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Subsurface MIMO: A Beamforming Design in Internet of Underground Things for Digital Agriculture Applications

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MDPI

Article

Subsurface MIMO: A Beamforming Design in Internet of Underground Things for Digital Agriculture Applications

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Abstract: In underground (UG) multiple-input and multiple-output (MIMO), the transmit beamforming is used to focus energy in the desired direction. There are three different paths in the underground soil medium through which the waves propagates to reach at the receiver. When the UG receiver receives a desired data stream only from the desired path, then the UG MIMO channel becomes three path (lateral, direct, and reflected) interference channel. Accordingly, the capacity region of the UG MIMO three path interference channel and degrees of freedom (multiplexing gain of this MIMO channel requires careful modeling). Therefore, expressions are required for the degree of freedom of the UG MIMO interference channel. The underground receiver needs to perfectly cancel the interference from the three different components of the EM-waves propagating in the soil medium. This concept is based upon reducing the interference of the undesired components to a minimum level at UG receiver using the receive beamforming. In this paper, underground environment aware MIMO using transmit and receive beamforming has been developed. The optimal transmit beamforming and receive combining vectors under minimal inter-component interference constraint are derived. It is shown that UG MIMO performs best when all three component of the wireless UG channel are leveraged for beamforming. The environment aware UG MIMO technique leads to three-fold performance improvements and paves the wave for design and development of next generation sensor-guided irrigation systems in the field of digital agriculture. 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.

Keywords: Digital Agriculture; Wireless Underground Channel; Underground Communications; MIMO; Beamforming; Internet of Underground Things

1. 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 [2], [3], [4].

Internet of Underground Things (IOUT) have many applications in precision agriculture [5], [6], [7], [8], [9], [10], [11], [12], [2], [3], [4], [13], [14], [15], [16], [17], [18], [19], [1], [20], [21], [22], [23]. Border monitoring is another important application area of IOUT, where these networks are being used to enforce border and stop infiltration [24], [25]. Monitoring applications of IOUT include land slide monitoring, and pipeline monitoring [9], [26], [27], [28]. IOUT provides seamless access of information collected from agricultural fields through the Internet. IOUT include in situ soil sensing capabilities (e.g., soil moisture, temperature, salinity), and provide the ability to communicate through plants and soil, and real-time information about the environment (e.g., wind, rain, solar). When interconnected with existing machinery on the field (seeders, irrigation systems, combines), IOUT enable complete autonomy on the field, and pave the way for more efficient food production solutions. At agricultural farm level, IOUTs are being used to provide valuable information to the farmers.

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 [1,29]. 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.

UG transmit beamforming using phased array antennas at the transmitter [29] has been used in the underground (UG) communications to maximize the lateral wave [30] by transmitting energy at a particular angle. By using this approach, the energy wastage by sending signals in isotropic direction is reduced by forming the narrow-width beam and steering it accordingly. In underground wireless communications, the aim is to enhance the received signal strength and reduce the interference at the receiver. In over the air (OTA) wireless communications, a strong signal strength is attained by transmitting the signal from multiple antennas by different amplitudes and phases. Through this approach, the received signal components add coherently at the receiver. However, in underground communication due to different wave propagation speed in different communication mediums (e.g., soil and air), coherent combining at the receiver in a constructive manner can not be achieved. Therefore, an environment aware UG multiple-input and multiple-output (MIMO) design is required.

The line-of-sight (LoS) component between the UG transmitter and receiver has limitations because of the higher attenuation in the soil medium. An example power delay profile (PDP) of wireless UG channel is shown in Fig. 1. Moreover, the direct path has shorter range and can not be used to reach at longer distances in the underground medium. Therefore, combined transmit and receive beamforming needs developed using non-LoS components (e.g., lateral and reflected). Since, multipath underground channel well-known [30] and has been studied and empirically validated, UG

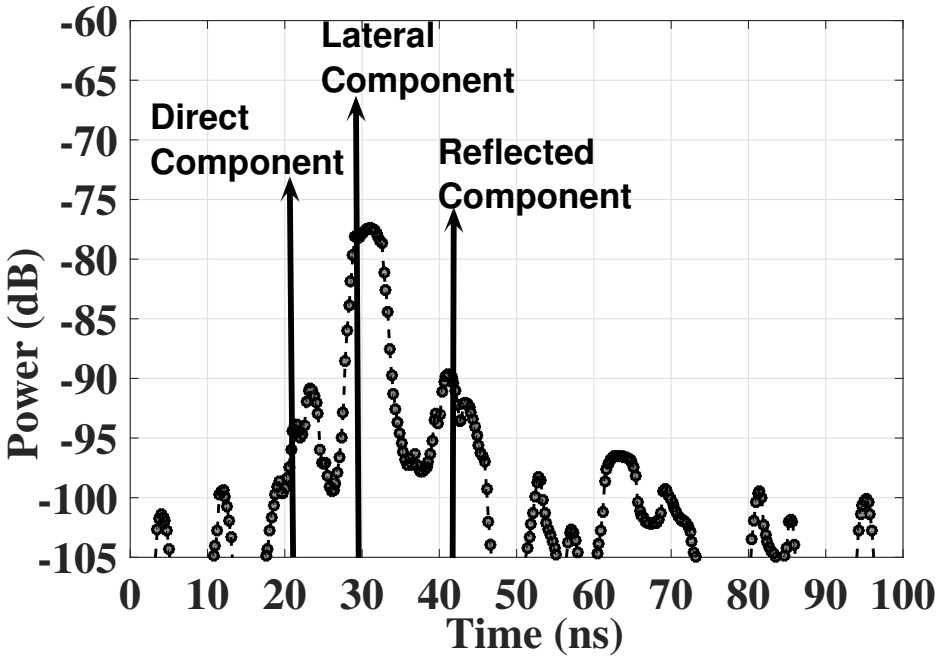
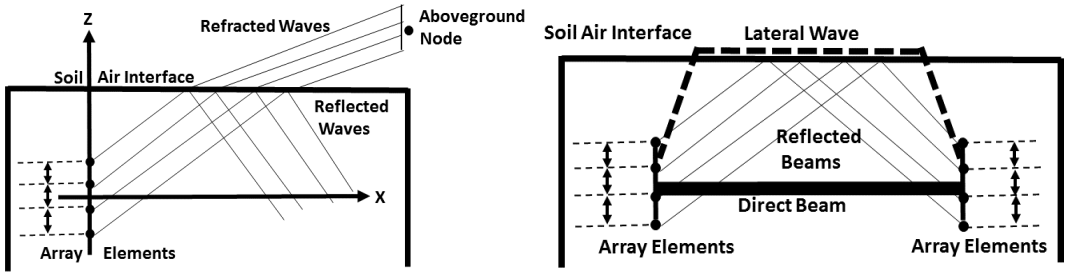


Figure 1. An example power delay profile (PDP) of the impulse response model of the wireless UG channel [30].



(a) Transmit Beamforming **(b)** Receive Beamforming

Figure 2. The communications schematic for UG MIMO.

MIMO can be developed for high data rate and log range communications. In this work, techniques have been developed to maximize the signal strength and minimizing the interference at the receiver. Moreover, UG MIMO beamforming expressions have been developed to maximize the capacity of the underground communications.

The rest of the paper is organized as follows: the background and major contributions of this work are discussed in Section 3. The UG MIMO is modeled in Section 4. Performance evaluations are done in Section 5. The article concludes in Section 7.

2. Related Work

An empirical analyses using off-the-shelf sensor motes to characterize the path loss in UG channel has been conducted in [30], and accordingly path loss models for underground-to-underground (UG2UG) and underground-to-aboveground (UG2AG) channels have been developed in [19,20].

Moreover, digital agriculture solutions including enabling technologies [14], subsurface antenna design [17,18], underground cognitive radio [31], and soil moisture sensing using subsurface radio wave propagation [15] have been developed for Internet of Underground Things [22,23]. Accordingly, we devised an subsurface planar antenna [17,18], 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 [23], [22]. Moreover, it is shown that software defined operation in underground communications can extend the capacity of UG channel [12,32]. The development of IoT based smart security and monitoring devices for agriculture has been investigated in [33]. A survey on advances in magnetic induction-based wireless underground sensor networks has been presented in [34]. A secure smart agriculture monitoring technique through isolation is developed in [35]. The IoT vision, key features, applications, and open issues are discussed in [36]. IoT in agriculture, its recent advances, and future challenges are outlined in [37].

Beamforming antennas [38] are being used in wireless networks to reduce interference and improve capacity. Beamforming have been addressed in [39], [40], [41], [42], [43], [44], [45], [46], [47] for over-the-air (OTA) wireless channels and in [48] for MI power transfer, but no existing work has considered the underground beamforming. In UG communications, lateral component [49] has the potential, via beam-forming techniques, to reach at farther UG distances which otherwise are limited (10 m to 15 m) because of higher attenuation in soil [30].

3. Contributions of This Work

This is the first work to design a fully UG MIMO for the UG communications. The transmit and receive beamforming techniques are considered which communicate through the soil by using UG channel medium. Based on the receiver position, EM waves either travel completely through soil for UG communications or some part of it goes through the air for aboveground(AG) communications.

We leverage an UG channel impulse response model for UG beamforming perspective and identify the major EM wave components. Challenges in UG beamforming are highlighted and use of of UG MIMO is motivated. We present the effects of different soil properties on beamforming vectors of the transmitter and receiver. This proposed mechanism estimates the best beam steering angle based on the soil moisture sensing.

We have considered an UG MIMO transceiver system where both transmitter and receiver has the beamforming capability. Additionally, this approach removes the inter-component interference and enhance the received signal strength. Underground environment aware MIMO using transmit and receive beamforming is vital to increased spectral efficiency, enhance communication range, and energy efficiency in next-generation wireless underground networks, which are expected to include underground antenna arrays [29]. UG MIMO approach has potential applications in many practical scenarios such as precision agriculture, ground penetrating radars (GPR), hazardous object search, locating IEDs, transmission structures under the runways for aircraft communications, antennas for geographic research, communications from marshes, geology, and wireless underground sensor networks (WUSNs).

4. The UG MIMO System Models

The underground nodes communicate with other underground nodes (UG2UG link) and above ground nodes (UG2AG link). Communications schematic for UG MIMO communications is shown in Figs. 2. These aboveground nodes are fixed sinks and mobile nodes mounted on movable infrastructures such as center pivot. In aboveground communications, waves propagating to receiver nodes are refracted from soil-air interface, whereas in UG communications, lateral waves need to be utilized. Desired beam patterns for both scenarios are shown in Figs. 2. In Fig. 2(a), that refractions and reflections of EM waves from the soil-air interface effect the beam patterns propagating to the above-ground node.

In UG MIMO, transmit beamforming [29] is used to focus energy in the desired direction, there are three different paths [30] in the underground soil medium through which the waves propagates to reach at the receiver. When the UG receiver receives a desired data stream only from the desired path, then the UG MIMO channel becomes three path (lateral, direct, and reflected) interference channel. Accordingly, the capacity region of the UG MIMO three path interference channel and degrees of

freedom (multiplexing gain of this MIMO channel requires careful modeling. Therefore, expressions are required derived the degrees of freedom of the UG MIMO interference channel.

The underground receiver needs to perfectly cancel the interference from the three different components of the EM-waves propagating in the soil medium. in UG transmit beamforming, limited number of antenna can only achieve low spatial directivity, that leads to presence of signals in undesired direction that cause interference at the receiver. This UG MIMO concept is based upon reducing the interference the undesired components to minimum at UG receiver using the receive beamforming. In this paper, underground environment aware MIMO using transmit and receive beamforming has been developed. The optimal transmit beamforming and receive combining vectors under minimal inter-component interference constraint are derived. Accordingly, UG MIMO techniques are designed and investigated in the underground soil medium. Next we present the system model:

We consider an UG MIMO transceiver system where both transmitter and receiver has the beamforming capability. We also consider that the transmitter node is equipped with two or more transmit antennas and has the beam steering capacity. The receiver node is also equipped with multiple antennas and can receive all three components propagating through underground medium. In this paper, we also assume that the UG MIMO receiver has path selection and switching capability through a selection mechanism which is based on the strength of the received paths at the receiver. Throughout the development of this approach, we also assume equal power allocation at the UG MIMO transmitter. To analyze the achievable capacity using environment aware MIMO using transmit and receive beamforming, we also assume a total power constraint.

Next, we present a zero forcing (ZF) UG MIMO transceiver technique. This approach does not requires the availability of the channel state at the receiver in contrast to the OTA MIMO techniques. Additionally, this approach removes the inter-component interference and enhance the received signal strength. The channel between the underground transmitter T and underground receiver R is represented by $\mathbf{TR}$ of size $N_t \times N_r$ with complex values, where N_t and N_r represents the number of transmit and receive antennas, respectively. The k spatial underground components are distinguished using the $w_1, \ldots, w_k$ where w is associated with component. A $N_t \times N_r$ matrix $\mathbf{I_k}$ denotes the interference between different components. The received signal at the underground receiver by using equal power constraint is given by [50]:

$$y_k = \mathbf{w}_k^* \, \mathbf{TR} \, \mathbf{f}_k \, x_k + \mathbf{w}_k^* \, \mathbf{I}_k \, \mathbf{f}_i \, x_i \; + \; \mathbf{w}_k^* \, n_k \tag{1}$$

where x_k is the transmitted signal of the UG component k, and w_k and f_k are the transmit and receive beamforming vectors, n_k is additive white Gaussian noise (AWGN) vector.

Next, we present the expression to maximize the capacity for the low SNR case. From the (1), the received SINR at the UG receiver at the kth component can be expressed as:

$$SINR_k = \frac{\mathbf{w}_k \, \mathbf{f}_k \, \mathbf{f}_k * \mathbf{TR} \, \mathbf{TR}^* \, \mathbf{w}_k^*}{\mathbf{w}_k^* (\mathbf{I}_k \, \mathbf{I}_k * \, \mathbf{f}_i \, \mathbf{f}_i^*) \mathbf{w}_k^*} \tag{2}$$

The achievable capacity for the three underground EM components is defined as:

$$C = \sum_{k=1}^{3} \log_2(1 + SINR_k) \tag{3}$$

Since the objective of this approach is to enhance the channel gain and to remove the inter-component interference, we have only considered the beamforming vectors under the lower bound of achievable capacity. Therefore, maximum rate is not achieved because only the product achievable rate is utilized. Next we present the approach to completely remove the inter-component interference. The the instantaneous SNR for every sensed component can be defined as follows when the receive beamforming is not employed at [32]:

$$\gamma_i = \frac{E_b |h_i|^2}{N_0}, \tag{4}$$

where i represents the L, D, or R components. The E_b is the energy per bit and the $|h_i|$ denotes the impulse response.

A three fold increase in SNR (in comparison to a single antenna match filter based design) can be achieved by employing the maximum ratio combining (MRC) approach [32,51]:

$$\gamma = \sum_{i=1}^{3} w_i \frac{E_b |h_i|^2}{N_0}, \tag{5}$$

where w_i is the weighting factor used for combining. Although SISO approach can be used to maximize the gain, but the reflected components still cause some interference. Therefore, in order to eliminate the undesired interference, the UG MIMO uses transmit beamforming vectors. Accordingly, the received signal can be expressed as [50]:

$$y_k = \mathbf{w}_k^* \, \mathbf{TR} \, \mathbf{f}_k \, x_k + \mathbf{w}_k^* \, \mathbf{I}_k \, \mathbf{f}_i \, x_i \; + \; \mathbf{w}_k^* \, n_k \tag{6}$$

$$y_k = \frac{\mathbf{w}_k^* \, \mathbf{TR} \, \mathbf{f}_k \, x_k}{||\mathbf{TR} \, \mathbf{f}_i||} + \frac{\mathbf{w}_k^* \, \mathbf{I}_k \, \mathbf{f}_i \, x_i}{||\mathbf{TR} \, \mathbf{f}_i||} \; + \; \frac{\mathbf{w}_k^* \, n_k}{||\mathbf{TR} \, \mathbf{f}_i||} \tag{7}$$

To completely eliminate the interference from (7), MRC approach should satisfy following:

$$\mathbf{w}_1^* \, \mathbf{I}_1 f_i \; = \; 0 \tag{8}$$

that can be satisfied by using the transmit beamforming vector. Using this zero interference constraint, MRC beamforming vectors are generalized eigenvectors.

In addition to environment aware weights of UG MIMO, which are based on soil moisture sensing, feedback signals are used to adjust the weights by using the array gain feedback loops. This problem is formulated as maximizing the array gain by using the pilot signals. In this method, UG MIMO array at the transmitter receives the pilot signal in receive mode and then accordingly adjusts its parameters for the transmit mode. In receive mode at the transmitter, scan angles are varied to get the estimate of channel state. The best SNR statistics are used and with change in soil moisture, parameters are adjusted accordingly.

For an array of identical elements, the far-field power density is expressed as [52]:

$$P_{den} = \frac{|E(\theta, \phi)|^2}{120\pi}, \tag{9}$$

where $E(\theta, \phi)$ is the electric filed intensity of the individual array element and is given as:

$$|E(\theta, \phi)| = \sqrt{P_{et}} \sqrt{G_{et}} \frac{\sqrt{30}}{d}, \tag{10}$$

where P_{et}, G_{et} are element transmit power and gain, respectively, and d is the distance. E-field contributions (E_a) from all elements are added together to calculate the array gain G_a [52]. Therefore,

$$G_a(\theta, \phi) = \frac{d^2}{30} \frac{|E_a \, \varsigma(\theta, \phi)|^2}{P_t}, \tag{11}$$

where ς is the element phase factor and

$$E_a = \frac{\sqrt{30}}{d} \sum_n \sqrt{P_{et}} \sqrt{G_{et}}. \tag{12}$$

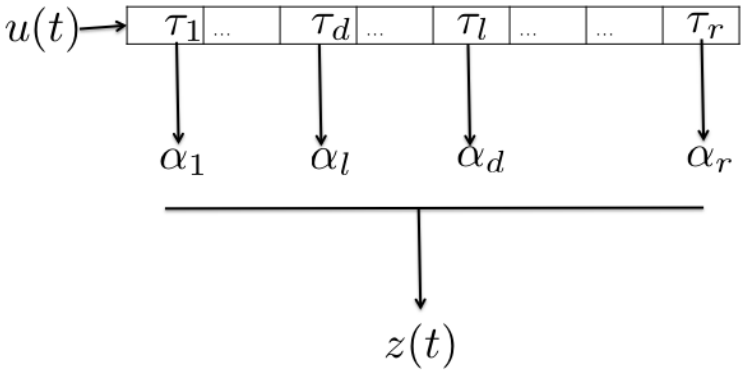


Figure 3. A realization of the UG channel model with three components.

The received power is presented next. Effective isotropic radiated power (EIRP) can be expressed as product of the transmitted power and antenna gain:

$$P_{rad} = G_t P_t, \tag{13}$$

where P_t is the transmitted power and G_t is the array gain.

The far-field power density P_{av} can is expressed as [53]:

$$P_{av} = P_{av}^D + P_{av}^R + P_{av}^L \,. \tag{14}$$

where D, R, L denotes the power densities of the direct, reflected and lateral component [30]. The received power is calculated as the product of far-field power density P_{av} and antenna aperture ($\lambda_s^2/4\pi$). The received power is given as [53]:

$$\begin{aligned} P_r^d &= P_t + 20\log_{10}\lambda_s - 20\log_{10} r_1 - 8.69\alpha_s r_1 \\ &\quad -22 + 10\log_{10} D_{rl}\,, \\ P_r^r &= P_t + 20\log_{10}\lambda_s - 20\log_{10} r_2 - 8.69\alpha_s r_2 \\ &\quad +20\log_{10}\Gamma - 22 + 10\log_{10} D_{rl}\,, \\ P_r^L &= P_t + 20\log_{10}\lambda_s - 40\log_{10} d - 8.69\alpha_s(h_t + h_r) \\ &\quad +20\log_{10} T - 22 + 10\log_{10} D_{rl}\,, \end{aligned} \tag{15}$$

where Γ and T are reflection and transmission coefficients [53], and λ_s is the wavelength in soil. The received power, for an isotropic antenna, is expressed as [53]:

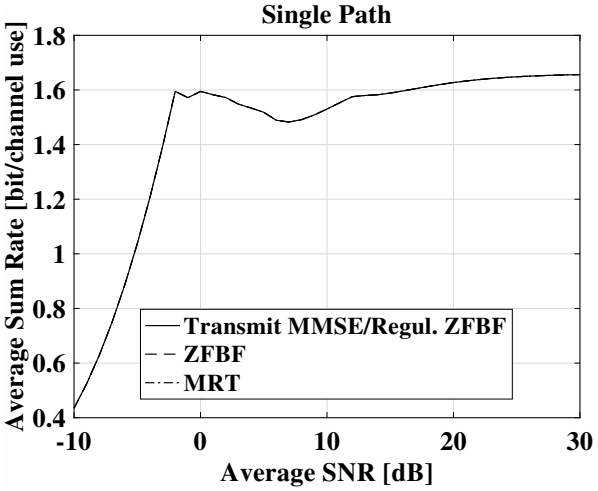
$$P_r = 10\log_{10}(10^{\frac{P_r^d}{10}} + 10^{\frac{P_r^r}{10}} + 10^{\frac{P_r^L}{10}})\,. \tag{16}$$

5. Performance Analysis

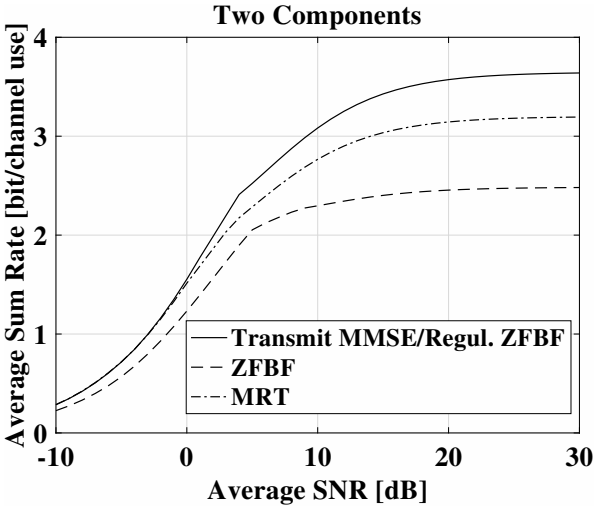
In this section, we present the performance analysis of the UG MIMO. First, the model evaluations and results of the transmit beamforming are presented in the next section.

5.1. Transmit Beamforming

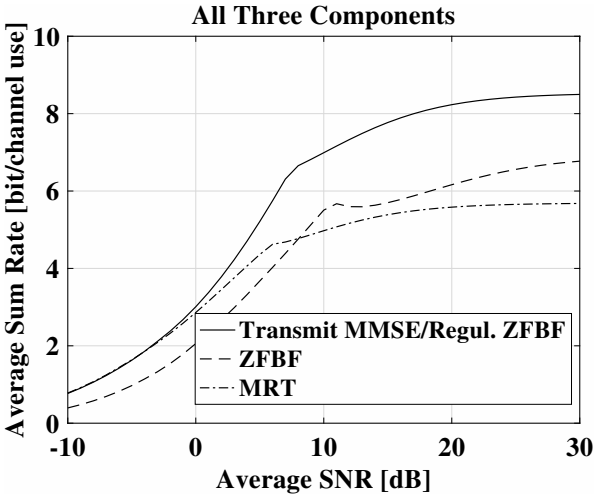
To evaluate the developed scheme, we consider the transmit MMSE, ZFBF, and MRT beamforming of [54]. The implementation of the heuristic beamforming schemes (MRT, ZFBF, transmit MMSE/regularized ZFBF/SLNR-MAX beamforming, and the corresponding power allocation) is also



(a) Single Path



(b) Two Components



(c) Three Components

Figure 4. UG MIMO: The average sum rate (bit/channel use) as a function of change in average SNR.

based on the [54]. For the UG MIMO application, instead of randomly generating OTA channels, we use the UG channel impulse response [30], where root mean square (RMS) delay spread, distribution of the RMS delay spread, mean amplitude across multiple profiles for a fixed T-R displacement, effects of soil moisture on peak amplitudes of power delay profiles, mean access delay, and coherence bandwidth statistics are presented based on the measured data collected from UG channel experiments. A realization of the UG channel model is shown in Fig. 3. It is important to note here that the calculation of optimal beamforming is not performed in this work because of its computational complexity [55]. The range of the considered SNR values is -10 dB to 30 dB.

For the simulations, the beamforming matrices are generated for sum rates with different beamforming strategies (e.g., MRT, ZFBF, transmit MMSE/regularized ZFBF/SLNR-MAX). Accordingly, UG MIMO evaluation is done for different paths of the underground channel. The direct, lateral, and the reflected paths of the underground channel are considered. After the channel matrices are generated for all realizations, accordingly, for each realization normalized beamforming matrices are computed for each approach. Furthermore, by using the branch-reduce-and-bound (BRB) algorithm, based on the proposed approach, pre-allocate matrix serves as the feasible starting points for the BRB algorithm.

Accordingly, the system iterates through all powers. Due to its dependancy on the transmit power, the normalized beamforming vectors for transmit MMSE beamforming (which is the same as regularized ZFBF and SLNR-MAX beamforming) are also computed similarly. The sum rate is calculated accordingly for the three different beamforming approaches.

Next, we present the evaluations done using these beamforming approaches for the three different components. In Figs. 4, the average sum rate (bit/channel use) is shown as a function of change in average SNR. The case in which only the single (direct) element is considered is shown in Fig. 4(a). It can be observed that the average sum rate range is 1.5 to 1.7 and it does not change significantly with change in average SNR. Because, in the case of single component, there is no beamforming involved. Therefore, all three approaches have the same avergae sum rate.

In Fig. 4(b), the average sum rate for the direct and reflected components (two component case) is shown. In comparison to the single path scenario, it can be observed that average sum rate has increased from 1.6 to 3.1 at the average SNR value of 10dB. Moreover, for the two component case, it can also be observed that the at the lower average SNR of 0dB, there is only minor difference of 0.1 average sum rate between the three beamforming approaches. At the average SNR of 10dB, the difference between ZFBF and MMSE is increased to 0.7, which shows that the UG MIMO approach has the better performance as compared to the ZFBF. This difference further increases with increase in SNR which shows that in higher SNR regimes, the UG MIMO transmission approach leads to even improved performance gain.

This better performance of the UG MIMO transmit beamforming improves further in the three component scenario where all three components (e.g., direct, lateral, and reflected) are used transmit beamforming. This scenario has been shown in Fig. 4(c). Overall, the three components beamforming scenario leads to significant performance improvements as compared to the two path transmit beamforming case. In comparison to the two path scenario, it can be observed that average sum rate has increased from 3.1 to 6.6 at the average SNR value of 10dB. Moreover, for the three component case, it can also be observed that even the at the lower average SNR of 0dB, there are minor difference of average sum rate between the three beamforming approaches. At the average SNR of 10dB, the difference between ZFBF and MMSE is increased to 2.7. It is also interesting to note that at the average SNR of 30dB, the average sum rate reached at the maximum value of 8.4 which shows that the UG MIMO approach performs best when all three components are used for underground transmit beamforming.

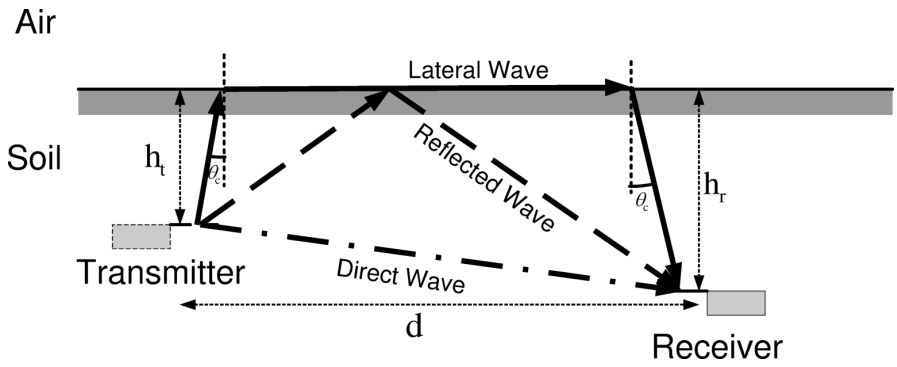


Figure 5. The direct, reflected, and lateral waves in the underground channel [30].

5.2. Receive Beamforming

For the receive beamforming of the UG MIMO, a 16-element uniform linear array with inter-element distance of half wavelength is used. The operation frequency of 300 MHz is employed. In underground communications, a higher path loss is observed at higher frequencies [30]. The soil has higher permittivity as compared to the air, which leads to the wavelength shortening. Due to the soil permittivity factor, frequency bands in lower spectrum are more suitable for long range communications. Moreover, distance, depth, and soil water content also affects the path loss in underground communications, which requires environment-aware operation frequency selection.

We consider the reception of the received signal through the UG MIMO receive beamforming. In UG communications, there are three main components (e.g. direct, lateral, and reflected (see Fig. 5). The received signal that originates from 10-15^o azimuth has the highest received power. The UG channel has excess delays extending up to 100 ns and root mean square (RMS) delay spread values up to 50 ns. The attenuation varies over 50 dB dynamic range. The direct wave (second received signal) is received from 90^o azimuth (direct path, line-of-sight component). It is also known that arrival time of multipath components follows lateral wave based 3-wave UG channel model such that the direct wave reaches at the receiver first before the lateral and reflected components for shorter communication distances [30]. The third wave (the reflected signal) travels towards to the soil-air interface and reaches at the receiver from 45^o azimuth. Its total path is also completely through the soil.

The three received signals at the UG MIMO receiver are not correlated with each other and can be distinguished because of different propagation speed in the stratified soil medium. This leads to different inter-element delays that assist different these elements in time. The uniform white noise is considered across all array elements. A beam-scan spatial spectrum estimator is used based on the arrival directions of these three components of the underground channel impulse response.

In Fig. 6, the spatial spectrum of the three components in the UG MIMO receive beamforming is shown. The plot shows a high power gains at 10^o which corresponds to the lateral wave. The lower power gain is exhibited at the 90^o, which represents the direct wave. The lower peak at the 45^o indicates the reflected wave that due to the lower path in the soil has the lowest gain.

6. Air-Soil Interface Impact Adjustment

In this section, we discuss the air-soil interface impact adjustment mechanism of the subsurface MIMO, which constitutes as the new contribution of this paper as compared with the preliminary conference version [1]. 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 [56]. 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.

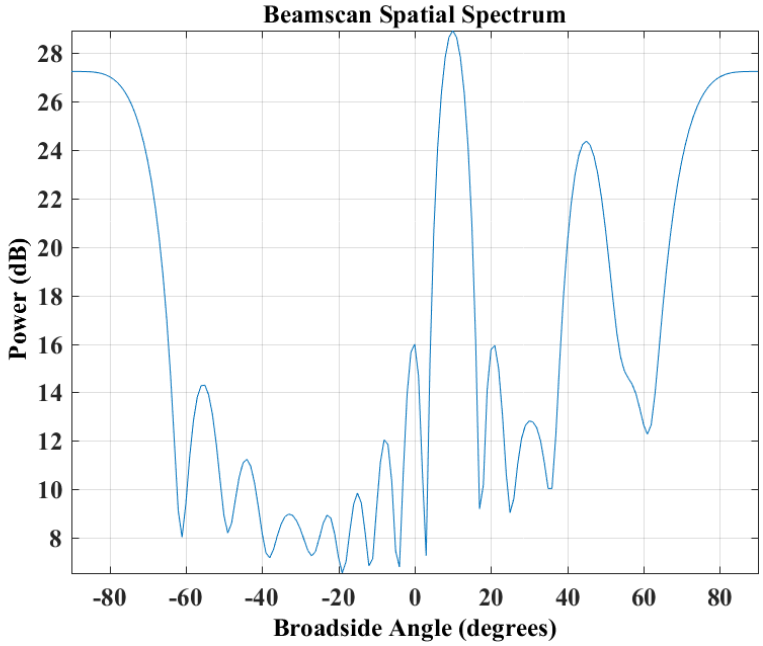


Figure 6. The spatial spectrum of the three components of the UG MIMO receive beamforming.

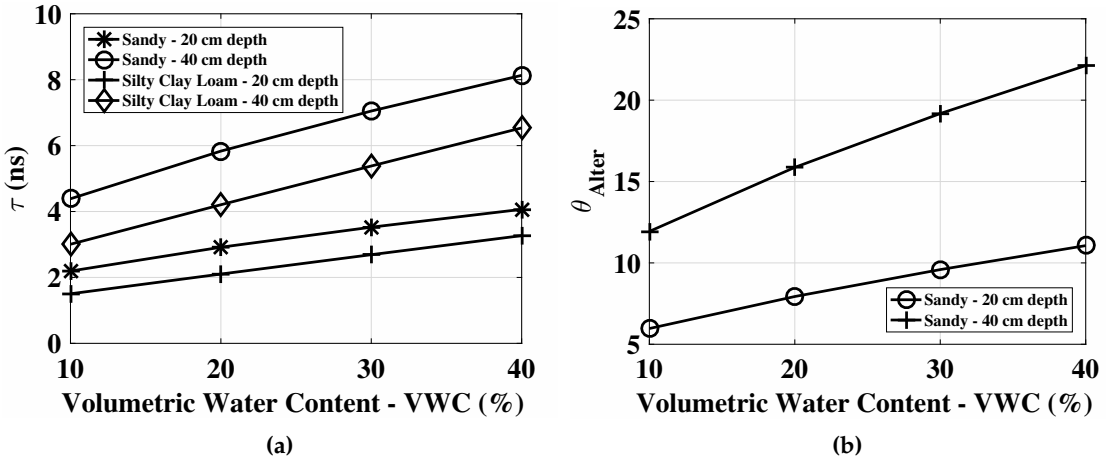


Figure 7. (a) τ with 10%-40% change in soil moisture in sandy and silty clay loam soils at 20 cm and 40 cm depth. (b) Corresponding phase shift adjustment to original phase in sandy soil for 10%-40% change in soil moisture at 20 cm and 40 cm depth.

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 (τ) and optimum angle adjustment.

In Fig. 7(a), τ 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.7(a). Therefore, larger adjustments are required for higher soil moisture levels and higher depths.

6.1. 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

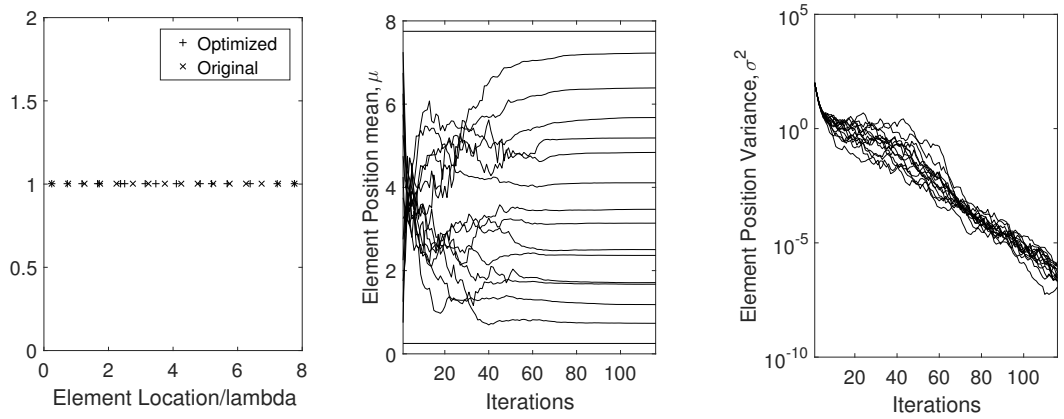


Figure 8. The array optimization results.

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 [56], 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 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. 8.

7. Conclusions and Future Work

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. An UG MIMO technique is developed for transmit and receive beamforming in the underground soil medium. The optimal transmit beamforming and receive combining vectors under minimal inter-component interference constraint are derived. It is shown that UG MIMO performs best when all three component of the wireless UG channel are leveraged for beamforming. The environment aware UG MIMO technique leads to three-fold performance improvements and paves the wave for design and development of next generation sensor-guided irrigation systems in the field of digital agriculture.

The transmit beamforming is used to focus energy in the desired direction, there are three different paths in the underground soil medium through which the waves propagates to reach at the receiver. When the UG receiver receives a desired data stream only from the desired path, then the UG MIMO channel becomes three path (lateral, direct, and reflected) interference channel. Accordingly, the capacity region of the UG MIMO three path interference channel and degrees of freedom (multiplexing gain of this MIMO channel requires careful modeling. Therefore, expressions are required for the degree of freedom of the UG MIMO interference channel. The underground receiver needs to perfectly cancel the interference from the three different components of the EM-waves propagating in the soil medium. This concept is based upon reducing the interference the undesired components to minimum at UG receiver using the receive beamforming. Accordingly, an underground environment aware

MIMO using transmit and receive beamforming is developed. Moreover, environment aware UG MIMO techniques are designed and investigated in the underground soil medium.

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. For future work, the decreasing cost and complexity of hardware, and utilizing the long range, high data rate UG communications, compared to conventional solutions, makes subsurface phased array a viable candidate for the next generation wireless UG communication systems.

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