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# Underground Environment Aware MIMO Design Using Transmit and Receive Beamforming in Internet of Underground Things

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# Underground Environment Aware MIMO Design Using Transmit and Receive Beamforming in Internet of Underground Things

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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 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. This 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. 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.

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

## 1 Introduction

Internet of Underground Things (IOUT) have many applications in precision agriculture [1], [2], [5], [8], [10], [11], [12], [14], [15], [23], [25], [29], [21], [20], [22], [24], [16], [17], [18], [19], [34], [35], [36]. Border monitoring is another important

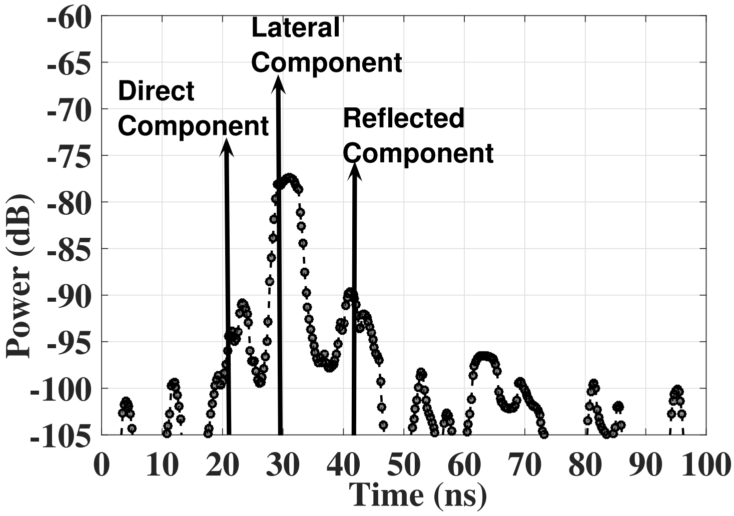



**Fig. 1.** An example power delay profile (PDP) of the impulse response model of the wireless UG channel [28].

application area of IOUT, where these networks are being used to enforce border and stop infiltration [3], [32]. Monitoring applications of IOUT include land slide monitoring, and pipeline monitoring [10], [33], [30], [31]. 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.

UG transmit beamforming using phased array antennas at the transmitter [26] has been used in the underground (UG) communications to maximize the lateral wave [28] 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 [28] and has been studied and empirically validated, UG 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.

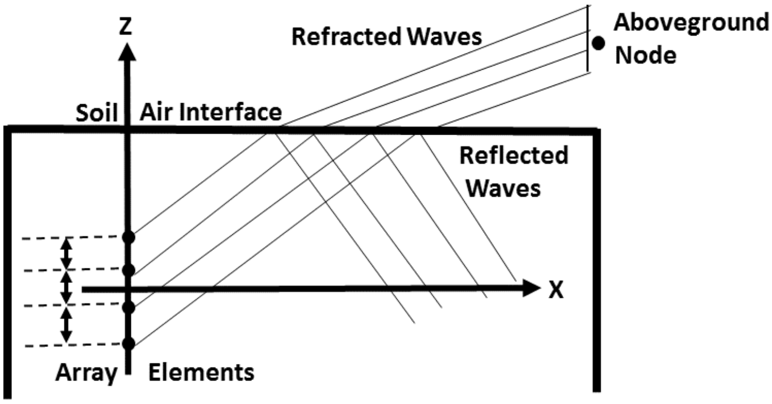
The rest of the paper is organized as follows: the background and major contributions of this work are discussed in Section 2. The UG MIMO is modeled in Section 3. Performance evaluations are done in Section 4. The article concludes in Section 5.

## 2 Contributions of This Work

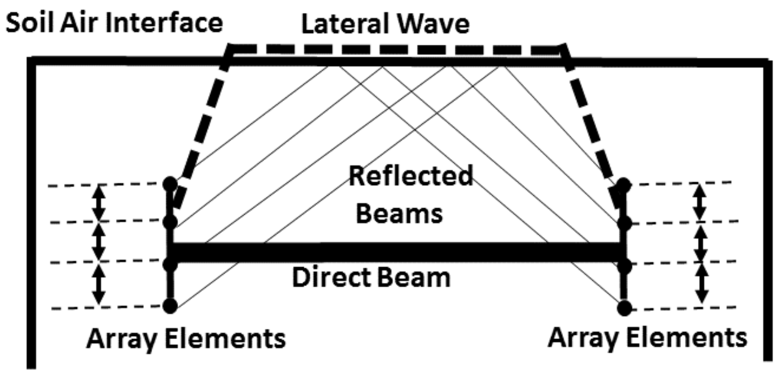
This is the first work to design a fully UG MIMO for the UG communications. The transmit and receive beamforming techniques are considered which communicate through the soil by using UG channel medium. Based on the receiver position, EM waves either travel completely through soil for UG communications 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 [26]. 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).




(a) Transmit Beamforming




(b) Receive Beamforming

**Fig. 2.** The communications schematic for UG MIMO.

## 3 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 [26] is used to focus energy in the desired direction, there are three different paths [28] 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 **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 [6]:

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

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 $k$th 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 [27]:

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

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 [13, **?**]:

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

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 [6]:

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

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

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 [9]:

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

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 $G_a$ [9]. Therefore,

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

where $\varsigma$ is the element phase factor and

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

The received power at the receiver 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 [7]:

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

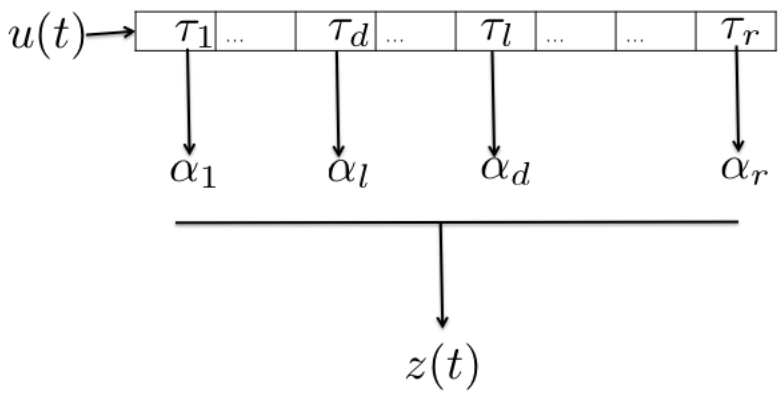



**Fig. 3.** A realization of the UG channel model with three components.

where $D$, $R$, $L$ denotes the power densities of the direct, reflected and lateral component [28]. 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 [7]:

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

where $\Gamma$ and $T$ are reflection and transmission coefficients [7], and $\lambda_s$ is the wavelength in soil. The received power, for an isotropic antenna, is expressed as [7]:

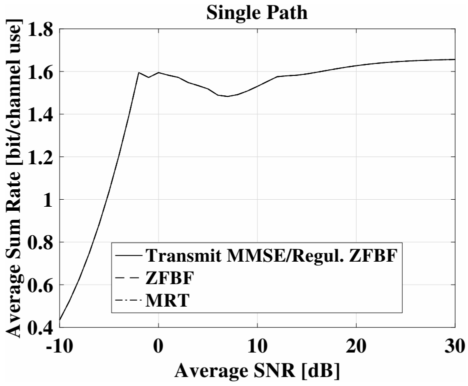
$$P_r = 10\log_{10}(10^{\frac{P_r^d}{10}} + 10^{\frac{P_r^r}{10}} + 10^{\frac{P_r^L}{10}})\ . \tag{16}$$

## 4 Performance Analysis

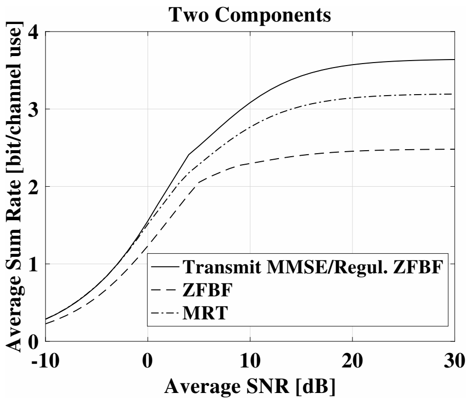
In this section, we present the performance analysis of the UG MIMO. First, the model evaluations and results of the transmit beamforming are presented in the next section.

### 4.1 Transmit Beamforming

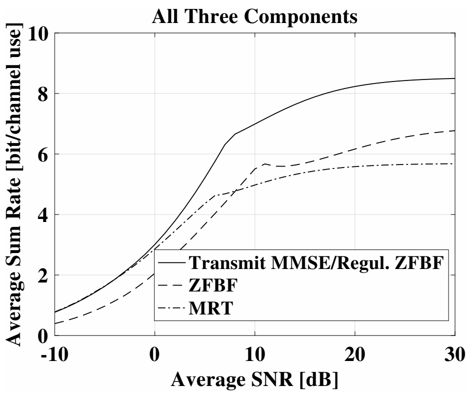
To evaluate the developed scheme, we consider the transmit MMSE, ZFBF, and MRT beamforming of [4]. The implementation of the heuristic beamforming




(a) Single Path




(b) Two Components




(c) Three Components

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

schemes (MRT, ZFBF, transmit MMSE/regularized ZFBF/SLNR-MAX beamforming, and the corresponding power allocation) is also based on the [4]. For the UG MIMO application, instead of randomly generating OTA channels, we use the UG channel impulse response [28], 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. 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.

### 4.2 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 [28]. 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 [28]. 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.

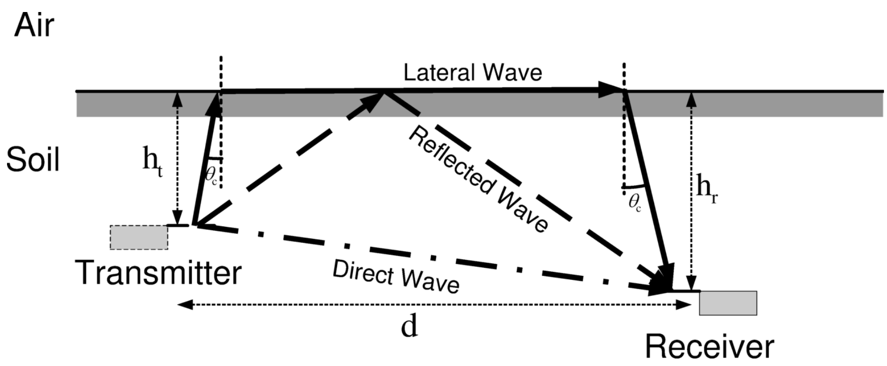



**Fig. 5.** The direct, reflected, and lateral waves in the underground channel [28].

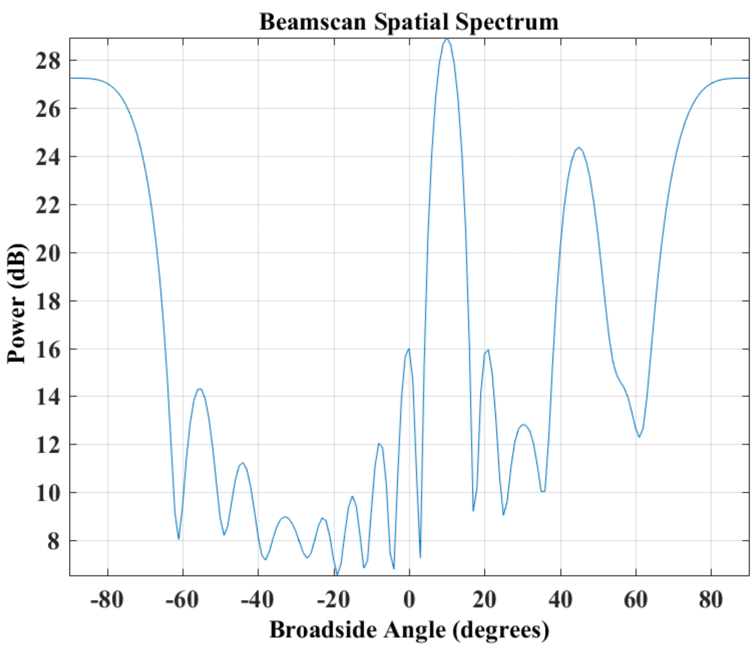



**Fig. 6.** The spatial spectrum of the three components of the UG MIMO receive beamforming.

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.

## 5 Conclusions

In this paper, 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.

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