Wireless Communication of Buried IoT Sensors Utilizing Through the Soil Wireless Power Transfer for Precision Agriculture

Michael Tidwell[1], *Student Member*, Chris Swindell[2], *Student Member*,
Christopher S. Johnson[2], *Student Member*, Maanak Gupta[3], *Senior Member*
C. W. Van Neste[2], *Senior Member*
[1]Center for Energy Systems Research
[2]Electrical and Computer Engineering Department
[3]Computer Science Department
Tennessee Technological University
Cookeville, TN, 38505
mjtidwell43@tntech.edu

2023 IEEE Wireless Power Technology Conference and Expo (WPTCE) | 979-8-3503-3737-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/WPTCE56855.2023.10215906

Abstract—**The decline in farming is a systemic global problem that can be linked to inefficient resource management. More advanced digital tools are needed to enhance efficiency and the overall profitability of agriculture. Of the tools/sensors currently in use, nearly all of them require batteries and above ground wireless communications which can interfere with farming operations/equipment. To address these challenges, a through the soil, long range wireless power transfer technique was developed that powers sensor modules connected to the soil. To improve upon this system, a communication technique is presented that utilizes conduction currents to communicate information completely underground. Networking topologies are also presented with a discussion and analysis of circuit operation.**

Index Terms—**Wireless power transfer, Peer to Peer, Pulse mode power electronics, Non-tradional wireless communication**

I. Introduction

According to statistics gathered from the USDA [1], the number of U.S. farms has been in steady decline. Much of this decline is due to the difficulties in generating a profitable income. If resources could be managed more efficiently, less waste would lead to costs savings while lowering environmental impacts. With the low cost electronics revolution, research toward precision agriculture has gained popularity, reinvigorating the agriculture industry. The amount of tools that enable precision agriculture are increasing exponentially [2]. One such tool that potentially could have significant benefits is the development of networked sensors known as the Internet of Things (IoT). Instrumenting farmland with a high density of IoT systems could lead to cost savings and increased productivity by relaying accurate data real-time such as soil humidity and temperature. [3] proposes a wireless power scheme that utilizes conduction currents in the soil to transmit power over vast distances and complex terrain. One downside of this wireless power transmission method is that traditional communication methods used for IoT sensors is rendered ineffective due to RF signals being attenuated by the soil.

Very little literature exists at the present moment that investigates communication methods through lossy dielectric mediums. One such industry that utilizes communication through the ground is mining and is discussed at length in [5]. Typical ways of communications for mining are wireless systems with repeater nodes that increase the survivability of the communication signals but require continual battery replacement. More commonly found is a hard wired system, similar to dial telephones. The downside of this approach is the need to instrument a massive wire network to connect phone lines to the surface. It seems very little research into alternate forms of underground communications has been produced.

This manuscript investigates a non-traditional sensor network and communication scheme that utilizes the Through the Soil (TTS) Long-Range Wireless Power Transfer (LR-WPT) system technique to achieve reliable underground data transmission in tandem to power. The proposed method is not line of sight dependent and is possibly viable in a variety of environments. Utilizing the TTS LR-WPT system will allow buried IoT sensors to receive charge through conduction currents in the soil, eliminating the need for battery replacement. The proposed communication method seeks to transmit communication pulses whenever the TTS system is inactive, allowing for real-time, uninterrupted wireless communication. Theoretical models and waveforms will be presented and experimental results will be shown as a proof of concept.

II. Theory of Operation

A. Through the Soil Wireless Power Transfer

A long-range wireless power transmission concept was proposed in [3] using continuous waves injected into the soil to power sensors on the surface. The TTS transmitter consists of two electrodes in direct contact with the soil to induce conduction currents. While [3] focuses purely on

National Science Foundation Award Number 2226612.

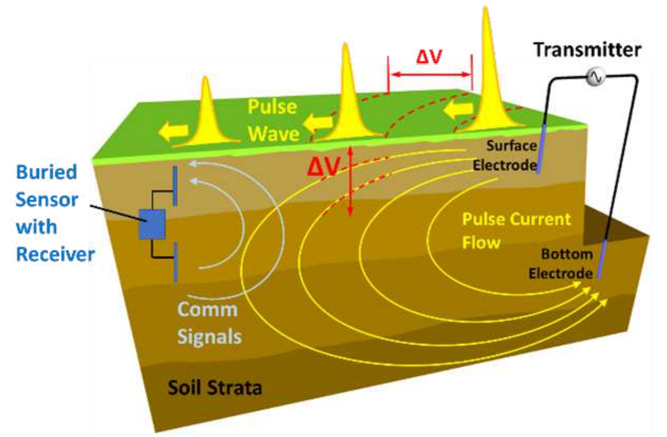

Fig. 1: Schematic of the proposed TTS system driven through high repetition-rate pulses.

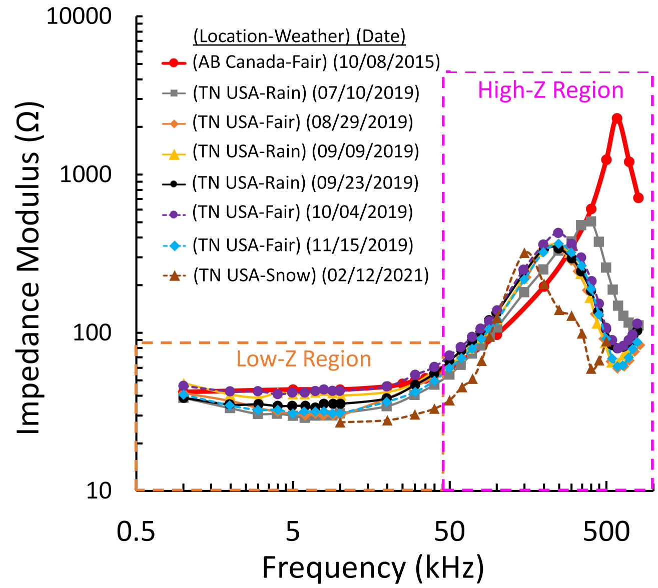

Fig. 2: Long-term impedance measurements over several months, weather conditions, and two different geographical locations taken from [3].

sinusoidal continuous waves, such as 60 Hz power, [4] includes data obtained with high amplitude, high repetition-rate pulses. In the TTS system, pulses require significantly less power to propagate large distances and can be seen at the receiver and transmitter. Electromagnetic waves attenuate when propagating through soil due to the soil acting as a conductive medium and producing eddy current effects. This is a significant issue prevalent in far-field radio transmission and principles, leading to the necessity of new underground communication schemes. Therefore, a modified version of the TTS system is shown in Fig. 1 using the pulsed waveform properties to the systems advantage. Due to the lower energy requirement to transmit pulsed signals, modified IoT sensors with pulse-driven power electronics will be able to send lower amplitude communication signals to the transmitter. Through the implementation of communication protocols and sensor network theory, buried sensors should have the capability to send low latency data packets between power pulses to the transmitter that will circumvent issues seen in modern communication systems.

B. Using Pulse Position Modulation for TTS Communications

Pulsed Position Modulation is an ideal candidate for TTS communications. It was shown that waveforms within a particular bandwidth of the soil will propagate to a significant distance. By selecting a pulse width where the majority of the Fourier components of the pulse reside in this frequency range highlighted in Fig. 2, efficient communication signals can be transferred throughout a large radius. A consumer grade pulse position modulation (PPM) protocol, known as the NEC protocol, is a form of PPM that is wide spread and has many freely-available microcontroller libraries. Using NEC, it is possible to transmit up to 4 bytes of information [6]. A benefit of this protocol is that the designer is able to utilize a carrier frequency to send pulses to the system if needed. Many systems take advantage of this protocol and its benefits such as televisions, phones [7], and electronic devices that tend to infrared wireless controllers. The default NEC protocol starts with a 9 milliseconds leading burst pulse that signals to listening systems that a data signal is being prepared to be sent. Once the initial 9 milliseconds burst is sent, the signal has a 4.5 milliseconds delay before the system begins to send the 8-bit address by signal pulses for the listening devices to receive. The protocol then sends the inverse of the address signal to allow the receiving device to have two copies of the address signal to check, one being the actual address bits and the other being the logical inverse of the address. Both the address and the inverse address all together take 27 milliseconds to pulse in the proposed system. After the addresses are sent the protocol then dictates that the 8-bit command is sent next. The method that which the command is sent is similar to the address and that is by first sending the desired command data bits then sending the inverse of the command data bits. The amount of time that the command data bits take to send is the same as the amount of time the address bits are sent, which is 27 milliseconds. Lastly to finish the sending of the signal, the system will pulse a final 562.5 microsecond burst to tell the listening signal that the system has completed the transmission of the signal. All together the system will be able to pulse one set of the data in 67.5 milliseconds as seen in Fig. 3.

To utilize the NEC protocol for this TTS system, each sensor will need to be set to have a certain address that allows them to be pulsed in NEC from the transmitter through the soil. The sensors will then be buried and allowing them to charge their capacitors using through the TTS wireless power transfer. Once the capacitors are fully charged the transmitter will stop sending power through the soil and allow the underground sensor to be set in stand by mode until receiving the NEC pulse from the transmitter telling the sensor to transmit. The

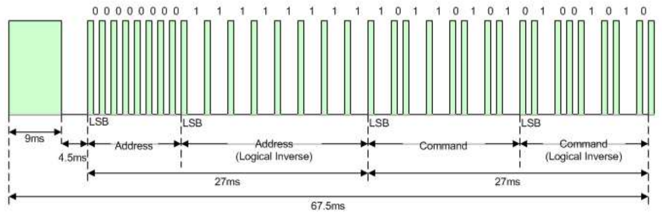

Fig. 3: Photograph of NEC Protocol Example with the address in bits being 00000000 and command in bits being 10101101. [6]

underground sensor will then pulse the desired data back to the transmitter via TTS in the form of the NEC protocol to be inputted appropriately into an data collection storage.

C. Peer to Peer Sensor Network

In addition to developing a new method for how agricultural IoT sensors will communicate individually on a hardware level, some thought must also be given to how these sensors should behave as a collective network. A more traditional server-client-style network is not viable given the power constraints of a TTS power system. As stated in [13], the power source of a sensor node is typically a battery or capacitor, which includes a mandatory replacement or minimum charging time and can be a nuisance at best or unreasonable at worst. A TTS power system would be a more economic power source for a network of such sensor nodes.

It cannot be assumed that all sensors (i.e. clients) will or should be capable of communicating directly to a base station (i.e. server) because such sensors usually must work off of low power levels in order to be efficient. Even for a base station with its own power source (although it would also ideally be powered by the same TTS system as the sensors), this would be too taxing on the sensor node hardware to keep up with network traffic and to maintain low power consumption and could potentially draw a greater than ideal amount of power from its power source. If powered by a TTS source, this could potentially lead to downtime in the network due to a loss of enough energy to power all the nodes in the network; if powered by an external source, this could lead to increased cost in time and capital depending on how the external source is recharged or replaced. Therefore, low-powered wireless communication techniques are necessary between sensor nodes. [13] highlights long range (LoRa) and Bluetooth low-energy (BLE) as such possible techniques among others. Due to the drawbacks of implementing a server-client system for transferring information, a peer-to-peer (P2P) style network should be considered instead. This would allow groups/clusters of sensors to work mostly independently in collecting data in separate areas of farmland, with base station interaction being reduced down to single nodes within a cluster (i.e. sub-base stations) communicating directly with a base station relaying information from all other nodes in the cluster. An example of P2P file sharing over time using the BitTorrent protocol is shown in Fig 4. The colored bars beneath all of

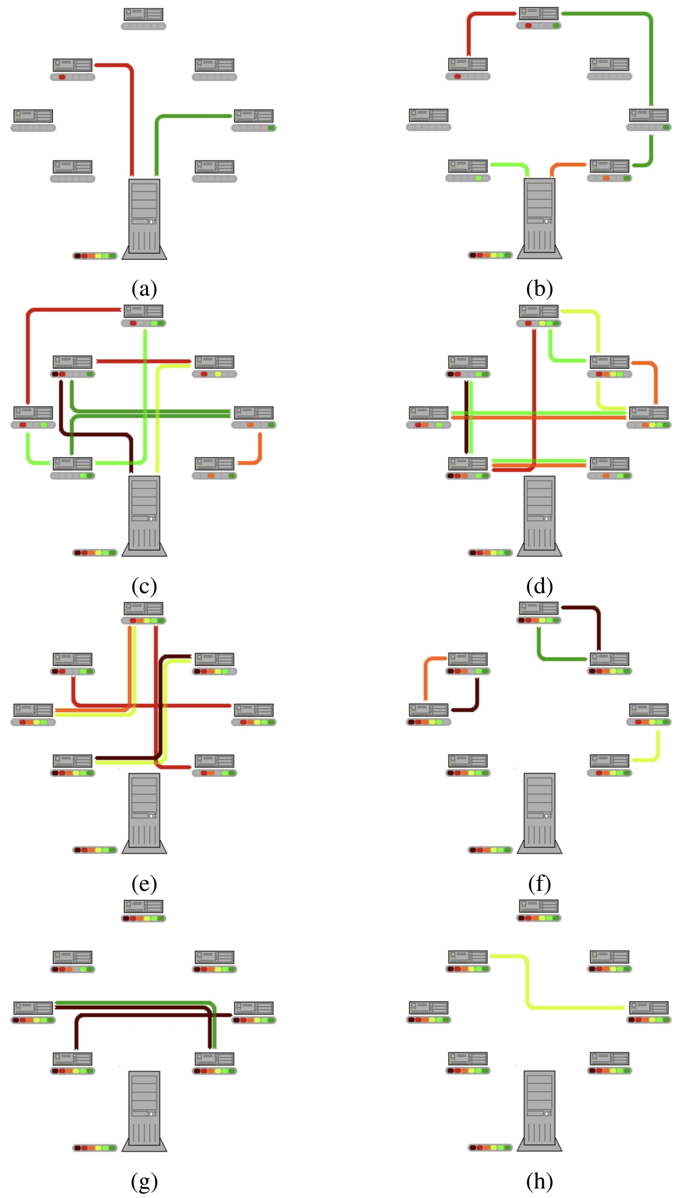

Fig. 4: P2P file sharing example: The BitTorrent protocol. File transfer over time occurs in order from a-h. Different colored lines correspond to separate parts of a file transferred between different nodes in the P2P network at each timestep. This process continues until all nodes in the network contain a copy of the file, as can be seen in h. [12]

the 7 clients in the upper region above represent the file being shared, with each color representing an individual piece of the file. After the initial pieces transfer from the seed (large system at the bottom), the pieces are individually transferred from client to client. The original sender only needs to send out one copy of the file for all the clients to receive a copy. This would cause less power consumption and theoretically more efficient use of network bandwidth due to the buffering of information from all nodes in a cluster sent as one message instead of separate messages from each node. An additional

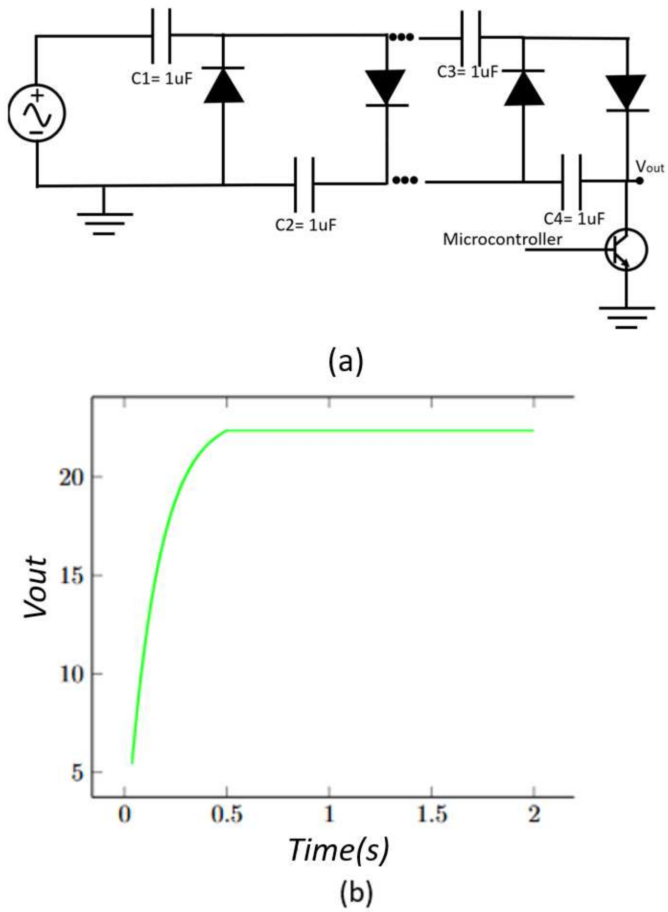

Fig. 5: (a) Circuit diagram of Experimental Communication System using 6 Cockcroft Generators (b) Charging of the Cockcroft generators located in the embedded communications of the sensor

benefit would be the ability for the network to dynamically determine and assign nodes to be sub-base stations based on a certain metric or combination of metrics (e.g. link connectivity with the base station, power consumption, response time with the base station, etc). However, a P2P-style network brings to light an additional constraint in an IoT system: All nodes in the network are commercial off-the-shelf microcontrollers, with the possible exception of the base station which might potentially be a more power consumptive device such as a Raspberry Pi or other personal computer. This means that complex methods for the logic behind the P2P-style network, such as those described in [11] using AI-based schemes, will likely be unfeasible to implement as such scheme's likely require a personal computer (PC) level of hardware, which microcontrollers are inadequate for. The challenge, therefore, will be to implement an intelligent P2P-style network using only microcontroller-level hardware that can operate within the power constraints of a TTS system as well as efficiently propogate information using low-power wireless communication methods. The logic for such a system will need to be adapted from current methods that rely on more sophisticated hardware and is something still currently being explored.

III. Experimental Results

For the TTS sensor communication data to be measured, the sensor module needed a high voltage pulse. A Cockcroft–Walton circuit topology [8] was selected to boost the low AC voltage received by the sensor module to a higher DC voltage. This higher DC voltage was then switched to produce the required pulses for data communication. A Spice simulation of the Cockcroft circuit was conducted (Fig. 5(a)). In the simulation, a 5V peak sinusoidal voltage was boosted to 25V utilizing 6 capacitive stacks. The output was then switched via a mosfet using an NEC pulse train as the gate drive signal.

After validating the circuit operation through simulation, the circuit in Fig. 5(a) was fabricated and experimentally tested in the laboratory before deployment in the field. A 1 kΩ resistor was used to represent the soil resistance. Fig. 6(a) shows the initial pulse from the preliminary circuit's microcontroller when set to have a command of 0xFF and address of 0xFFFF. Fig. 6(b) shows that the boosted NEC signal across the 1 kΩ load resistor.

Next, the circuit was taken to the field and connected to the receiving electrodes of the sensor module, shown in Fig. 1. The TTS reciever with sensor module was placed at a 12m distance from the TTS transmitter (also shown in Fig. 1). The NEC carrier frequency was set to 3kHz and the communication signals from the sensor module were pulsed into the ground. At the TTS transmitter, the communication signals were detected. Due to noise from a local substation, the sensor module's communication signals were most easily observable when a fast fourier transform of the TTS transmitter's output signal was taken. Fig. 7(a) shows the results of a fast Fourier transform, measured from the TTS transmitter, when the NEC carrier frequency is not transmitting. Fig. 7(b), shows the 3 kHz signal communication signal when data from the sensor module's receiver. The 3kHz peak in the FFT is clearly visible.

Conculsions

This work investigated a novel, pulsed approach, to sending communication signals underground. Although the preliminary circuit only applied 25V to the TTS receiver electrodes, the communication signals could be detected in the TTS transmitter (when the transmitter was turned off, not sending power). Future work seeks to improve this topology by increasing the boosted voltage in the sensor modules such that the system can be detected at rangers beyond 12m. Despite the promising results obtained in the initial experiments, further work is needed to determine the long-term feasibility and commercial viability of wireless communication of buried IoT sensors for practical applications.

Acknowledgment

This work was funded by the National Science Foundation Award Number 2226612.

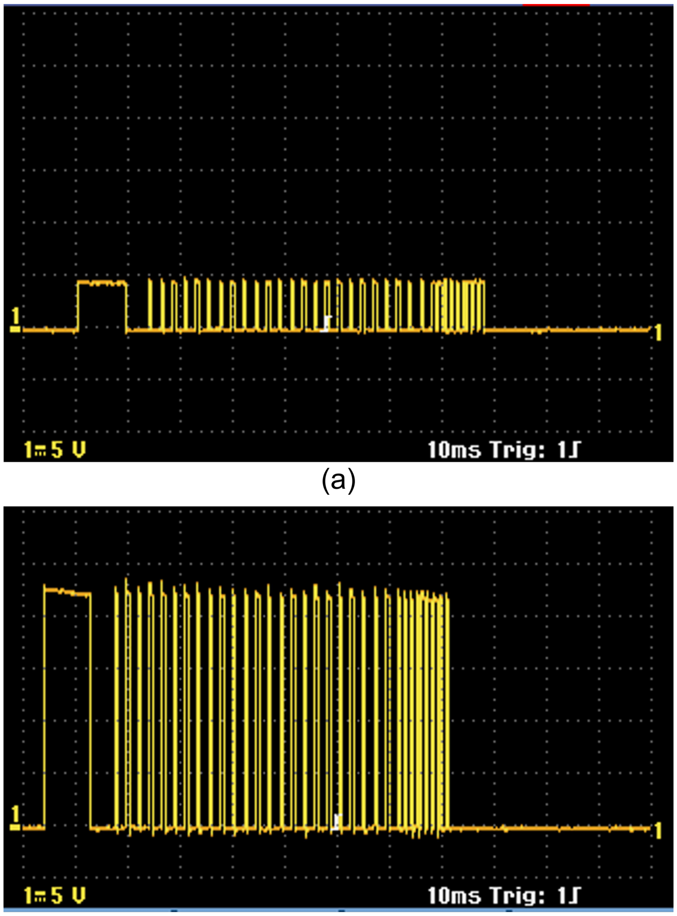

Fig. 6: **(a)** Original NEC pulse from an microcontroller. **(b)** High Voltage NEC pulses across the soil(1 kΩ Resistor).

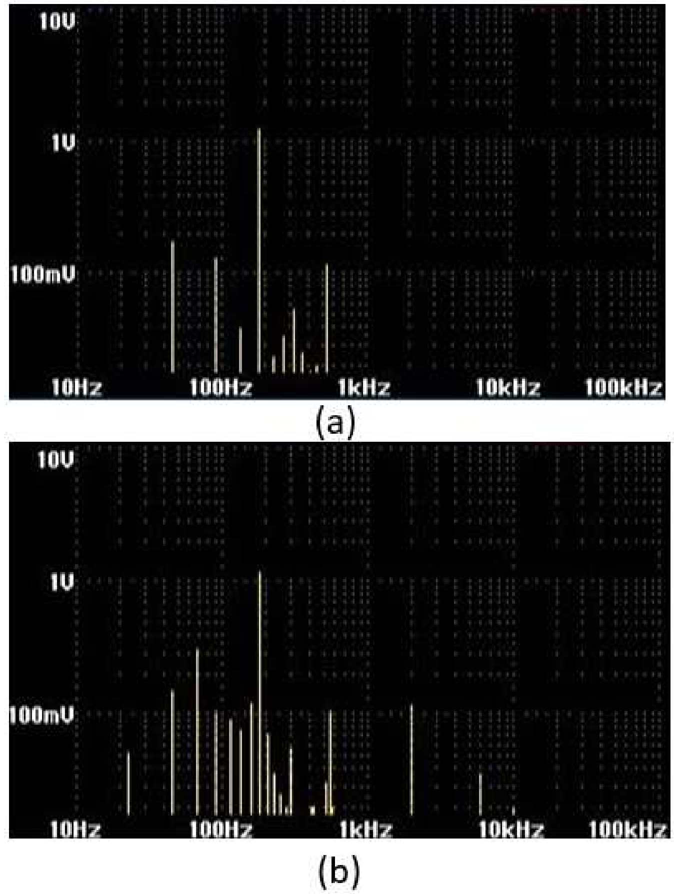

Fig. 7: (a) Fast Fourier Transfrom when the system is not pulsing. (b) Fast Fourier Transfrom when the system is pulsing at 3 kHz.

References

[1] “Benefits and Evolution of Precision Agriculture: USDA ARS.” https://www.ars.usda.gov/oc/utm/benefits-and-evolution-of-precision-agriculture/ (accessed Feb. 08, 2023).

[2] “USDA ERS - Farming and Farm Income.” https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/farming-and-farm-income/ (accessed Feb. 08, 2023).

[3] B. Nieman, C. S. Johnson, M. Pearce, T. Marcrum, M. C. Thorne, C. Ashby, and C. W. Van Neste, “Through the Soil Long Range Wireless Power Transfer for Agricultural IoT Networks”, Feb. 2023.

[4] B. T. Nieman, M. G. Pearce, C. S. Johnson, M. Tidwell, J. Whitehead, and C. W. Van Neste, “Thru-the-Soil Long Range Wireless Power Transfer,” in 2022 Wireless Power Week (WPW), Jul. 2022, pp. 372–377.

[5] ”CDC-Mining-Basic Wireless Communication and Electronic Tracking”, https://www.cdc.gov/niosh/mining/content/ emergencymanagementandresponse/ commtracking/commtrackingtutorial1(accessed Feb. 15, 2023)

[6] Altium, ”NEC Infrared Transmission Protocol.”, https://techdocs.altium.com/display/FPGA/ NEC+Infrared+Transmission+Protocol (accessed Feb. 10, 2023).

[7] Voicecom Plus, ”An Overview of NEC Phone Systems, ”https://voicecomplus.com/overview-nec-phone-systems/ (accessed Feb. 10, 2023).

[8] Dalya H. Al-Mamoori, Omar Muhammed Neda, Zaid H. Al-Tameemi, Ali Assim Alobaidi and Mohanad Aljanabi,”Generating High Voltage DC with Cockcroft-Walton Voltage Multiplier for Testing Locally Assemble Electric Field Sensor”

[9] S. Ding et al., ”Wireless Power Transfer Through Soil for Energizing an Underground Soil Moisture Sensor,” 2022 IEEE Sensors, Dallas, TX, USA, 2022, pp. 1-4.

[10] Hardie M, Hoyle D. Underground Wireless Data Transmission Using 433-MHz LoRa for Agriculture. Sensors (Basel). 2019 Sep 29;19(19)

[11] S. K. Das, N. Dey, R. G. Crespo, E. Herrera-Viedma, ”A Non-Linear Multi-Objective Technique for Hybrid Peer-to-Peer Communication”, Information Sciences, vol. 623, April 2023.

[12] ”Peer-to-peer”, wikipedia.org. https://en.wikipedia.org/wiki/Peer-to-peer (accessed 15 Feb 2023).

[13] A. Khalifeh, F. Mazunga, A. Nechibvute, B. M. Nyambo, ”Microcontroller Unit-Based Wireless Sensor Network Nodes: A Review”, Sensors, 18 November 2022. Available: https://www.mdpi.com/1424-8220/22/22/8937. [Accessed: 27 April 2023].