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# Design of Subsurface Phased Array Antennas for Digital Agriculture Application

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***Abstract*—With the advancement in subsurface communications technology, an overarching solution to a underground phased array antenna design for digital agriculture requires interdisciplinary research involving topics ranging from insights on the constitutive parameters of the soil medium and impact of soil moisture on the array factor to antenna measurements and subsurface communication system design. In this paper, based on the analysis of underground radio wave propagation in subsurface radio channel, a phased array antenna design is presented that uses water content information and beam steering mechanisms to improve efficiency and communication range of wireless underground communications. It is shown the subsurface beamforming using phased array antenna improves the wireless underground communications by using the array element optimization and soil-air interface refraction adjustment schemes. This design is useful for subsurface communication system where sophisticated sensors and software systems are used as data collection tools that measure, record, and manage spatial and temporal data in the field of digital agriculture.**

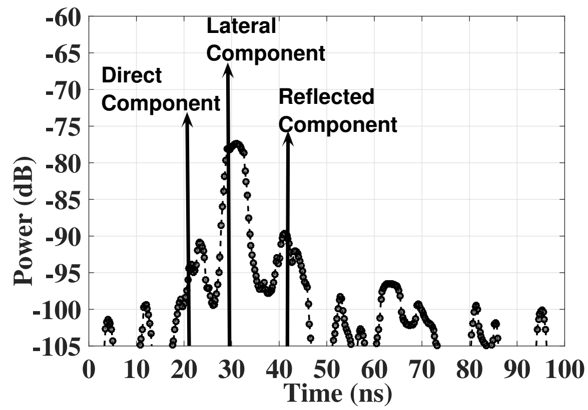


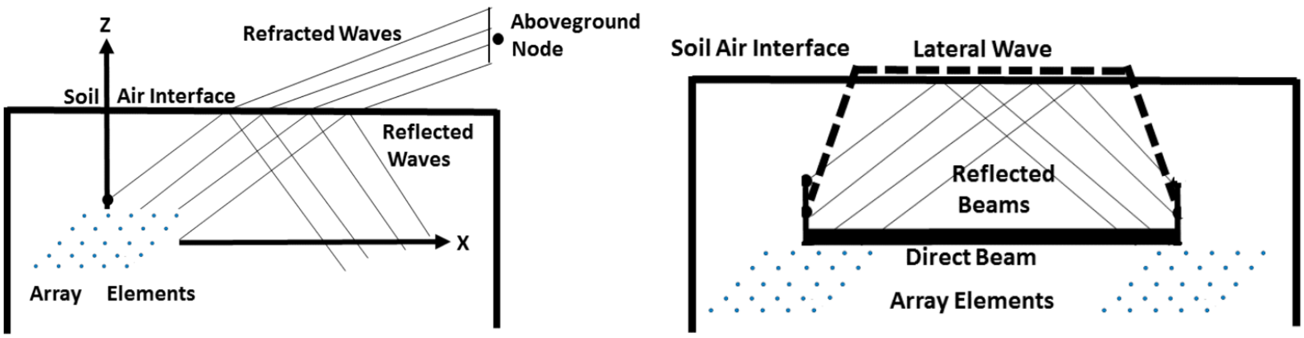

Fig. 1: The arrival time and associated power of different multi-path components at the receiver of the wireless subsurface channel [51].

## I. Introduction

The purpose of digital agriculture is to tailor agricultural inputs and processes to localized environment in the farm to apply correct practices in the field in a timely and correct manner. It leads to development of smart and digital sensing, communications, and real-time decision making systems to sense, analyze, detect, and manage the soil and farm specific spatial and temporal patterns in the field for sustainability, profitability and to protect the environment [23], [45], [47].

By using software defined control of individual antenna elements, steering solutions for communications with static and mobile above-ground devices in digital agriculture can be implemented [50], [22], [52], [48], [49], [55], [54], [13], [45], [47], [23], [44], [46], [30], [24], [26], [28], [43], [29], [53], [27], [25], [33], [42], [34], [31], [39], [38], [35], [40], [36], [37], [41], [32]. This kind of implementation of underground (UG) beamforming is challenging due to many reasons. The major challenge is the phase shift between antenna elements. To get a desired beam pattern, the phase shifts between antenna elements need to be equal in the desired direction. This requires calibration of phase shifters and dynamic on-the-fly phase correction to achieve the desired beam. To address these challenges, digital beamforming using phased array antennas based on soil moisture conditions to form dynamic beam patterns can be employed. We have investigated three different array designs. First design consists of two separate linear arrays each with its own phase shifter with pre-defined parameters for communication with underground and aboveground arrays. Furthermore, beams are stitched such that a number of beam patterns are determined and designed based on the analyses of underground and above-ground devices and stored in configuration database for on-demand usage. The second design is based two arrays stacked at different UG depths with phase shifting done in the software. This approach is based on processing in the software defined radio to adapt to wavelength changes due to soil moisture conditions. The advantage of using this approach is that dynamic changes in the wavelength and phase variations due to UG channel dynamism can be compensated without changing physical array arrangements. Moreover, less energy is required in comparison to traditional mechanical phase shifters. In the third design, the multi-dimensional arrays structure such as rectangular, planar, and circular arrangements to to have simultaneous beams in multiple planes are used.

The aim of this paper is to present a software defined implementation of novel subsurface beamforming using phased array antennas [6], [7]. The fundamental research problem being addressed is the utilization of the novel phase change material properties of $VO_2$ [17] to design and integrate an efficient phase shifter technology for hybrid underground electronically scanned arrays [4], [10], [18]. This design can be realized




(a) At the transmitter (b) At the receiver

Fig. 2: Overview of subsurface beamforming.

because of the recent advancements in film deposition techniques [13], soil material and medium characterization [20], device fabrication [46], phase shifter, transmission line design, beam forming, phased array design and full-wave simulation, underground antenna measurements [24], and underground communication systems [23].

The rest of the paper is organized as follows: the related work is presented in Section II. The design of the subsurface beamforming transceivers using phased arrays antennas has been discussed in Section III. Different subsurface phased array implementation schemes including software defined implementation and hardware components are discussed in Section IV. The paper is concluded in Section V.

## II. Related Work

An empirical analyses using off-the-shelf sensor motes to characterize the path loss in UG channel has been conducted in [51], and accordingly path loss models for underground-to-underground (UG2UG) and underground-to-aboveground (UG2AG) channels have been developed in [26], [29].

Moreover, digital agriculture solutions including enabling technologies [44], subsurface antenna design [46], [24], underground cognitive radio [43], and soil moisture sensing using subsurface radio wave propagation [30] have been developed for Internet of Underground Things [55], [54]. Accordingly, we devised an subsurface planar antenna [46], [24], which combats adverse effects of time-variant subsurface radio channel characteristics and extends communication ranges of underground radios. This allows for development of architectures for connected soil moisture sensing networks and automated irrigation solutions [55], [54]. Moreover, it is shown that software defined operation in underground communications can extend the capacity of UG channel [22], [49].

Beamforming antennas [16] are being used in wireless networks to reduce interference and improve capacity. Beamforming have been addressed in [15], [14], [21], [19], [2], [3], [56], [1], [5] for over-the-air (OTA) wireless channels and in [12] for MI power transfer, but no existing work has considered the underground beamforming. In UG communications, lateral component [11] has the potential, via beam-forming techniques, to reach at farther UG distances which otherwise

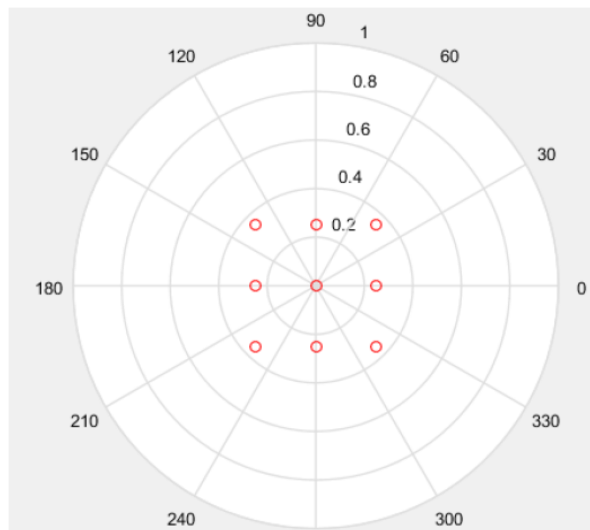



Fig. 3: An example 3×3 patch array with integrated phase shifters.

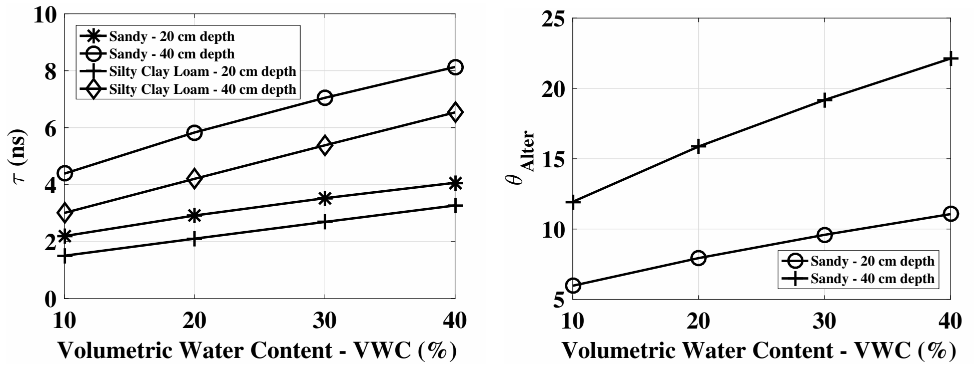
are limited ($10\,\mathrm{m}$ to $15\,\mathrm{m}$) because of higher attenuation in soil [51].

## III. Design of Transceivers

In this section, we present a phased array transceivers design with large antenna arrays for large-scale underground deployment. The design consist of three major steps: 1) design of low-cost electronically scanned arrays, 2) design of systematic low-complexity hybrid beamforming schemes for the arrays, and 3) array optimization and soil-air interface reflection adjustments for high-performance UG networking of deployed nodes. We discuss these steps in the following:

### *A. Underground Array Design*

In this section, an energy-efficient, low-cost hybrid ESA design capable of beamforming at microwave frequencies (e.g., sub GHz - in 100MHz to 800MHz) for next-generation high data-rate underground communications systems is presented. Specifically, a novel phase change material (vanadium dioxide) [17] to form low-loss phase shifters (switched time-delay lines) integrated with a UG antenna array that will enable a hybrid ESA architecture [10] is used. It is first of its kind hybrid efficient underground phased array for next-generation




(a) (b)

Fig. 4: (a) $\tau$ with 10%-40% change in soil moisture in sandy and silty clay loam soils at 20 cm and 40 cm depth. (b) Corresponding phase shift adjustment to original phase in sandy soil for 10%-40% change in soil moisture at 20 cm and 40 cm depth.

wireless underground communication systems. The overview of the subsurface beamforming at the transmitter and receiver is depicted in Fig. 2. The design of the array is shown in the Fig. 3.

When subsurface beam is directed in isotropic directions particularly to the air-soil interface, the refraction mechanism leads to beam disorientation when incident at the soil-air interface. The soil-air interface separates the soil medium form air and both have different properties which give rise to refraction of waves. This phenomena is also called the beam squint [9]. The resulting error because of beam squint can range from $5$ to $15\,\deg$ depending on the the amount soil water content present in the medium. It also depends on the incidence angle at the air-soil interface. The refraction also impacts the wave propagation velocity both in the soil and air medium. This effect can be corrected by using the time delays ($\tau$) and optimum angle adjustment.

In Fig. 4(a), $\tau$ is shown for 10%-40% change in soil moisture values in sandy and silty clay loam soils at 20 cm and 40 cm depth. It can be observed that higher soil moisture levels lead to increase in delay and it further increases by increasing the depth. The corresponding phase shift adjustment to original phase in sandy soil for 10%-40% change in soil moisture at 20 cm and 40 cm depth is shown in Fig.4(a). Therefore, larger adjustments are required for higher soil moisture levels and higher depths.

### *B. Array Optimization*

In the UG settings, wavelength variations not only effect the directivity and but also cause grating lobes, which cause beam patterns to appear in undesired directions. We analyze this effect in the UG communications. This problem can be solved by either frequency-agile operation to keep the wavelength fixed by using tuning, or by selecting the elements to mitigate the effects of wave length changes.

By using genetic algorithm [9], that work on the natural selection process. Overall, this results in complete optimization of array, which is robust to mechanisms taking place in the soil. By using this technique, an initial inter-element

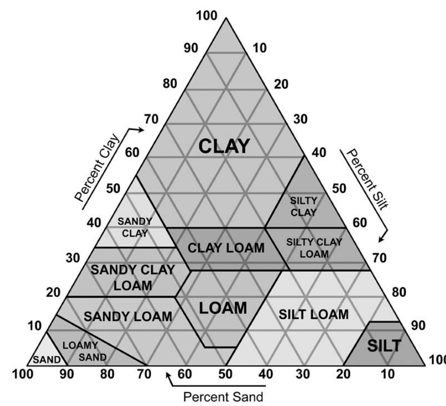



Fig. 5: Soil textural triangle.

position can either be specified or chosen arbitrarily. A priori position is based on the actual position without consideration of the particular soil moisture level. Cost (score) function of is evaluated and desired inter-element spacing is determined. Element position optimization results are shown in Fig. 6.

Soils are classified in textural triangle (Fig. 5). The exact composition of the different soils are given in Table I.

## IV. Subsurface Phased Array Implementation

In this section, we discuss software and hardware implementation aspects of the subsurface phased array implementation.

TABLE I: Percentage of clay, sand and silt in different soil types.

| Soil Type | Clay % | Sand % | Silt % |
|---|---|---|---|
| **Silt** | 9 | 10 | 81 |
| **Silt Loam** | 20 | 30 | 50 |
| **Silty Clay Loam** | 35 | 15 | 50 |
| **Silty Clay** | 55 | 10 | 35 |
| **Loam** | 20 | 50 | 30 |
| **Clay Loam** | 35 | 42 | 23 |
| **Clay** | 60 | 38 | 2 |
| **Sandy Clay** | 40 | 58 | 2 |
| **Sandy Clay Loam** | 30 | 65 | 5 |
| **Sandy Loam** | 15 | 65 | 20 |
| **Loamy Sand** | 10 | 80 | 10 |
| **Sand** | 8 | 91 | 1 |

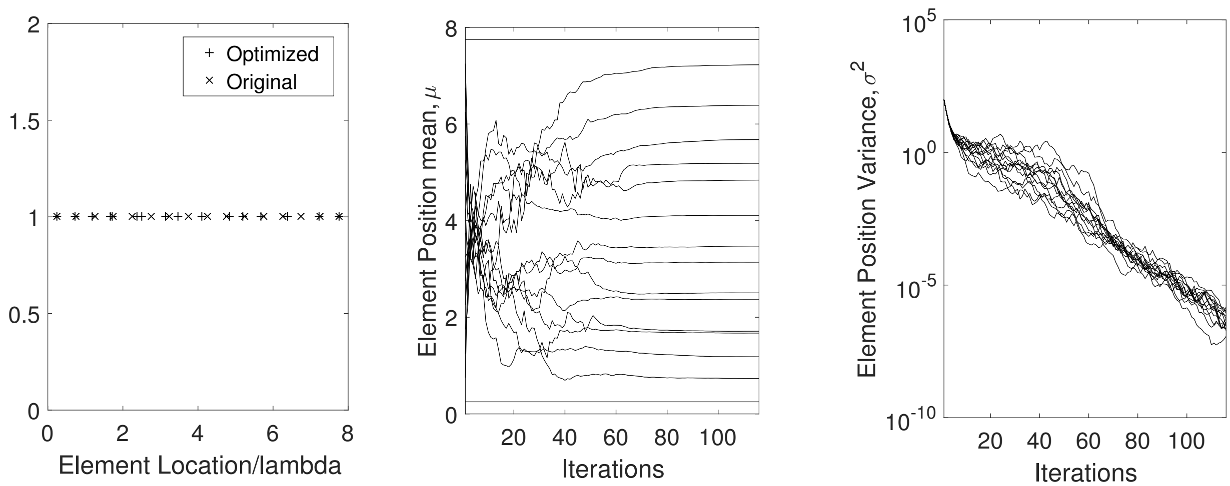


Fig. 6: The array optimization results.

**Software Defined Implementation:** Recent advancements in SDR technology and digital equipment allows efficient implementation of subsurface phased array. Through software defined control of individual array elements, steering solutions can be used for communications with static and mobile AG devices. Moreover, complex algorithm processing capabilities can be implemented easily. SDR implementation [21] of UG beamforming is challenging due to many reasons. The major challenge is the phase shift between antenna elements. To get a desired beam pattern, the phase shifts between antenna elements needs to be equal in the desired direction. This requires calibration of phase shifters and dynamic on-the-fly synchronization and phase correction to achieve the desired beam.

Digital beamforming based on soil moisture conditions to form dynamic beam patterns can be used. This design consists of a planar array with its own phase shifter with pre-defined parameters for communication with UG and AG arrays. Furthermore beams can be stitched such that a number of beam patterns can be determined and designed based on the analyses of UG and AG devices and can be stored in configuration database for on-demand usage.

Another SDR approach is based on phase shifting done in the software. This approach is based on processing in the software defined radio to adapt to wavelength changes due to soil moisture conditions. The advantage of using this approach is that dynamic changes in the wavelength and phase variations due to UG channel dynamism are compensated without changing physical array arrangements. Moreover, less energy be required in comparison to traditional mechanical phase shifters [8].

**Hardware Components:** For subsurface phased array implementation, the hardware array elements can use dipole and printed circuit antennas. Other microwave components such as phase shifters, amplifiers, dividers, and hybrids can also be implemented as printed circuits through inexpensive equipment [8]. Beamforming network can consist of stripline configuration. Good wideband characteristics can be achieved within limited underground volume by using large diameter, closely spaced, conducting tubular subsurface phased array elements. EM simulations can be used for design of prototype system. Use of resistive (dummy) elements at the edges of the array can be used to avoid performance degradation at the edge of the array due to abrupt changes. Once the simulated design meets the desired specifications, then an initial array layout configuration can be selected and optimized by observing the performance using a vector network analyzer. A vector network analyzer is used to measure the return loss (antenna reflection coefficients).

## V. Conclusions

Underground wireless communications in the soil medium is challenging due to the impacts of soil texture and soil water content. In subsurface radio wave propagation, the phased array antennas can be utilized to direct the wave power by using the Zenneck waves which leads to underground communication range extension and energy conservation. In this paper, a design of subsurface phased array antennas for digital agriculture applications has been presented. Any implementation of subsurface phased array is likely to be complicated and expensive as compared to existing solutions. Moreover, practical implementation of subsurface phased array integrated with soil moisture sensing, and optimization is a challenging task. Decreasing cost and complexity of hardware, and importance of long range, high data rate UG communications, compared to conventional solutions, makes subsurface phased array a viable candidate for next generation wireless UG communication systems.

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