TERAHERTZ ELECTRONICS RESEARCH FOR DEFENSE: NOVEL TECHNOLOGY AND SCIENCE

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ABSTRACT

The general objectives and motivations for a terahertz-frequency (THz) electronics research program are overviewed and discussed from the U.S. Army and national defense perspective. The potential impact of THz electronics research is defined in the context of the Army's future strategic vision. As illustrated, THz electronics has the potential for augmenting and enhancing the Army's concept of a Future Combat System within a microsensor network scenario. Hence, this paper demonstrates that present Army investments in THz electronics research are future enablers for a full spectrum (electromagnetic) capability in battlefield sensing and communications.

I. INTRODUCTION: A GENERAL PERSPECTIVE ON THE PROGRAM.

The direction and evolution of the Terahertz (frequency-regime) Electronics Research Program at the U.S. Army Research Office (ARO) is strongly tied to national defense issues and therefore follows general ARO objectives. The principle objective of the Electronics Division, within the ARO, is to generate a new and fundamental base of knowledge within the field of electronics. Here, the overwhelming focus is towards novel scientific and engineering investigations that possess the potential for revolutionary solutions to the U.S. Army's most critical research problems, both now and in the future [1]. Collectively, research programs in Electronics are relevant to nearly all Army systems; therefore, high quality research from this area has applicability to a wide variety of developmental efforts and has the potential to impact many technological areas. Indeed the efforts toward expanding the science and technology base by the ARO Electronics Division is classified into two major areas, namely, (1) Physical Electronics Research and (2) Communications, Signal Processing and Target Acquisition, and these components strongly contribute to the concept of "Digitization of the Battlefield." The purpose of this paper is to address the general science and technology goals of the "Quantum and High Frequency Electronics" thrust within the Electronics Division. Here, the specific emphasis is upon science and engineering research related to the terahertz (THz) frequency regime. The research challenges and the technological advantages, associated with achieving and utilizing, a robust THz-frequency electronics capability has some relevance to all the major ARO thrust areas in electronics (i.e., Solid State Device

Research, High Frequency Electronics, Quantum and Optoelectronics, Information Processing and Circuits, Communications and Networks, and Electromagnetics). In addition, THz-frequency electronics introduces scientific features that have foreseeable impact to many multidisciplinary areas (e.g., chemistry, biology, molecular physics and medical science) and also has the potential to introduce new and revolutionary capabilities.

Today, ARO exists as an important component of the U.S. Army Research Laboratory (http://www.arl.mil) and assumes the primary role of identifying and supporting fundamental research and development that is external to the Army Laboratory system. Specifically, ARO seeks innovative research proposals from educational institutions, nonprofit organizations and private industry that possess current and future value to the Army Material Command (AMC). The overall strategic vision of ARO's research programs [2] are formulated in concert with ARL's directorates, AMC's Research, Development and Engineering Centers (RDECs), the Army Medical Research and Material Command (AMRMC), the Army Corps of Engineers and the Army Research Institute for Behavioral and Social Science. The mission of ARO is to seed scientific and far reaching technological discoveries that will enhance Army capabilities. Therefore, the majority of the programs are direct-funded from Army Program Elements "Defense Research Sciences" and "University/Industrial Research Centers" and the Office of the Secretary of Defense (OSD) Program Element "University Research Initiatives" (URI). Here it is important to note that the OSD programs fall under the executive oversight of the Defense Committee on Research chaired by the Director of Research, Office of the Deputy Under Secretary of Defense (Science and Technology). Research is also supported utilizing customer funds from other Department of Defense (DoD) agencies (e.g. Department of Defense Research Projects Agency (DARPA) with closely aligned goals to those of the Army. In addition, ARO participates in joint research programs with the Office of Naval Research (ONR) and the Air Force Office of Scientific Research (AFOSR) through Defense Reliance under the executive direction of the Defense Basic Research Panel. Hence, the investment strategy in the Quantum and High Frequency Electronics program is strongly influenced by the strategic vision and by the peer review participation of the Army and DOD (for specifics see Army Investment Strategy in [2]). However, the new ideas, the discoveries and the ongoing scientific/technological advancements that occur within academic and other non-DoD institutions also naturally influence practical program formulation.

In this paper, ARO's program in Terahertz Electronics Research for defense will first be reviewed in the context of the current needs and future directions of the Army and the DoD. In addition, the Terahertz Electronics program formulation will be presented in relation to the advancement of science and technology occurring at universities and other external research institutions. In Section II of this paper, the potential impact of THz electronics research will be demonstrated from the perspective of the Army's future strategic vision. Here, the insight will be developed via surveying the Army's critical needs, the long-range goals, and from the focus and current direction of some of its major research and laboratory programs. In Section III of this paper the current investment and anticipated future direction of the ARO program in THz electronics is overviewed and discussed. As will be shown, a robust and integrated THz electronics has the potential for significantly enhancing and extending the Army's capability in sensing and communications. Specifically, THz sensing and communications is compatible with the Future Combat System concept of a battlefield force integrated via a microsensor network.

II. THE U.S. ARMY: AN OVERVIEW OF THE STRATEGIC VISION.

The future value of any science-based research program to the U.S. Army is best defined through a consideration of the Army's overall strategic vision. Indeed, valuable insight into the potential impact of a THz electronics capability to the Army can be determined from the critical needs, the long-range goals, and from the focus and current direction of its present research and laboratory programs. This section will assess the value of THz electronics in relation to the U.S. Army's strategic vision and place the many virtues of THz electronics into a national defense perspective.

The strategic vision of the U.S. Army has been clearly defined by its leadership. For example, the Honorable Louis Caldera, Secretary of the Army, envisions an Army that possesses *"strategic dominance across the entire spectrum of operations."* Here, an Army is required that is responsive and dominant for all perceivable land force missions and against all existing military obstacles (e.g., weapons of mass destruction [3]). Specifically, this means an Army that is *"deployable, agile, versatile, lethal, survivable, and sustainable."* In addition, these forces must be *"affordable and capable of reversing the conditions of human suffering rapidly and resolving conflicts decisively."* This same future vision was also echoed in the words of General Eric Shinseki, Army Chief of Staff, in his speech at the Army Chief of Staff Arrival Ceremony on June 22, 1999. In this speech [4], General Shinseki indicated a commitment to maintaining an Army that is *"preeminent in land warfare"* through improvements that allow for *"responding to a wider range of missions."* Specifically, General Shinseki seeks *"early entry forces that can operate jointly without access to fixed forward bases,"* and recognizes that today *"our heavy forces are too heavy and our light forces lack the staying power."* To correct these mismatches, General Shinseki seeks to change the paradigms where *"heavy forces must be more strategically deployable and more agile with a smaller logistical footprint, and light forces must be more lethal, survivable, and tactically mobile."* How this strategic vision influences programs in the Army and what specific opportunities it offers for THz electronics is best revealed by a review of some individual research and development efforts. As will be shown, this strategic vision is pervasive across many Army research and development programs and defines many insertion points for THz – frequency science and technology.

Perhaps the best starting point for observing how the Army's strategic vision shapes its research and development efforts is the Office of the Assistant Secretary of the Army (Acquisition, Logistics and Technology) (ASA(ALT)) [5]. ASA(ALT) serves, when delegated, as the senior research and development office for the Department of the Army. Within ASA(ALT), the Office of the Deputy Assistant Secretary for Research and Technology established the *Army Science and Technology Master Plan* (ASTMP). The

ASTMP [6] is the Army's key Science and Technology (S&T) planning document and provides guidance to the entire Army S&T program. Here, the goal is to insure a strong and stable S&T program that can achieve "the timely development and transition of technologies into weapons systems and system upgrades and to explore alternative concepts to provide future warfighting capabilities for Force XXI, Army Vision 2010 and Army After Next (AAN)." It should be noted that these three previously sited blueprints for the Army's future vision were conceptual models to provide guidance for the S&T programs. Furthermore, while the Army's vision is continuously evolving (i.e., recently to just Army Vision 2010 and AAN) its historical and even most recent concept, namely "Objective Force," contains elements for achieving dominance across a full spectrum of military operations. The ASTMP addresses all of the individual DoD S&T program areas namely, The Basic Research (6.1) Program, The Applied Research (6.2) Program and The Advanced Technology Development (6.3) Program. Needless to say, the ASTMP provides guidance across a vast array of S&T efforts and is in a constant state of transformation in efforts to identify the patterns of operations needed for the Army to fulfill its role of full spectrum dominance in the future. As will be now shown, the ASTMP and some of the recent evolutions in Army S&T programs are in direct agreement with the Army's overall strategic vision. Most important, this collective vision and the S&T efforts to realize the final objective define specific areas where a THz Electronics Research Program can make important contributions.

The primary goal under the Army's Strategic Vision is a concept that has been referred to as "full spectrum dominance" and to address this the Army S&T Program is currently undergoing a major realignment and acceleration in one specific area related to ground combat. In particular, the new Future Combat Systems (FCS) program seeks to focus science and technology towards meeting future Objective-Force capability requirements [7]. The FCS is envisioned to be an ensemble of manned and potentially unmanned combat systems and represents the future centerpiece of the Army's ground combat force. Specifically, this future system is to be a highly mobile, deployable, lethal and survivable platform, and the combat effectiveness will be enhanced via the incorporation of advanced technology. The Army S&T program is now working in partnership with the Defense Advanced Research Projects Agency (DARPA) to develop and refine systems concepts and to conduct technology demonstrations. Here, a system-of-systems is targeted that will be multi-functional, multi-mission and re-configurable and that will be able to accomplish an array of strategic missions including direct and indirect fire, air defense, reconnaissance, troop transport, counter mobility, non-lethal, and command & control (C2) on the move.

Major General Lon Magget, then commanding general of the U.S. Army Armor Center at Fort Knox, Kentucky, has been attributed with first introducing this FCS vision, in 1996 [8]. This original FCS concept of a futuristic "tank" that sought greatly increased levels of lethality, survivability, deployability, mobility (agility) and sustainability also recognized the serious need for revolutionary technology insertion. One of the key specifications of the concept from the very inception was significantly reduced weight (i.e., from the present 68 tons of the Abrams M1A2). Indeed, the original targets for the manned-tank components were in the 40-45 tons range to enhance mobility and enable force-projection transport and deployment (e.g., via C17's). More recent projections emerging from Army Science and Technology Working Groups (ASTWG) organized by ASA(ALT) and from DARPA [9] indicate that weight requirements are evolving to even lower levels (e.g. ~ 20 tons). While issues of weight and size (i.e., target silhouette) are only one of many strategic elements, they are certainly valuable assets for rapid deployment (via air transport), mobility and survivability (via reduction in target signature). On the other hand, reductions in size and weight introduce new difficulties when one considers the requirements for defense against agents of mass destruction (e.g., chemical and biological (CB) agents). Indeed, a contrast between FCS limitations on size and weight and state-of-the-art CB detection systems is very valuable for revealing areas where THz electronics has the potential to make important contributions in the future.

The issue of establishing an automatic detection, alert, avoidance and protection system for areas contaminated by weapons of mass destruction has always been a component of the FCS concept. Furthermore, the threat of CB agents against manned vehicles, troop carriers and the foot soldier is one of increasing concern. For example, in the past decade there has been a proliferation of CB agents as instruments of warfare and terrorism. An adequate military defense against CB warfare agents will require rapid detection and identification of both known and unknown threat-agents. Clearly, the most serious threat of CB agents is the potential harm they present to the short and long-term health of the victim(s). However, the actual or perceived threat of CB warfare agents can impact the operational capability of a military force in the field even when conventional counter-measures (i.e., protective equipment and clothing) are successfully employed. This is true because protective equipment can interfere with vision, speech intelligibility, personal recognition and dexterity. For these reasons, the development of reliable approaches for the detection and identification of CB agents in the field of operation has been a high imperative.

In fact, the Department of Defense maintains an entire effort (i.e., Office of the Deputy Assistant to the Secretary of Defense for Counterproliferation and Chemical and Biological Defense Programs DATSD (CP/CBD)) dedicated to addressing the problem of defense against weapons of mass destruction [10]. Indeed, there are a long list of CB detector and monitor systems supported under this program that exist both in the fielded and development states. While some systems are quite compact, these are usually somewhat limited in either the number of agents that they detect (e.g., limited to certain nerve agents) or in the level of agent specificity (e.g., only assay size and number of particles). The Army's state-of-the-art for CB agent detection actually exists at this time as two large platform systems, namely, one primarily for chemical and one for biological [11]. The FOX System (M93A1 Block I), and planned upgrades to it, represents the Army's most general approach to Nuclear, Chemical and Biological (NCB) Defense. The FOX, which is actually identified as a reconnaissance vehicle, incorporates an M21 Remote Sensing Chemical Agent Alarm (RSCAAL), which is an 8-12 micron FTIR (Fourier Transform Infrared) spectrometer for passive standoff detection of nerve and mustard agents. The system also incorporates an M22 Automatic Chemical Agent Detector/Alarm (ACADA), which is an ion mobility spectrometer (IMS) for detecting nerve and blister agent vapors. It also has a Mobile Mass Spectrometer (MM1) for chemical liquid detection using a pair of silicone wheels that roll on the ground behind the vehicle and in an alternating fashion are lifted up to the inlet gas port of the MM1. It is also equipped with an AN/VDR2 radiacmeter (an ion gauge/Geiger counter) for radiological monitoring. The biological capability of the FOX is presently limited to glove-port sampling whereby a suspect biomaterial is collected and contained for transport back to a laboratory where it can be cultured and assayed to determine if it is a biological agent. The currently fielded version of the FOX now weighs 20-tons combat-loaded and the upgraded version, dubbed Joint Services Lightweight NBC Recon System, targets either a High-Mobility Multipurpose Wheeled Vehicle - HMMWV (11,500 lbs.) or a light armored vehicle (28,200 lbs.) platform. The currently fielded Biological Integrated Detection System (BIDS) is the Army's state-of-the-art ground based biological aerosol point detector. The BIDS is an aerosol collection system (i.e., via high impedance airflow stacks) combines an ultraviolet particle sizer, a liquid sampler, an adenosine triphosphate (ATP) luminometer, a mini-flow cytometer, an immunosensor, and a mass spectrometer [11]. The BIDS has a reported [10] capability of "detecting and presumptively identifying four BW agents simultaneously in less than 45 minutes," and is acclaimed as the DoD's "first credible and rapidly deployable biological detection capability." The entire BIDS system consists of a shelter unit mounted upon a dedicated vehicle (M1097 Heavy HMMWV) plus a trailer-mounted 15-kw generator (PU-801) to provide the necessary electrical power. Hence, the BIDS system approaches at least several tons in total weight. The previous descriptions make it evident that the state-of-the-art systems for both chemical and biological agents are grossly incompatible with the size and weight requirements of the FCS vision.

As noted earlier, weapons of mass destruction are broadly recognized as a very serious threat to the war fighter and the general public. Hence it is not surprising that there exists a great and concerted effort within the DoD for applying S&T toward anticipating CB threats and for developing innovative countermeasures. While much work remains to improve the overall capability of chemical sensing in the field (e.g., sensitivity, size, weight, etc.), methods for point-detection are available for all *known* chemical agents. On the other hand, the present capability for point-detection of biological (bio) agents is limited to the identification of only four species. This limitation in point-detection and the absence of any standoff (i.e., remote) capability has recently drawn considerable attention. In fact, the development of a bio early-warning capability is of the *highest priority* to the Joint Future Operation Capability [12], as well as to the Joint Service Leader for Contamination Avoidance [13] and most importantly to the Department of Defense [14]. When these general problems are combined with the need to realize a compact (i.e., very small size and weight) total CB systems package for the FCS concept, it is obvious that new approaches will be necessary. Recent scientific work in both chemical and biological spectroscopy at very high frequencies has suggested a novel avenue for a THz electronic approach to warfare agent detection and identification [15]. Specifically, a portion of the submillimeter-wave spectra (i.e., ~ 0.1 – 1.0 THz) obtained from DNA and complete cellular biological samples has revealed unique numerical structures possibly due to vibrational lattice and local phonon modes and other physical mechanisms of interactions between radiation and the biological material. Hence, there is significant evidence of a new THz spectroscopic-based approach for both the point and standoff detection of biological aerosols. In addition, fundamental physical phenomenon leads to a peaking of the intensity profile for chemical molecules in the submillimeter-wave regime and this suggests certain advantages for THz-based detection techniques. A more detailed discussion of new scientific research in the area of THz-frequency spectroscopy will be given in the next section of this paper. However, it is most important to note here that a fully-integrated electronic-based THz-frequency technology has very important ramifications to the Army vision of a effective FCS that is survivable against CB warfare agents.

The goals under the Army's new *Objective Force* vision and its highest priority S&T initiative, namely the FCS, introduce a great number of technological challenges. Leadership within the Army also recognizes the need for the S&T community to provide imaginable possibilities for making projections on what transformations in the Army are required to meet these specified future goals [16]. The latest vision of FCS is a fighting ensemble of capabilities that meets the weight constraints for C-130 transport (i.e., 20 ton class) and one that can provide land combat platforms with the levels of force and mobility emphasized by General Shinseki (see earlier comments). Concept development for the FCS is underway through a joint effort between DARPA (LTC M. Van Fosson [17]) and the Army, and initial studies indicate that a network-centric distributed combat capability has the potential to deliver the more lethal, survivable, mobile and supportable fighting force that is envisioned. This system-of-systems concept will achieve lighter and more mobile future-combat-vehicle (FCV) based force, and one that possesses the desired levels of lethality and survivability, by integration of innovative operational concepts. This system-of-systems concept will integrate such elements as direct and indirect fire, nonlethal technologies, active and passive protection, tactical internet for enhanced situational awareness, and a common-chassis multifunctional tactical force [16]. Here, the U.S. Army is envisioned to reach a condition of combat-overmatch against foreseeable enemies through a combination of manned and unmanned (robotic) vehicles that are equipped with modern fire support, novel protective technology, and through an advanced electronic-based tactical capability. But what does all this mean in more simple terms. Clearly one interpretation of the goal is a transformation from the existing heavy ground forces to a lighter and more mobile force while at the same time maintaining and increasing lethality and survivability [17]. What does this really mean? Well one might characterize it as a lighter force with less traditional firepower and armaments, however, one that relies on completely new warfare concepts. Here, new concepts for increasing survivability such as smaller vehicle signatures, active armor (e.g., missile defense systems), greater situational awareness (e.g., advanced sensors and wireless internet) and improved battlefield tactics (e.g., integrated units). In addition, increased lethality is sought through such assets as advanced weapons (e.g., electromagnetic gun), weapon systems (e.g., robotic platforms) and more rapid identification of, and response to, the enemy (e.g., advanced sensors and sensor fusion). In the simplest of terms the goals are to be extremely mobility, to be difficult to detect, to see the enemy first and to deliver an integrated and lethal attack.

While the early phases of Army's transformation to the FCS concept will certainly be carried by S&T efforts at the 6.2 and 6.3 levels, many of the far term goals must be augmented by fundamental research contributions (i.e., 6.1). For example, many of the technological elements required for achieving the FCS are being developed in the U.S. Army Research Laboratory's (ARL) Federated Laboratory (FedLab) Program. The ARL FedLab Program is one of the Army's largest research and development efforts and also reflects many aspects of the FCS future strategic vision. Indeed, the theme of the ARL FedLab 2000 Symposium [3] was "transforming the Army through science and technology" and clearly demonstrated support to the Army in creating a lighter and more lethal force through the application of science and technology. Furthermore, FedLab provides an excellent platform for anticipating the needs of the future warfighter and military system. Hence the FedLab program is an excellent guide for envisioning where and in what capacity THz electronics might play an important role in the future.

The ARL FedLab Program represents a partnership between ARL's research teams and those from the academic and industrial communities. The FedLab program was first launched in 1996 and established three consortiums to focus on military-specific objectives in the areas of Advanced Sensors, Advanced Displays & Interactive Displays, and Advanced Telecommunication & Information Distribution [19]. The Advanced Sensors Consortium (ASC) focuses on enabling technologies for the next generation of more affordable and more capable Army sensor systems. The work under the AXC is divided into five technical areas, namely, Multi-Domain Smart Sensors (MDSS), Multi-Sensor Fusion Automation Target Recognition (MSFATR), Radar (Millimeter-Wave and Ultra-Wideband), Signal Processing, and Microsensors. This array of research and development work on advanced sensing and imaging is directly in line with the FCS needs for expanded battlefield situational awareness. The Advanced Telecommunications & Information Distribution Consortium (ATIDC) focuses on research in the area of mobile wireless communications with the goal of providing support to the Army's digitization efforts. The work under the ATIDC seeks to provide fundamental advances that will enable the rapid and secure transmission of large quantities of multimedia information (speech, data, graphics and video). Hence, this work is also strategically important to future FCS needs. The Advanced Displays & Interactive Displays Consortium (ADIDC) focuses on developing new technologies for facilitating human-computer interaction in areas related to battlefield information. Hence, the ADIDC is concerned with the efficient and effective processing (i.e., filtering, analyzing and displaying) of information for the warfighters and commanders and it is an excellent compliment to the ASC and the ATIDC.

The ARL FedLab Program has collective efforts in sensors, telecommunications and information displays and is certainly a good road map for looking forward to how the FCS concept of a system-of-systems might function in the future. More to the point of this paper, the FedLab program can be used as a guide for envisioning future uses of a THz electronics capability. Specifically, some of the new concepts and the bottleneck problems that exist within the FedLab program are valuable in finding future advantages of an integrated electronics technology with an operating capability at THz frequencies. Historically, the THz portion of the frequency spectrum has not been an issue for either remote sensing or communications, within lower portions of the atmosphere, due to the extremely high propagation attenuation that exists between about 300 GHz and a few

THz [20]. Indeed, there is a large preference for large and small molecules to absorb electromagnetic energy within the THz band. Hence, it is not too surprising that THz spectroscopy is a good tool for the interrogation of chemical and biological agents as was noted earlier. While the THz regime offers a number of general advantages (e.g., wider bandwidth, improved spatial resolution, and compactness) it is certainly a good question, in light of the high attenuation, to ask why this frequency region would have any value to remote sensing or communications in a battlefield environment. However, the FCS concept where the military force will be heavily dependent on a tactical internet does allow for new paradigms where THz frequency sensing and communications is feasible and may offer dramatic advantages.

To illustrate specific technological areas where THz electronics may make contributions, it is valuable to consider some of the recent evolutions within the ARL FedLab Program. For example, remotely deployable self-configurable micro-sensor networks are an area of interest within the FedLab Program to enable continued unmanned surveillance at very-low energy requirements [21]. In one particular concept, called Sensing Position Integrated Network (SPIN), full situational awareness (i.e., where am I, where are my friends, and where is everyone/everything else) is proposed for the dismounted soldier through an integration of microsensor networks (wireless) and GPS technology. In the SPIN [22] approach low-bandwidth information (i.e., achieved by embedded processing capabilities) and routing through multiple short intermediary links are combined to realize low-power transmitter (i.e., and battery) requirements. Certainly this type of tactical internet has tremendous potential value to the warfighter. Specifically, when emerging microsensor technologies (i.e., unattended ground sensors such as acoustic, seismic, magnetic, visual, and IR) are efficiently and effectively wireless-linked one can expect new levels of battlefield C4I (command, control, communications computers and intelligence) such as vehicle identification, area surveillance, perimeter defense, troop movement and communications infrastructure support. Furthermore, while such integrated sensor concepts need more demonstrations and advancements to prove their full utility in tactical situations [23], there is certainly reason to believe that they will directly support the FCS vision.

So what if anything does THz electronics have to offer sensing and communications on the battlefield? To begin, it should be noted that THz frequency sensing and communications does not exist in any fieldable capacity (i.e., military or commercial) at the present time. Clearly, the absence of an application of a THz based technology is due to the large atmospheric attenuation (i.e. 100's of dBs per kilometer) over the band. Of course, the solid-state electronics capability within the THz frequency regime remains extremely limited from a basic signal source and systems perspective but this lack of development may be largely due to the lack of applications. However, it is also true that traditional remote sensing and communications is considered in a venue of at least many kilometers. However, if we consider sensing and communications from a shorter-range perspective (i.e., as in the tactical network picture discussed about) then the requirements, as well as the conclusions, are seen to change dramatically. Consider for a moment the plot of transmission function, given in Fig. 1, for a series of short-range distances at sea level and standard pressure and humidity. The simulated results indicate that a number of feasible windows exist for a number of large bands in the region 300 GHz to 2 THz as well as in the region 6 THz to 10 THz. Indeed, below 1 THz there are two large windows with transmission reaching over 50 % at 100 meters (i.e., ~ 600-700 GHz and 800-900 GHz). These results clearly demonstrate that THz-frequency sensing and communications is viable, or at least possible, in situations where the link extends up to, and possibly exceeds, hundreds of meters.

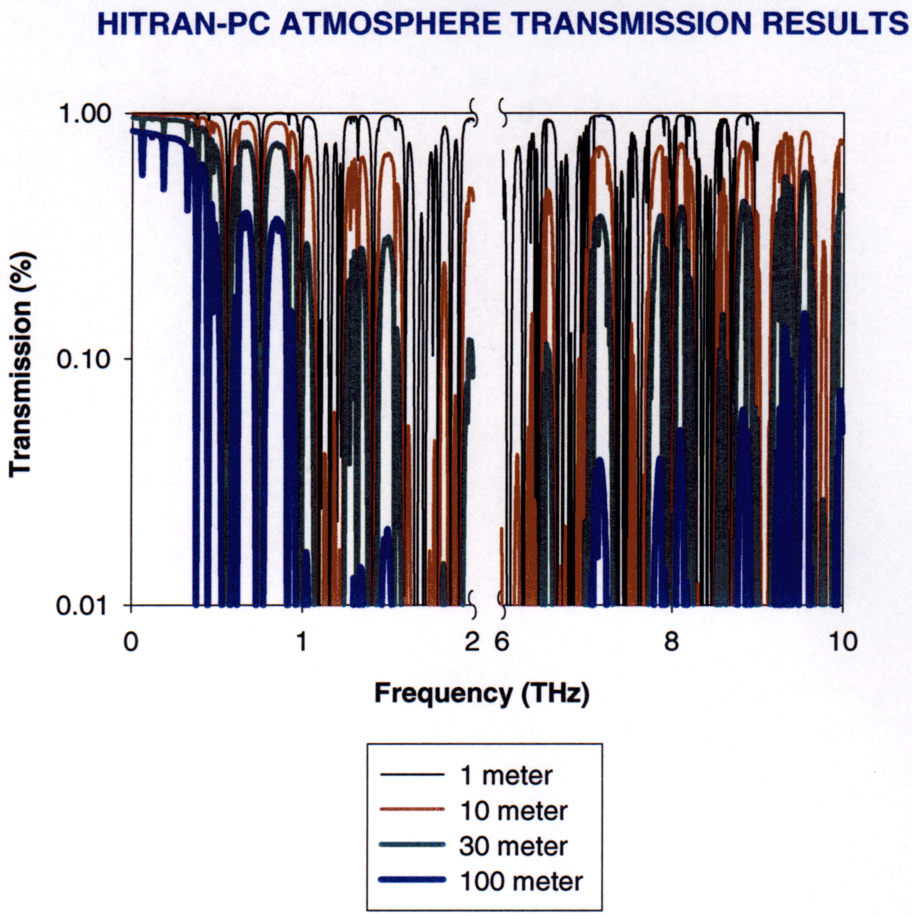

Figure 1. Percent transmission, as a function of THz frequency, calculated from the program HITRAN-PC. A special thanks to Professor SJ Allen, of UCSB, for providing these results.

The results of Fig. 1 show that a tactical system for sensing and communications could be successfully employed on the battlefield if a wireless-network with short-range links were utilized. However, one aspect of going to THz frequencies is in direct contradiction with the existing conceptualizations (i.e. as in SPIN discussed above). Specifically, it is true that utilizing high frequencies, where the transmitting attenuation is greater, will increase power requirements for the ground sensors and ground links. On the other hand, there are significant efforts within the area of signal processing (i.e., on the remote nodes [24]) aimed at accommodating the large data payloads to the limited bandwidths available on existing communication channels. As the requirements for more sensing and imaging data grows in the future, as can be expected from the FCS vision, the tradeoffs requirements on power consumption between bandwidth-use and signal processing may not be so clear. Also, it is all together possible that the existing communications channels that are now in use may not be able to handle the data demands for the FCS of the distant future. Finally on this point, the development of an integrated electronics capability at requirements on power consumption between bandwidth-use and signal processing may not be so clear. Also, it is all together possible that the existing communications channels that are now in use may not be able to handle the data demands for the FCS of the distant future. Finally on this point, the development of an integrated electronics capability at THz frequency would also support and augment the realization of very high-speed digital hardware that could be used for enhanced signal processing. Hence, THz electronics has the potential to impact both sides of this general argument.

The implementation of an integrated sensor-network at THz frequency also affords other advantages in communications. For example, the increased bandwidth-space at THz would further enhance traditional spread spectrum techniques, therefore reducing the communicator's detectability and further combating the problem of enemy-introduced interference (i.e., jamming) [25]. The proposal of introducing a THz frequency communications system also represents a conceptual extension of a newly emerging theme in modern communications, namely what is being refereed to as Ultra-WideBand (UWB) [26]. The UWB technological concept is seen as a new wave in wireless technology and is being lauded as a revolution in wireless communications, radar and positioning. For example, UWB Code Division Multiple Access (CDMA) communication schemes such as *Impulse Radio* [27] utilize a train of sub-nanosecond pulses and a resultant low power spectral density (e.g., spread over ~ 2 GHz). Hence, the Impulse Radio approach possesses advantages such as a high immunity to fading (i.e., less multi-path interference), a large processing gain (i.e., integrates over a WB), a low probability of interception/detection (i.e., individual spectral components are below the noise), and is more energy efficient (i.e., pulsed or nonlinear operation). Finally, moving to a higher-frequency technology offers a potential reduction in the size of sensor elements due natural reduction in the integrated-circuit elements and antennas at the shorter wavelengths.

The application of THz sensing and imaging also has possible feasibility within an integrated wireless-network. The pursuit of multi-sensor fusion schemes [28] that utilize imaging and non-imaging sensors both above and below the THz domain are presently an active and important part of the Army's research and development effort. For example, the MSFATR project under the ARL FedLab program combines infrared (IR), multi/hyperspectral (MS/HS), synthetic aperture radar (SAR) and laser radar (LADAR) to improve the detection of camouflaged targets. In addition, combinations of ground penetrating radar (GPR) and forward looking IR (FLIR) have been used for improvements to buried mine detection. Of course, airborne platforms have already demonstrated the remarkable success of UWB radar in detecting tactical targets concealed by foliage and of surface and subsurface landmines. Furthermore, millimeter wave (MMW) is useful for high-resolution target acquisition and has demonstrated marked advantages (i.e., over IR and optical) in imaging through common obscurants. When implemented in a sensor-network type scheme, THz technology offers the possibility of further extending the Army's electronic capability to the "full electromagnetic (EM) spectrum." Hence, in addition to the use of THz sensing for CB detection as discussed earlier, this shorter wavelength region possess enhanced target resolution. Indeed, a long-standing and analogous use of THz technology can be found in work being performed, and supported by, the U.S. Army's National Ground Intelligence Center (NGIC) [29]. Here, NGIC combines unique high frequency (0.16 – 1.5 THz) compact radar ranges, computational EM codes and down-scaled, precision-engineered models of military vehicles to rapidly and efficiently derive radar signatures for lower frequency systems. This higher resolution capacity of THz systems may also offer advantages to actual battlefield imaging (e.g., enhanced identification and end-game missile guidance). Finally, extending the operating range of sensors and imaging into the THz domain may afford for completely new tactical strategies. For example, in one futuristic scenario, designer obscurants might be used in combination with shorter-wave imaging sensors to increase both the lethality and survivability of Army forces in close combat engagements.

Hence, a robust and integratable THz technology has much relevance on the future battlefield when viewed from an electronic-based sensing and communications perspective. In particular, THz electronics has the potential for augmenting and enhancing the Army's concept of a Future Combat System within a microsensor network scenario. In the next section, ARO support of THz electronics research will be outlined.

III. A BRIEF OVERVIEW OF THE ARO PROGRAM IN THZ ELECTRONICS.

The U.S. Army Research Office (ARO) maintains active support for THz electronics under its Quantum and High Frequency Electronics research program within the Electronics Division. It should also be noted that general support from this part of the ARO electronics program is used to address many diverse areas (e.g., low-power electronics, ultrafast switching transistors, fundamental quantum device concepts, nanolithography, etc) that have technological relevance to the future Army. However, the goal of establishing a solid foundation of scientific and engineering knowledge for THz electronics has extremely high merit and is one that has particularly significant relevance to some of the Army most critical needs. Furthermore, this goal of establishing a knowledge base and electronics capability within the THz regime may be viewed as the ultimate high frequency electronics challenge. Indeed, the last research frontier in high-frequency electronics now lies in the THz (or submillimeter-wave) regime between microwaves and the infrared (i.e., 0.3 – 10.0 THz). While the THz frequency regime offers many technical advantages (e.g., wider bandwidth, improved spatial resolution, compactness), the solid-state electronics capability within the THz frequency regime remains extremely limited from a basic signal source and systems perspective (i.e., < μwatts). Historically, this limited development results from the confluence of two fundamental factors. First, extremely challenging engineering problems exist in this region where wavelength is on the order of component size. Second, the practical and scientific applications of this shorter-wavelength microwave region have been restricted in the past to a few specialized fields (e.g., molecular spectroscopy).

However as we enter the new millennium, important applications of THz technology are rapidly emerging that are extremely relevant to national defense. As discussed earlier in this paper, THz electronics has relevance to the problem of defense against weapons of mass destruction (i.e., chemical and biological) and to battlefield sensing and communications. Of course, THz electronics and related ultra-fast processes can be expected play future roles in such areas as space communication, high speed information processing & computing, material characterization, molecular science, biology, and in medical applications. Hence, ARO is proud of the role it plays in encouraging the pursuit of fundamental investigations within this specialized field of electronics.

At the present time, the ARO provides support for THz electronics research within three main thrust areas. Specifically, ARO is coordinating with other Army components and DoD agencies (e.g., ARL-SEDD, SBCCOM and DARPA) to support research and development in sensing science at THz frequency, novel quantum and nanotechnology based solutions for THz sources and detectors, and robust and integrated (i.e., semiconductor based) THz devices and components.

For example, ARO, ARL-SEDD and SBCCOM has previously established a base for the use of both millimeter-wave and submillimeter-wave spectroscopy as a tool for the identification and interrogation of biological agents [30]. More recent university research [31] supported by this collective Army group has demonstrated that phonon modes within the DNA provide a unique and repeatable signature for the biological agent under test. More recently this Army group has joined with DARPA to engage in a seed program that will assess the utility and feasibility of a "GHz and THz Spectroscopic-based Perimeter Defense System." Under this support, both the experimental science and the theoretical interpretation of molecular resonance phenomenon is being pursued. Furthermore, this general area of sensing science is currently being emphasized and is being supported broadly (e.g., DURIP) out of the ARO electronics division. Another noteworthy effort of mention is the near-THz (200 GHz) research on spectroscopy of biological aerosols which is attempting to put sensitivity boundaries on signature detection in lieu of extended future studies. Finally, ARO assists DARPA with the support of research on the development of a compact, cost-effect and robust Terahertz (THz) spectroscopic instrument for application toward the detection and identification of large molecules within the THz regime.

ARO is also a leader in seeding research that seeks to identify novel device concepts for the generation and detection of THz radiation. One very noteworthy example is the work on "Gain and Loss in Semiconductor Quantum Structures," carried out by Professor Allen from UCSB (see www.qi.ucsb.edu), which has subsequently become a part of the new DARPA program for "THz Sources for Sensing and Satellite Communications." ARO contributes core support for research in the areas of interband resonant tunneling structures (RTD), intrinsic oscillations in convention RTD's and in coupled quantum dot-laser structures as potential new approaches for THz sources. ARO also supports work in plasma wave technology and in Fermi electronics (noise-correlated) research both of which target novel approaches for very high sensitivity receivers. The goal of these high-risk efforts is to assess, and possibly identify, new forms of electronic technology for the future.

ARO certainly recognizes the difficult challenge of realizing an electronic capability at THz frequency. Hence, ARO is also presently challenging the high frequency device and circuits community to extend existing solid-state technology (e.g., multipliers) to bridge the THz technology gap. Recognizing that a militarily useful terahertz technology must be compact and cost effective, ARO funds research into maturation of planar semiconductor-based approaches. At present, support is being provided for establishing a robust diode-based monolithic millimeter (& submillimeter) -wave integrated circuits (MMIC's) technology. A recently announced Small Business Innovative Research (SBIR) will provide funding starting in Fiscal Year 2002 (FY02) to facilitate the development of semiconductor-based, fully-integrated, terahertz-frequency, transmit/receive modules. Here, the most successful terahertz device technologies (e.g., Schottky and Heterostructure Barrier Varactors and Schottky mixers) will be targeted to realize frequency agile and reliable components in a cost effective manner. This research and development will provide valuable test beds for facilitating additional innovations in sensing and for conceptualizing new uses of THz technology (e.g., communication networks).

The significant potential impact of THz technology towards battlefield sensing and communications (i.e., in a microsensor network scenario) and the extreme challenges of realizing robust sources imply that that ARO will continue to support innovation in very high frequency electronic-based technology. New areas of potential contribution include the further leveraging of nanoscale device concepts, molecular electronics and dynamical phenomenon at THz frequency. The investigation of THz-frequency capability towards new communication techniques (e.g., possibly even THz/Optical hybrids), its implementation for very high-speed data processing and its application to medical uses are also anticipated areas of emphasis. Indeed, the potential impact of THz electronics in future Army applications suggests its continued support and emphasis.

IV. CONCLUSIONS.

This paper has addressed THz electronics research from the U.S. Army and national defense perspective. In particular, the potential role of THz electronics is evaluated from a consideration of the Army's overall strategic vision. This paper has shown that a THz electronics capability would address critical needs and long range goals of the U.S. Army. Specifically, the development of a robust and integrated THz electronics capability would have significant value when placed into the context of the Army's Future Combat System (FCS) concept. Furthermore, fundamental research in the field of THz electronics will enhance and extend electronic capabilities that presently exist in Army science and technology programs (e.g., ARL FedLab). The U.S. ARO is presently investing in novel science and technology within the THz frequency regime to enable a full electromagnetic-spectrum capability for sensing and communications. There is certainly significant evidence to suggest that the ARO program in THz electronics will contribute to the Army's future ability to achieve the "full spectrum of dominance" articulated by its leadership.

ACKNOWLEDGEMENTS

The author would like to extend his sincere gratitude to Dr. William Sander of ARO, and Drs. Alan Samuels and Jim Jensen, of SBCCOM, for supplying valuable information that was used in the preparation of this manuscript.

REFERENCES

[1] "U.S. Army Research Office Electronics Division: 1999 Selected Significant Accomplishments", see the Proceedings to the 1999 Electronics Program Review, April 20-21, 1999.

[2] "U.S. Army Research Office in Review – 1999", see Army Research Office Publications, internet site (http://www.aro.mil).

[3] "The Army Vision: Soldiers On Point for the Nation ... Persuasive in Peace, Invincible in War", see The Secretary of the Army internet site (http://www.hqda.army.mil/secarmy).

[4] "Army Chief of Staff Arrival Ceremony Remarks", June 22, 1999, see Army Chief of Staff on internet site (http://www.army.mil).

[5] The Office of the Assistant Secretary of the Army (Acquisition, Logistics, and Technology) see internet site (http://www.sarda.mil).

[6] "1998 Army Science and Technology Master Plan," see internet site (http://www.sarda.mil/AboutUs/about/sardzt.htm).

[7] "Future Combat System," see Federation of American Scientists web site (http://www.fas.org/man/dod-101/sys/land/fcs.htm).

[8] A.H. Sharoni and L.D. Bacon, "The Future Combat System (FCS)," *ARMOR*, pp. 7-11, July-August, 1997.

[9] M. H. Van Fossen "Future Combat System," presented at the FY01 Sensors & Electron Devices Directorate (SEDD) Program Formulation Workshop, 28 Feb. – 01 March, 2000.

[10] The Office of the Under Secretary of Defense for Acquisition, Technology and Logistics internet site (http://www.acq.osd.mil).

[11] Information derived from conversations with Dr. A. Samuels and Dr. J. Jensen of The Soldier Biological and Chemical Command (SBCCOM), Edgewood, MD.

[12] LTC M. Lamphere, "DoD Needs for CB Detection," presented at the Army Research Office Workshop on Nanostructures for DoD Applications, Ga. Tech, Atlanta, GA, Oct 14-16, 1998.

[13] K. Phelps, "DoD Chem/Bio Detection Program," presented at the Army Research Office Workshop on Nanostructures for DoD Applications, Ga. Tech, Atlanta, GA, Oct 14-16, 1998.

[14] The 1996 edition of "Defense and Technology Strategy" published by DDR&E lists the capability for standoff detection of biological agents and as "our most pressing single need". The May 1996 issue of the "Joint Warfighting Science and Technology Plan" states that early warning of biological attack is the "highest CINC counter proliferation priority".

[15] D. Woolard, R. Kaul, R. Suenram, A. Height Walker, T. Globus and A. Samuels, "Terahertz Electronics for Chemical and Biological Warfare Agent Detection," Keynote paper presented at focus session on Submillimeter-wave and Terahertz Technology, 1999 International Microwave Symposium, June 13-19, Anaheim, CA.

[16] Dr. A. M. Andrews II and Dr. T. Killion, "Accelerating the Pace of Transformation," *Army & ALT*, pp. 13-16, March-April, 2000.

[17] Future Combat Systems Program description under DARPA - Tactical Technology Office (TTO), see internet site (www.darpa.mil/tto).

[18] MG J. M. Cosumano Jr., "Transforming the Army to a Full-Spectrum Force," *Army & ALT*, pp. 13-16, March-April, 2000.

[19] 2000 Annual Report(s) on the ARL Federated Laboratory (Consortiums on Advanced Sensors, Advanced Displays & Interactive Displays, and Advanced Telecommunications & Information Distribution) available via website (http://atirp.isr.umd.edu).

[20] RF and Microwave Circuit Design for Wireless Communications, edited by L. E. Larson (Artech House, Boston, 1997).

[21] D. G. Mills, "Low-Energy Communications and Routing for Microsensor Networks," Proceeding of the ARL Federated Laboratory 4th Annual Symposium on Advanced Telecommunications & Information Distribution, College Park, MD, March 21-23, 2000.

[22] J. Agre, L. Clare, N. Romanov, V. Panov, J. Kelly and R. Klingeman, "Sensing Positioning Integrated Network (SPIN): Providing Situational Awareness to the Warfighter," Proceeding of the ARL Federated Laboratory 4th Annual Symposium on Advanced Sensors, College Park, MD, March 21-23, 2000.

[23] S. R. Blatt, D. M Hull and A. M. Filpov, "Microsensors in a Changing World: Extended Sensing," Proceeding of the ARL Federated Laboratory 4th Annual Symposium on Advanced Sensors, College Park, MD, March 21-23, 2000.

[24] S. Natkunanathan, A. Sipos, S. Avery, G. J. Pottie and W. J. Kaiser, "A Signal Search Engine for Wireless Integrated Network Sensors," Proceeding of the ARL Federated Laboratory 4th Annual Symposium on Advanced Sensors, College Park, MD, March 21-23, 2000.

[25] L. B. Milstein and M. K. Simon, "Spread Spectrum Communications," Chapter 11 in The Mobile Communications Handbook, Edited by J. D. Gibson (CRC Press, 1996)

[26] see Proceedings to The 1999 International Ultra-Wideband Conference, Washington, DC, September 28-30 (1999).

[27] S. S. Kolenchery, J. K. Townsend and J. A. Freebersyer, "A Novel Impulse Radio Network for Tactical Military Wireless Communications," Proceedings of MILCOM 98, pp. 1-7 (1998).

[28] see 1999 the ARL FedLab Annual Report of the Advance Sensors Consortium.
[29] M. J. Coulombe, T. Ferdinand, T. Horgan, R. H. Giles and J. Waldman, "A 585 GHz Compact Range for Scale Model RCS Measurements," in the Antenna Measurements and Techniques Association Proceedings, Dallas, TX, Oct. 1993.
[30] D. L. Woolard, et. al., "Millimeter Wave Induced Vibrational Modes in DNA as a Possible Alternative to Aminal Tests to Probe for Carcinogenic Mutations," The Journal of Applied Toxicology, 17, pp. 243-246, May (1997).
[31] T. R. Globus, D. L. Woolard, M. Bykhovskaia, B. Gelmont, J. L. Hesler, and T. W. Crowe, "FTIR-Spectroscopic Characterization of DNA Macromolecules," in the Proceedings to the International Semiconductor Device Research Symposium, December 1-3, Charlottesville, VA, 1999.