Recent System Applications of Short-Pulse Ultra-Wideband (UWB) Technology

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Invited Paper

***Abstract*—Developed in the early 1960s, time-domain electromagnetics, the study of electromagnetic-wave propagation from a time-domain perspective, has given birth to a fascinating new technology, which today is commonly referred to as ultra-wideband (UWB). It has now been slightly more than 25 years since the 1978 seminal paper of Bennett and Ross, which summarized UWB's early applications. It thus seems appropriate, given the tremendous increase in interest in the technology since the Federal Communications Commission modified its Part 15 rules to accommodate UWB transmissions, to take a look at more recent system applications of this unique technology. This paper provides a brief historical perspective of UWB, discusses recent techniques for the generation and reception of short-pulse electromagnetic waveforms, and examines a number of recently developed UWB systems in the communications, radar, and precision-positioning fields. Finally, a brief assessment of future trends for the technology is provided.**

***Index Terms*—Broad-band communication, electromagnetic transient analysis, position measurement, pulse-shaping methods, radar, radar applications, transient propagation, ultra-wideband (UWB).**

I. Introduction

Although often considered a recent breakthrough in broad-band wireless technology, ultra-wideband (UWB) has actually experienced well over 40 years of technological advancement. The origins of the technology stem from work in the early 1960s on time-domain electromagnetics [1], the study of electromagnetic-wave propagation as viewed from a time domain, rather than from the more common frequency-domain perspective. In fact, one might reasonably argue that UWB actually had its origins in the spark gap transmission designs of Marconi in the late 1890s and in his celebrated cross-Atlantic transmission using spark techniques on December 12, 1901.

Much like spread-spectrum signaling, which originated in military applications during World War II as a means for defeating enemy torpedoes and which reached commercial awareness only some 40 years later (Federal Communications Commission (FCC) Notice of Inquiry, June 1981), UWB followed a somewhat similar path, with early systems designed for military, low probability of detection (LPD) (i.e., covert) radar, and communications applications, and with commercial interest being "sparked" only much later by an FCC Notice of Inquiry in 1998 [2] and a subsequent Report and Order in February 2002 [3]. The term "UWB" originated with the Defense Advanced Research Projects Agency (DARPA) in a radar study undertaken in 1990, serving as a convenient means for discriminating between conventional radar and those utilizing short-pulse waveforms having a large fractional bandwidth (i.e., $>25\%$) [4]. The first (1973) fundamental patent on UWB communications systems simply referred to the technology as "base-band pulse" [5].

In its infancy, UWB was commonly referred to as "carrier-free," "baseband," or "impulse," reflecting the fact that the underlying signal generation strategy was the result of a broad-band extremely fast rise time, step, or impulse, which shock, or impulse, excited a wide-band antenna (e.g., TEM, mode horn). Interestingly, several of the early patents in UWB failed to recognize the myriad of contributions made to the discipline by researchers who had patented their results using the earlier terminologies.

The underlying excitation for these early UWB systems was typically generated at baseband using either step recovery or tunnel diodes, with the resultant radiated spectrum produced without the use of conventional carrier-based technologies (i.e., local oscillators, mixers, etc.). Due to the extremely short time duration of this baseband excitation, the generated waveform was essentially the impulse response of the radiating element. Thus, in these early systems, the operational center frequency, as well as the instantaneous bandwidth of the radiated emission, was strongly dependent upon the electromagnetic characteristics of the antenna itself.

From a radar perspective, short-pulse UWB techniques exhibit at least seven distinct advantages over more conventional radar approaches. These advantages include: 1) higher range measurement accuracy and range resolution due to the shorter spatial extent of the transmitter waveforms; 2) enhanced target recognition due to detection of additional information from a target's separate elements; 3) immunity to passive "interference" (i.e., rain, fog, clutter, aerosols, metallized strips, etc.) because the radar cross section (RCS) of the interference is now comparable with that of the target's RCS; 4) increased immunity to co-located radar transmissions due to decreased pulse-on-pulse probabilities; 5) increased detection probability for certain classes of targets due to the elimination of the lobing structure of the targets' secondary patterns (i.e., signals scattered by separate target elements do not interfere); 6) increased

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radar operational security because of the extremely large spectral spreading; and 7) ability to detect very slowly moving or stationary targets [6].

For communications applications, short-pulse UWB techniques offer increased immunity to multipath cancellation due to the ability to discriminate between direct and time-orthogonal reflected waves, low interference to legacy systems when properly designed to minimize the effects of spectral lines, and increased communications operational security. Furthermore, low-pulse-rate UWB systems have the additional advantage of having extremely low duty cycles, which translate into low average prime power requirements, ideal for battery-operated equipment.

Finally, for active RF tracking and positioning applications, short-pulse UWB techniques offer distinct advantages in precision time-of-flight measurement, multipath immunity for leading edge detection [i.e., first time of arrival (TOA)], and low prime power requirements for extended-operation RF identification (RFID) tags.

Today, however, because of the broad definition promulgated by the FCC for UWB transmission technologies in its recent UWB Report and Order—namely, 20% fractional or 500-MHz minimum bandwidth regardless of the modulation type or method of transmission—a number of broad-band "UWB" variants of more conventional modulation strategies [e.g., wide-band orthogonal frequency division multiplexing (OFDM) and code division multiple access (CDMA)] are being considered for application to such areas as wide-band personal area networking (WPAN).[1] In this paper, however, we restrict our discussion to those systems that utilize impulse, or short-pulse, techniques. Short-pulse systems, typically characterized by very low duty cycles with resultant high peak-to-average power ratios, are quite unlike modern UWB variants of conventional modulations that are typically characterized by constant envelopes, which result in nearly equal peak and average power densities.

The remainder of this paper will include a brief historical perspective of short-pulse UWB techniques, a brief overview of short-pulse generation and reception techniques, an examination of several recently developed UWB systems, and a brief assessment of future trends for the technology. While several companies have developed short-pulse UWB systems (e.g., Time Domain Corporation's RadarVision through-wall radar, Aether Wire and Location's UWB Localizer, McEwan Technologies' Motion Sensor and Range Finder, etc.), this paper will restrict discussion to those systems developed by the author's company, Multispectral Solutions Inc. (MSSI), Germantown, MD.

II. Brief Historical Perspective

The origins of UWB technology stem from work in time-domain electromagnetics begun in the early 1960s to fully describe the transient behavior of certain classes of microwave networks by examining their characteristic impulse response [7]–[12]. The approach was actually motivated by research and development performed nearly a decade earlier at the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, Lexington, and at the Sperry Corporation, Natick, MA, to develop phased-array radar systems [13]. The problem encountered was that the wide-band properties of the network used to steer the array (in this case, a Butler hybrid phasing matrix, an interconnection of 3-dB TEM mode branch-line couplers) were not well understood and exceedingly difficult to model. It became clear that working in the time domain, where the responses of these microwave networks were easier to interpret and more compact mathematically, would result in a more straightforward determination of the correct solution.

The fundamental concept was quite simple and had been known for many years. Instead of characterizing a linear time-invariant (LTI) system by the more conventional means of a swept frequency response (i.e., a series of amplitude and phase measurements versus frequency), an LTI system could alternatively be fully characterized by its time-domain response to an impulsive excitation—the *impulse response* $h(t)$. In particular, the output $y(t)$ of such a system to any arbitrary input $x(t)$ could be uniquely determined by the convolution integral [14]

$$y(t) = \int_{-\infty}^{\infty} h(u)x(t-u)du \tag{1}$$

where $x(t)$ is the input signal, $h(t)$ is the impulse response of the network, and $y(t)$ is the corresponding output waveform. However, this was easier said than experimentally accomplished. For up until 1962, there were no convenient means to observe, let alone measure, waveforms having subnanosecond durations, as were required to suitably approximate an ideal impulsive excitation. Fortuitously, at about the same time [15], Hewlett-Packard introduced the time-domain sampling oscilloscope, which greatly facilitated these measurements.

Time-domain electromagnetics would have probably remained a mathematical and laboratory curiosity, however, had it not occurred that these techniques could also be applied to the measurement of wide-band radiating antennas [16], which are also LTI systems. However, unlike a microwave circuit such as a microstrip filter, in which the response to an impulsive voltage excitation could be measured in circuit, the impulse excitation of an antenna results in the generation of an electromagnetic field that must be detected and measured remotely. The time-domain sampling oscilloscope, with an external wide-band antenna and amplifier, was used to perform this remote measurement. It became immediately obvious that one now had the rudiments for the construction of an impulse radar or communications system [1].

The last element that needed to be developed before real system development could begin was the short-pulse, or threshold, receiver. In the early 1970s, both avalanche transistor and tunnel diode detectors were constructed in attempts to detect these very short duration signals. The tunnel diode, invented in 1957 by Esaki who would later receive the Nobel Prize in physics in 1973 for this accomplishment, was the first known practical application of quantum physics. This unique device, with its extremely wide bandwidth (at the time, tens of

[1]See, for example, the IEEE 802.15 WPAN High Rate Alternative PHY Task Group 3a (TG3a). [Online]. Available: http://grouper.ieee.org/groups/802/15/pub/TG3a.html

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gigahertz) permitted not only subnanosecond pulse generation essential for impulse excitation, but also could be used as a sensitive thresholding device for the detection of short-pulse waveforms. In 1962, both Tektronix and Hewlett-Packard introduced time-domain sampling oscilloscopes based upon the tunnel diode for high-speed triggering and detection, first enabling the capture and display of UWB waveforms. The successful implementation of a sensitive portable short-pulse receiver [17] further accelerated system development. Early UWB receiver work culminated in the development by Nicolson and Mara [18] of the tunnel diode constant false-alarm rate (CFAR) receiver, with improved versions still in use today [19], [20].

With all the system building blocks in place, numerous applications of short-pulse technology were developed for short-range radar sensing, metrology, communications, and more recently, precision positioning [21]. One of the best bibliographies on short-pulse UWB technology up to the 1998 FCC Report and Order can be found in the U.S. Patent and Trademark Office *Reexamination Certificate* upholding the patentability of McEwan's *Ultra-Wideband Radar Motion Sensor* (U.S. Patent 5 361 070) [22]. The public record in FCC Docket ET 98-153,[2] "Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems" also contains extensive biographical material, analyses, and data on short-pulse techniques from 1998 to the present.

III. Short-Pulse Technology

Early techniques for the generation of short-pulse RF waveforms utilized the rapid rise or fall times of a baseband pulse to impulse or shock excite a wide-band antenna. The antenna, in turn, generated its characteristic impulse response which, for a wide-band structure, typically consisted of an electromagnetic burst containing only a few RF cycles of energy (Fig. 1). By varying the physical dimensions of the antenna, the frequency and bandwidth characteristics of the resulting UWB pulse could be adjusted.

One of the earliest baseband sources [1] used a Marx generator to develop a fast rise-time high-voltage step, which, would, in turn, be applied to a step recovery diode (SRD) positioned at the aperture or feed point of the antenna. Invented by Marx in 1924, the Marx generator is a clever technique for generating high-voltage short-duration waveforms by charging a number of capacitors in parallel, then quickly discharging them in series. While originally based upon the use of air-dielectric spark gaps to provide the switching mechanism, solid-state variants utilizing avalanche diodes or other solid-state switching devices have been used to generate nanosecond duration pulses having amplitudes exceeding several thousand volts of dc [23]. The SRD further sharpens the rise time of the Marx generator output to approximate a true baseband impulse excitation [24]. Since SRDs are generally limited to breakdown voltages of less than 100 V or so, multiple SRDs were often connected in series across the antenna aperture to permit the development of a very large voltage impulse or baseband excitation. The resultant baseband pulse $p(t)$ typically consisted of a relatively fast subnanosecond rise time followed by a slower multiple nanosecond decay. However, there were several problems with this approach.

First of all, the energy in the baseband excitation pulse drops logarithmically with frequency, a natural consequence of the doubly exponential time-domain behavior. For example, a simplistic mathematical model for the baseband excitation pulse is given by the relationship

$$p(t) = t \exp\left(\frac{-t}{\alpha}\right) u_{-1}(t) \tag{2}$$

where α is the effective rise time (for a positive-going pulse) and u_{-1} is the unit step function. The magnitude squared of the Fourier transform of $p(t)$, i.e. the signal energy density, has an asymptotic behavior given by

$$|P(f)|^2 = \frac{\alpha^4}{16\pi^4 f^4} \tag{3}$$

which exhibits a -12 dB per octave decay with frequency. Fig. 2 illustrates this phenomenon for an SRD baseband source with $\alpha \sim 130$ ps.

As a result, the amount of energy available at microwave frequencies is significantly lower than the full bandwidth baseband power. As an example, a 350-V peak output baseband exciter, which used a GaAs thyristor switch (PowerSpectra PGS 102), generated 2450 W into a 50-Ω load for approximately 250 ps. When applied to a 500-MHz bandwidth antenna at L-band (1.5-GHz center frequency), the measured peak power output was approximately 1 W. Thus, nearly all of the power was dissipated as heat, albeit for only a 250-ps duration. In addition, the much higher amplitude low-frequency content has an undesirable tendency to impulse excite other portions of the circuitry—e.g., the antenna feedline, circuit board traces, etc.—all of which results in emissions at other than the desired operating frequency. Furthermore, if the antenna is modified, either intentionally or unintentionally, the frequency and bandwidth of the resultant emission can change appreciably [25].[3]

Using such techniques, the pulse repetition frequency (PRF) of the impulse source is ultimately limited by heating effects at the higher duty cycles, as most of the energy is returned as an unwanted reflection. PRFs of greater than a few hundred kilohertz are, thus, very difficult to obtain if significant peak output power is desired.

More recently, several alternative approaches for the generation of short-pulse waveforms have been developed [26]. These techniques have included time-gated oscillators, low-level impulse sources with time-gated power amplification for prime power minimization, and a combination of conventional heterodyning and gated power-amplifier design. The latter combination design remedies the logarithmic power drop off with a purely baseband excitation. Unique to many of these more modern approaches is the ability to incorporate additional

[2]The public record in FCC Docket ET 98-153 can be accessed by logging into the FCC's Electronic Comment Filing System (ECFS) website. [Online]. Available: http://svartifoss2.fcc.gov/prod/ecfs/comsrch_v2.cgi

[3]Reference [25] is available on the FCC's E-filing site and on the MSSI website. [Online]. Available: http://www.multispectral.com/pdf/MSSI_091200.pdf

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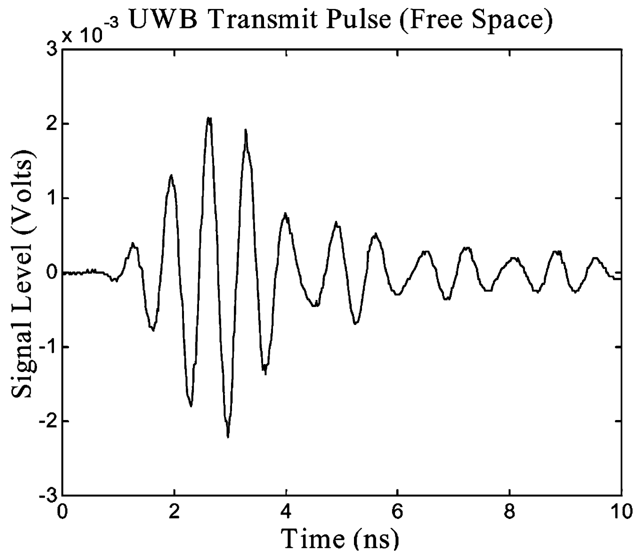

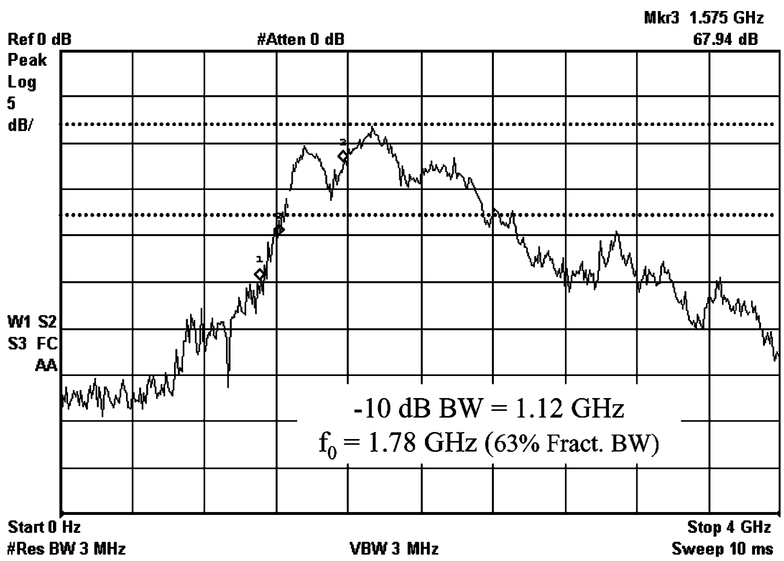

Fig. 1. Typical UWB pulse in time and frequency domains. (a) Typical UWB pulse—a few cycles of RF energy. (b) Typical UWB power spectrum from an impulse excited wide-band antenna.

filtering, which greatly reduces electromagnetic susceptibility problems, particularly at the lower microwave and VHF/UHF frequencies. Figs. 3–6 illustrate a number of these more modern short-pulse UWB transmitter designs. In Fig. 3, a low-level impulse-gated or "switched" oscillator is used to produce an extremely wide-band pulse, which can operate at elevated pulse repetition frequencies well in excess of several hundred megapulses per second. Precise control of radiated frequency is governed by the choice of oscillator, which can either have a known stable frequency or be voltage-controlled for short-pulse frequency-hopping applications. Switched-oscillator UWB sources have been used well into the millimeter-wave bands for applications to electromagnetic susceptibility testing of legacy systems [27].

A variant of the impulse-gated oscillator UWB source is derived through the use of analog or digital time gating, as illustrated in Fig. 4. Rather than utilizing an external mixer, an oscillator is either turned on/off with an external control signal, or a free-running oscillator is time gated using an external switch. Additional frequency, phase, and amplitude control can be used to produce a wide variety of UWB modulations.

Finally, Fig. 5 shows the use of a low-level impulse generator (e.g., SRD, avalanche, or break-over device, etc.) and a bandpass or pulse-shaping filter. This circuit design is particularly useful for nonfrequency-agile operation at frequencies below 5–6 GHz. In this case, the UWB signal's center frequency and bandwidth are primarily determined by the characteristics of the bandpass or pulse-shaping filter, rather than the characteristics of the antenna response. This is particularly important in the design of UWB transmitters whose frequency response characteristics cannot be either unintentionally, or intentionally, altered by modifications to the radiating element [25].

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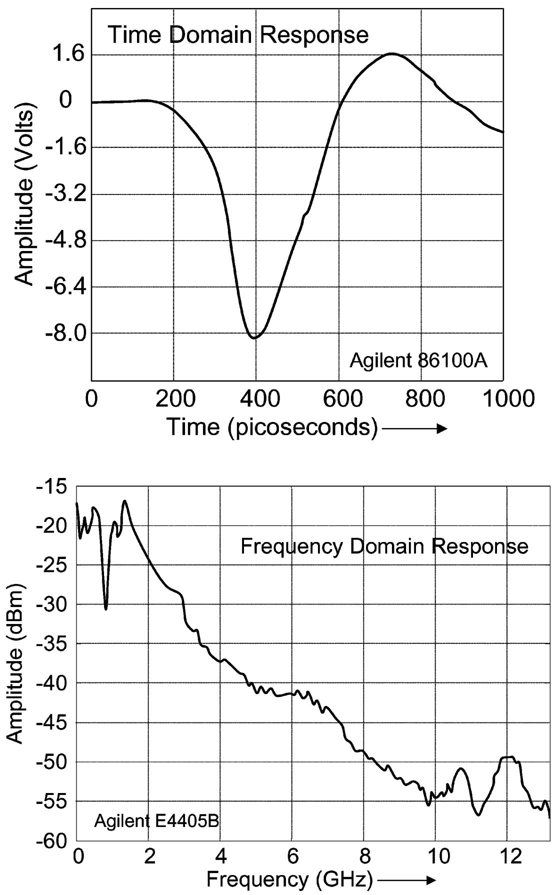

Fig. 2. Doubly exponential baseband pulse in time and frequency domains. (MSSI, Model TFP1001 Impulse Source).

Note that, for lower power short-pulse transmitters such as those required to meet FCC Part 15 limitations, the fast rise time of a modern digital chip is often sufficient to generate the requisite power levels. In this case, the PRFs exceeding several hundreds of megahertz are achievable without device heating limitations; however, such techniques have limited applicability to short-pulse systems requiring ranges greater than a few meters. For longer range systems, such as those described below, the output of a low-level impulse source is typically followed by some form of gated power amplifier, where time gating is employed to reduce average power consumption.

For short-pulse receiver design, several techniques have been used ranging from simple threshold and energy detectors [17], [19], [20] to more complex correlation techniques [28]. Interestingly, in the case where the received waveform accumulates a uniformly distributed random phase offset from that of the transmitted burst (e.g., due to reflections, noncoherent pulse generation, etc.), the simple threshold detector (matched filter—envelope detector) can be shown to perform optimally [29]. A modern tunnel diode threshold receiver [19], in which tunnel diode bias is adaptively adjusted to obtain a desired receiver operating characteristic, i.e., probability of detection versus false-alarm rate, is illustrated in Fig. 6. Here, an extended dynamic range is also achieved through the use of decision-directed automatic gain control (AGC).

Even today, the most sensitive short-pulse receivers continue to use the Esaki tunnel diode in an energy-detection configuration. As a detector, the tunnel diode requires no bias, has an extremely broad-band and flat frequency response (extending well into millimeter waves), exhibits excellent temperature stability (typically ± 0.5 dB typical over temperature extremes), and has very low $1/f$ noise. Also, the tunnel has been used with a constant current bias source, adjusted to position the diode's quiescent operating point near the peak of its *I–V* curve, i.e., just before its negative resistance region. In this configuration, the diode behaves as a charge sensitive device where a small amount of received charge forces the diode to transition its negative resistance region (the transition typically measured in tens of picoseconds) to produce a measurable voltage output. One very important advantage of energy detection is that the received pulse shape is irrelevant. This becomes particularly advantageous in severe multipath conditions where pulse-shape distortion occurs due to time-varying frequency-selective fading.

In Section IV, a number of UWB system designs will be presented to illustrate some of the more unique features of short-pulse technology. In each of these designs, the receiver utilizes a tunnel diode energy detector and the transmitter uses a spectrally shaped or filtered waveform prior to excitation of the antenna.

IV. Recent Short-Pulse UWB Systems

Here, we consider a set of representative examples of short-pulse UWB systems, which highlight the more unique properties of the above-mentioned UWB waveforms. These systems span the gamut of UWB communications, radar sensing, precision localization, and RFID. Each of the systems presented below has been developed and fielded by MSSI over the past three years and represent recent examples of a variety of short-pulse electromagnetics applications.

A. Recent Short-Pulse Communications Systems

In the area of short-pulse communications, we consider the three recent UWB transceiver examples: 1) DRACO; 2) ORION; and 3) airborne wireless intercommunications system (AWICS). Each UWB transceiver is configured as a network radio, accommodating multiple simultaneous users; however, each design also has an unique application.

DRACO, a UWB mobile ad hoc radio, utilizes a combination of frequency-division multiplex (FDM) and time-division multiple access (TDMA). The transceiver is designed to automatically reconfigure its routing paths based upon estimates of dynamic changes in the environment. Designed for extended-range operation over multiple kilometer ranges, DRACO supports both encrypted voice/data and higher speed (nonencrypted) video transmissions.

ORION, on the other hand, has a fixed TDMA architecture and utilizes a "star" network configuration in which a single master is used to coordinate transmissions among multiple slave units. As such, it was designed for squad-level-type communications, where all transceivers are in communications range with the master. Unique to ORION is its dual-frequency mode, which permits both line-of-sight (LOS) operation at low microwave frequencies (L-band), and extended non-LOS propagation through the use of low VHF frequencies.

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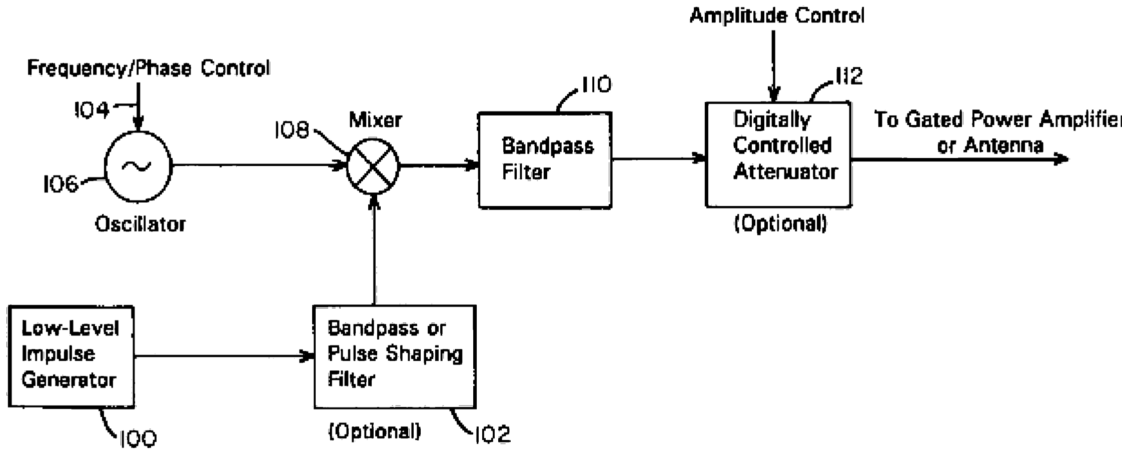

Fig. 3. Switched-oscillator UWB source [26, from, U.S. Patent 6 026 125].

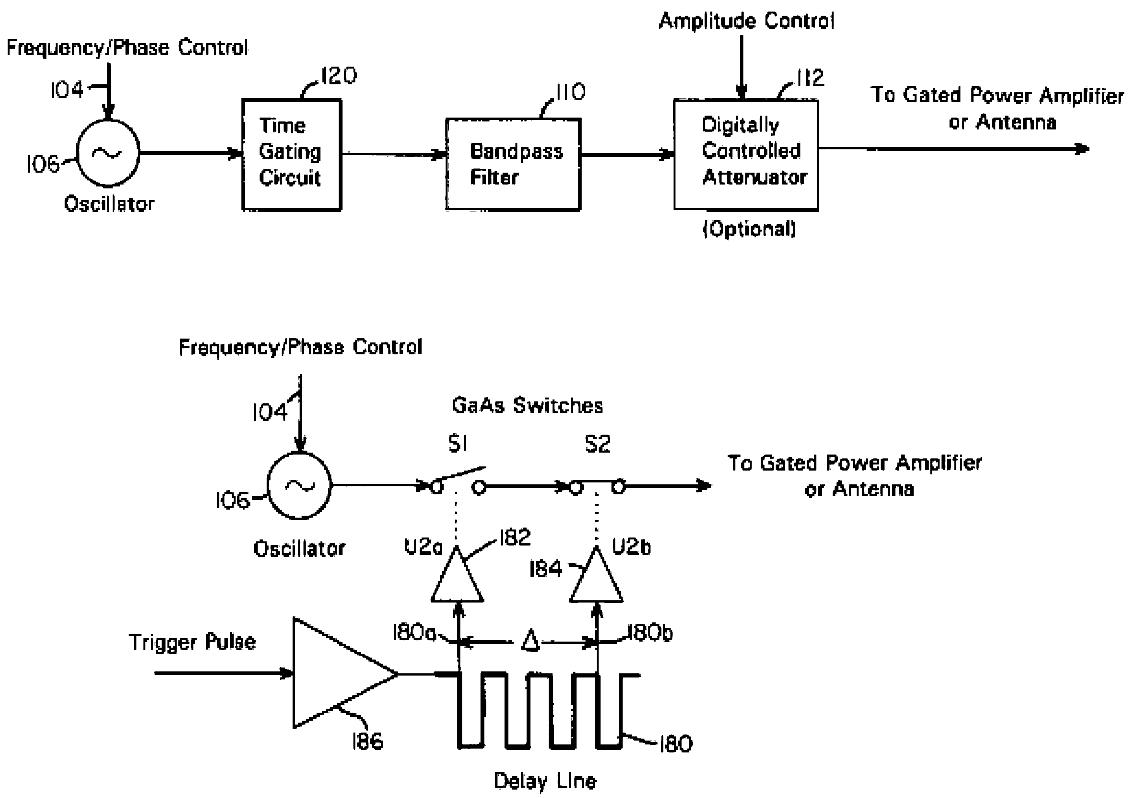

Fig. 4. Alternative configurations for gated oscillator UWB sources [26, from U.S. Patent 6 026 125].

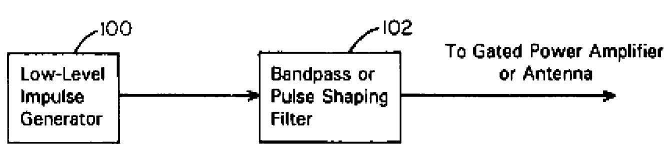

Fig. 5. Filtered low-level impulse UWB source [26, from U.S Patent 6 026 125].

AWICS, another example of a short-pulse TDMA architecture, is specifically designed for use in extremely high multipath environments such as those commonly encountered inside helicopters and aircraft. As such, its data rate and packet structure was selected to permit operation in the presence of severe signal reverberation.

Each of these transceiver designs will now be considered in more detail.

1) DRACO UWB Network Transceiver: The vast majority of work performed to date in UWB communications has been related to militarily critical applications requiring LPD, multiuser capability, and/or extended operational ranges. One of the more interesting examples is a system that achieves all three of these objectives. DRACO is a proof-of-concept high-speed multichannel UWB network incorporating both communications security (COMSEC) and transmission security (TRANSEC) capabilities. COMSEC is achieved through the use of Type-1 encryption, while TRANSEC is accomplished through the use of an unique spectrally filtered UWB waveform design. The operational range for a DRACO transceiver pair is

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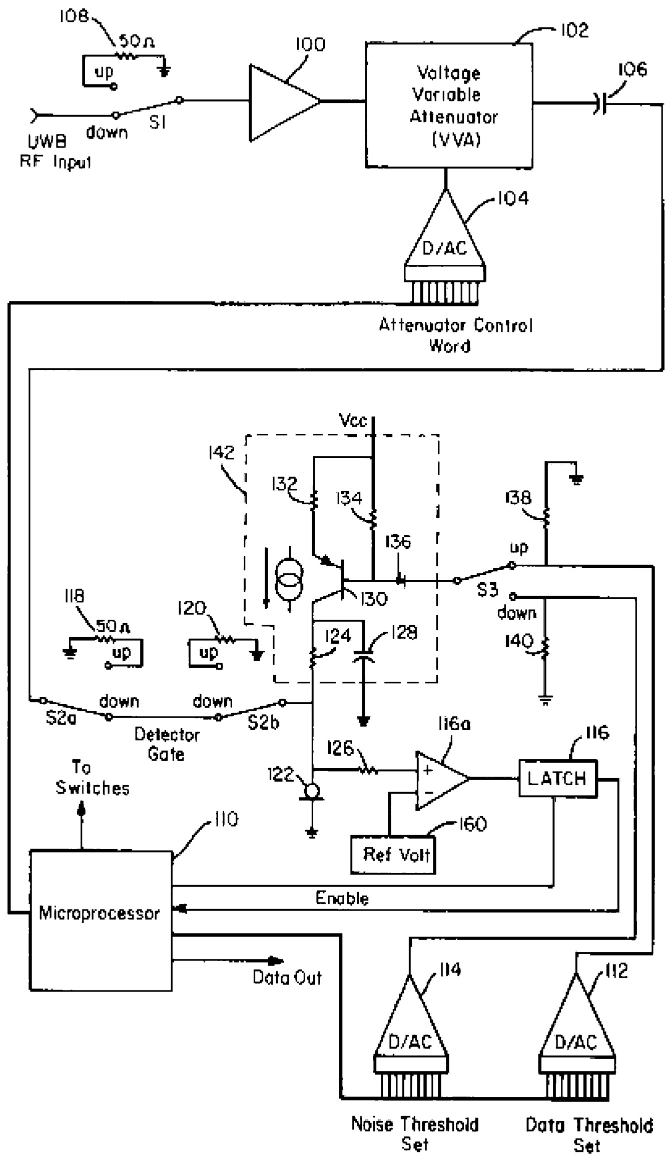

Fig. 6. Active tunnel diode threshold receiver [19, from U.S. Patent 5 901 172].

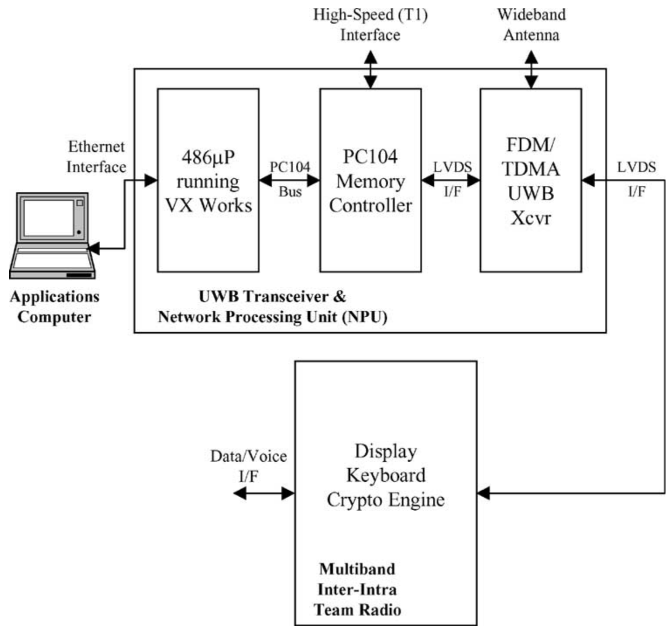

Fig. 7. DRACO UWB transceiver system block diagram.

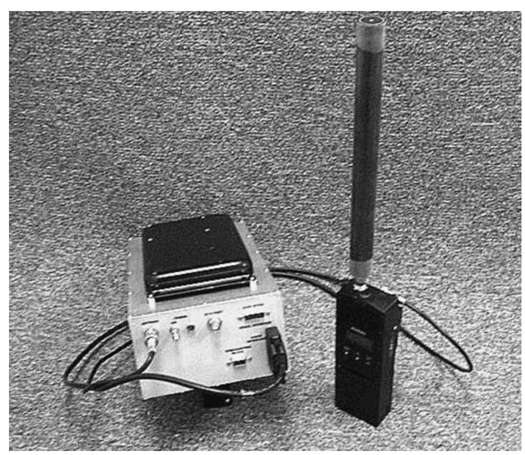

Fig. 8. DRACO UWB communications node. MBITR handheld interface on right-hand side, UWB transceiver with NPU unit on left-hand side.

approximately 1–2 km, depending upon terrain. The hardware configuration of a single DRACO transceiver node is illustrated in Fig. 7.

Each DRACO node (Fig. 8) consists of a handheld user interface incorporating a modified Thales Communications Inc. (formerly RACAL Communications), Alexandria, VA, multiband inter/intra team radio (MBITR), FDM/TDMA UWB transceiver and network processing unit (NPU). The external MBITR electronics includes control and crypto interfaces, digital voice vocoder, RS232 serial data interface, keypad control, and liquid crystal display (LCD). All modes of operation for the DRACO transceiver are controllable via the MBITR front-panel keypad.

DRACO nodes support full network functionality using either Type-1 encrypted voice or data (12–16 kb/s) or unencrypted medium- to high-speed data at rates from 115.2 kb/s to 1.544 Mb/s (T1). A DRACO transceiver node can be operated as an unattended communications relay, originating sensor (e.g., video, seismic, acoustic, etc.) communications node, reachback satellite packet node, or destination terminal. DRACO UWB electronics include a VHF/UHF multichannel UWB transmitter, companion multichannel UWB Receiver, and digital processor.

Within the DRACO hardware, a field-programmable gate-array (FPGA)-based digital processor implements all high-speed UWB transceiver functions including RF control, timing recovery, and synchronization, and Reed–Solomon forward error correction (FEC). The PC-104 based memory controller manages the interfaces between the UWB transceiver, MBITR electronics, and NPU. NPU electronics, consisting of a 486 microprocessor running VxWorks[4] and 10baseT Ethernet interface, provides an open-architecture high-performance real-time operating system (RTOS) with sophisticated networking facilities.

Unique to DRACO's UWB electronics is a UWB FDM architecture, which provides an adaptive physical layer with orthog-

[4]VxWorks is a registered trademark of Wind River Systems Inc., Alameda, CA.

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Fig. 9. ORION L-band UWB radio transceivers.

onal wide-band frequency channels. Each FDM channel is created from the direct impulse excitation of a multipole bandpass filter [26] within a bank of such filters, with subsequent gated power amplification to reach the desired peak output power. This approach significantly increases network throughput by enabling simultaneous transmissions of network management and data packets from units in close proximity without mutual interference. DRACO also utilizes a single-pulse UWB detection capability (i.e., 1 bit per UWB pulse), which permits high data-rate communications without an excessive increase in PRF. Such low burst-rate transmissions are particularly effective in maintaining an LPD.

A set of eight DRACO nodes was tested (2002) in field demonstrations at Ft. Campbell, KY. Ranges in excess of 1 km between nodes with full *ad hoc* wireless connectivity were demonstrated. A more recent version of the DRACO transceiver replaces the separate NPU with a single FPGA chip containing all networking algorithms.

2) ORION UWB Network and Ground Wave Non-LOS Transceiver: Another UWB network radio transceiver, ORION, was designed for small infantry and platoon operations with both a short-range ($\sim$1 km) and long-range ($\sim$50–60 km) back-haul capability (Fig. 9).

Unlike DRACO, which operates in the VHF/UHF bands, the short range portion of ORION operates at L-band (1–2 GHz) with an approximate 30% fractional bandwidth. The transceiver's peak output power of 0.8 W, and maximum packet burst rate of 2 Mp/s, yields a 4-mW average power, or roughly 8 pW/Hz given the transceiver's 500-MHz instantaneous bandwidth. With a short stub antenna (broad-band sleeve dipole), the units have a demonstrated operational LOS range of approximately 1 km. Packet burst transmissions are used to achieve full duplex digital voice and data at rates of up to 1 Mb/s.

For short-range tactical communications, system operation relies upon the use of a single "master" unit, which has RF coverage to all other ("slave") units. Slaves communicate through the master in a conventional star topology. Once granted channel access by the master, a slave unit continues to transmit either voice or data packets through the master to its ultimate destination. The communications channel established through the master node is symmetric in that both source and destination can communicate in full duplex fashion once the link is established. A system level block diagram of the ORION radio is shown in Fig. 10.

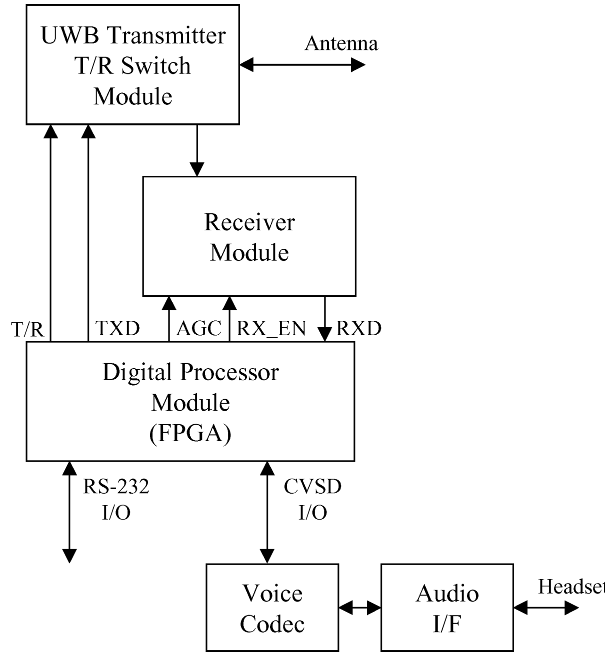

Fig. 10. ORION system block diagram.

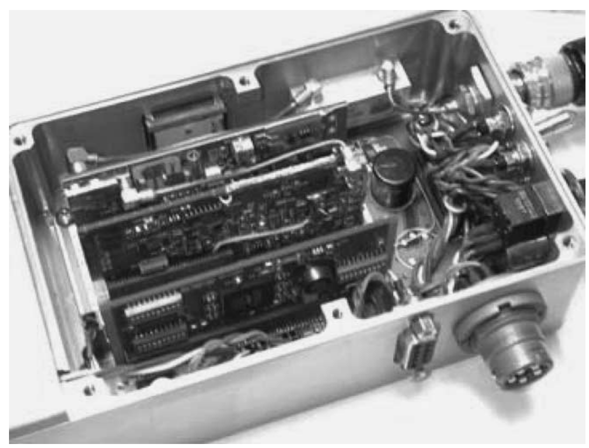

Fig. 11. Modular ORION architecture. (Top to bottom: receiver, transmitter, and processor modules).

ORION was designed to be modular in construction and consists of a motherboard and three plug-in daughter cards including UWB transmitter and transmit/receive (T/R) module, UWB receiver module, and digital processor module (Fig. 11). The modular architecture was selected to permit ORION operation in several different frequency bands.

The ORION digital processor module is also implemented in a single FPGA and performs a number of tasks including clock and timing recovery, RF gain control (AGC), bit stream processing for continuously variable slope detection (CVSD) voice, RS-232 data generation and recovery, FEC encoding and decoding, burst interleaving and randomization, and all formatting

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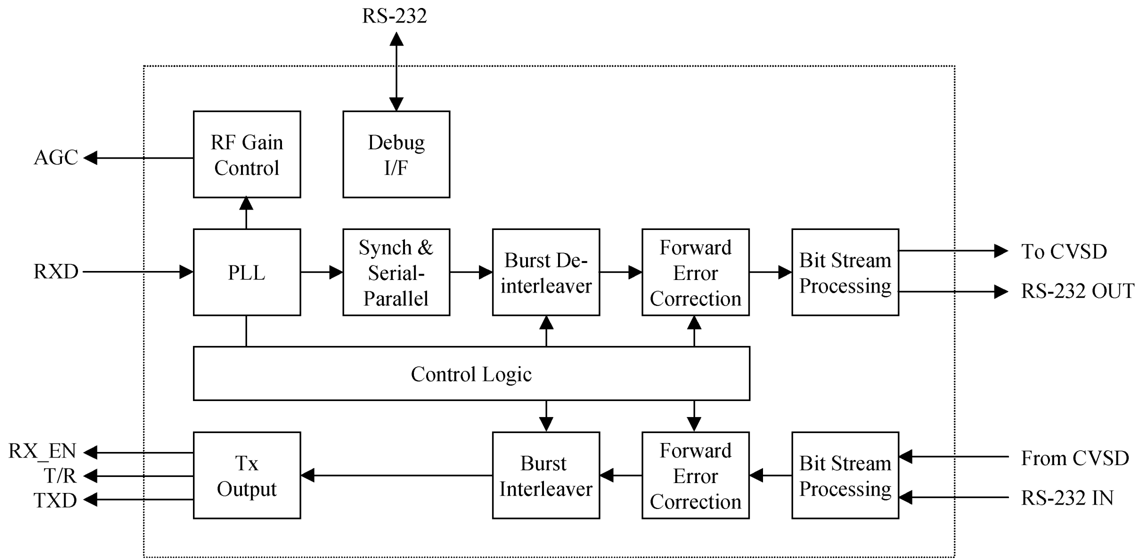

Fig. 12. Digital processor module FPGA block diagram.

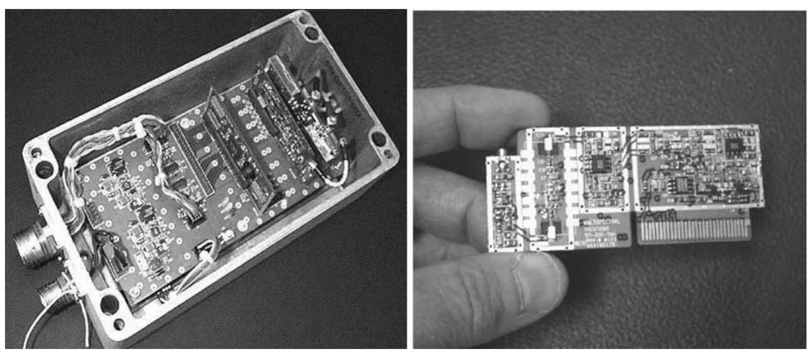

Fig. 13. Modular ORION VHF UWB transceiver. (Transceiver shown with RF front-end module.)

and sequencing logic. A block diagram of the ORION FPGA architecture is illustrated in Fig. 12.

In addition to an L-band LOS capability, ORION also incorporates an additional long-haul (~50–60 km) backbone capability. To achieve these extended ranges, frequencies in the lower VHF band were used to take advantage of surface-wave propagation, the natural tendency of an electromagnetic wave to propagate along the earth/atmosphere boundary as a result of earth currents induced by the transmitted signal's magnetic field. Signal losses using surface-wave phenomenon are considerably less than those encountered with direct wave transmission in which multipath cancellation from the ground reflected signal essentially cancels the direct path. However, surface-wave propagation is essentially a low-frequency phenomenon, which becomes increasingly inefficient for electromagnetic propagation as the frequency increases above the HF band. For the ORION non-LOS mode, a sub-band within military frequency range of 30–88 MHz was chosen. While somewhat higher in frequency than optimum for strong surface-wave propagation, this band has the unique feature that a large number of ruggedized broad-band antennas are available from a wide range of manufacturers.

For the ORION non-LOS mode, a spectrally flat 50% fractional-bandwidth waveform was used in the lower part (30–50 MHz) of the military band. With an instantaneous peak power of approximately 120 W, the transceivers achieved non-LOS ranges in excess of 8 mi on land, and over 60 nmi over water. The data throughput was 850 kb/s, permitting the transmission of simultaneous compressed video and data traffic. The low-VHF UWB transceivers are illustrated in Fig. 13 with spectral density and time-domain waveforms shown in Fig. 14.

The ORION transceivers were operated with both standard Single Channel Ground and Airborne Radio System (SINCGARS) 30–88-MHz whip antennas and a custom 30–50-MHz broad-band "fat" dipole.

3) AWICS: The Department of the Navy has long recognized the limitations and dangers of tethered long-cord intercommunications on board its Navy and Marine Corps helicopters. During the mid 1990s, the Navy began to investigate candidate technologies for a wireless intercommunications system (ICS) link replacement. A conventional spread-spectrum system was tested on board a CH-53E helicopter, the largest in the U.S. military inventory. However, with spread spectrum, multipath signal degradation was prevalent within the confines of the aircraft fuselage. Deleterious multipath effects were also encountered in communications between an internal base unit and a remote user standing outside of the aircraft while the rotor system was engaged and turning. In the latter case, the degradation was found to be caused by multipath reflections from the large rotor system. The receiver essentially

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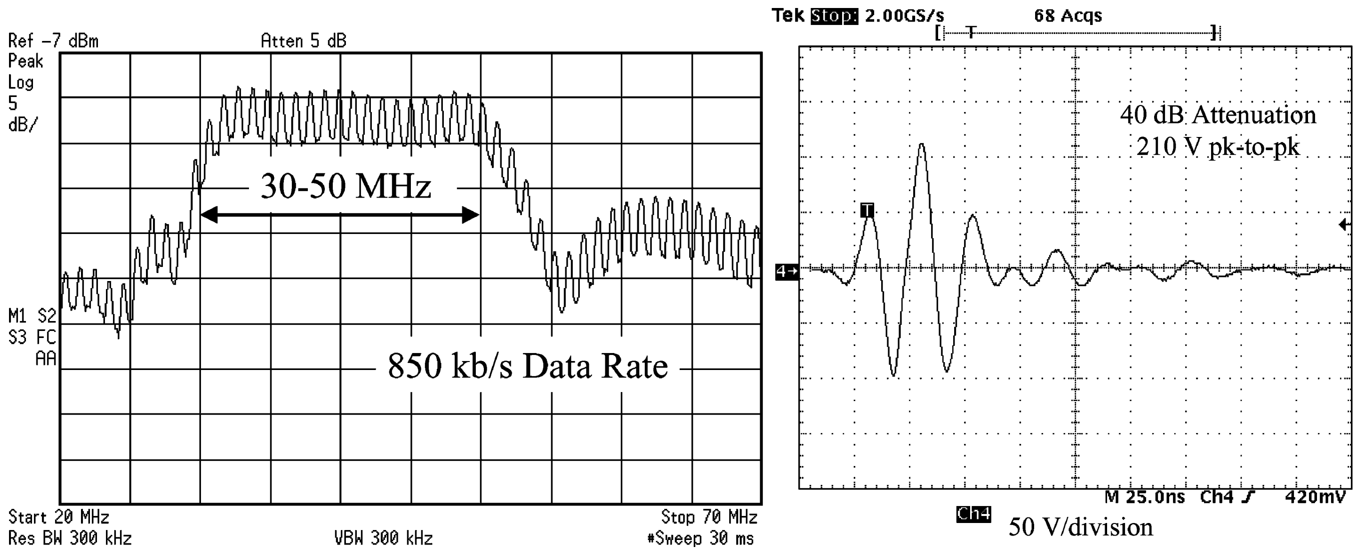

Fig. 14. Power spectrum and time-domain waveform for ORION transceiver.

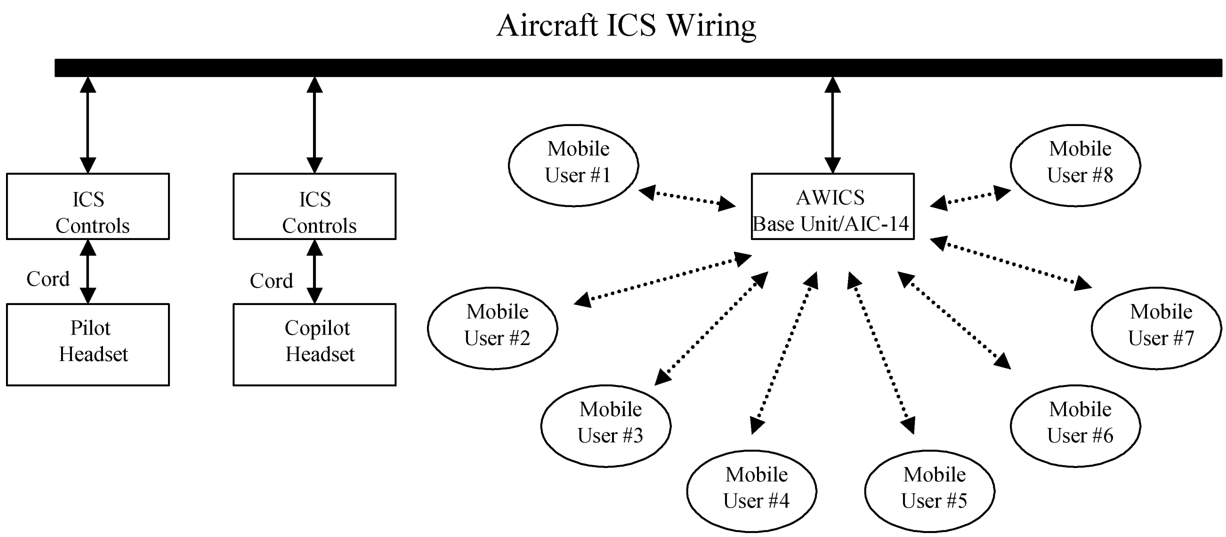

Fig. 15. AWICS conceptual design.

encountered a self-jamming situation from its own signal reflections. After an initial exploration of spread-spectrum signaling, UWB eventually emerged as a leading candidate technology for AWICS applications.

To meet Navy operational requirements, AWICS had to satisfy a number of stringent technical requirements. Among these requirements were the support for eight simultaneously transmitting (i.e., "party line") mobile users. Quality of service had to be sufficient to guaranteed reliable communications from all eight users within the fuselage of the aircraft without dropouts due to multipath or from on-board electromagnetic interference either to or from the UWB transceivers. Systems sensitive to electromagnetic interference included the automated flight control system (AFCS), electronic engine control systems, global positioning satellite (GPS) system, and other navigational aids including tactical air navigation (TACAN), very high-frequency omni range (VOR), instrument landing system (ILS) and distance measuring equipment (DME). In addition, the UWB transceivers had to exhibit an LPD capability, which would prevent unauthorized electromagnetic intercept from any appreciable distance from the helicopter.

Due to severe restrictions on available space and mounting points, antenna placement also became a critical parameter. Furthermore, mobile units were required to be of a physical size that could easily be worn and carried in a standard military survival vest. An 8-h operational lifetime for mobile units required careful attention to UWB transceiver power management issues. The basic system concept is illustrated in Fig. 15. As shown, both pilot and copilot remain tethered, whereas crewmen are permitted to be mobile.

The AWICS UWB transceiver was designed as a two board stack with dimensions 3(5/8) $\times$ 2(3/8) $\times$ 1 in, containing UWB RF, digital, power, and audio interface electronics. A separate broad-band antenna is provided, which is mounted on the front panel of the existing wired intercom (AIC-14) housing. A simplified AWICS block diagram is illustrated in Fig. 16.

The prototype vest-mounted mobile unit is shown in Fig. 17.

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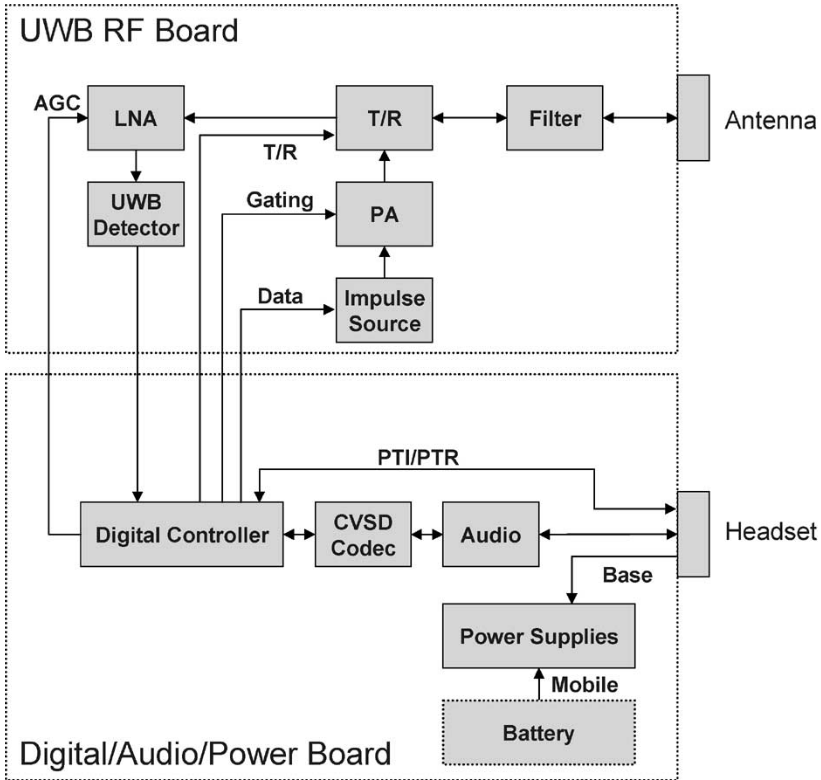

Fig. 16. Simplified AWICS system block diagram.

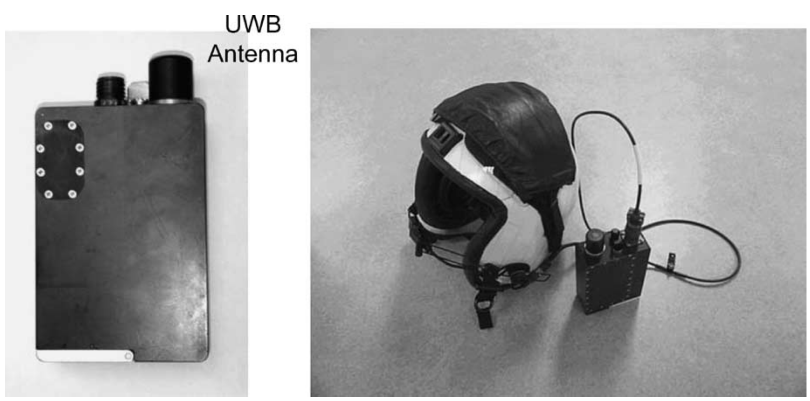

Fig. 17. Prototype AWICS UWB mobile transceiver with headset.

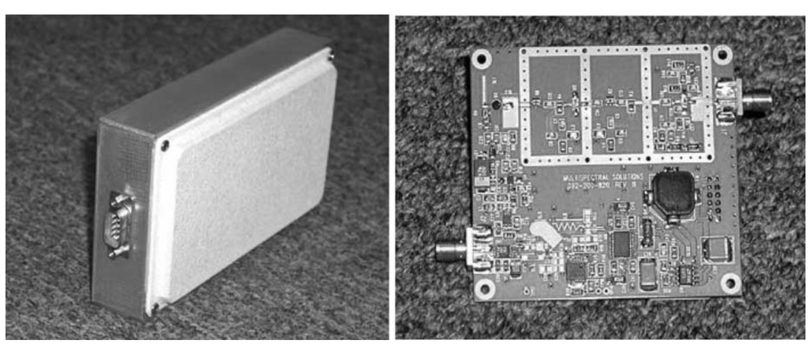

Fig. 18. SPIDER Part 15 UWB radar.

The AWICS system operates at L-band with an instantaneous -3-dB RF bandwidth of approximately 400 MHz and an effective isotropic radiated power (EIRP) of approximately $+26$ dBm. The transmitter utilizes bias control gating of the output power amplifier to lower the average battery drain requirement. With a receiver noise figure of approximately 5 dB, the system can accommodate a path loss of nearly 100 dB. A tunnel diode detector is used in the UWB receiver to

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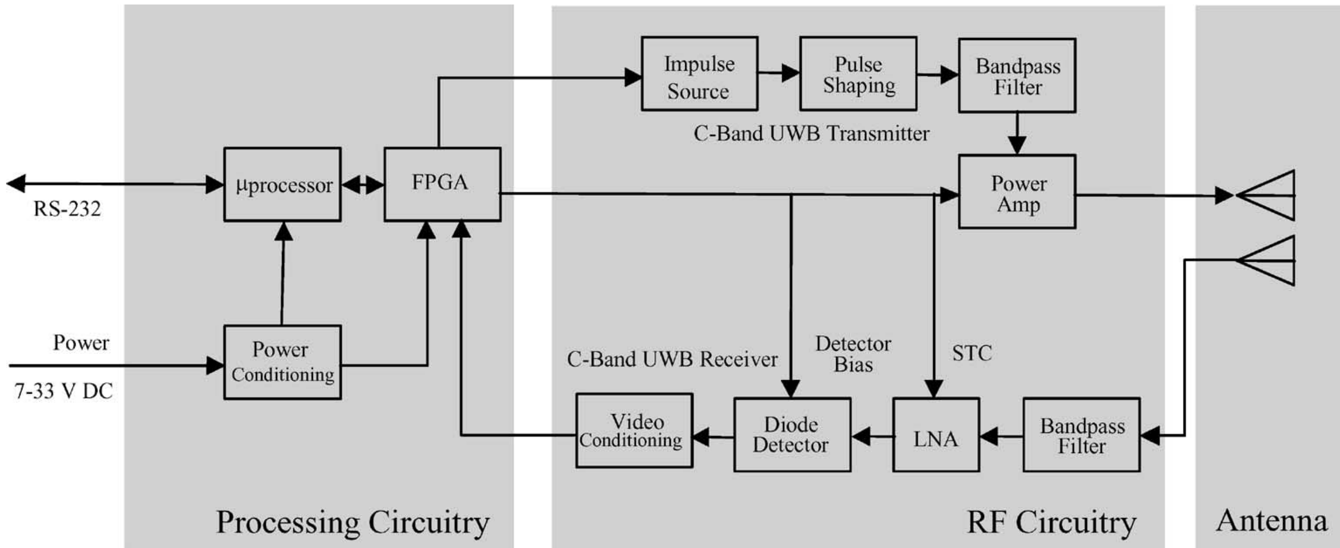

Fig. 19. SPIDER system block diagram.

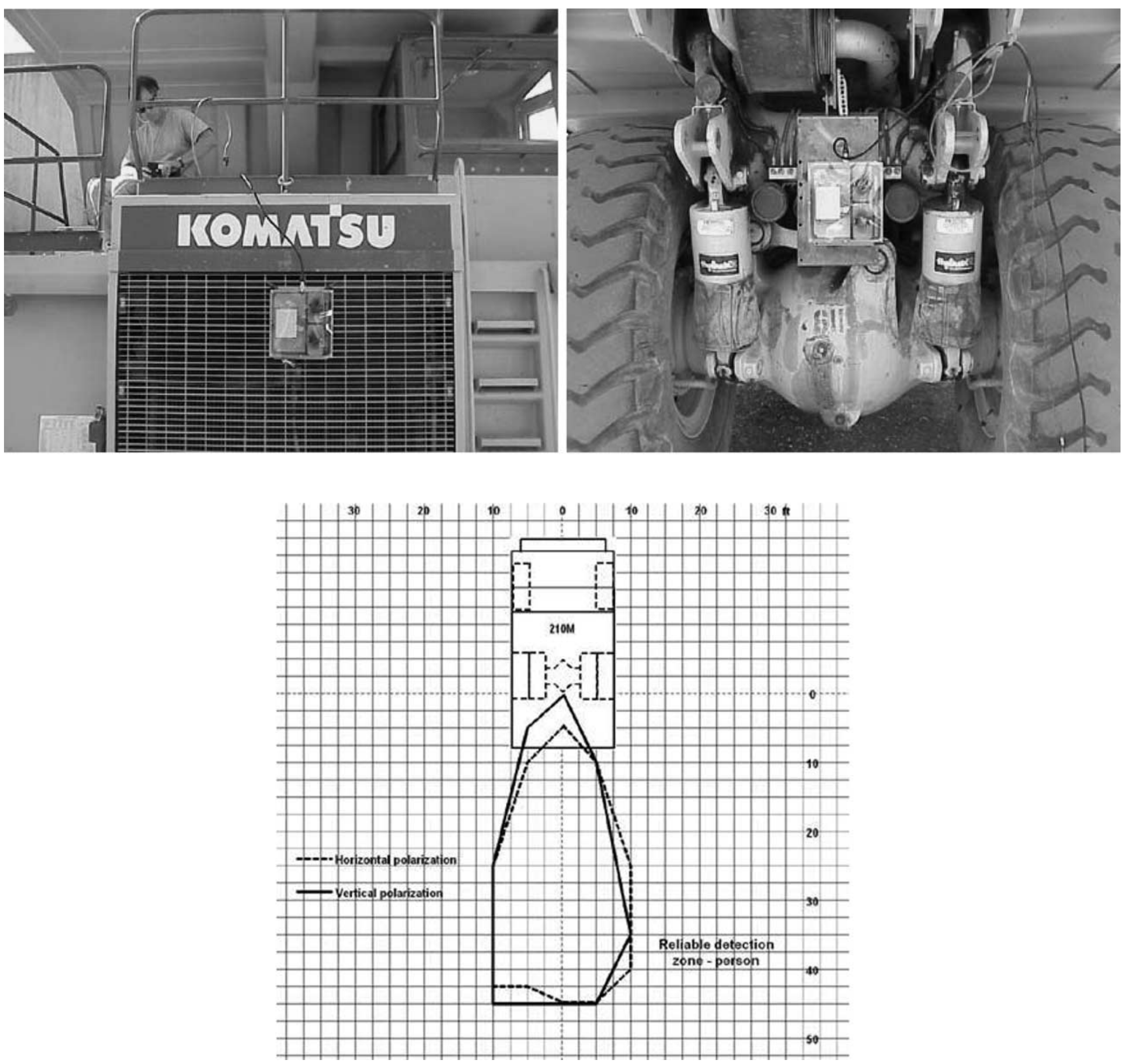

Fig. 20. SPIDER deployed as backup sensor with measured detection pattern.

permit single pulse detection, particularly important for reliable performance in the severe multipath conditions experienced within the helicopter fuselage.

In order to accommodate eight simultaneous mobile users, a TDMA protocol is used and a 64-kb/s CVSD codec is utilized for digital voice transmission, providing high-quality audio repro-

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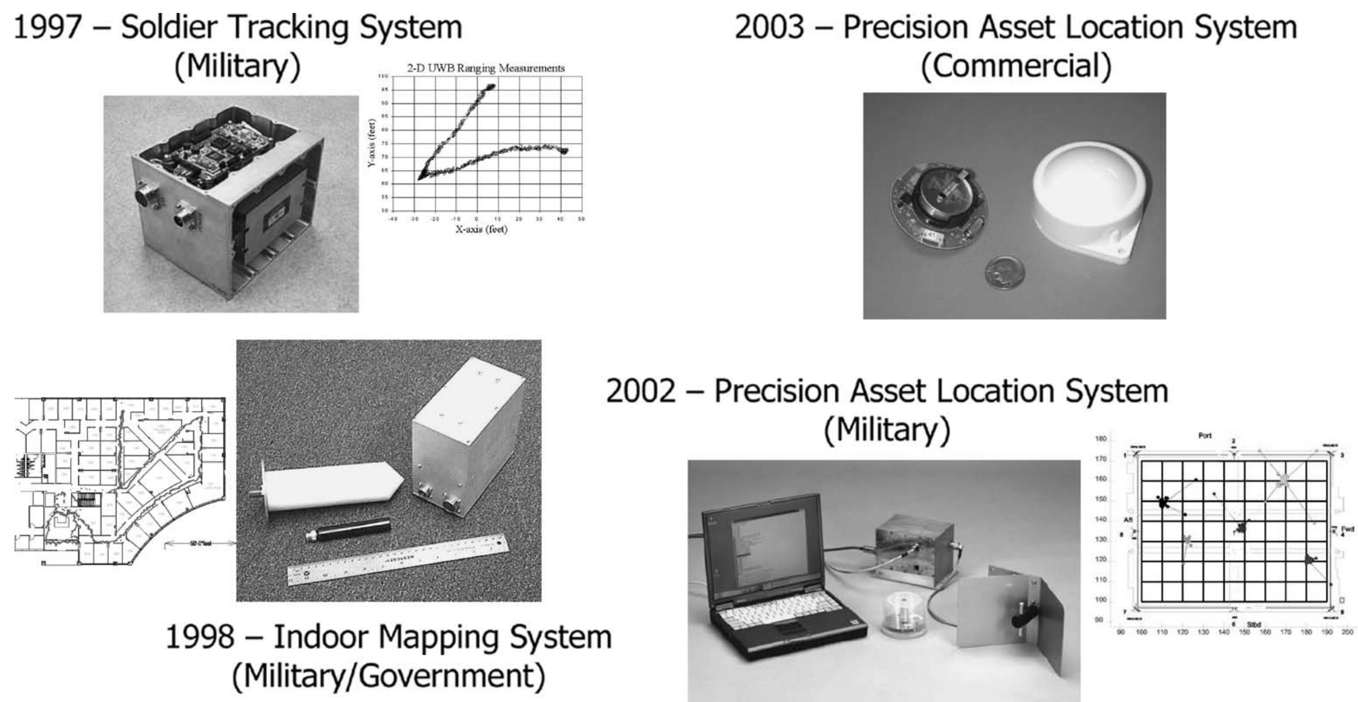

Fig. 21. Recently developed PALSs.

Fig. 22. PAL650 precision asset location system. (From top left: UWB active tag with radome, ceiling mounted UWB receiver, and central processing hub).

duction. Synchronization is reestablished on each packet burst, further improving multipath performance. The synchronization preamble also contains a short training sequence for establishing the optimum receiver gain setting [receiver signal strength indication (RSSI)]. Key to both LPD and multipath performance is the extremely low duty cycle of the UWB waveform.

The system was successfully tested in February 2003 on board both CH-53E Super Stallion and CH-46E Sea Knight helicopters at the Marine Corps Air Station (MCAS) Quantico, VA. Performance was robust within the fuselage skin of both types of aircraft, with no loss of communications experienced in any location within the aircraft skin. Testing included having the user lie facedown on the deck of the aircraft, completely smothering the antenna and unit with his body. This was done to simulate a crew member looking through the access hatch on the deck of the aircraft, which is an operationally routine occurrence on both aircraft. The mobile units were also placed behind spars and other structures within the aircraft to rigorously test blockage potential. No performance degradations were noted throughout internal testing.

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B. Recent Short-Pulse Radar Systems

There has been extensive work performed in the field of short-pulse radar [30], [31], and it is virtually impossible to give even a cursory treatment to this fascinating area within the scope of this paper. Thus, here, we restrict the discussion to a rather unique short-pulse radar system, which has been recently certified by the FCC for commercial use under the new Part 15 Subpart F (UWB) rules. This short-pulse radar was originally developed for the U.S. Navy for unmanned aerial vehicles (UAVs), and has been applied to such applications as collision and obstacle avoidance, radar altimetry, suspended wire detection, through-wall sensing, and others [32]–[34]. The FCC Part 15 certified version of this radar (Fig. 18), nicknamed SPIDER, was further developed under DARPA's micro air vehicle (MAV) program as a miniature version of the original Navy collision-avoidance sensor. The MAV version of the sensor was designed to fit on a small 6-in helicopter. The sensor, weighing less than 15 g, consists of a single 65×70 mm circuit board with digital electronics and dc-to-dc converter on one side, and impulse generation and microwave components on the other. A block diagram of the C-band unit is shown in Fig. 19.

SPIDER utilizes an instantaneous -3-dB bandwidth of approximately 500 MHz and a design center frequency of 6.35 GHz. Both a low-power (30-mW peak) and high-power (0.8-W peak) version are available, the latter developed for other than Part 15 commercial use. The higher power output is intended to allow SPIDER to be used for precision radar altimetry applications at ranges of up to 1000 ft.

The primary advantages of UWB for short-range radar sensing include extremely fine range resolution (better than 1-ft resolution achieved using leading edge-detection techniques), high power efficiency because of low transmit duty cycle, and very LPD. The latter also translates into low probability of interference to legacy systems. One of the more important attributes of the UWB sensor is its ability to detect stationary targets. More specifically, the rather radar operates as a presence sensor, and does not rely upon the detection of a Doppler shift. This feature was found particularly useful for slowly traveling and hovering MAVs, and has applicability to collision and backup sensors for vehicles, perimeter and wide area security, and intrusion detection. As an example of the former, the SPIDER radar was deployed as a backup sensor for a large mining vehicle (Fig. 20).

In this application, the primary problems with previous system approaches (microwave and millimeter-wave radar, optical, acoustical, etc.) have been either excessive false alarms caused by rocks and debris thrown from the vehicle tires or environmental deterioration or overload of the sensor (e.g., lens blockage, excessive noise, etc.). The UWB system was the only sensor tested that did not have this problem. This can probably be attributed to two factors. First of all, with a precise range gate cutoff having subfoot resolution, the UWB radar can gate out clutter from the ground. Secondly, since the effective interaction volume of the radar signal is very small due to the short-pulse nature of the waveform, the radar return from airborne debris and clutter is relatively small.

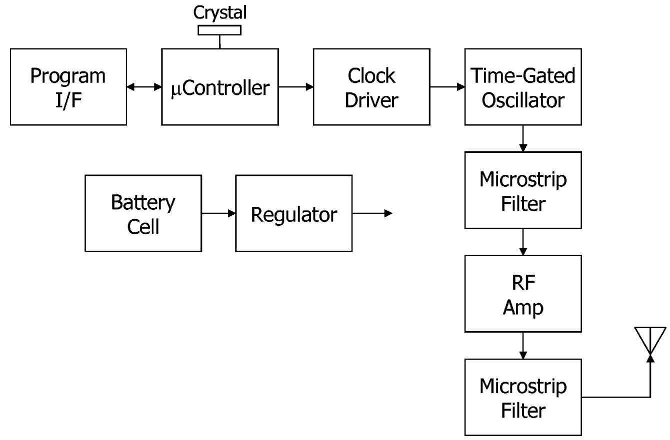

Fig. 23. Simplified block diagram of PAL650 tag.

Fig. 24. Antenna side of PAL650 tag.

To date, more traditional radar approaches have not enabled large sections of the commercial marketplace due to excessive cost, size, complexity and power. UWB may indeed be capable of remedying this situation; however, current commercial use of UWB radar continues to be somewhat restricted by application limitations imposed by the FCC under the present report and order [3]. These restrictions may be relaxed somewhat in the near future as the FCC addresses certain broader issues within the Commission's rules for unlicensed operation. Reference [35], submitted to the FCC by the National Telecommunications and Information Administration (NTIA), contains a very recent and interesting technical discussion of these issues.

C. Recent Short-Pulse Positioning and RFID Applications

One of the more recent and fascinating application areas for UWB technology has been in the area of precision localization. In these applications, one takes advantage of the fact that short-pulse waveforms permit an accurate determination of the precise TOA and, hence, the precise time of flight of a burst transmission from a short-pulse transmitter to a corresponding receiver. With a tunnel diode receiver, for example, TOA measurements with resolutions of better than 40 ps have been made [36]. With distances computed from the time of flight, or relative time-of-flight measurements, one can then determine two-dimensional (2-D) and three-dimensional (3-D) positions of a UWB transmitter using conventional multilateration algorithms [37].

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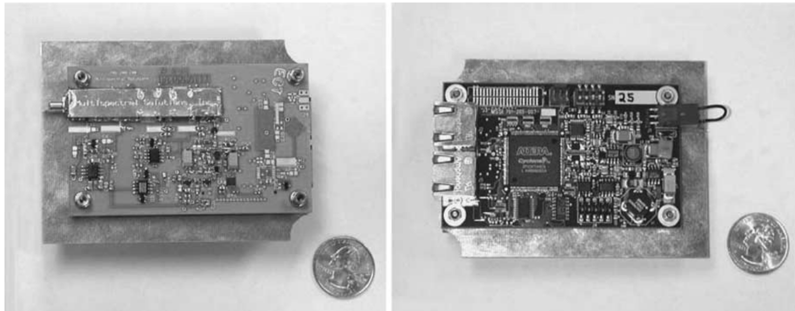

Fig. 25. PAL650 receiver RF (left) and digital boards.

To date, several UWB precision localization systems have been fielded [36], [38], [39]. Fig. 21 illustrates a few of the more recent systems designs. The soldier tracking system was the first to be developed and fielded, and was designed to track personnel and vehicles without the use of GPS over areas exceeding a few square kilometers. The system was tested at the Ft. Benning, GA, McKenna military operations in urban terrain (MOUT) site in 1997 and demonstrated the ability to achieve foot-type resolutions over a 4-km^2 area. A smaller version of this system was subsequently developed in 1998 to perform indoor mapping, wherein the UWB tracking system was used to correlate position information with video still imagery to construct a 3-D AutoCAD model of the inside of a facility. A further size reduction and improvement in performance resulted in development in 2002 of the precision asset location system (PALS) [38], which was used for tracking of ISO containers inside a Navy ship, a particularly severe multipath environment with all metal floors, walls, and ceilings. Each of these systems operated at L-band and, hence, could not be used commercially. In 2003, a commercial version of the Navy PALS system, PAL650, was developed, which had a two orders of magnitude improvement in power efficiency and operated in the 3.1–10.6-GHz band, enabling certification under the new FCC Part 15 Subpart F (UWB) rules.

The PAL650 UWB PALS system consists of a set of active UWB tags (one of which is used as a calibration or reference tag), UWB receivers, and central processing hub. The hub interfaces with an external computer for user display and application software via either serial RS-232 or Ethernet. These components are illustrated in Figs. 22–24.

The UWB active tag operates at a center frequency of approximately 6.2 GHz and has an instantaneous -10-dB bandwidth of 1.25 GHz. A simplified block diagram of the PAL650 tag is shown in Fig. 23. The tag uses a time-gated oscillator and microstrip filter [26] to produce the desired UWB emission.

A picture of the antenna side of the tag electronics (with copper ground plane) is illustrated in Fig. 24. A broad-band monopole design was used to achieve the requisite bandwidth. With its polyethylene radome housing, the tag diameter is 2 in and height 1 1/8 in. The tag operates at 3.0 V with a current consumption of approximately 30 μA. The tag life expectancy, with a 3.0-V 1A-h Lithium cell battery, is approximately four years at a blink rate of once per second. Tag power efficiency is one of the most important aspects of the short-pulse design, and is realized because of the exceedingly low duty cycles. In the current example, the transmission duty cycle is only 0.002%.

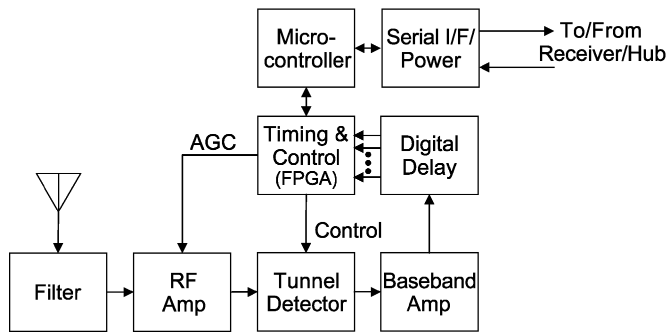

Fig. 26. PAL650 receiver block diagram.

The PAL650 UWB receivers consist of two separate boards, one containing the C-band RF electronics and high-speed UWB detector, and the other containing control and interface electronics (Fig. 25). A simplified receiver block diagram is illustrated in Fig. 26.

A wide-band low insertion-loss microstrip filter and pseudomorphic high electron-mobility transistor (pHEMT) low-noise amplifier provide the input to a high-speed tunnel-diode detector. The tunnel diode's superb performance at low RF levels makes it an ideal device for achieving leading edge detection on short microwave bursts. After baseband amplification and pulse conditioning, a TOA measurement is made to 1-ns resolution through the use of a tapped delay line and FPGA-based comparator. Finally, raw TOA data is transmitted to the hub processor, either directly or via a daisy-chain loop through other remote receivers.

The system operates as follows. A set of three or more receivers (four receivers are typically used) are positioned at known coordinates within, or about the periphery of, the area to be monitored. Fig. 27 illustrates an experimental laboratory configuration in which a set of four receivers are located on the vertices of a rectangle of approximately 40 ft $\times$ 100 ft.

Short-pulse RF emissions from the tags are subsequently received by either all, or a subset, of these sensors and processed by the central hub CPU. A typical tag emission consists of a short burst, which includes synchronization preamble, tag identification (ID), optional data field (e.g., tag battery indicator), and FEC bits. In the current configuration, the tag data repeats once every second; however, rates of up to approximately 5200

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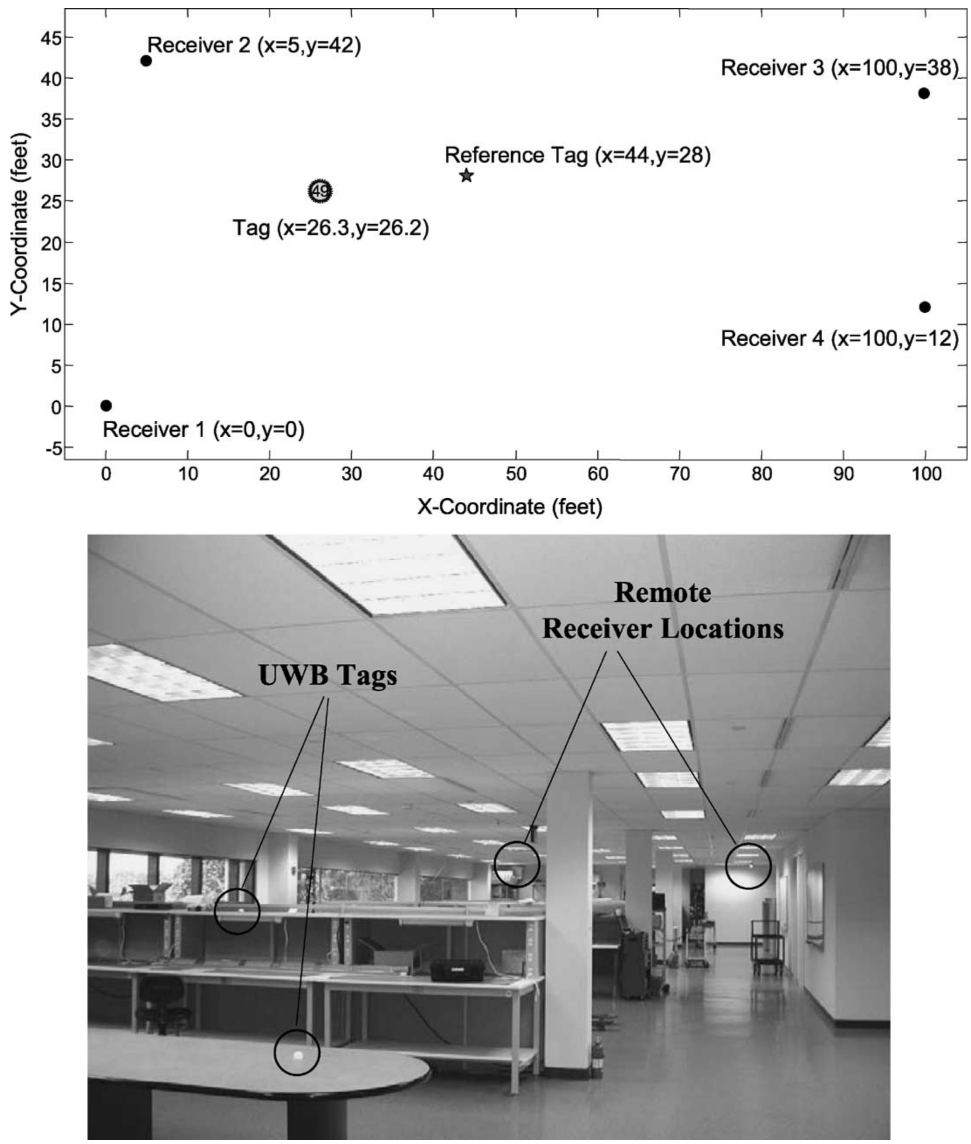

Fig. 27. MSSI Engineering Laboratory tag deployment.

updates per second can be accommodated without exceeding FCC Part 15 limits. Time differences of arrival (TDOA) of the tag burst at the various receiver sites are measured and sent back to the central processing hub for processing. Calibration is performed at system startup by monitoring data from a reference tag, which has been placed at a known location. The PAL650 system does not rely upon the use of precision cable runs for the relay of RF signals; rather, standard CAT-5 cables are used to carry digital data from the receivers back to the hub.

The PAL650 RF Tag complies with the requirements of FCC Part 15.517(b). A power spectral density plot is shown in Fig. 28. The tag has a -10-dB bandwidth of approximately 1.25 GHz, in excess of the 500 MHz minimum required under the FCC rules; however, it is the -3-dB bandwidth of approximately 400 MHz that establishes the instantaneous pulsewidth of roughly 2.5 ns. Position resolution to better than 1 ft has been achieved without averaging, and less than 3 in with averaging, suggesting that the receiver operates on the leading edge of the received pulse in high SNR environments.

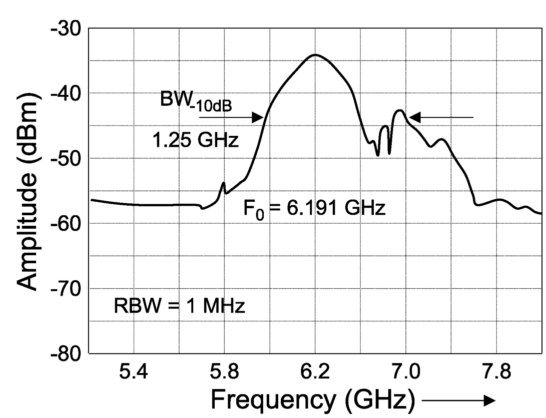

Fig. 28. Measured PAL650 power spectral density.

The LOS range for the tag was measured in excess of 600 ft at FCC Part 15 levels. Indoors, the range is further limited by attenuation from walls, partitions, and potential blockages. However,

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ranges in excess of 200 ft have been demonstrated at C-band through as many as ten commercial-grade walls. Positioning accuracy, of course, depends upon several factors, including precise knowledge of all receiver and reference tag locations; however, absolute tag position accuracy of better than 1 ft is routinely achieved.

V. Future Trends

Over the past 40+ years, UWB technology has taken many interesting twists and turns along its course toward commercial utilization. Thus far, no major application, i.e., a "killer app," has been found. As a consequence, it has been somewhat difficult to predict where the first "killer app" will emerge. For example, even over the course of the FCC's deliberations in ET Docket 98–153 from its original Notice of Inquiry in 1998 to the First Report and Order in 2002, application focus has shifted considerably .

While many believe that high-speed wireless networking is the UWB "killer app," FCC peak and average power constraints will ultimately affect the viability of UWB for this application. Given these constraints, it is expected that networking products having only very short range (i.e., less than a few meters) are likely to achieve FCC certification in the foreseeable future [40]. The perceived need for standardization (e.g., IEEE 802.15.3a) further complicates the process of bringing the technology rapidly to market.

An area that has been significantly overlooked, although now making somewhat of a comeback,[5] is that of low data-rate (i.e., less than a few megabits per second) applications of UWB. It is in this regime that many of the unique properties of UWB—namely, LPD and interference, multipath immunity, superb power management, etc.—are observed. As illustrated in the examples above, there are numerous niche markets for systems that exhibit these properties and, to date, the FCC has certified four such systems from two manufacturers for commercial use under Subpart F.

With the impact of September 11, 2001 on the world psyche, increased interest is being paid worldwide to systems that can provide RFID, tagging, and precise localization, particularly for applications to homeland security (e.g., personnel ID, container manifest and tracking, intrusion detection, etc.). Another application area of interest is in automotive radar for collision and obstacle avoidance [41]. All of these are typically low data-rate applications, but require ranges far in excess of what is being envisioned for 802.15.3. It is here where the author believes that UWB will make its first foray into the commercial world. Indeed it is already happening [39]. Moderate data-rate (less than a few megabits per second) moderate-range (100–300 m) UWB applications have unique advantages in that they are achievable today under the current FCC limits as evidenced by recent Commission certifications.

While the UWB market has been enabled within the U.S. by the FCC's changes to its Part 15 regulations, such is not the case internationally and much is yet to be accomplished from an international regulatory perspective. The European Conference of Postal and Telecommunications Administrations (CEPT), for example, is not expected to submit recommendations for UWB frequency allocations in Europe until at least October 2004. CEPT is particularly concerned that the accelerated pace of the FCC UWB process has prevented a comprehensive review of the impact of UWB devices on aviation infrastructure components [42]. In Asia, similar concerns have prevented early adoption of the technology. Singapore, for example, recently created an "UWB friendly zone" (UFZ), which enables localized licensed experimentation over a two-year period; however, no authorization for UWB usage within the country will be granted until at least first quarter 2005 [43].[6] Japan's Ministry of Public Management, Home Affairs, Posts and Telecommunications, while granting two experimental licenses for UWB equipment, is also not expected to revise its regulations until second quarter 2004. The International Telecommunications Union (ITU),[7] [8] is also expected to deliver its final recommendations by the end of 2004.

While most international organizations have closely monitored the FCC UWB deliberations, there are still many contested issues, particularly as related to interference to legacy systems for safety of life and safety of flight. Thus, blanket international approval for UWB commercial use is still far from certain and, for the near future, this will be a major limiting factor for its widespread adoption.

Acknowledgment

The author wishes to thank Dr. G. F. Ross, Anro Engineering Inc., Lexington, MA, a long-time friend and associate, who introduced me to the fascinating area of short-pulse electromagnetics nearly 20 years ago. The author also wishes to thank R. Mulloy, MSSI, Germantown, MD, for his support over the past ten years in helping to bring UWB to a commercial reality. The author's thanks is also extended to the scientists and engineers at MSSI, without whose efforts over the past 15 years the author would have been unable to write this paper.

References

[1] C. L. Bennett and G. F. Ross, "Time-domain electromagnetics and its applications," *Proc. IEEE*, vol. 66, pp. 299–318, Mar. 1978.

[2] Revision of part 15 of the commission's rules regarding ultra-wideband transmission systems. [Online]. Notice of inquiry, adopted August 20, 1998, released September 1, 1998. Available: http://www.fcc.gov/oet/dockets/et98-153

[3] "Revision of part 15 of the commission's rules regarding ultra-wideband transmission systems,", Report and order, adopted February 14, 2002, released July 15, 2002.

[4] "Assessment of ultra-wideband (UWB) technology," Ultra-Wideband Radar Rev. Panel, R-6280, Office of the OSD/DARPA, Washington, DC, July 13, 1990.

[5] See, for example, IEEE 802.15 WPAN Low Rate Alternative PHY Study Group 4a (SG4a). [Online]. Available: http://grouper.ieee.org/groups/802/15/pub/SG4a.html

[6] Technical discussions with Dr. G.L. Tan, Director, Technology Group, Singapore Infocomm Development Authority, 18 September 2003. In discussing UWB applications for Singapore, it was pointed out that homeland security applications takes precedent and would likely be approved quickly through a waiver process.

[7] See Task Group 1–8—Compatibility Between Ultra-Wideband Devices (UWB) and Radiocommunication Services, International Telecommunication Union. [Online]. Available: http://www.itu.int/ITU-R/study-groups/rsg1/rtg1-8/index.asp

[8] See the FCC's website for a synopsis of current U.S. activity within ITU Task Group 1/8. [Online]. Available: http://www.fcc.gov/oet/info/TG-18/

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[5] G. F. Ross, "Transmission and reception system for generating and receiving base-band duration pulse signals without distortion for short base-band pulse communication system," U.S. Patent 3 728 632, Apr. 17, 1973.
[6] I. I. Immoreev and D. V. Fedotov, "Ultra wideband radar systems: Advantages and disadvantages," in *Proc. IEEE Ultra Wideband Systems and Technologies Conf.*, Baltimore, MD, May 2002, pp. 201–205.
[7] G. F. Ross, "The transient analysis of multiple beam feed networks for array systems," Ph.D. dissertation, Dept. Elect. Eng., Polytech. Inst. Brooklyn, Brooklyn, NY, 1963.
[8] F. Davis and H. W. Loeb, "Time-domain measurements for transistor and network characterization up to 1 GHz," *Proc. IEEE*, vol. 53, pp. 1649–1650, Oct. 1965.
[9] G. F. Ross, "The transient analysis of certain TEM mode four-port networks," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-14, pp. 528–547, Nov. 1966.
[10] J. D. DeLorenzo, "A range for measuring the impulse response of scattering objects," in *Northeast Electronics and Engineering Meeting Rec.*, vol. 9, Nov. 1967, pp. 80–81.
[11] A. Nicolson, "Broadband microwave transmission characteristics from a single measurement of the transient response," *IEEE Trans. Instrum. Meas.*, vol. IM-17, pp. 395–402, Dec. 1968.
[12] C. L. Bennett, "A technique for computing approximate electromagnetic impulse response of conducting bodies," Ph.D. dissertation, School Eng., Purdue Univ., West Lafayette, IN, 1968.
[13] C. E. Cook and M. Bernfeld, *Radar Signals: An Introduction to Theory & Application*. New York: Academic, 1967.
[14] A. Papoulis, *The Fourier Integral and Its Applications*. New York: McGraw-Hill, 1962, ch. 5.
[15] "Time domain reflectometry," Hewlett-Packard, Palo Alto, CA, Applicat. Note #62, 1964.
[16] G. F. Ross, "A time domain criterion for the design of wideband radiating elements," *IEEE Trans. Antennas Propagat.*, vol. AP-16, p. 355, Mar. 1968.
[17] K. W. Robbins, "Short baseband pulse receiver," U.S. Patent 3 662 316, May 9, 1972.
[18] A. M. Nicolson and R. Mara, "Detector having a constant false alarm rate," U.S. Patent 3 983 422, Sept. 28, 1976.
[19] R. J. Fontana and J. F. Larrick, "Ultra wideband receiver with high speed noise and interference tracking threshold," U.S. Patent 5 901 172, May 4, 1999.
[20] R. J. Fontana, "UWB dual tunnel diode detector for object detection, measurement, or avoidance," U.S. Patent 6 239 741, May 29, 2001.
[21] G. F. Ross, "A historic review of UWB radar and communications and future directions," presented at the IEEE Radio and Wireless Conf., Boston, MA, Oct. 12, 2003.
[22] "Reexamination certificate (4084th)," U.S. Patent B1 5 361 070, May 16, 2000. [Online]. Available: http://www.multispectral.com/pdf/Reexam_Certificate.pdf.
[23] R. J. Baker and B. P. Johnson, "Applying the Marx bank circuit configuration to power MOSFETs," *Electron. Lett.*, vol. 29, no. 1, pp. 56–57, 1993.
[24] M. J. Lesha and F. J. Paoloni, "Generation of balanced subnanosecond pulses using step-recovery diodes," *Electron. Lett.*, vol. 31, no. 7, pp. 510–511, 1995.
[25] "Response to FCC notice of proposed rule making ET Docket 98-153, 'Revision of part 15 of the commission's rules regarding ultra-wideband transmission systems'," Multispectral Solutions Inc., Germantown, MD, Sept. 12, 2000.
[26] R. J. Fontana and J. F. Larrick, "Waveform adaptive ultra-wideband transmitter," U.S. Patent 6 026 125, Feb. 15, 2000.
[27] R. J. Fontana, E. A. Richley, L. C. Beard, and J. Barney, "A programmable ultra wideband signal generator for electromagnetic susceptibility testing," in *Proc. IEEE Ultra Wideband Systems and Technologies Conf.*, Reston, VA, Nov. 2003 [CD-ROM], Session A1—NETEX.
[28] M. Z. Win and R. A. Scholtz, "Impulse radio: How it works," *IEEE Commun. Lett.*, vol. 2, pp. 10–12, Jan. 1998.
[29] H. L. Van Trees, *Detection, Estimation, and Modulation Theory*. New York: Wiley, 2001, pt. 1, ch. 4.4.1.
[30] J. Taylor, Ed., *Introduction to Ultra-Wideband Radar Systems*. Boca Raton, FL: CRC, 1995.
[31] *Ultra-Wideband, Short-Pulse Electromagnetics 1, 2, 3 and 4*. New York: Plenum, 1993, 1994, 1997, and 1999.
[32] R. J. Fontana, J. C. Koppier, and R. W. T. Mulloy, "A low cost ultra wideband (UWB) radar altimeter," in *Proc. AUVSI'96*, Orlando, FL, July 15–19, 1996, pp. 297–301.
[33] R. J. Fontana, J. F. Larrick, and J. E. Cade, "A low cost ultra wideband system for UAV communications and high resolution radar applications," in *Precision Strike Technology Symp.*, Baltimore, MD, Oct. 8–9, 1997.
[34] R. J. Fontana, J. F. Larrick, J. E. Cade, and E. Rivers, "An ultra wideband synthetic vision sensor for airborne wire detection," presented at the Enhanced and Synthetic Vision, Orlando, FL, Apr. 1998.
[35] M. D. Gallagher, F. R. Wentland, E. Drocella, P. Roosa, and D. Anderson, "Comments of the National Telecommunications and Information Administration, in the matter of revision of part 15 of the commission's rules ET docket no. 98-153," NTIA, Washington, DC, Jan. 15, 2004.
[36] R. J. Fontana, "Experimental results from an ultra wideband precision geolocation system," presented at the EuroEM 2000, Edinburgh, Scotland, May 30, 2000.
[37] S. Bancroft, "An algebraic solution of the GPS equations," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-21, pp. 56–59, Jan. 1985.
[38] R. J. Fontana and S. J. Gunderson, "Ultra wideband precision asset location system," in *Proc. IEEE Ultra Wideband Systems and Technologies Conf.*, Baltimore, MD, May 2002, pp. 147–150.
[39] R. J. Fontana, E. Richley, and J. Barney, "Commercialization of an ultra wideband precision asset location system," in *Proc. IEEE Ultra Wideband Systems and Technologies Conf.*, Reston, VA, Nov. 2003, Session D4—Radar and Position Location Applications.
[40] V. Lipset. (2002, Dec.) Cellonics: Home networking UWB's killer app?. *Ultrawidebandplanet.com* [Online]. Available: http://www.ultrawidebandplanet.com/technology/article/0,10850_1557911,00.html
[41] I. Gresham *et al.*, "Ultrawide-band radar sensors for short-range vehicular applications," *IEEE Trans. Microwave Theory Tech.*, vol. 52, pp. 2105–2122, Sept. 2004.
[42] "Compatibility between ultra wide band services—Aviation systems and provisional limits," NATO NATMC, Brussels, Belgium, Information Doc. CEPT SE24, ver. 3.0, Mar. 2002.
[43] T. G. Leng, "An update on UWB activities and developments in Singapore," presented at the 10th Infocomm Horizons Seminar, Singapore, Sept. 18, 2003 [Online]. Available: http://www.i2r.a-star.edu.sg/events/horizons.htm.

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