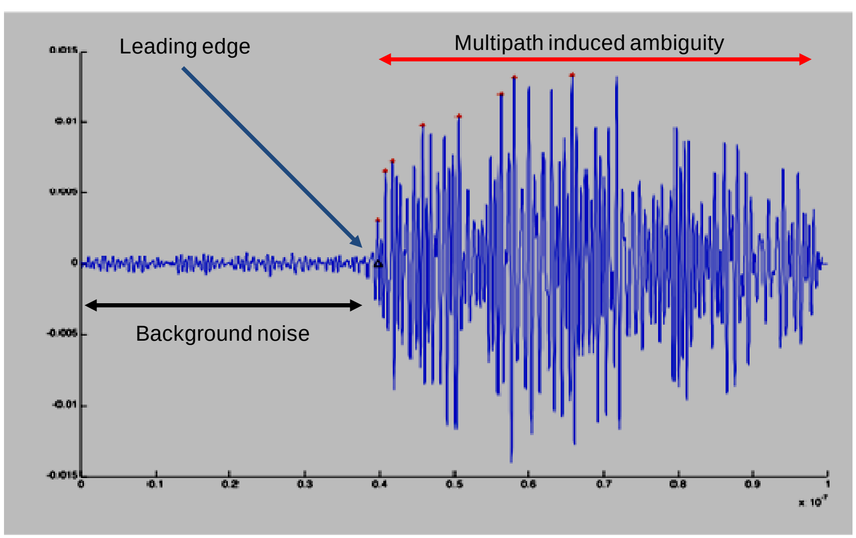

Fig. 3: Received signal in moderate multipath environment

Radio Perspective: Normally the direct path is the shortest and strongest signal. But this is not always the case. In **Figure 3**, the direct path is relatively weak compared to the stronger signals marked with a red dot. A UWB system can resolve any of these strong signals. In fact, because of constructive multipath interference, there are signals that are actually much stronger than the first arriving pulse. By acquiring and locking on to the strongest signal present, a UWB radio effectively uses multipath to enhance the received signal strength.

Ranging Perspective: From a ranging perspective, the user is interested in the amount of time elapsed between transmission of a signal and its subsequent reception. In the case shown in **Figure 3**, it is relatively easy to determine the moment when the first pulse arrives at the receiver. That point is marked with a small triangle. Time Domain refers to this point as the "Leading Edge."

One should note that its exact location is still a bit ambiguous, but that this ambiguity is limited to less than a single RF cycle or about 6" of range. With a bit of integration and advanced algorithms, this range measurement ambiguity can be reduced to less than a few inches. With signal processing efforts and a cooperative environment the ambiguity could, in principle, be reduced to less than 2mm.

This is an example of why a short duration pulse is the best tool for determining range and also makes the best radar. The waveform is small relative to the targets (walls, furniture, people, appliances) it might encounter. It is small relative to the mutual separation distances of the targets. It is small relative to the separation distance being measured. Because of these factors, one can use the leading edge to precisely measure range and one can implement radars to distinguish between targets.

Comparison with narrowband systems. The communications world has spent a great deal of effort characterizing in-building RF propagation. The tool of choice is the use of Channel Impulse Response (CIR) models. Basically, these models characterize the impulse response of a given environment and then inject a variety of waveforms so that one can evaluate the resultant response. (A more rigorous description of this tool can be found in Molisch, A.F.; Cassioli, D.; Chia-Chin Chong; Emami, S.; Fort, A.; Kannan, B.; Karedal, J.; Kunisch, J.; Schantz, H.G.; Siwiak, K.; Win, M.Z.; , "A Comprehensive Standardized Model for Ultrawideband Propagation Channels," *, IEEE Transactions on Antennas and Propagation*, vol.54, no.11, pp.3151-3166, Nov. 2006).

Figure 4a shows the line of sight (LOS) CIR in a typical residential environment. The horizontal axis indicates time in nanoseconds relative to the arrival time of the direct path and the vertical axis indicates response magnitude and polarity. Into this environment one can inject either UWB waveform "b" or narrowband waveform "d". It should be noted that in this context "narrowband" means any waveform with less than 20 MHz of bandwidth.

Figures 4c and **4e** respectively show the resultant received waveform for UWB and narrowband transmissions. The dashed vertical line indicated the time of the arrival of the direct path. That point is crystal clear for the UWB waveform. Not so for the narrowband signal. Which would you prefer to use to find a precise range?

The bottom line is simple. Narrowband range measurement inside buildings, at best, is painful to analyze and results are ambiguous. This is simply because its operating waveform of several hundred feet is much larger than the environment in which it is expected to operate.

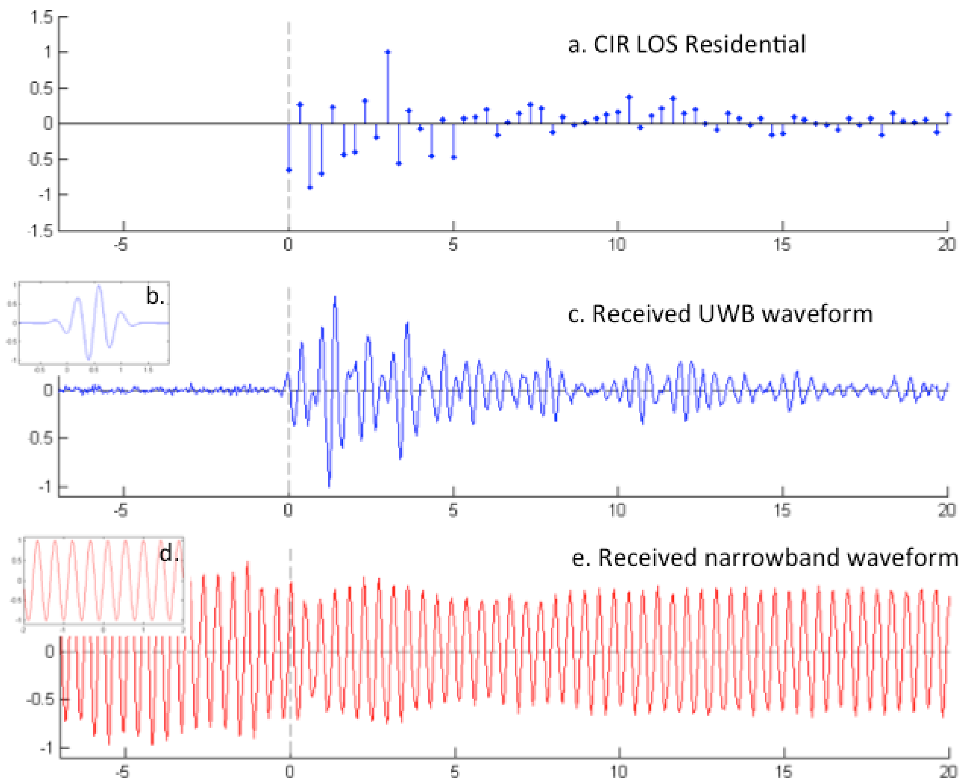

Fig. 4: Channel impulse response (a), UWB waveform (b), received UWB waveform (c), narrowband waveform (d), and received narrowband waveform (e)

But regardless of the type of application, bandwidth is the key to multipath resistance. Bandwidth allows multipath to be resolved and allows the system to select the strongest signal available (in the case of communications) or the earliest arriving energy (in the case of a ranging system) or resolve differences between adjacent targets (in the case of a radar).

Extending Operating Range – Coherent Signal Processing

Most UWB systems are non-coherent. This means that the power in each transmitted pulse must be significantly larger than the ambient noise power, otherwise the signal will be lost in the noise. Such systems have no mechanism for summing the energy of individual pulses because doing so will add equal amounts of power and noise, thus yielding no net gain. In spite of this limitation, such systems enjoy two advantages. First, they achieve many of the benefits of UWB and second, they can be implemented inexpensively.

Time Domain's UWB is fully coherent. Systems that use coherent transmissions maintain the phase information of each pulse. This allows the voltage of several pulses to be summed. Since the received power is proportional to the square of the received voltage, summing pulse voltages means that signal power increases as the square of the number of pulses. Since noise is incoherent it will sum linearly.

Consequently, a coherent UWB system that spreads a data bit over multiple pulses will enjoy a SNR improvement of 3 dB for each time the pulses per data bit is doubled. For example, a system that transmits 1 bit over 4 pulses will enjoy a 6 dB SNR advantage over a system that transmits only one pulse per bit. Increasing the number of pulses per bit (also referred to as the integration rate) to 256:1 will result in a 24dB SNR advantage. This technique basically trades maximum data rate or update rate for increased SNR. Greater SNR translates into greater operating range and/or more accurate range (or radar) measurements. In a clear LOS environment, quadrupling the integration rate will double the operating range of radios, rangers and bi-static radars.

Figure 5 illustrates the benefit offered by coherent integration. The waveform on the top was taken using an integration level of 16:1. The one on the bottom was taken in the same environment but using an integration level of 512:1. The net benefit is clearly visible and corresponds to an improvement in SNR of 15dB.

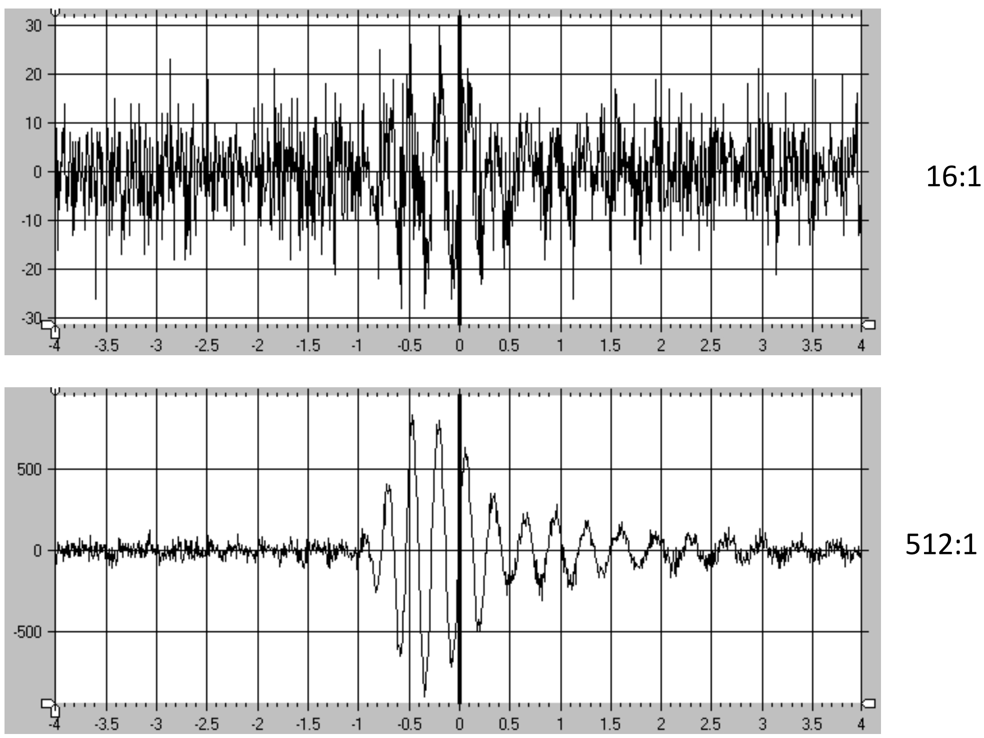

Fig. 5: Integration increases signal-to-noise ratio allowing increase in operating range

By increasing the integration, users can improve the robustness of their systems and/or increase the range of operation. However this improvement comes at two distinct costs. First, the complexity of a coherent system is significantly greater than for a non-coherent system. This complexity can require custom silicon solutions such as Time Domain's P400. Second, the improvement in SNR is achieved by increasing the amount of time it takes to make a measurement, thus reducing the update rate.

Coherent processing benefits communications, ranging and radar systems. In each case one uses the integration level to trade operating time for operating range or SNR. In other words, a communication system will trade data rate for operating range and/or improved SNR, while radars and ranging system trade update rate for operating range and/or improved SNR.

Providing Waveforms – A Tool That Enables Innovation

The waveforms shown in **Figures 3** and **5** would normally be taken using a UWB transmitter and a sampling scope under the control of a common triggering source. This is illustrated in **Figure 6**.

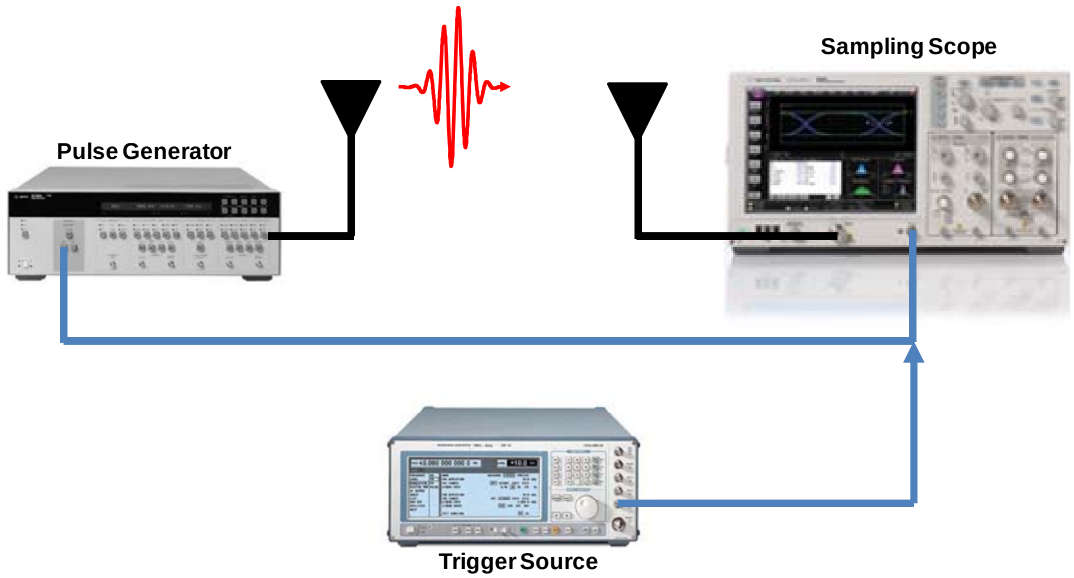

Fig. 6: Typical apparatus for capturing waveforms

However, because the P400 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 P400 modules.

In fact, it would be more accurate to describe the P400 as an engine that performs direct sequential pulse sampling. This capability is critical to the accurate measurement of range and the operation of bi-static and multi-static radars. It can also be used to range gate mono-static radars.[1]

Direct sequential pulse sampling is a critical capability and it is unique to Time Domain's UWB platforms.

Furthermore, not only does the P400 use this information to produce range measurements and radar[1] detections, but the raw scans are also available to the user. Providing these waveform scans enables the user to further optimize performance by providing more robust ranging or more intelligent radars. This capability gives the user a tool to innovate and provide better solutions for any given application.

Precision Ranging

Because a UWB system can synchronize the transmitter with a receiver and maintain that link over time, it is capable of measuring the received waveforms in great detail. This makes it possible to accurately measure distance between a transmitter and receiver. Basically, the shortest distance between two P400 RCMs is the direct path taken by a transmitted pulse. The leading edge of the first arriving energy of a pulse is therefore a measure of the distance between transmitter and receiver.

Capture and analysis of received waveforms is essential for measuring ranges in building or in other high multipath environments. It also enables different means for taking range measurements. For example, it is possible to construct ranging systems based on Time Difference of Arrival, Angle of Arrival and Two-Way Time-of-Flight (TW-TOF).

Of these ranging methods, Time Domain has found TW-TOF to be the most robust and reliable. This technique has been implemented in the P400 RCM. It provides range measurements with an accuracy of less than 4 inches and works well in extremely challenging environments. The technique is based upon the transmission of a packet of pulses from a requesting P400 to a responding P400 and the subsequent transmission of a packet from responder to the receiver. At a high level, the first packet is used to measure the arrival time and the second packet provides a time reference for determining the transmit time. A more comprehensive description of the technique can be found in the next section, *Part Three: Two-Way Time-of-Flight (TW-TOF) Ranging*.

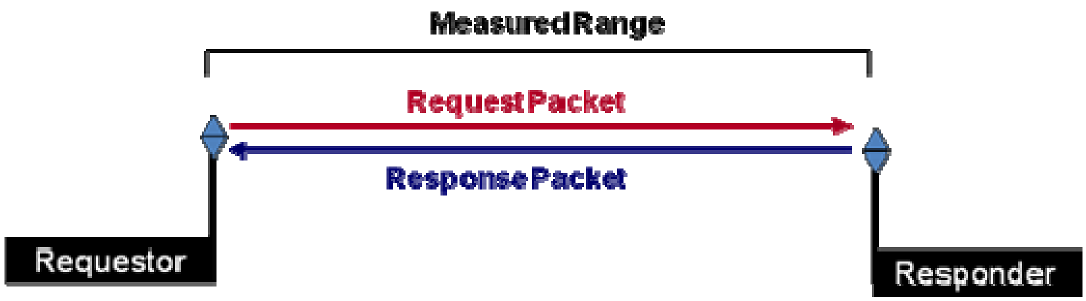

Fig. 7: Packet transmissions required by Two Way Time of Flight range measurement

This ranging capability can be incorporated at the system level to provide accurate determination of location in three dimensions. Location of a target can be updated at a high rate as the target moves through a given area.

UWB ranging can be used as a standalone system. However, it can also be used in conjunction with, or as a supplement to, other technologies. This allows the best features of different technologies to provide a higher reliability system. For example, UWB can be used as a supplement to GPS to improve system reliability in GPS-denied or challenged environments by using location measurements taken inside or in close proximity to a building. Similarly, UWB can be used to increase the reliability of Inertial Navigation Systems by helping to correct accumulated drift error.

UWB Radar – Clutter Rejection, Resolution & Discrimination

A UWB radar offers the highest resolution at the lowest possible center frequency. With a bandwidth of almost 2 GHz, our UWB radars have a resolution of about 4 inches. A resolution of 4 inches means that a UWB radar can detect quite small targets and discriminate between targets that are close together. Additionally, this resolution is achieved with a center frequency of 4+ GHz. In contrast, radars such as X band can achieve such resolutions but they do so at much higher frequencies where propagation characteristics are much less favorable.

A UWB radar uses coherent integration to either increase the effective range of the system or to increase the SNR of returned signals. This enables the radar to detect slight movements and provide robust operation in cluttered environments, areas where traditional radars fail. Moreover, it is very easy to time gate a UWB radar. Doing so allows the radar to focus on items of interest and ignore clutter associated with targets that are outside of the time gate.

In order to distinguish targets in high clutter it is important to maximize dynamic range. The more dynamic range a system supports, the more subtle the differences it can detect. This allows the radar to detect targets in high clutter. By integrating 1,000:1, Time Domain's UWB radar can increase its instantaneous dynamic range by 30 dB. Increasing integration to 10,000:1 increases dynamic range by 40db. The user can also time gate the response. This allows the user to focus analysis time on areas of interest and avoid clutter. For example, the performance of a short-range radar operating on a forest floor is not effected by canopy clutter, because this clutter is outside the range of interest and can be ignored through the use of a simple time gate.

An additional advantage of Time Domain's UWB radars is that they are not simply mono-static. By taking advantage of the built-in communications and system synchronization, the devices are easily configured for operation as bi-static and multi-static radars. For example, a bi-static radar can be implemented by transmitting a radio packet and then having the receiving radio measure the received waveform. By analyzing and comparing waveforms from subsequent packets it is possible to implement a robust, short-range radar. A multi-static radar can be implemented by broadcasting radio packets to multiple units, measuring all of the received waveforms and then processing the data accordingly.

The combination of bandwidth at low center frequency, coherent processing, integration to improve SNR and dynamic range, range gating and clock distribution for bi- and multi-static radars is quite powerful. This radar is ready and easy to use, thus allowing a system integrator to address target applications quickly and economically.

Time Domain has produced a variety of radars including:

- Mono-static radars that alarm if any motion is detected within a given radius of the radar.
- Bi-static radar triplines that alarm if any target moves through the radar field of view.
- Multi-static radar arrays that detect, locate and track targets as they move through the field of view of the array.
- Arrays of 2 dimensional multi-static radars that detect, locate, track and classify targets as they move through the field of view.

Figure 8 illustrates the results from one of the 2 dimensional multi-static radar arrays. The photo on the left shows an image of a deer that moved through the field of view. This deer produced the radar image shown in the middle of Figure 8. The image on the right is that of a person.

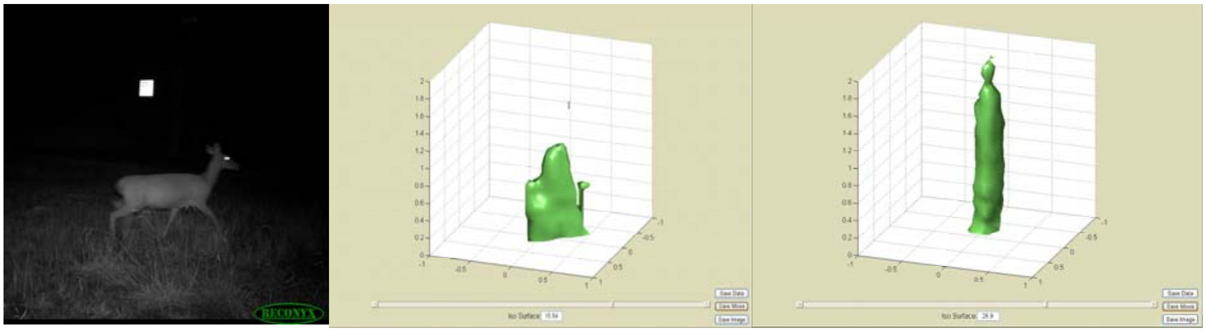

Fig. 8: Photo of deer (at left), radar image of deer (center), and radar image of person (at right)

Using these images, it is possible to build a robust algorithm that classifies targets as deer or people.

Fused Operations – 3 Functions in One Platform

Because the UWB P400 transmits and receives the same waveform (regardless of whether it is operating as a radio, ranger or radar) it is possible to consider the P400 for fused applications. In other words, the same platform could be used to handle all three functions. In contrast, conventional systems typically use one technology for radar, another to perform ranging or location and a third to provide communications. This translates into three antennas, three RF sections and three dedicated processors. Consequently, for many applications, a P400 can provide the same functions with a less complicated architecture, in a smaller form factor and at a lower cost.

Furthermore, Time Domain has optimized the P400 design so that each transmitted pulse can be ***simultaneously*** used for data, measurement of range, and operation as a radar.[1] In other words, there is no need to transmit some pulses as data, others for ranging and even more for radar functions. This multiple use reduces time and thereby increases system performance.

Low Cost / Size / Power

Time Domain has instantiated the key UWB components into individual, high performance, mixed signal ASICs. Building a full system requires the addition of a Digital Baseband (currently implemented with an FPGA), a supervisory processor, a communication channel (such as Ethernet or Serial) and power supply.

The footprint for these devices is quite small and the associated part count is quite low. For example, the entire P400 includes all of these components (as well as multiple types of user interfaces) and still fits in an area of 3"x 4". Furthermore, there are relatively simple steps that can be taken to reduce the footprint by an additional 25 to 35%. Based on customer specific requirements, it is possible to further reduce the size and cost of the entire device.

Power consumption is a function of the "on time" of the system, and overall system architecture. If it is possible for the unit to remain in a quiescent state for much of the time, then the average power used can be significantly reduced.

Fast Update Rate

Implementing UWB in silicon not only reduced system size and cost, but it also allowed Time Domain to implement a highly parallel receiver architecture. Multiple correlating receivers are used to greatly reduce acquisition time and to more rapidly record and analyze received waveforms. This has allowed Time Domain to provide the highest ranging update rates in the RF industry. The P400 update rate of up to 50 Hz is one to two orders of magnitude faster than that provided by others. For example, WIFI based systems provide updates every 1-10 seconds and RTLS systems top out at 5-10 Hz. Finally, parallel processing is also used to more rapidly analyze radar signals.

Timing and Clock Distribution – Synchronizing Remote Systems

In order to operate efficiently, Time Domain's UWB devices need to maintain system timing accuracies of < 10ps. This requirement has been accommodated through the implementation of an extremely agile timing system, built into custom silicon. This timing system has been used to electrically steer phased arrays.

Furthermore, operation of a radio link requires that the transmitter and receiver be synchronized in time with an accuracy of <10ps. Since the transmitter and receiver are typically distant from one another and because a radio link can be established between one transmitter and many receivers, this system can also be viewed as a system to distribute high precision clock between many units. Such an approach has been successfully implemented achieving accuracies of 50ps. In principal, it should be possible to distribute such a clock with accuracies of <10ps.

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[1]The P400 Ranging & Communications Module (RCM) does not include radar functionality. To learn more about the radar capabilities of PulsON technology, visit our website at www.timedomain.com/p400-radar.php or www.timedomain.com/technology.php.