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14. ABSTRACT

Under this Phase II SBIR effort, Directed Energy Inc.'s (DEI) proprietary ultraviolet (UV) emitters and the best available electro-optic components are employed to implement a functional prototype demonstrating short range, medium data rate non-line-of-sight (NLOS) optical communication data links operating in the solar blind region (200–280 nm). The intended application is covert wireless transfer of medical data for battlefield combat casualty care. During the course of this effort and after detailed investigation pertinent to this technology through simulation, system studies, field trials, and review of current and future technologies, hardware components were designed and integrated into a functional breadboard system demonstrating: (1) unidirectional communication of medical data in outdoors environment; and (2) bidirectional communication of medical data with encryption and forward error correction. Work in the second half of the Phase II project will extend the test bench implementation to be capable of mobile ad-hoc networking, and will repackage the system as a brassboard module suitable for field trials.

15. SUBJECT TERMS
Non-line-of-sight (NLOS), networking, optical communication, plasma-shells, short range, ultraviolet (UV) light

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Introduction

This project investigates the efficacy of short range (up to 50 m), medium data rate (at least 57.6 kbps) non-line-of-sight (NLOS) optical data communication using ultraviolet (UV) light in the solar blind region (200–280 nm wavelength). The application is wireless transfer of medical data for battlefield combat casualty care. The investigated scenario is medical data transfer between a patient-worn vital sign monitor to a medic PDA from the initial site of trauma in outdoor environments with diverse atmospheric conditions to indoor areas including evacuation vehicles and forward combat support hospitals. To date, no researchers have experimentally demonstrated compact transceivers capable of adequate range and data rate. In the previous Phase I effort, Directed Energy Inc.'s (DEI) parent company Imaging Systems Technology (IST) demonstrated feasibility of several key concepts. These are being developed into a working prototype in the Phase II effort to meet Army requirements for a UV NLOS communication device.

Body

Under this Phase II SBIR, DEI's main objective is to develop prototype UV optical communication hardware to create a flexible hardware platform that can be easily integrated into a variety of applications relevant to the Army medical mission. In this context, research progress from May 2014 to May 2015 is outlined in this section.

Task 1. Simulation

Monte Carlo photon scattering simulation requires considerable processing power to accurately model high path loss. Custom photon scatter code was rewritten for parallel execution on a graphics processing unit (GPU). The NVidia CUDA environment was set up and support functions for the parallel cores were optimized for distributing and collecting data to/from each core. The link performance of transmitters and receiver was simulated with varying pointing angles and fields of view. The working Monte Carlo (MC) photon scatter code, was validated against current published research.

The working Monte Carlo (MC) photon scatter code was then ported to MATLAB to use the Parallel Processing Toolbox that allows code to run on multiple CPU and GPU cores. As a first step the C code was rewritten from a form based on sequential branching code, to a non-branching matrix form. This eliminates code branches that incur a significant performance penalty, and uses matrix operations that scale well on parallel hardware. Execution time was reduced from 450 minutes per billion photons with the C code running on 4 CPU cores, to 4.5 minutes per billion photons with the MATLAB code running on 192 GPU cores. Additional tweaks realized a speedup of ~30X; In the future, the code will be used to explore design tradeoffs of the switched-beam LED transmitter concept that consists of multiple LED die surrounding a ball lens, in terms of the required number of LEDs and angular separation between LEDs.

Task 2. Plasma-shell Improvement

Investigations were conducted that focused on the electrodes of the Plasma-shells. A novel 3-electrode drive scheme was development. The scheme enables UVC emission at higher brightness and efficiency without significantly increasing drive voltage. This requires two electrodes printed with silver conductive ink and the third with resistive ink ranging from 2 to 4 MΩ. Gap between the resistive "trigger electrode and the conductive electrodes was reduced to 250 µm. The turn-on voltage was reduced from 600 to 450 V.

Additional work has been done on the step-up transformer used in the switching power supply, and by custom-winding bobbins for E-core ferrites with ratios between 22:1 and 30:1 were investigated. Higher voltage coupled into the Plasma-shells was demonstrated to improve output emission. However a significant improvement in UVC LED output, has led the team to conclude UVC LEDs are a better choice for use in the transceiver.

The Plasma-shells have superior life, and may be of value in some applications. Aging data for UVC Plasma-shells manufactured at the start of Phase I are shown in Figure 1 where average power for two shells is normalized to burn-in time of 24 hours. Output power at 26,000 hours is 50% of initial power at 24 hours! This demonstrates that Plasma-shells have superior lifetime compared to UVC LEDs with lifetimes as short as 1000 hours.

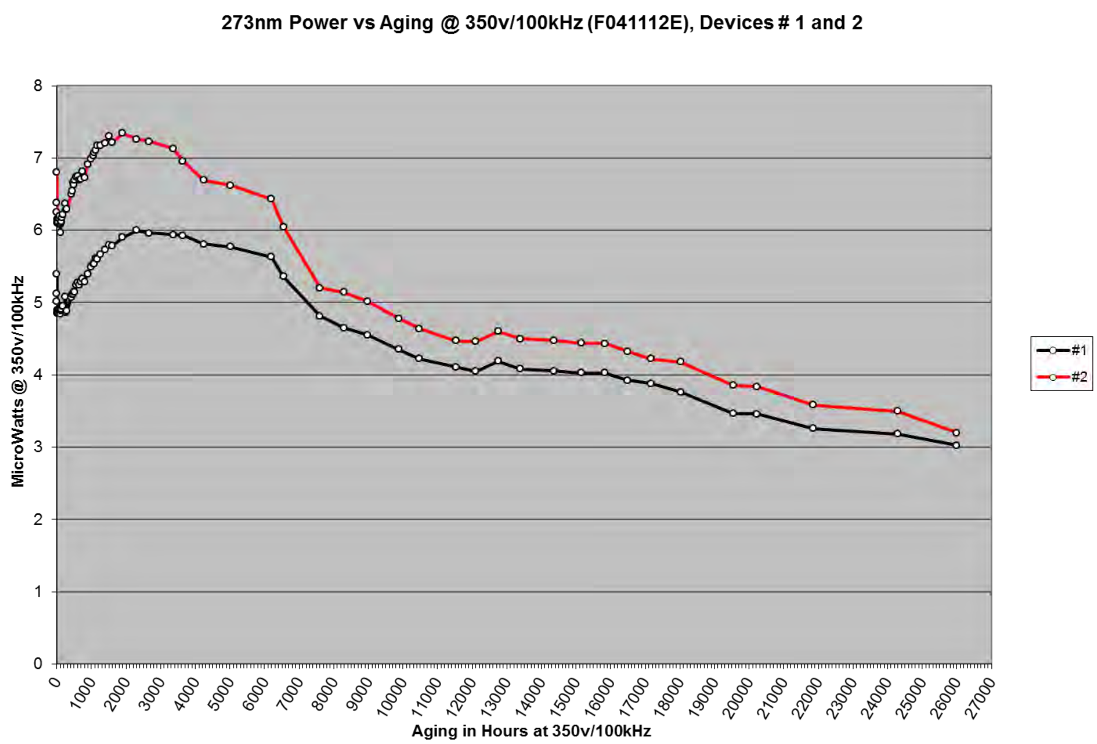

Figure 1: Plasma-shell UVC power at 26,000 hours is greater than 50% of initial value.

Task 3. Transceiver Hardware

Packaging was reduced. Work will continued on improving each sub assembly.

Packaging

The transceiver hardware was repackaged to fit within a breadbox-sized volume of 12 in. × 6 in. × 6 in. The two UV transceivers were repackaged into a volume of 7.5” (L) × 5” (W) × 5.5” (H) as shown in Figure 2. This was achieved by integrating circuits and power supplies onto a reduced

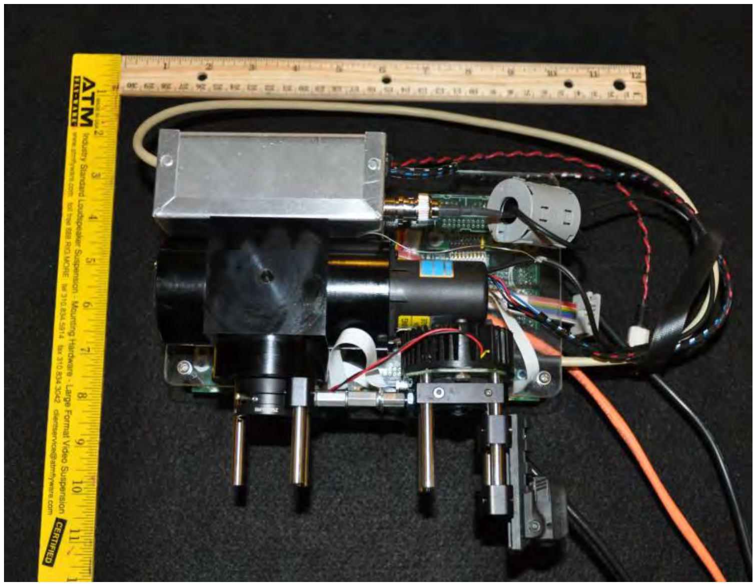

Figure 2: Reduced size transceiver hardware.

number of PCBs with cleaner interfaces. Key boards that were improved include the discriminator, the FPGA board, and the LED driver. The discriminator was mounted in a shielded enclosure, and the discriminator circuit was integrated with its power supplies and the PMT power supplies on one board, and the output cable that goes to the FPGA logic was reduced to a single cable with signal and power. The FPGA board now includes the LCD interface board with mounting points (this is used as a convenient user interface during field testing), and it directly connects to discriminator board and LED driver board. The LED driver, which had been integrated with the LED and lens assembly, is now a separate board that mounts on the FPGA board and connects to the LED with a short cable to allow LED pointing. Minor bugs were addressed during the integration process. The repackaged modules still contain a significant amount of empty space and have the potential to be reduced in size much further in future development efforts. An Altera Cyclone V system-on-chip (SoC) was employed to further the integration effort. The SoC FPGA has a dense logic array and a powerful 32-bit processor in one package, and this will reduce part count for future single-board transceiver modules.

Two complete systems have been integrated into bread box sized enclosure with a small commercially available battery and charger to allow an untethered demonstration. Figure 3 is a photograph of the transceiver system. In addition to the UV LED and the photomultiplier tube the system includes an LCD screen to display bioharness data, a tilt stand to position the system for test and evaluation and a strap handle for transportation. The system also includes a number of I/O ports for firmware updates, troubleshooting, and data collection.

Figure 3: Packaged UV NLOS transceiver.

LED

The LED subassembly was miniaturized to the fullest extent using the Crystal IS LED with a customized heatsink and fan. Further optimizations have been identified and will be employed in future work.

A reduced-volume LED emitter in 4 was designed and built around the new Crystal IS Optan UVC LED, which is their UVC LED die packaged in a hermetic TO-39 package with a ball lens that collimates output to 15° beam width. The custom heat sink and fan package provides optimal thermal management in a package of 25 cm on edge. It is believed that future fielded systems can achieve adequate LED thermal control without forced air cooling as LED efficiency improves, but the current fan is needed to operate with higher LED drive currents during developmental testing.

Figure 4: Reduced size LED emitter assembly with 5 mm LED, heat sink, and fan.

Solar Blind Filter

Additional Solar blind filter manufacturers were identified in order to determine the best possible solution. Existing filters are not well matched to the LED spectrum, are limited to ~1" diameter, and are thick (~1"). Improvement in any of these areas would directly benefit SWaP and link performance. Two potential suppliers were identified: Ofil and Delta Imager.

The solar blind (SB) filters available from Ofil are expensive at $17,000 per filter. Delta Imagers filters were $3,000 per filter. Subsequently DEI placed an order with Delta Imager for integration into the transceiver.

In parallel with this, DEI investigate SB filter prior art. Expired U.S Patent 4,317,751 and 4,597,629 issued to ITT provide a detailed description of a solar blind filter. In these patents, several filters are stacked to achieve the desired band pass. The chemical composition of each filter is defined. Additional research uncovered strategies for adjusting filter chemistries to further "sculpt" the pass band. The opportunity exists to develop a tailored filter optimized for a very narrow band of between 275 nm – 280 nm. This will be an important part of future optimization path.

Photon Detector

A major improvement of the transceiver architecture will be the use of the Photonis hybrid photodiode (HPD). The Photonis HPD was procured and support circuitry developed within the constraints of the budget. Hardware was designed and ordered for the Photonis HPD photon-counting sensor and initial testing begun. Long lead times for the Photonics HPD hindered the integration of this component into the breadboard transceiver module. Because the HPD sensor has 19 channels to digitize, a single-chip multi-channel discriminator IC would be an ideal solution to digitize the sensor output using a minimum of board space and power. Ultimately a custom ASIC will be required to realize the full potential of this device. This will be explored in future development efforts.

Task 4. Network Protocol

In this task, networking protocols were investigated to support the project objective of seamlessly integrating UVC communication nodes into complex multi-hop network architectures.

The network protocol was simplified to a master-slave polling architecture to simplify implementation. Protocols were developed for packetization of data with an ACK/NAK response and automatic adjustment of signal levels until confirmation. Packets include routing information, payload, channel transmit and receive conditions and quality, and error detection. The packets allow for multiple-node communication. Bi-directional communication has been tested using a combination real channel (UV transmit and receive) and simulated additional channel using a cable, but with combined receive channels response to simulate the real conditions of half-duplex echo and collisions.

Task 5. Testing

Testing was conducted to determine the effects of UVC on night vision goggles. Testing was conducted to verify the performance of the network protocol.

UVC Effect on Night Vision Goggles

A basic test was done to estimate the effects of UVC emissions on night vision goggles (NVG). Helicopter pilots use the AN/AVS-6 aviator's night vision (ANVIS) goggles that use third generation (Gen 3) image intensifier tubes to greatly amplify ambient light. A unique feature of AN/AVS-6 goggles is the incorporation of a "blue-cut" filter on the objective lens that blocks nearly all light of wavelengths shorter than 625 nm. The purpose of this filter is to allow internal aircraft lighting and displays to be viewed by the naked eye using shorter wavelength colors such as green, yellow, and blue, while outside scenery is viewed through NVGs that amplify red and near infra-red wavelengths that are the dominant illumination wavelengths from moonlight and starlight.

The test setup in Figure 3 was used to measure visual acuity in low-light conditions. It is intended to estimate the effect of a UVC transmitter illuminating the cockpit and windshield from a distance of 1 meter, potentially interfering with observation of the instrument cluster and outdoor scene. A Snellen-style eye chart was scaled for use at 1 m and printed on a white sheet, and the chart is illuminated by a red LED that represents the outdoor scene with low ambient light levels. For reference, starlight radiance is 0.002 Cd/m^2 and moonlight can be as bright as 1 Cd/m^2. Eye chart radiance was spot-checked with a hand-held light meter. The eye chart was additionally illuminated with a UVC LED, and a bandpass filter was included to limit emission wavelengths to 270 ± 10 nm. The minimum required LED transmit power for indoor environments is estimated to be 50 µW for 50 kbps communication over 1 m, and this test was conducted at a level 1600× greater than this power level in order to have an observable effect. Direct UVC illumination on the chart was equivalent to a powerful 84 mW source with a 30° beam angle. The visual acuity of a human observer was measured at 1 m distance using the standard Snellen pass criteria of 5 out of 6 correctly identified letters per row.

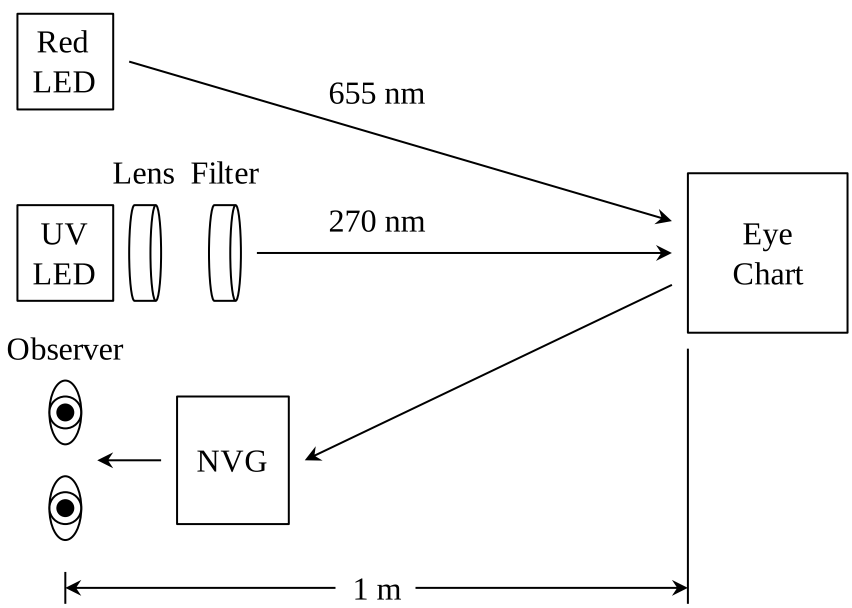

Figure 3: NVG compatibility test setup.

Visual acuity was measured at different ambient light levels, with and without UVC illumination. The visual acuity of the observer was 20/20 with normal white lighting and chart radiance of 44 Cd/m^2. Table I shows that strong UVC illumination had no effect on visual acuity, and was barely discernable even at the lowest tested light level that is below starlight illuminance. In fact, even with the red LED turned off and only stray light illuminating the chart, acuity was measured at 20/200 and added UVC illumination did not improve acuity.

Table I. Visual acuity versus ambient light level.

	Red Light Intensity:		
UVC Light	**0.1 Cd/m^2**	**0.01 Cd/m^2**	**0.001 Cd/m^2**
Off	20/40	20/30	20/50
On	20/30[1]	20/30[1]	20/50[2]

Note 1: Could not see UVC light at all.

Note 2: UVC light was barely perceptible; no effect on letter recognition.

Our conclusion from this experiment is that an active UVC emitter, even when emitting far above the minimum required power level and directly illuminating visible surfaces, does not affect visual acuity in low light environments. It is not expected to interfere with visual tasks and did not cause NVG blooming or blinding. It appears from this testing that the NVG has excellent UVC rejection.

The reduced-volume LED emitter (built from a Crystal IS Optan UVC LED, custom heat sink, and fan) was tested to confirm proper operation.

Network Protocol Testing

A Benedict computer model DLM400 serial protocol analyzer was purchased for testing Bit-Error-Rate (BER) between the units. A BER test packet was sent repeatedly by the DLM400 to one unit, via RS422, transmitted to the other unit, then back to the DLM400 over RS422 for analysis. The baud rate was 57600. The results are summarized in Table II below. The general results are that no errors occurred. This is due to the built-in cyclic redundancy check (CRC) in the UVNLOS protocol. It will not knowingly emit a corrupted packet through the RS422 port. Data will not be sent unless the entire packet including CRC is correct. The corrupt packet will be ignored, and then re-transmitted by the sender at increased UVC power level. As the packet error rate increases, the endpoint throughput decreases due to the increased number of re-transmitted packets. The addition of forward error correction to the protocol will allow the units to transmit at the minimum power level to achieve the required data throughput.

Table II. Results of Bit Error Rate Test

Chars sent	51200
Char Recv	51200
Rec in sync	51200
Elap Second	23
BERT (%)	0
Average trip time per block (ms)	237
Block Error	0
Bit errors	0
Blocksize	512
Error Free Sec (%)	100
BLERT (%)	100

Milestone 3 – Brassboard

A brass board implementation was realized that included packaging of the tranciever and battery into a breadbox size system. The systems were integrated with a Zephyr bioharness and biometric data was successfully transmitted at a rate pf 57K BAUD. The Zephyr bioharness protocol was analyzed and linked using its standard Bluetooth communication interface to one of the units, displaying the relevant data and simultaneously transmitting to the other unit over the UVC link. Both units then display the bioharness data. Figure 6 is a screen shot of the bioharness data display that has been and received via a NLOS UV unit.

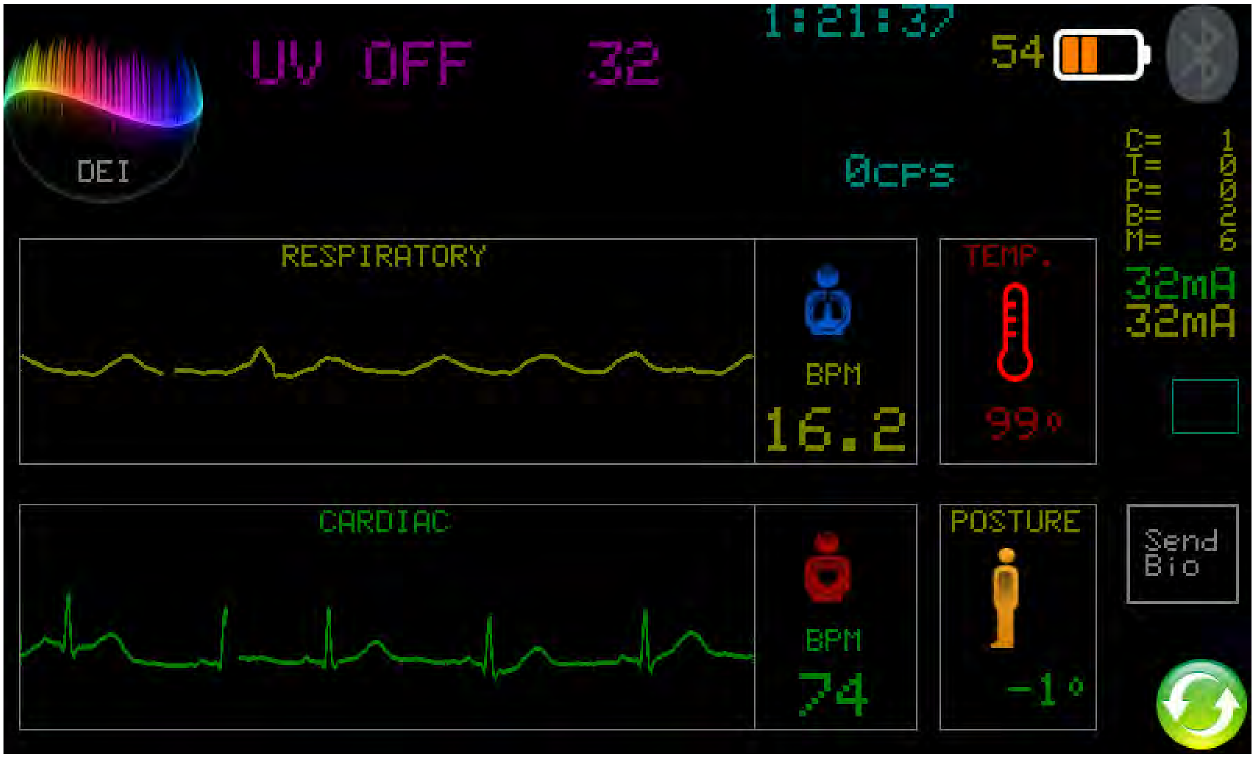

Figure 4: Bioharness data transmitted and displayed via UVNLOS transceivers.

The software and FPGA equations have been “cleaned-up” to make room for the demonstration software. Old test-performing code and display features were removed and replaced with a new GUI-like control panel emphasizing the bioharness link feature.

Milestone 4 – Prototype demonstrated

Two breadbox sized communication systems were integrated and demonstrated non-line-of-sight bidirectional communication at Ft. Detrick. One of the transceivers was connected to a Zephyr bioharness worn by IST personnel. Biometric data was transmitted in real time from one system to the other. Figure 4 is one of two breadbox size transceivers.

Key Research Accomplishments

- Integrated two portable NLOS transceivers in breadbox sized system capable of bidirectional communication at 57K BAUD
- Interfaced NOLS transceivers to Zypher bioharness and transmitted relevant real-time biometric data
- Identified clear path toward reduced size and weight of transceiver

Reportable Outcomes

- Submitted 2nd Phase II SBIR for UVNOLS and was subsequently given notice of award
- Recent commercialization activities of synergistic UV Plasma-shell technology:
  - Contracted by Aquionics to produce UVA Plasma-shell modules for UV sterilization.
  - Contracted by EPA to produce UV Plasma-shell water purification modules.

Summary and Conclusion

The UV spectrum is currently unused and is not susceptible to RF interference, jamming, or microwave attack. This presents opportunities for achieving covert communication especially in situations requiring radio silence. Potential applications beyond combat casualty care include: voice communication within fire teams and squads; unmanned aerial/ground vehicle (UAV and UGV) operation; convoy networking, and unmanned ground sensor (UGS) networks.

In this report that covers the second year of research and testing, the required networking theory, prototype hardware and firmware of UV NLOS optical communication system was investigated, and a hardware and software brassboard was successfully implemented. A strategy to reduce weight and size of the brassboard was identified and will be implemented in the second Phase II.