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Before the
Federal Communications Commission
Washington, DC 20554

In the Matter of Revision of Part 15 of the FCC's Rules Regarding Ultra-wideband Transmission Systems	ET Docket 98-153

Comments of Time Domain Corporation

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Executive Summary

The FCC is to be commended for issuing its Notice of Inquiry on Ultra-Wideband technologies. Time Domain urges the Commission to use this promising new technology as an opportunity to put into practice its recent and widely publicized initiative to "fast track" promising technologies.

Ultra-wideband technology ("UWB") is a "fundamental" and "enabling" technology with the potential to create not only numerous highly beneficial services, but to create entirely new industries as well. Indeed, some respected technologists predict that UWB could have a potential beneficial impact similar to the transistor or the microprocessor. (A recent article by Bennett Z. Kobb, author of the respected *Spectrum Guide* summarized the sentiment of many technologists with the headline "Ultra Wide Technology is Ultra Promising.") It is vital the United States maintain its lead in this field. Yet, with the existing regulatory uncertainty this technology cannot progress beyond prototypes for non-military applications without a clear and rapid regulatory path forward.

All segments of society can eventually benefit from advanced UWB devices. For example:

- Public Safety & Law Enforcement. Public safety and law enforcement officials are already on record with the FCC in support of this technology. Ground-penetrating radars are already being used to find buried evidence. "See-through-wall" radars could detect survivors in building rubble and provide situational-awareness to law enforcement personnel preparing to "break down" doors.

- Business and Electronic Commerce. UWB may enable the realization of exceptionally high performance, low cost wireless communication networks with exceptional capacity.
- Mobility and Medically Impaired. UWB has the potential to develop precision navigation systems for the visually impaired; reliable panic alarms for the estimated 50 million Americans; and highly reliable, low power biometric telemetry networks.
- Consumers. Ultra-high-speed LANs, ultra-low power wireless links for HANs (home area networks) and RANs (room area networks) will allow untethered communication at a thousandth of the power of current systems. Advanced security wireless security sensors will enhance security and reduce false alarms. Moreover, long distance wireless fences are also feasible.
- Military. The military can benefit from spin-offs of these commercial applications.

Traditional wireless technologies are running into physical limits. By avoiding those limits UWB technology is a leap forward in three areas: wireless communications, geo-positioning, and radar. Moreover, these capabilities can be fused in a single system.

In the field of communications, the limits imposed by multipath prevent ultra-low emitted power communications from being reliable and also effectively prevents ultra-high speed wireless communications except over short, unobstructed paths.

In the field of sub-centimeter geo-positioning, the physical requirement for large bandwidths traditionally forces the use of millimeter wave frequencies where propagation is severely degraded within buildings and built up areas.

This same bandwidth/center frequency trade-off plagues high resolution radars. Also, traditional high resolution imaging radars are too expensive and complex for use outside of the military. But UWB may eventually bring affordable tomographic imaging radars into the commercial and public safety marketplace.

Time Domain recommends that UWB transmissions be allowed within the existing emission limits for unintentional digital devices. Under these limits UWB are operating at such low emitted power levels that there is essentially no likelihood of harmful interference to existing systems. This point is emphasized by the fact that there are literally billions of unlicensed Part 15 devices and an uncountable number of uncontrolled "incidental" radiators (e.g., electric shavers and hair dryers, that can emit at power levels greatly in excess of these Part 15 limits) in operation.

The Commission should note that while the emissions from digital devices serve no functional purpose, the emissions from UWB devices are effectively "refarming" the spectrum, improving the total capacity of spectrum that is already in heavy use.

UWB, when operated at these low levels, meets the spirit of existing regulations. However, because UWB devices were never envisioned by present FCC regulations, the regulations do not permit them. Nonetheless, they can fit quite comfortably into existing Part 15 rules. There are three definitional areas requiring change. The first two are relatively minor, i.e., pulse desensitization and Class B damped sine wave. There is consensus in the technical community that these are straightforward definitional changes with no substantive impact.

The more significant definitional change involves "intentional" versus "unintentional" emissions. Currently, billions of devices can put "unintentional" and "incidental" emissions into the restricted spectrum. However, "intentional" emissions even at the same or lower power are not allowed. There is an emerging consensus in the industry and with regulators that "intent" is not the proper criteria; rather, it should be "interference" potential. Intent, as one technologist recently commented, is less important than actual interference: "If a bullet hits you, you do not care if it was fired intentionally or unintentionally. It is the impact of the bullet that counts."

Obviously, extra care should be taken to ensure there is no disruption of important government safety-of-life systems such as those operated by the FAA. However, it should be noted that these systems function well even with billions of devices currently emitting into their bands, and that additional ultra-wideband devices at the same or lower power levels should not create problems. Some straightforward tests have already been conducted that should alleviate these concerns. We would strongly encourage additional joint testing on the part of the UWB community, the FCC, the NTIA, government spectrum owners, and any other interested parties to further identify under what circumstances critical systems might be jeopardized.

Another, often aired, concern is the "aggregation" issue: Will the proliferation of UWB devices raise the noise floor? Time Domain's analysis strongly suggests that it will not. However, stronger proof exists in the form of the billions of Part 15 approved digital devices and incidental radiators that already are in operation and which are not causing the noise-floor to rise immeasurably.

In summary, UWB technology has the potential to do things that no other technology in the world will do and can create extraordinary benefits for public safety, law enforcement, the military, the disadvantaged, consumers, and corporations.

Time Domain believes it is absolutely in the national economic and security interests for the United States to take a leadership position in this technology. We predict that whichever country allows deployment of this remarkable technology the fastest will gain an important economic and social advantage. Therefore, we urge a rapid, thorough, and critical examination of this potentially revolutionary technology.

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Comments of Time Domain Corporation

Introduction

Time Domain Corporation ("Time Domain" or "TDC") has developed highly beneficial products using its time modulated ultra-wideband ("TM-UWB") technology. Unfortunately, it is prevented from introducing these products to the US marketplace because of FCC regulations – even products that have the potential to save lives are not permitted. Other companies have ultra-wideband ("UWB") products in daily use for which there are no adequate substitutes. Yet their sale and use in the US is not clearly covered by existing regulations.

The rules that prevent the lawful introduction of UWB devices were not conceived for the purpose of preventing the introduction of UWB technology, but rather the technology was not anticipated. Minor changes to the wording of existing regulations, changes that

would not violate the spirit of the existing regulations, would allow the introduction of many beneficial UWB products. Other changes would allow the properly controlled sale and usage of higher powered UWB products and still not violate the spirit of today's regulations. With the primary exception of the prohibition against intentional emissions into the restricted bands, existing regulations would allow the introduction of UWB devices.

This document discusses why UWB technologies are badly needed, why there are no substitutes for UWB technologies, how the controlled introduction of low powered UWB devices will not cause harmful interference, and regulatory structural issues surrounding UWB.

The Value of Ultra-Wideband

Ultra-wideband radio technology is in its infancy, but UWB could be the RF technology of the 21st century because, as the FCC's Notice of Inquiry ("NOI") into Ultra-Wideband states, "UWB systems have unique and valuable characteristics."[1] The technology can yield improvements in traditional technologies, e.g., it requires less emitted RF power for communications in severe multipath environments such as within buildings. More significantly, the technology enables previously unfeasible applications, e.g., Gigabit per second wireless local area networks, micro-powered implanted biomedical telemetry systems, integrated wireless command, control and tracking systems, precision (sub-

centimeter) positioning/navigation systems, high fidelity imaging radar systems. Moreover, the federal government and military have also recognized the value in UWB radar, which has been in use for decades but with no commercial avenue. In the last ten years, there have been over 50 contracts awarded by the federal government to further development of UWB radar.[2]

The FCC has historically recognized the value of new RF technologies. The FCC's structure for regulating UWB resulting from this NOI and a follow-on Notice of Proposed Rulemaking will be crucial in allowing the United States to lead the world beyond traditional radio technology with new technologies that can provide services and capabilities that were previously unavailable.

Ultra-Wideband Background

There are numerous ultra-wideband techniques being practiced or under theoretical consideration. Among those that Time Domain is familiar with are:

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[1] ____FCC Rcd _____ (Sept. 1, 1998). Notice was given in the *Federal Register* on September 21, 1998. 63 FR 50184 (1998)

[2] The following examples highlight the government's interest in UWB by outlining the projects using ultra-wideband technologies:

U.S. Environmental Protection Agency, Region V and the Ohio State University, *Proceeding of the Second Government Workshop of GPR, Advanced Ground Penetrating Radar Technologies and Applications*, October 1993.

Jet Propulsion Laboratory, *Sensor Technology Assessment for Ordnance and Explosive Waste Detection and Location*, prepared for U.S. Army Corp of Engineers,

- Time modulated ultra-wideband (practiced by Time Domain);
- Short pulsed CW and impulse;
- Giga-chip per second direct sequence spread spectrum;
- Fast slewing chirp or stepped frequency;
- Frequency hopper spread spectrum; and
- Multiplexing large numbers of direct sequence spread spectrum carriers.

Each technology has its own characteristics. Time Domain has focused on time modulated ultra-wideband (TM-UWB) because of performance considerations necessary to meet its customers' specific requirements. All of Time Domain Corp.'s products utilize TM-UWB technology. Typical characteristics of time modulated ultra-wideband emissions are:

- Half–power bandwidths in excess of 60% of center frequency, and
- Noise-like signals in both time and frequency domains.

A further description of TM-UWB can be found in Appendix A.

Time Domain has developed significant expertise in ultra-wideband, especially in the area of UWB signals measurements, UWB electromagnetic compatibility, and regulatory issues.

Huntsville Div. and Army Yuma Proving Ground, California Institute of Technology, 1994.

Attributes of Time Modulated Ultra-Wideband

Time Domain exclusively uses TM-UWB because of the unique capabilities of systems based on the technology. For example:

- TM-UWB radios exhibit very large processing gains. TM-UWB radios achieve processing gains of approximately 45 dB at 32 kbps for a TM-UWB radio centered at 2 GHz. Achieving this processing gain allows systems that are highly resistant to multipath fading and jamming. For in-building communication systems, large processing gains translate into lower emitted power levels than are feasible for conventional radios, typically 20 dB lower. Achieving similar performance would drive conventional radio designs to millimeter wavelengths and to GigaHertz chip rates, which would reduce propagation performance and increase cost and power consumption.

- TM-UWB can have a large number of channels. Similar to code division multiple access (CDMA) spread spectrum systems, many links can be operated simultaneously in the same bandwidth by virtue of different code sequences. It has been estimated that more than 10,000 users could operate 10 kbps links with a bit-error-rate (BER) of 10^{-3} from a single cell.[3] Radars can benefit similarly by allowing co-site operation of many radars.

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[3] Scholtz, R., A., "Multiple-Access Capacity Estimate for Pulson's Digital Impulse Communications System, ", University of Southern California, January 1993 (for Pulson Communications).

- TM-UWB signals are noise-like. The random nature of the timing of the pulses means that most systems will perceive the TM-UWB signal as a low level white noise source. Such a source is difficult to detect and will not result in structured noise. The TM-UWB receiver yields a similar benefit in that other signals tend to be randomly sampled and countered using a variety of coherent processing techniques.

- TM-UWB offers high resolution with low operating frequencies. For radars, range resolution is dependent upon RF bandwidth and independent of RF operating frequency. However, propagation through typical construction materials is far superior at lower frequencies[4] and is necessary for some applications. For example, radars for public safety search and surveillance need to operate at frequencies below 4 GHz to ensure operation in as many environments as possible. Practical considerations force conventional RF designs to millimeter wavelengths, i.e., above 10 GHz, if GigaHertz of bandwidth is required. For communications, this high resolution increases a receiver's ability to separate multipath signals and enables the use of rake receivers to optimize and enhance reception.

- TM-UWB radios are capable of exceptional timing precision. Existing TM-UWB radios achieve a precision that is a thousand times greater than GPS, and can function in places where GPS cannot. Existing prototypes are operating with sub-centimeter precision. Actual performance depends on atmospheric perturbations and

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[4] Frazier, L.M., "Radar Surveillance through Solid Materials", SPIE Photonics East Conference, Enabling Technologies for Law Enforcement and Security, Boston, MA November 18 – 22, 1996. Paper 2938-20 (SPIE Vol. 2938, pg 139 – 146.)

environmental conditions. Thus, if precision range resolution is required within and around buildings and foliage, it is necessary to use lower frequency signals, below 4 GHz, to penetrate various materials.

- TM-UWB radios and radars utilize fully coherent receivers. (i.e., coherent in both frequency and phase.) This enables the use of coherent signal combining techniques to create extremely high performance imaging radar systems such as, sparse array radars[5], synthetic aperture radars, and electronically steered beam antenna arrays for extremely high performance communications.

- TM-UWB systems achieve high performance at an affordable cost. TM-UWB transmitters are essentially digital; they consist of a crystal-controlled digital clock, an ultra-precise digital programmable time delay, and a high speed digital switch that drives a switching edge into an antenna. Receivers consist of simple homodyne correlators (which convert RF into baseband signals) followed by digital signal processing. Time Domain has invested in developing advanced custom silicon-germanium integrated circuits in order to deliver low cost, high performance systems.

- TM-UWB systems have less "range ambiguity". Range ambiguities arise because traditional radars cannot distinguish between sinusoidal radar pulses transmitted at

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[5] A sparse antenna array is very much like a phased array antenna, but with a critical difference. The difference is that antenna elements are not spaced at quarter wavelength intervals, but rather at significantly larger intervals. Quarter wavelength spacing is necessary for narrowband systems to minimize grating sidelobes. By using waveforms with one or just a few zero crossings, UWB systems have minimal sidelobes even without quarter wavelength spacing. An example of this can be found in: F. Anderson, et

different times. Using purely randomized time hopping codes, TM-UWB can distinguish between pulse sequences transmitted at different times. Communication systems reap similar benefits by having less inter-symbol interference in environments with large delay spreads.

Ultimately, Time Domain Corporation foresees TM-UWB technology contributing to the more efficient use of spectrum, a long term goal espoused by the FCC. Moreover, Time Domain believes TM-UWB enables unique and beneficial products, while transmitting signals that are more noise-like and emit less power in a given bandwidth compared to traditional radio techniques.

Applications of TM-UWB

Law Enforcement & Public Safety Applications

Precision ranging radios and through-wall sensing radars could be of great potential benefit to both law enforcement and public safety organizations.

- Short range public safety command and control network radio. These radios can also provide geo-ranging information. Such a system can be expanded to provide position information. This information would be invaluable for situational assessment and rescue operations. In addition, the signals from these radios can not be intercepted with conventional scanners or detectors by illegal entities or the media.

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al, "Ultra-wideband Beamforming in Sparse Arrays", IEEE Proceedings-H, Vol. 138, No.

- Motion detection radar to provide an indication of movement behind walls and doors.
- Motion tracking and imaging radar to help visualize activity within buildings.
- Penetrating radar to aid in searching for people trapped in collapsed or bombed buildings and avalanches.

Automotive Applications

- Airbag deployment sensor (to determine the location of passengers to allow safe triggering of airbags).
- Automotive proximity ("pre-collision sensing") radar.

Terrestrial Applications

- Medical telemetry system.
- Navigation systems for those who are mobility impaired.
- RF Identification tagging & tracking.
- Wireless local area network for offices, homes, rooms, and people.
- Wireless Business Telephone Systems.
- High performance wireless microphone.
- Guidance systems for robotics.

4, August, 1991.

Subsurface Inspection Radars

Because of the low operating frequencies of UWB radars and their very high resolution, WB radars can be used to look into walls, structures, and soil to determine their condition. For example:

- Roadway, runway & bridge inspection systems. (For example, the Federal Highway Administration has purchased an UWB road and bridge inspection system.)
- Building construction compliance, surveying, & condition testing.
- Locating buried hazardous wastes and unexploded ordnance.
- Buried evidence for criminal investigations.
- Buried archaeological artifacts.
- Location of underground conduits and utilities.
- Sinkhole detection (such sinkholes cause over three million dollars in property damage a year).

Security Sensor Systems

- Proximity detection sensor that would dramatically reduce false alarms through the use of a range gated radar to detect intrusion, which can be installed within or behind walls.
- Security fence and intruder tracking system (for effective out-of-doors security sensors).
- Concealed weapons detection.

Aeronautical and Aviation Safety Applications

There are numerous aeronautical applications of ultra-wideband radar and communications. UWB may have the potential to provide functionality at a cost that allows general aviation to purchase capabilities that currently are available only to the best equipped commercial airliners. Among these are:

- Precision automatic landing system (an alternative or back up to GPS for zero visibility landing aid).
- Ground proximity warning.
- Low cost collision avoidance radar.
- Obstacle Warning System for helicopters (to help helicopters avoid wires).
- Ultra-high resolution (better than 3") airborne synthetic aperture radars for ground mapping.
- Ground traffic control systems.
- Low Altitude Radar.

The table below presents some example applications and frequency range in which these devices would most likely operate.

Frequency (GHz)	Frequency Description	Applications
0.1		
	VHF & UHF	Low Frequency Ground Penetrating Radar Long Range Military Communications
1.0		
	L	Law Enforcement and Emergency Service Motion Detection Security Proximity Detector Basic Construction Sensor Security Fence High Performance Microphone Wireless Mouse
2.0		
	S	Airborne Synthetic Aperture Radar Mapping Road and Runway Inspection Radar Law Enforcement and Emergency Service Mobile Imager Buried Victim Rescue Robotic Navigational Systems RF Asset ID and Tracking Short Range Public Safety Network Medical Telemetry Wireless Local Area Network
4.0		
	C	Precision Altimeter Ground Proximity Warning Collision Avoidance Helicopter Obstacle Warning Building Construction and Inspection Airbag Deployment, Interior Sensor Long Range Collision Avoidance Precision Automatic Landing Wireless Business Telephone Ad Hoc Network
8.0		

Time Domain's Corp.'s Ultra-Wideband Experience

Time Domain Corporation is a leader in the field of ultra-wideband radio frequency technology. In business since 1987, Time Domain has built numerous ultra-wideband radios and radars. Among the prototypes that Time Domain has tested are:

- A simplex radio with a center frequency of 650 MHz and a half power bandwidth of 600 MHz. Output power was ½ mW (-3 dB_m). With 2 dB_i antennas this system was tested to ranges in excess of 7 kilometers.
- The same communication system described above was operated in a coal mine, 600 meters beneath the earth's surface. The test included communicating around 90 degree corners from one tunnel into another. In a straight segment of the mine, the system provided quality audio communication to a range of 305 meters, the longest line-of-sight path available at the site.
- A simplex digital radio with a center frequency of 1.3 GHz and a half power bandwidth of 800 MHz. Output power was 33 μW (-15 dB_m). Transmitting through 6 to 8 centimeters of lossy material (6 dB/cm), simulating biological tissue, from a –9.6 dB_i antenna, this prototype transmitted 125 kbps with a BER of 10^{-6} to a 10.2 dB_i receive antenna an additional 2 to 3 meters away.
- Full duplex radios with a center frequency 1.3 GHz and a bandwidth in excess of 800 MHz were demonstrated to a government agency. Output power was 1 mW (0 dB_m). At 156.25 kbps the range was nearly 5 kilometers using 8 dB_i antennas.

- Full duplex radios with a center frequency near 2 GHz and a bandwidth in excess of 1.6 GHz were demonstrated to the United States Marine Corps and other government agencies. Output power is 1.8 mW (2.6 dB_m). At 32 kbps the range was nearly 1 kilometer using 2 dB_i antennas. These radios now incorporate sub-centimeter radio ranging.
- A through-wall motion detection system with a center frequency near 2 GHz and a half power bandwidth in excess of 1.6 GHz. Output power is 50 μW (-13 dB_m). Radar range resolution is better than 4 inches. The device can detect motion to a distance of approximately ten meters.

TDC's Law Enforcement & Public Safety Waiver Request

In an effort to bring badly needed through-wall surveillance radars and advanced small unit command and control covert communication/location systems to public safety and law enforcement, Time Domain requested a limited waiver from selected Federal Communications Commission Part 15 regulations[6]. The commission should consider granting such limited waivers to help collect data to aid in the inquiry and rule change process. This action will allow both the FCC and industry to get real world data in order to make more informed decisions concerning future rule making.

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[6] Time Domain Corporation's Waiver Request submitted on February 2, 1998.

Regulatory Treatment

Regulatory Philosophy

In several ways, this NOI reflects many of the same questions and issues dealt with during the inquiry related to spread spectrum in 1981. At that time the Commission noted that the rules did not foresee such wideband techniques and in some cases actually "implicitly forbid the use of some new technologies in this area."[7] Since that NOI, the Commission has modified the rules to allow for spread spectrum techniques, yet did not envision ultra-wideband techniques and their advantages. The Commission's spectrum management philosophy as stated in the spread spectrum NOI[8] remains valid today:

> 4. *Historically spectrum management policy has evolved around narrowband communication systems. In the early days of radio there were few radio systems and much spectrum in which to operate. Users were assigned a carrier frequency and their transmissions were required to remain in a small band of frequencies (bandwidth) about the carrier. As time progressed more users wished access to the spectrum. Advancing technology provided relief in two ways: 1) it increased the upper limit of usable spectrum; and 2) it provided the means for reducing the bandwidth occupied by existing stations. So as the Commission's frequency allocations were pushed higher and higher, users*

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[7] Authorization of Spread Spectrum and Other Wideband Emissions, Notice of Inquiry, 87 FCC 2d 876, 877-78 (1981)

were required to "consume" less and less of the spectrum. In the land mobile services, allotted bandwidths were actually halved a number of times.

5. *This environment of advancing technology leading to smaller and smaller bandwidths has established a trend among radio regulatory agencies, including the Commission, of reducing bandwidths to achieve higher spectrum efficiency. Obviously, reducing bandwidth is at least one way of increasing spectrum efficiency, but it may not always be the best way. In a 1959 paper, J.P. Costas showed the somewhat surprising result that decreasing bandwidth does not always increase spectrum efficiency, but that under certain communication conditions very large bandwidths are needed for efficient spectrum use. Wideband modulation techniques in certain applications may actually increase spectrum efficiency over narrowband techniques, due to both natural interference and interference caused by other users.*

This excerpt reflects the Commission's understanding that spectrum can be more efficiently utilized using wideband and ultra-wideband techniques. Time modulated UWB epitomizes Shannon's famous dictum in information theory, "that the most efficiently coded message was indistinguishable from noise, unless you had the right key to the encoding beforehand." [9]

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[8] Authorization of Spread Spectrum and Other Wideband Emissions, Notice of Inquiry, 87 FCC 2d 876, 877-78 (1981)

[9] Carl Sagan, *Contact*, Pocket Books, Simon & Schuster, page 44, 1985.

Definition of Ultra-Wideband

An essential step in the regulatory process is defining the criteria for ultra-wideband. As was stated before, typical UWB technologies include techniques involving very short pulses, direct sequence, and fast slewing chirps or stepped frequencies. In considering ultra-wideband systems, it is customary to relate the bandwidth to the center frequency of the band. This is typically expressed as the "fractional bandwidth", which is defined as [10]

$$\text{Fractional Bandwidth} = \frac{2(f_H - f_L)}{(f_H + f_L)}$$

There is no accepted standard usage for UWB bandwidth terms; percent bandwidth, proportional bandwidth, and relative bandwidth are also used instead of fractional bandwidth.

In 1990, the OSD/DARPA Ultra-Wideband Radar Review Panel accepted the following definition: "Ultra-wideband radar is any radar whose fractional bandwidth is greater than 0.25 regardless of the center frequency or the signal time-bandwidth product."[11] This definition was developed under a DARPA contract to assess UWB technology, specifically ultra-wideband radar. Another reference for this definition can be found in J.

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[10] Assessment of Ultra-Wideband (UWB) Technology, OSD/DARPA Ultra-Wideband Radar Review Panel, R-6280, Defense Advanced Research Projects Agency (July 13, 1990); see also *Introduction to Ultra-Wideband Radar Systems*, James D. Taylor, ed., CRC Press, at p. 2 (1995)

Taylor's, *Introduction to Ultra-Wideband Radar Systems*, which states, "The term *ultra-wideband* refers to electromagnetic signal waveforms that have instantaneous fractional bandwidths greater than 0.25 with respect to a center frequency."[12] Time Domain proposes that this definition be adopted as the criteria for intentional ultra-wideband emissions:

> *Ultra-wideband system: An ultra-wideband system is a radiator whose intentional emissions have a fractional bandwidth greater than or equal to 25%, in which the fractional bandwidth is the 20 dB bandwidth divided by the center frequency.*

Further, Time Domain would like to work with the FCC and others in the UWB community to resolve measurement issues related to the criteria for intentional ultra-wideband emissions. A measurement procedure should be established that specifies a minimum sweep time as well as other receiver settings to exclude very slow frequency agile devices, which more closely resemble narrowband systems, from being considered UWB.

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[11] Assessment of Ultra-Wideband (UWB) Technology, OSD/DARPA Ultra-Wideband Radar Review Panel, R-6280, Defense Advanced Research Projects Agency (July 13, 1990)

[12] James D. Taylor, ed., *Introduction to Ultra-Wideband Radar Systems*, CRC Press, at p. 2 (1995)

Part 15 – Low Power Unlicensed Devices

Time Domain Corporation agrees with the view expressed in the NOI that Part 15 is the most appropriate regulatory framework for many UWB operations. Part 15 regulates the authorization and operation of devices that have a low probability of interference and that can reasonably be expected to function well without interference protection under the Commission's Rules. As such, Part 15 has been employed successfully by the Commission to implement numerous new technologies and services without the necessity of licensing as a frequency management tool. Part 15 offers a ready means by which the Commission can move toward the introduction of UWB operations in keeping with the statutory mandate of Section 7 of the Communications Act, 47 U.S.C. § 157, that "it shall be the policy of the United States to encourage the provision of new technologies and services to the public." Thus, Part 15 provides a well-developed framework for regulation of low power short range UWB devices.

As discussed below, the Part 15 emissions limits for digital devices can be employed to regulate the emissions from UWB devices in a manner that will be consistent with the Commission's prior experience and with the technical characteristics to be expected from UWB devices such as those under development by Time Domain Corporation. Part 15 also offers the flexibility needed to accommodate many of those situations in which devices may be operated at greater than the Class A and Class B digital device limits without the likelihood of harmful interference. Thus, as has been done in certain other situations, *in situ* measurements could be employed for special indoor applications such an data links within a factory, which would be installed and maintained by professional

technicians. If the emissions levels outside the factory walls, for example, could be shown to be consistent with Part 15 levels, such an approach would allow the benefits of UWB technology to be employed to a greater extent in such a controlled environment.[13] In short, the Commission has great flexibility within Part 15 for establishing regulations that will allow UWB to develop, yet not jeopardize existing radio services.

Options for Licensed Services

The NOI also asks whether there are cases in which licensed operations may be the correct framework for UWB operations. In a limited number of situations in which more power than could be permitted for uncoordinated Part 15 operation would be needed Time Domain Corporation submits that licensing, on a secondary basis, would be appropriate. In general, these would involve temporary operations conducted by personnel trained in the operation of equipment and the necessity to avoid causing interference to primary services. Such operations would need to be conducted under constraints designed to minimize the likelihood of interference. In addition to limits on field strength (or radiated power), antenna height, and bandwidth, such operations may

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[13] *See* Sections 15.201(c) and (d), 15.209(g), 15.221(b)(2), and 15.307 of the Commission's Rules. For installations that are uniquely configured to buildings, the FCC could condition approval testing for the actual installation as is permitted for certain ISM devices. *See* FCC Methods of Measurements of Radio Noise Emissions from Industrial, Scientific, and Medical Equipment, FCC/OST MP-5 (Feb. 1986), ¶ 6.2. If the system cannot feasibly be tested on an open range, the FCC could require the proponent to conduct tests of three installations as part of the approval testing. If found compliant in three such sites, it could be accepted for similar sites without additional testing. *See* American National Standard for Methods of Measurement of Radio-Noise Emissions

also need to be coordinated with those primary users most likely to be affected by the UWB operation.

The benefits of UWB should not be cast aside, however, simply because of the need to craft licensing arrangements. In the Radiolocation Service, for example, there could well be situations involving ground penetrating radar (GPR) in which licensed operation of UWB equipment would be appropriate. While radars operating under Part 15 could allow law enforcement and fire fighters to detect motion through walls, there could be situations involving "heavy rescue" operations that would be possible only if more power could be employed to look through many feet of ruble. In such cases, the public interest would be well-served by allowing technicians to operate radars that would function at emissions levels in excess of those typically allowed under Part 15. There may also be cases involving other applications of radars or even communications devices in which the need for the benefits of UWB technology such as high resolution, precise ranging, or low probability of detection and interception merit its operation on a secondary licensed basis. As such the FCC should implement a regulatory framework beyond that now existing in Part 5 (experimental) of the Rules. Initially, and until the Commission gains a greater base of experience with UWB operations, such operations should be considered on a "case-by-case" basis under Part 90 of the Commission's Rules, including provisions for the processing of any special temporary authorizations needed on a timely basis. Eventually, the Commission should consider a new rule part governing licensed UWB

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from Low-voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz, ANSI C63.4-1992, § 5.6.

operations. Any such action, however, should come after the agency has gained experience with Part 15 operations and with limited licensed operations.

Emissions Limits

Current and Proposed Limits

The current radiated emissions limits were established to protect licensed services and equipment operating in the restricted bands. Radiators, under Part 15, have been divided into two groups, "intentional" and "unintentional". The type of radiator group defines how much power can be emitted, as well as limitations on spectrum usage.

Intentional radiators are now allowed to emit anywhere in the spectrum, outside of TV and restricted bands, under a general emissions limit. However, traditional intentional radiators may output significantly more power if constrained to bands set aside for a particular application or technology. Further, intentional radiators can place energy into the restricted bands, as long as the energy is a spurious emission, and falls under the general limit.[14]

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[14] Section 15.205(a) of the Commission's Rules. The term *intentional radiator* is defined in Section 15.3(o) as "a device that intentionally generates and emits radio frequency energy by radiation or induction." Section 15.205(a) applies only to intentional radiators. It does not apply to unintentional radiators such as computers. Section 15.3(z) defines the term *unintentional radiator* as "a device that intentionally generates radio frequency energy for use within the device, or that sends radio frequency signals by conduction to associated equipment via connecting wiring, but which is not intended to emit RF energy by radiation or induction." The semantic challenge facing UWB devices is further complicated by the fact that the term *spurious emission* is defined in Section 2.1 of the

Unintentional digital device radiators are further divided into two classes, Class A and B. The classes denote the type of operating environment, industrial and commercial versus residential, respectively. The Class B emissions limits are the same as the general limits for intentional radiators with one key difference, these radiators are allowed to emit into restricted bands. The Class A emissions limits are 6 dB higher than the general limits, and once again radiation, from millions of these devices, is allowed into restricted bands. These limits were established to protect receivers at a range of 10 m for Class B devices and 30 m for Class A devices.[15]

Over many years, with billions of devices operating at Part 15 levels, these limits have proven that there is sufficient protection against harmful interference to licensed users and restricted band systems. These limits would also provide the same protection to equipment from emissions generated by UWB devices as from currently regulated devices. Moreover, these limits provide adequate power to allow for some commercially viable products; see Appendix B for product examples and classification. Time Domain

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Rules as an "emission on a frequency or frequencies which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products, but exclude out-of-band emissions." This definition, which was developed decades ago and appears in the International Radio Regulations never contemplated UWB operations. Thus, despite the fact that the fundamental emissions from UWB devices can be limited to field strengths no greater than those emitted by unintentional radiators, these emissions are not allowed in the restricted bands in accordance with Section 15.205.

[15] Amendment of Part 15 to Redefine and Clarify the Rules Governing Restricted Radiation Devices and Low Power Communication Devices, First Report and Order, Docket No. 20780, 46 RR 2d 473, 79 FCC 2d 28,49 and 66 (1979).

recommends that the present class A and B radiated emissions limits and structure for unintentional digital device radiators be applied to UWB. Likewise, Time Domain advises that the current class A & B conducted emissions limits for unintentional digital device radiators be applied, since these limits will provide the same protection to equipment from conducted emissions generated by UWB devices as from presently regulated devices. Further, Time Domain agrees with the 20 dB peak limit over the average limit for frequencies above 1 GHz, using the measurement technique described later in this document. This limit protects against very low PRF systems, which might have very high peak powers.

There are also important applications that would not be viable using the Class A and B digital device limits. These include, for example, wireless business telephone systems, ad hoc networks, large area wireless LANs, very high data rate wireless LANs, precision altimeter, obstacle warning for helicopters, airborne SAR mapping, low frequency ground penetrating radar, and long range collision avoidance. Obviously, consideration of the regulations that would be appropriate for such devices would involve substantially more effort and time than should be required for the introduction of lower powered UWB devices under Part 15. As recommended above, however, the Commission should work to develop a means for the authorization of some uses of UWB on a secondary licensed basis on a case by case basis outside of the Part 15 context. At a minimum, the Commission should delegate to its staff the authority to address such situations. By so

doing, the Commission will gain additional experience needed to determine the future role of licensed ultra-wideband operation and whether the agency should then propose rule changes to regulate such operations or alter the limits and conditions for UWB systems.

Discussion of Cumulative Impact

The low electric field strength of one UWB device, operating at Part 15 levels, can be appreciated to be innocuous. However, the NOI seeks information as to the cumulative impact of a large number of UWB devices. Specifically, as the number of UWB products increases, will the potential for harmful interference increase to an unacceptable level? The following numerous factors limit the buildup of UWB emissions, such that the cumulative impact should not be a concern.

Propagation

Some of the most important factors in estimating emission levels are propagation factors. These limit the amount of electromagnetic radiation at any given point a distance away from a transmitter by natural and man made sources of attenuation, which include foliage attenuation, absorptive soil, Fresnel attenuation, loss due to walls, people and structures, as well as blockages from buildings and hills. It is vital to understand these propagation factors and account for them in studying the cumulative impact. However, it is very difficult, if not impossible, to model each one of these sources of attenuation on a large scale for numerous UWB transmitters. Rather, these factors are grouped together for various environments

and modeled as a general trend or slow fading in order to monitor the average propagation losses.

In many cases the general trend is represented by a $1/R^n$ model, where R is the range between the transmitter and receiver, and n is the signal decay index. The table below notes three common environments and the appropriate ranges of n from T. Rappaport's studies.[16] Moreover, different models are used in specific environments. Several forestation models[17] exist for varying density levels of forests, and all of these models represent significant losses over smooth earth or free space losses.

Environment	Path Loss Exponent
Urban	4
Obstructed In Building	4.5
Obstructed In Factories	3.25

In order to accurately model the effects of an aggregate number of UWB emitters, it is essential to incorporate these sources of attenuation. A cumulative effects

[16] T.S. Rappaport, et al, "Propagation and Radio System Design Issues in Mobile Radios Systems for the GloMo Project", Bradly Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Revised January 31, 1997.

[17] For example: Weissberger, M., "An Initial Critical Summary of Models for Predicting the Attenuation of Radio Waves by Trees," IIT Research Institute, July 1982 (prepared under contract F-1962-80-C-0042 for the DoD Electromagnetic Compatibility Center).; and Saxton, J., Lane, J., "VHF and UHF Reception, Effects of Trees and Other Obstacles," *Wireless World*, May 1995.

model should not simply add the power from a large number of UWB devices with Part 15 limits. Rather, a model should account for the fact that these devices are distributed in space from one another and that there are significant losses between them which limit the aggregate energy. An example of a worst case scenario would be numerous UWB units operating in a building. However, the emissions are limited by the losses in the internal and external walls, larger losses between floors and through the roof, and attenuation due to objects such as office furniture.

User Density

The user density and distribution of UWB transmitters also plays a part in the cumulative impact. In modeling the emissions levels from an aggregate number of UWB sources, it is inaccurate to simply sum the power from each device. Instead, the separation among devices, i.e., density, needs to be accounted for. The fact that these emitters are spacially spread from one another reduces the overall emissions at any one point.

User Duty Cycle

Another factor that limits the buildup of UWB emissions is user duty cycle, or the percentage of time that any one of these UWB devices will be operating. In a real world scenario, very few products are in operation continuously. Therefore, the cumulative impact will be lessened due to the fact that not all UWB emitters will be operating simultaneously.

Time Domain has performed a simulation that shows that the cumulative impact is not a concern. A receiver's noise floor will generally be limited by the closest UWB device not the effect of all the total number of UWB products (Appendix C). TDC's analysis is not the only analysis with these findings. Others within the Ultra-WideBand Working Group, using different approaches, found similar results, which is what one would expect, given the low power, short range, and rapid signal attenuation of emissions in the real world.

TV Broadcast and Restricted Bands

Certain frequency bands have been set aside for important uses, such as public safety and navigation, which have been deemed restricted bands, meaning intentional emissions are prohibited. These bands were established in 1989 to prevent narrowband traditional systems from congregating in the restricted bands, when they could easily be moved into other spectrum to avoid these systems. However, their spurious emissions and emissions from unintentional radiators are allowed to place energy into these restricted frequency bands since they are broadband sources and cannot simply avoid these bands. In fact,

- Between 1 & 5 GHz, **47.6%** of the spectrum is within restricted bands and
- Between 1& 10 GHz, **44.6 %** of the spectrum is within restricted bands.

Thus it is nearly impossible to avoid placing unintentional radiation into the restricted bands. Emissions from incidental radiators, such as hair dryers, electric razors, power tools, automobiles, and arc welders, are not even regulated and have been found to radiate equal to or significantly greater than Part 15 power levels into the restricted

bands[18]. Ultra-wideband emitters are unlike traditional narrowband or wideband systems that can easily be frequency allocated and required to avoid intentionally emitting into the restricted bands. UWB bandwidths span several GigaHertz of spectrum, and similar to unintentional radiators, cannot be assigned to a frequency band outside of the restricted bands.

The Commission has asked: if the restricted bands were retained, how would this affect the viability of UWB? The restricted bands are very disruptive to the TM-UWB waveform, and the performance degradation is dependent upon the application. It is assumed that if restricted bands are retained that the only option available to UWB engineers would be to use notch filters to reduce the emissions within the restricted bands to field strengths below the already low limits of Part 15. It is further assumed that the rules would be modified to specify some acceptable limit that is practical from the UWB designer's perspective. [19]

Notch filters disrupt impulse signals by two mechanisms. First, they remove power in the notched band and any adjacent band necessary to make a realizable filter. For a fixed

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[18] See September 11, 1998, Ex Parte Presentation on the Time Domain Corporation Waiver Request.

[19] If some type of filtering were to be required, the rules should be amended to allow other than spurious emissions in the restricted bands, albeit at lower levels than in other parts of the spectrum. As it now stands, Section 15.205 of the Rules would allow no intentional emissions in the restricted bands other than those that can fit within the definition of "spurious." Thus, even notching would not be feasible in the strict semantic sense because a notched signal would still be other than a spurious signal.

power spectral density over the band, this removes total energy available for the UWB device. This equates to approximately half of the energy being eliminated for an UWB system between 1 and 5 GHz because of the large number of restricted bands. Typically much more energy is removed than is indicated by the restricted band fraction of bandwidth due to the skirts of the filter response function. Filters can be made sharper, but this requires more poles, higher Q, larger components, and results in a larger, higher cost product, and drastically increases the phase distortion of the UWB pulse.

The second mechanism of signal disruption is time dispersion of the waveform. This results from the complex ringing modes of the filter tuned circuits. When hit with an impulse, a notch filter would ring for an appreciable time. Because impulse receivers prefer to operate by correlating for one cycle, the spreading of the energy over time results in an additional loss that may be greater than the attenuation from the notched bands. Even with utilizing various tools and techniques, such as, rake receivers, complex matching templates and corrective filters, which significantly increase the size and complexity of the design, the detrimental impact of notch filters will never be overcome. Appendix D contains additional information about the distortion of TM-UWB waveforms that would result from notch filtering.

Notch filters will significantly degrade UWB communications links and geo-ranging systems in various ways. By filtering out some of the energy along with spreading the energy in time, notch filters obviously decrease the signal available to the receiver, and

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Notwithstanding this definitional issue, however, notching would be so disruptive as to

thus decrease the signal to noise ratio. For communication systems, the decrease in bandwidth reduces processing gain resulting in reduced channel capacity. Also, because of the distorted pulse, the place on the waveform where the receiver is locked is no longer known as accurately and therefore the ranging and positioning capability has been decreased. The extended pulse also adversely affects the ability of ranging devices to determine with precision the time of arrival of the first arriving signal associated with the direct path. Further, when the notch filters spread and distort the pulse in time, the bandwidth effectively decreases and the UWB system suffers unrecoverable losses of two major benefits: multipath immunity and jamming resistance. The UWB system becomes as vulnerable to fading effects and multipath problems as are wideband and narrowband systems. As for jamming immunity, UWB performance suffers in two ways: (1) energy has been taken away from the available signal and (2) the pulse has been distorted and lengthened, thereby weakening correlation properties and resistance to interference. As a result, notching drastically reduces or completely nullifies all of the factors, which make UWB technology a unique and superior solution.

The impact of notch filters on radar equipment is more severe than experienced in communication and geo-ranging systems. The distortion caused by notch filters effectively extends the duration of the pulse. This artifact degrades the range resolution prized by UWB systems. It also produces sidelobes in the radar's response, which will significantly degrade advanced processes such as imaging and object identification.

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render most UWB applications unfeasible.

Once again, the viability of UWB for radar applications would be greatly impaired by notch filters.

Furthermore, one of the key factors for the commercial viability of UWB technology is the low cost of implementation, which results from processes that may not be simple, but are substantially digital – leading to highly integrated ASIC designs. A requirement for notch filters, which cannot be implemented easily in ASIC form compromises the size, weight, and cost factors for UWB products. The consumer ultimately pays the price for unnecessary filters in significantly reduced performance, reduced convenience, and increased cost.

Measurement Technique

The current Part 15 radiated measurement technique for both intentional and unintentional radiators, which is laid out in detail in ANSI C63.4, specifies two different types of spectrum analyzer measurements with the division point at 1 GHz. For emissions below 1 GHz, the requirement is to utilize a quasi-peak detector with a resolution bandwidth (RBW) of 120 kHz, and video bandwidth (VBW) of 300 kHz. Above 1 GHz, the emissions limits require average and peak measurements. The peak measurement is performed using a peak detector, RBW of 1 MHz, and VBW of equal or greater bandwidth. This peak measurement is limited to 20 dB above the average limit. The average measurement is similar to the peak measurement, except the VBW is reduced to 100 Hz, and sometimes down to 30 Hz. This measurement is compared to the average limits specified for frequencies above 1 GHz. Note for frequencies above 1

GHz, the rules call out that a RBW of at least 1 MHz be used, however, all test labs appear to employ a 1 MHz RBW. The reasoning behind this is simple, most analyzers with 3 MHz RBW filters are unreliable with regard to shape factor from unit to unit. Therefore, the unwritten standard for resolution bandwidth is 1 MHz for frequencies above 1 GHz.

The rules also require, in an unclear and ambiguous way, that pulse desensitization be applied in pulsed signal cases. The exercising of pulse desensitization is based on a Hewlett Packard Applications Note 150-2, which was derived for a uniform pulse train of pulsed sinusoidal waveforms. This Application Note was originally written to help radar engineers determine the peak envelope power of their pulse, which is more desirable for radar performance estimates. The goal was to determine the total peak envelope power by adjusting for the duty cycle of the pulsed sinusoidal waveforms, or by backing out from the resolution bandwidth of the analyzer to the entire emitted RF bandwidth of the pulsed waveform. Time Domain has written several papers and letters to the Commission over the last couple of years explaining why pulse desensitization does not apply to the short pulses of UWB technologies. Below are several reasons why pulse desensitization is not applicable, and further details can be found in Appendix E.

- The purpose of applying a pulse desensitization factor is to ensure an accurate estimate of the radiated peak envelop power of the UWB emitter when the measurement instrument does not have sufficient bandwidth to intercept the whole signal. It is not used to estimate the interference potential of an emission, which is the goal of Part 15 measurement procedures. Since wideband and narrowband systems

can only intercept a small fraction of the total energy of the UWB pulse, a measure of the radiated peak envelop power of a UWB signal would greatly overestimate the interference potential of the UWB emission. If a receiver were able to receive the entire UWB radiated signal, then the receiver would also intercept emissions from significantly higher power transmitters such as those uses by licensed users. In addition, if it were proper to apply pulse desensitization to UWB signals, it would then be necessary to apply it to the measurements of spurious emissions from much higher powered licensed and even secondary allocation services, as well as high powered systems within the restricted bands.

- Pulse desensitization is not applied to unintentional radiators. The short pulses of UWB devices look much like the short pulses produced by computer motherboards due to the fast switching. (Appendix E shows measurements from personal computers, which show that their emissions are similar to those from TM-UWB systems.) Over the last 20 years, the Part 15 radiated emissions limits and measurement technique for unintentional radiators, where pulse desensitization was not being employed, have proven to furnish protection against harmful interference to licensed services and other valuable systems. Therefore, historically the application of pulse desensitization is unnecessary and unwarranted in the case of UWB emissions.

- A concern that gets at the heart of the pulse desensitization issue, revolves around the impact of short pulses on the front ends of wideband receivers. The concern is that these short pulses may cause the front ends of wideband receivers to become non-linear or exhibit compression. Time Domain provides results in Appendix F of an

experiment performed to test the impact of short pulses on wideband low noise amplifiers, generally the most vulnerable component of a receiver to interfering RF signals. The experiment found that all the amplifiers tested remained in the linear regime and were not affected by the short pulses inherent in UWB technologies. Time Domain has shown that the short pulses associated with UWB emissions do not cause the front ends of receivers to become nonlinear, which would be the primary reason for trying to find the peak envelope power by pulse desensitization. Therefore, there is more than adequate protection without applying this factor, which is inapplicable to UWB waveforms, and if used would overestimate the interference potential.

- Additionally, utilizing a pulse desensitization factor for UWB systems would needlessly penalize the available emissions by more than 20 dB. Cutting the allowed power by that factor would render UWB products no longer commercially viable.

Time Domain recommends that the Commission apply the current measurement techniques, outlined at the beginning of this section, to UWB technologies without the pulse desensitization factor. These measurement techniques fairly and adequately determine the electric field strength of a Part 15 device whether it is a traditional narrowband system, unintentional radiator, or UWB product. In addition, these techniques, in conjunction with the Part 15 emissions limits, have proven to provide protection against harmful interference to licensed services, restricted band operations, and other users of the spectrum.

There are other specific details of the measurement technique that need to be addressed involving ground-coupled ground penetrating radars (GPR). Time Domain suggests that

the Commission consider measuring the leakage radiation from ground-coupled GPRs in a scenario that better emulates their normal operating mode. A possible technique would be to measure the field strength at the appropriate measurement distance from the vehicle or antenna structure when it is situated above a two foot thick standard material with a dielectric constant that is equivalent to that of dry sand, a case when antenna coupling to the ground tends to be low.

Damped Sinewave Issue

Time Domain recognizes that some perceive a passing resemblance between UWB waveforms and damped sinewaves. However, UWB waveforms are not mathematically similar. Moreover, unlike damped sinewaves transmissions, TM-UWB receivers process all the emitted TM-UWB signal and through that process are spectrally efficient. Damped sinewaves are prohibited specifically because they are extremely spectrally inefficient.

Conclusion

UWB technologies, in general, and Time Modulated Ultra-Wideband technology, specifically, have unique, highly beneficial attributes. These technologies can be applied to both enabling new products as well as improving the performance of existing products. Many products such as through-wall motion detectors for law enforcement and public

safety and automotive sensors have the potential to save lives and the requisite performance is simply not achievable with narrowband or even wideband RF technologies. Beneficial UWB products can be introduced in the US marketplace within the spirit of the existing Part 15 regulations. The FCC can, with only minor modifications of existing rules, allow their introduction with knowledge that harmful interference will not occur if the regulations as proposed by Time Domain are adopted and adhered to.

Current Class A & B emissions limits that apply to digital devices will provide enough power for a variety of viable commercial systems and at the same time protect licensed users and restricted band operators. And just as these limits prevent harmful interference today, they will continue to prevent harmful interference even with the introduction of UWB devices.

Restricted bands are a rational regulatory mechanism for traditional narrowband or wideband systems that can operate within frequency allocations, however, the mechanism does not work for UWB devices. Nevertheless, the emissions limits already specified for unintentional digital devices are adequate to protect systems operating within the restricted bands. This is continuously being demonstrated by the billions of unintentional radiators currently emitting energy into these bands. Attempts to notch out UWB emissions from the restricted bands will defeat the purpose of using UWB systems.

The current measurement techniques, without the application of pulse desensitization are adequate for UWB.

Since the UWB industry already has products that it could introduce with the potential save lives, the Commission should expeditiously proceed with a Notice of Proposed Rulemaking with the goal of completing the process within the coming year.

Conclusion

Section 7 of the Communications Act states that it "shall be the policy of the United States to encourage the provision of new technologies and services to the public." 47 U.S.C. § 157 (1998). By implementing a regulatory framework that will provide for the regular authorization of ultra-wideband technology for a host of beneficial applications, the Commission will fulfill this statutory mandate. In so doing the Commission should move forward with the issuance of a notice of proposed rule making designed to bring the benefits of UWB technology to the American people.

Respectfully submitted,
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Appendix B	Field Strength Requirements of Time-Modulated Ultra-Wideband Systems for Various Applications
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TIME DOMAIN

THE NEW WIRELESS MEDIUM™

Appendix A

TIME MODULATED ULTRA-WIDEBAND TECHNOLOGY

TECHNOLOGY BASICS

TDC's TM-UWB transmitters emit ultra-short "Gaussian" monocycles with tightly controlled pulse-to-pulse intervals. TDC has been working with monocycle pulse widths of between 1.50 and 0.20 nanoseconds (billionths of a second) and pulse-to-pulse intervals of between twenty-five and one thousand nanoseconds. These short monocycles are inherently ultra-wideband.

The systems use pulse position modulation. The pulse-to-pulse interval is varied on a pulse-by-pulse basis in accordance with two components: an information signal and a channel code.

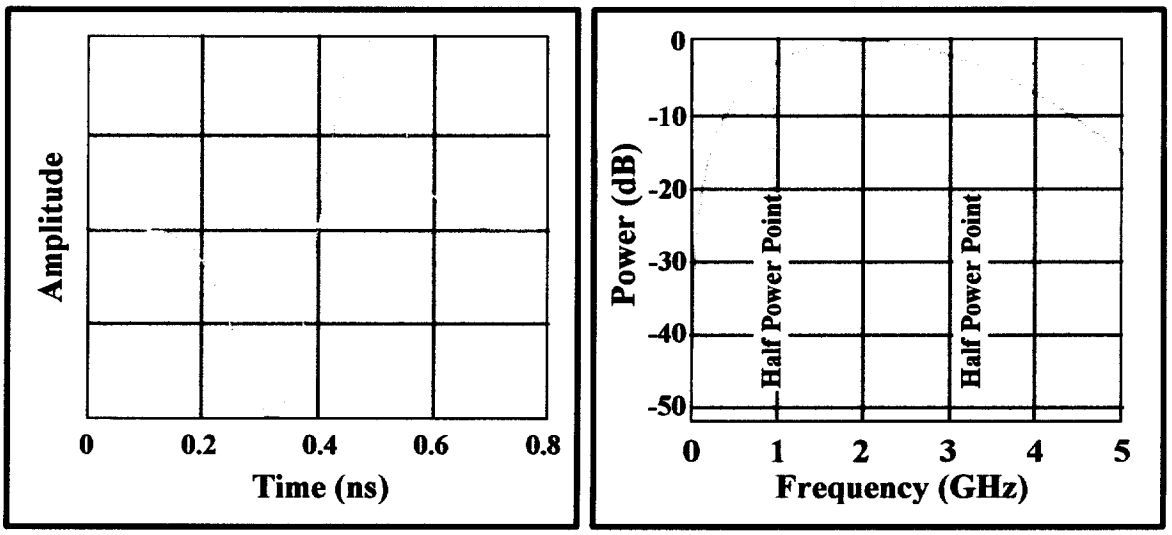
The TM-UWB receiver directly converts the received RF signal into a baseband digital or an analog output signal. A front end cross correlator coherently converts the electromagnetic pulse train to a baseband signal in one stage. There is no intermediate frequency stage, greatly reducing complexity.

A single bit of information is generally spread over multiple monocycles. The receiver coherently sums the proper number of pulses to recover the transmitted information.

GAUSSIAN MONOCYCLE

The most basic element of TDC's impulse radio technology is the practical implementation of a Gaussian monocycle. Figure 1 shows the monocycle in both the time and frequency domains.

2 GHz Center Frequency Gaussian Monocycle in Time and Frequency Domains
Figure 1



The monocycle is a wide bandwidth signal, with the center frequency and the bandwidth completely dependent upon the monocycle's width. In the time domain, the Gaussian monocycle is mathematically similar to the first derivative of the Gaussian function:

$$V(t) = 6A\sqrt{\frac{e\pi}{3}}\frac{t}{tau}e^{-6\pi\left(\frac{t}{tau}\right)^2} \tag{1}$$

Where, A equals the peak amplitude of the monocycle; tau is a time decay constant that determines the monocycle's duration; and t is time.

In the frequency domain, a Gaussian monocycle's spectrum is given by:

$$V(f) = -j\frac{2f(tau)^2}{3}\sqrt{\frac{e\pi}{2}}\,e^{\frac{\pi}{6}f^2(tau)^2} \tag{2}$$

The center frequency is:

$$f_c = 1/tau \tag{3}$$

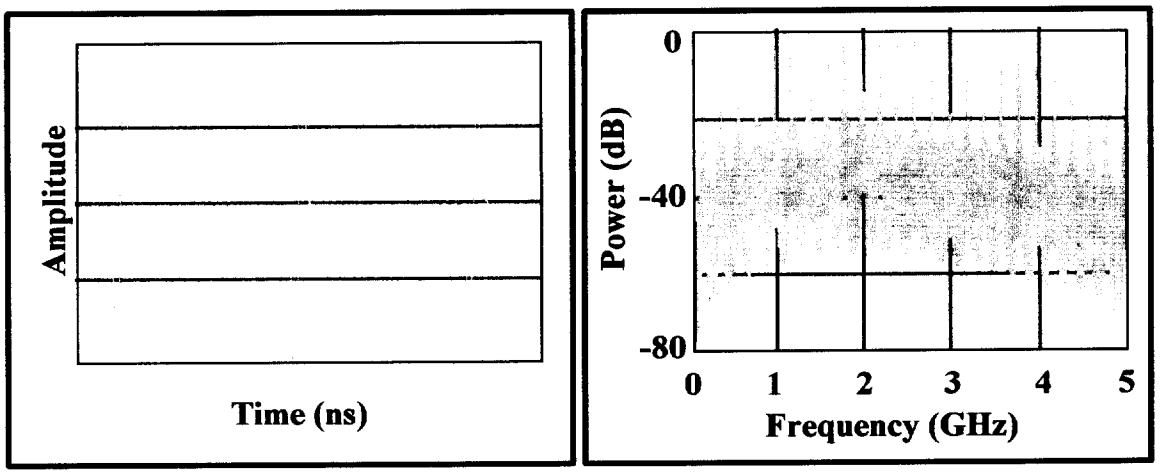
The center frequency of a monocycle is the reciprocal of the monocycle's duration and the bandwidth is 116% of the monocycle's center frequency. Thus, for the 0.5 ns monocycle shown in Figure 1 the center frequency is 2 GHz and the half power bandwidth is approximately 2 GHz.

A MONOCYCLE SEQUENCE

Time modulation systems use long sequences of monocycles, not single monocycles, for communications. TDC's prototypes have pulse repetition frequencies of between 1 and 40 million pulses per second (Mpps). Figure 2 contains an illustration of a Gaussian monocycle pulse train. In the frequency domain, this highly regular monocycle pulse train produces energy spikes ("comb lines") at regular intervals; thus, the already low power is spread among the comb-lines. This monocycle pulse train carries no information and, because of the regularity of the energy spikes, might interfere with conventional radio systems at very short ranges.

TM-UWB systems have very low duty cycles and Figure 2 exaggerates the typical duty cycle found in TDC's prototypes. In actual implementation the actual duty cycle is less than 1%.

A Monocycle Pulse Train In The Time and Frequency Domains
Figure 2

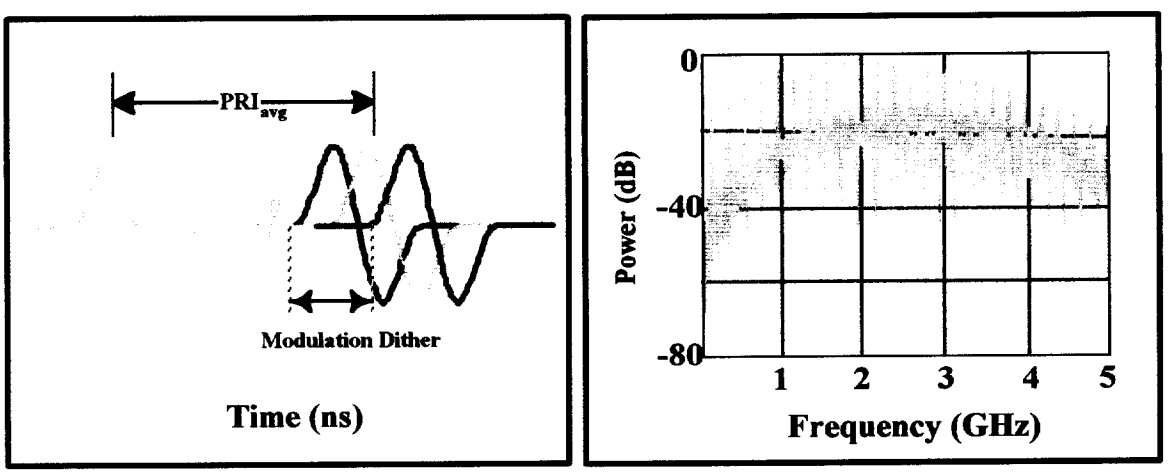


MODULATION

Additional processing is needed to modulate the monocycle pulse train, so the system can actually transmit information.

TDC's systems use pulse position modulation as this technique allows the use of an optimal receiving matched filter technique. TDC's receivers use a cross-correlator that gives the homodyne receiver the ability to find the signal well below the ambient noise level.

Pulse Position Modulation
Figure 3



As illustrated in Figure 3, pulse position modulation varies the precise timing of transmission of a monocycle about the nominal position. For example, in a 10 Mpps system, monocycles would

be transmitted nominally every 100 ns (represented in Figure 3 as the time period PRI_{ave}). In such a system a "0" digital bit might be represented by transmitting the pulse 100 ps early and a "1" digital bit by transmitting the pulse 100 ps late.

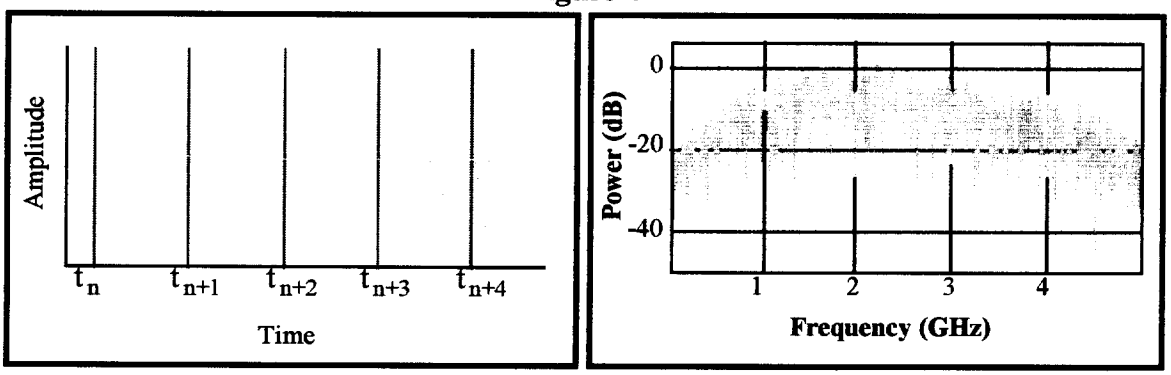
As shown in the right hand graph in Figure 3, pulse position modulation distributes the RF energy more uniformly across the band (it "smoothes" the spectrum of the signal), thus making the system less detectable. However, because information modulation only moves the pulses only a fractional part of a pulse width, this spectral smoothing impact is small.

PSEUDO-RANDOM NOISE CODING

Coding for channelization

At this point, any modulated pulse train looks like any other pulse train; it is not channelized. However, by shifting each monocycle's actual transmission time over a large time frame in accordance with a code one can channelize pulse trains. As illustrated in Figure 4, TDC applies a relatively large time offset (many nanoseconds) to each impulse. TDC uses "pseudo-random noise" codes ("PN codes") for this purpose. In a multiple access system, each user would have their own pseudo-random noise code sequence. Only a receiver operating with the same pseudo-random noise code sequence can decode the transmission.

The Impact of Pseudo-Random Time Modulation on Energy Distribution in the Frequency Domain
Figure 4



In the frequency domain, this pseudo-random time modulation make TDC's signal appear like pure white noise. As a result, anyone without knowledge of the PN code, attempting to detect the presence of the signal would have to be very close to the transmitter and even then would be unable to decode the transmission without significant effort.

RECEIVING MONOCYCLE TRANSMISSIONS

Having generated a signal with minimal spectral features, it is also necessary to have an optimal receiving system so that the power that must be transmitted is also minimized. The optimal receive technique, and the technique used in TM-UWB, is a correlation receiver ("correlator"). A

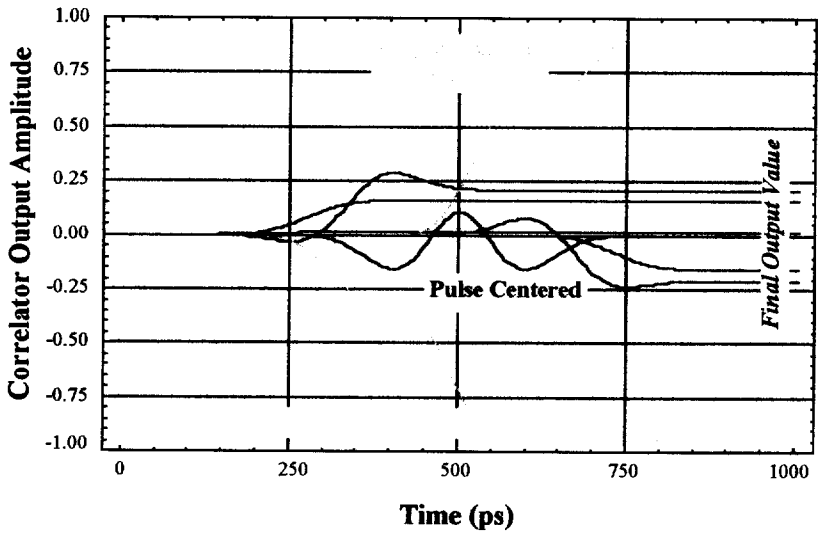
correlator multiplies the received RF signal with a "template" waveform and then integrates the output of that process to yield a single DC voltage. This multiply and integrate process occurs over the duration of the pulse and so it also occurs in less than a nanosecond.

With the proper template waveform, the output of the correlator is a measure of the relative time positions of the received monocycle and the template. Figure 5 shows the output of the correlator that corresponds to different time offsets between the template and the received waveform.

As shown in Figure 5, the correlator is an optimal early/late detector. When the received pulse is ¼ of a pulse early, the output of the correlator is a −1; when it is ¼ of pulse late, the output is +1; and when the received pulse arrives centered in the correlation window, the output is zero.

It is critical to note that the mean value of the correlator is zero. Thus, for in-band noise signals received by a TM-UWB the correlator's output value has an average value of zero. Moreover, the standard deviation (RMS) of the correlator output is related to the power of those in-band noise signals.

Correlator Output
Figure 5



When a monocycle is buried in the noise of other signals, it is impossible to detect the reception of a single TM-UWB pulse. However, by adding together numerous correlator samples, it becomes possible to receive transmitted signals. This process is called "pulse integration." Through pulse integration TM-UWB receivers can acquire, track and demodulate TM-UWB transmissions that are significantly below the noise floor. The measure of a TM-UWB receiver's performance in the face of in-band noise signals is processing gain.

Processing Gain and Jamming Resistance

Pseudo-random and random time modulation when combined with the correlator make time modulated radios and radars highly resistant to jamming from all radios. This is critical as all other signals within the band occupied by an time modulated signal act as jammers to the time modulated radio and, since there are no unallocated 1+ gigahertz bands available for time modulated systems, time modulated radios will have other signals within their operating band.

Processing gain is a measure of a radio's resistance to jamming. Time modulated radios have huge processing gain.

One definition of processing gain is the ratio of the bandwidth of the signal to the bandwidth of the information signal. For example, Qualcomm's spread spectrum system with a 8 kHz information bandwidth and a 1.25 MHz channel bandwidth yields a processing gain of 156 (22 dB). An impulse system transmitting the same 8 kHz information bandwidth and a 2 GHz channel bandwidth the processing gain is 250,000 or 54 dB.

Alternatively, the process gain for an impulse signal may be calculated from:

- The duty cycle of the transmission, e.g., a 1% duty cycle yields a process gain of 20 dB.
- The effect of pulse integration, e.g., integrating energy over 100 pulses to determine one digital bit yields a process gain of 20 dB.
- The total process gain is then the sum of these two components, e.g., 40 dB.

A 2 GHz / 10 Mpps link transmitting 8 kbps would have a process gain of 54 dB, because it has a 0.5 ns pulse width with a 100 ns pulse repetition interval = 0.5% duty cycle (23 dB) and 10 Mpps / 8,000 bps = 1250 pulses per bit (another 31 dB).

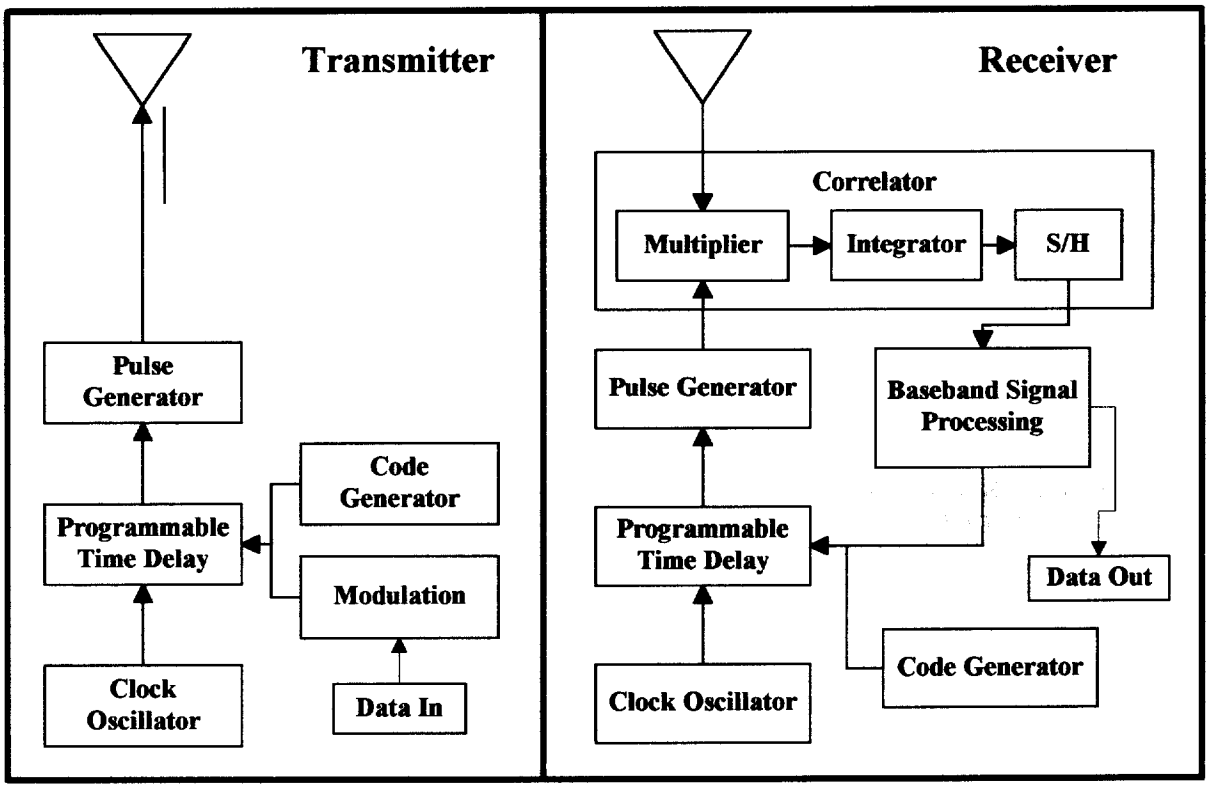
BLOCK DIAGRAM

Figure 6 is a high level block diagram of both a TM-UWB transmitter and receiver. As shown, the transmitter does not contain a power amplifier as the transmitted pulse is generated by a pulse generator at the requisite power. A critical part of the pulse generation circuit is the antenna, which acts as a filter.

The receiver resembles the transmitter, except that the pulse generator feeds the multiplier within the correlator. Also, baseband signal processing must extract the modulation and control signal acquisition and tracking.

The blocks in red have been implemented as full custom silicon germanium ICs. The blocks in green can be implemented in standard CMOS.

Block Diagram
Figure 6



SYSTEM CAPACITY

A theoretical analysis[1], conducted for TDC by University of Southern California Professor R.A. Scholtz suggests that TDC's impulse radio system could have thousands of voice channels per cell without special signal processing algorithms. Others have analyzed the system, and using more realistic assumptions, estimate the capacity to be between 200 and 1000 simultaneous duplex 64 kbps telephone conversations per base station, depending upon numerous environmental factors and also without special signal processing algorithms.

Using a cellular architecture and standard radio engineering practices, e.g., sectorized base station antennas, TDC can achieve even higher densities of simultaneous users.

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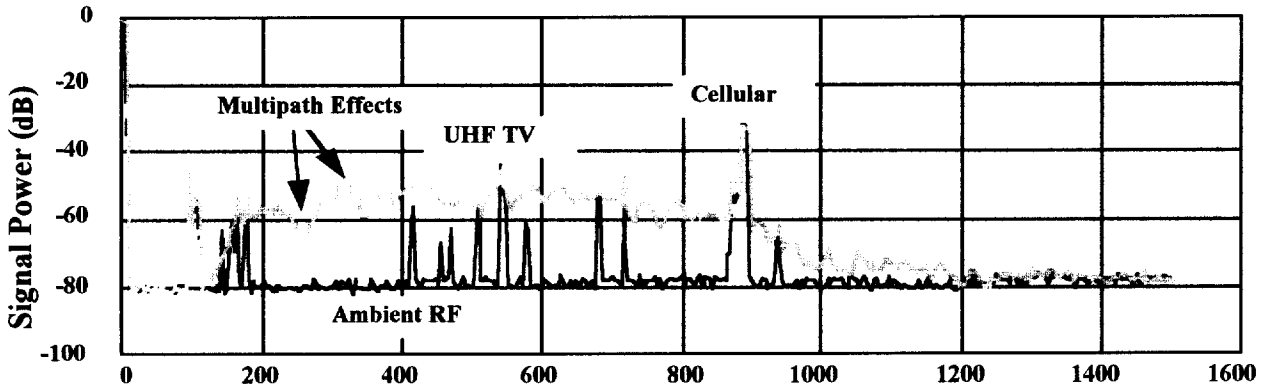
[1]See: R.A. Scholtz, "Multiple Access with Time-Hopping Impulse Modulation" (invited paper), MILCOM'93, Bedford, MA, Oct. 11-14, 1993.

PERFORMANCE IN THE REAL WORLD

TDC'S TEST SYSTEMS

Time Domain has built numerous prototypes. The prototypes include simplex and duplex communications systems and short range radars. Early prototypes were constructed of discrete off-the-shelf components. However, Time Domain is now using full custom silicon-germanium integrated circuits to perform the functions of the RF correlator circuitry and the timing subsystem. The programmable time delay IC parses time to 3 ps steps.

675 MHz Impulse Signal At 3 Meters*
Figure 7



*Measurements not adjusted to compensate for antenna performance.

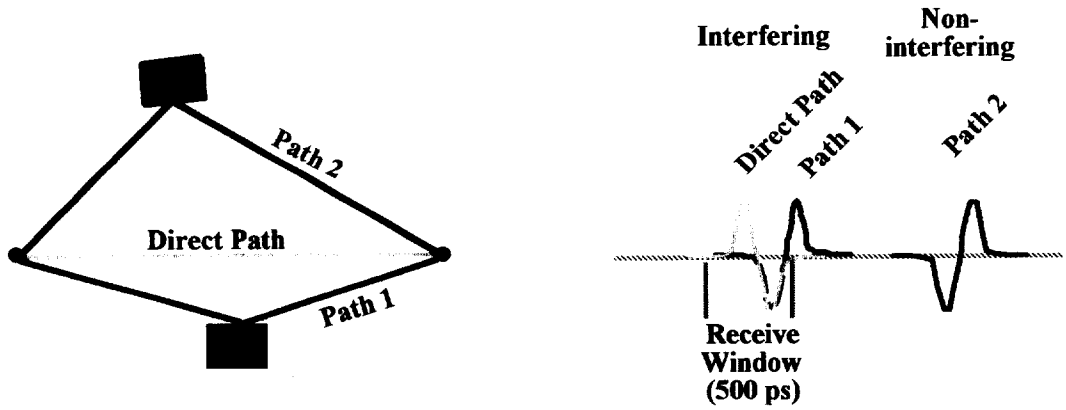
An early prototype built by TDC has an average radiated power of 450 μW. The center frequency is 675 MHz. Figure 7 shows the signal measured at 3 meters, as well as ambient signals. (The "bumpiness" of the TM-UWB spectrum reflects the impact of multipath. Moving the receive antenna around causes the location of nulls and peaks to move. This does not impact the performance of the impulse system. See "Multipath and Propagation" below.

In October 1997 Time Domain demonstrated a 1.7 GHz TM-UWB full duplex radio with an RF bandwidth in excess of 1.3 GHz. The output power was approximately 1.8 mW. At 32 kbps, the link range was in excess of 900 meters. Recent improvement to the design have integrated simultaneous radio ranging with a resolution of 0.1 foot and improved communications range substantially.

MULTIPATH AND PROPAGATION

Rayleigh, or multipath fading, so noticeable in cellular communications, is a continuous wave phenomenon. Multipath fading is not a problem for time modulated systems.

Multipath In An Impulse System
Figure 8



In a time modulated system, in order for there to be multipath effects, one of two conditions must persist. Either:

- The path lengthtraveled by the multipath pulse must be less than the pulse width times the speed of light. For a one nanosecond pulse, that equals 0.3 meters or about 1 foot, i.e., [1 ns] x [300,000,000 meters/second]. (See Figure 8); or
- The multipath pulse travels a distance that equals the interval of time between pulses times the speed of light might interfere times an integral number with the next pulse. (For a 1 Mpps system that would be equal to traveling an extra 300, 600, 900, etc. meters.) However, because each individual pulse is subject to the pseudo-random time modulation, these pulses are decorrelated.

Monocycles traveling between these intervals do not cause self-interference (in Figure 8), this is illustrated by the monocycle traveling Path 2). While pulses traveling grazing paths, as illustrated in Figure 8 by the narrowest ellipsoid, create impulse radio multipath effects.

Time Domain Measurement of 1.3 GHz Impulse Signal at 8 Meters
Figure 9

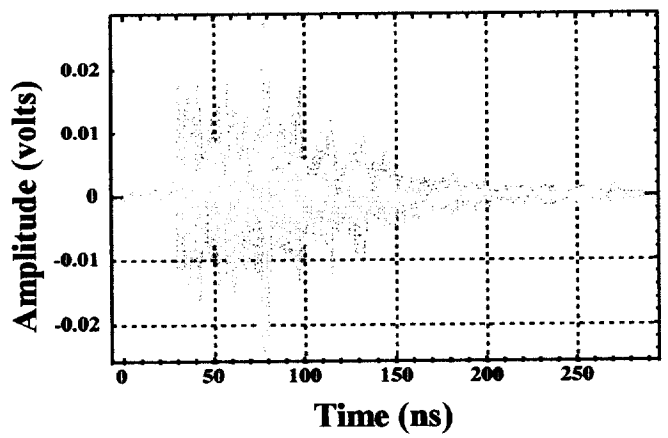


Figure 9 shows how easily a time modulated radio can resolve multipath. These measurements were made in a standard commercial office building. The transmit and receive antennas were 8 meters apart with three interior wall between them. These walls were constructed of steel studs and plaster board.

As can be seen in Figure 9, the environment disperses a sub-one nanosecond pulse over at least one hundred nanoseconds. In the frequency domain, this becomes Rayleigh fading; however, for TM-UWB radio, each of these reflections is an independent signal that can be received.

Channel models of TM-UWB signals do not exist. The difficulty is that such models must be developed using time domain data with at least several hundred picosecond resolution. At present this can be accomplished only at short ranges (less than 500 meters) with existing test equipment and only then under ideal circumstances. Time Domain is now constructing an instrument that will be able to measure the impulse response of the environment with sub-ten picosecond resolution. Data from this instrument will resemble the data in Figure 9, but over much longer time scales (microseconds if necessary). With such an instrument Time Domain expects to characterize TM-UWB channels many different environments. Such models will characterize for example the number of signal paths available, their power distribution, etc.

SIMPLICITY

TDC's time modulated radios are much simpler to build than equivalently sophisticated conventional radios.

The transmitter is much simpler than a narrowband transmitter, it is simply a single transistor that operates in a digital mode – it flips from a "0" state to a "1" state, this transition produces a step waveform that can be easily filtered to produce a monocycle. Thus, unlike conventional transmitters it does not contain a linear amplifier. This reduces cost and power consumption.

The receiver is also simpler than a narrowband receiver as it does not require IF stages. And unlike spread spectrum receivers, the control loop operates at very low frequencies, which also saves cost.

Preliminary studies suggest that a time modulated transmitter and receiver front end can be build on a single chip. TDC sees no impediments to producing an impulse radio and radar systems that could sell for less than $200.

SUMMARY

TDC's impulse radios have far superior performance in high multipath environments than narrowband radios, including spread spectrum technologies. Multipath is a critical problem for most radio system because people live in environments where there are lots of objects that reflect radio signals. In these environments, time modulated radios can operate at high data rates with lower bit error rates and with lower transmit powers than conventional radios.