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# Impacts of Soil Type and Moisture on the Capacity of Multi-Carrier Modulation in Internet of Underground Things

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**Abstract**—Unique interactions between soil and communication components in wireless underground communications necessitate revisiting fundamental communication concepts from a different perspective. In this paper, capacity profile of wireless underground (UG) channel for multi-carrier transmission techniques is analyzed based on empirical antenna return loss and channel frequency response models in different soil types and moisture values. It is shown that data rates in excess of 124 Mbps are possible for distances up to 12 m. For shorter distances and lower soil moisture conditions, data rates of 362 Mbps can be achieved. It is also shown that due to soil moisture variations, UG channel experiences significant variations in antenna bandwidth and coherence bandwidth, which demands dynamic subcarrier operation. Theoretical analysis based on this empirical data show that by adaptation to soil moisture variations, 180% improvement in channel capacity is possible when soil moisture decreases. It is shown that compared to a fixed bandwidth system; soil-based, system and sub-carrier bandwidth adaptation leads to capacity gains of 56%-136%. The analysis is based on indoor and outdoor experiments with more than 1,500 measurements taken over a period of 10 months. These semi-empirical capacity results provide further evidence on the potential of underground channel as a viable media for high data rate communication and highlight potential improvements in this area.

## I. INTRODUCTION

Internet of underground things (I-OUT) are types of networks, where communication is carried out through the underground sensors buried in the soil. I-OUTs are emerging from the recent prevalence and widespread use of wireless underground sensor networks (WUSNs) and has applications in many areas including environment and infrastructure monitoring [1], [18], [26], [39], [42], border patrol [2], and precision agriculture [15], [36]. These developments underscore the need of high data rates and makes it vital to determine the capacity limits of the wireless underground channel.

The ultimate potential of I-OUTs for high data rate communication depends on the underground channel characteristics, which is not well modeled. Therefore, experimentation is required to characterize its nature. Furthermore, interactions between soil and communication components, including antenna and wireless underground channel, result in unique performance characteristics in I-OUTs. Three components i.e.,

direct, reflected and lateral waves are observed as major propagation components of the underground channel. Based on the depth and distance between transmitter and receiver, these components are received with different delays. These delays in different components result in fading envelope of the received signal being decorrelated or partially decorrelated. In addition, variations in amplitude and phase of the received signal are observed. We provide three distinct examples in this paper, based on empirical measurements, on the effects of soil on antenna bandwidth and coherence bandwidth of the underground channel and discuss challenges faced in the design of an underground communication system.

Soil type, soil moisture, burial distance, and depth effect the communication performance [44], leading to dynamic changes in antenna return loss, channel impulse response, and root mean square (RMS) delay spread. In Fig. 1(a), empirical antenna return loss with change in soil moisture has been shown at a 40 cm depth in sandy soil. It can be observed that resonant frequency of antenna changes from 244 MHz to 289 MHz when soil matric potential (inversely proportional to soil moisture) changes from 0 CB to 240 CB. This significant change of 45 MHz necessitates a dynamic change in operation frequency with soil moisture to achieve maximum system bandwidth [13]. Similarly, with a decrease in soil moisture, antenna bandwidth, defined as the frequency range where the return loss is less than  $-10$  dB, has increased from 14 MHz to 20 MHz. Accordingly, soil moisture also impacts available system bandwidth.

Variations in RMS delay spread with soil moisture is another impairment in the underground communication system. In Fig. 1(b) the change in RMS delay spread with soil moisture is shown at a 50 cm distance, and 10 cm and 20 cm depths in silt loam [31]. It can be observed that RMS delay spread decreases first as soil moisture is decreased from near-saturation (0 CB) to 8 CB. Then, a consistent increase in delay spread is observed. The delay spread prohibits higher data rate communication in the underground channel which is in contrast to over the air wireless communication systems where higher data rates can be achieved by increasing the bandwidth

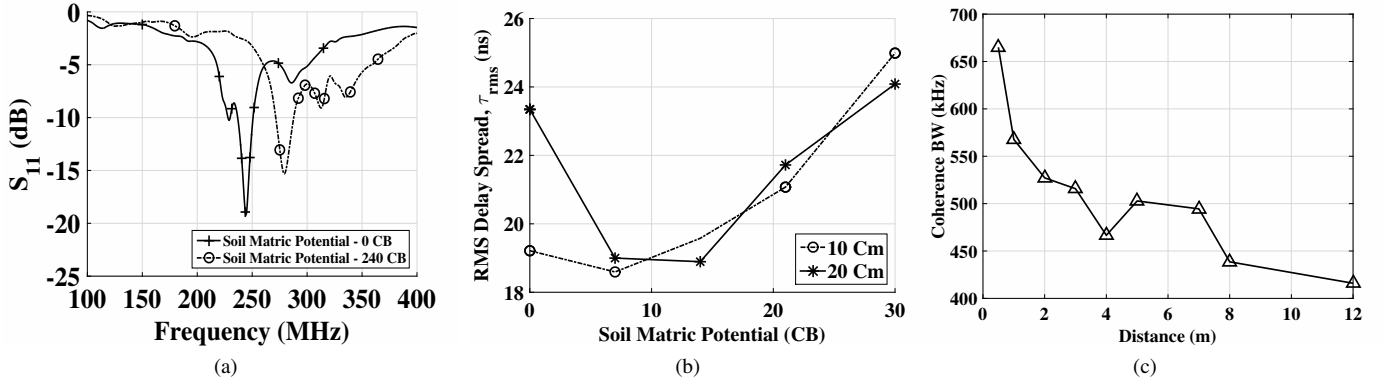


Fig. 1: (a) Antenna return loss with change in soil moisture at 40 cm depth in sandy soil, (b) RMS delay spread vs. soil moisture at 50 cm distance in silty clay loam soil (greater matric potential values indicate lower soil moisture and zero matric potential represents near saturation condition), (c) Coherence bandwidth as a function of distance at transmitter receiver depth of 20 cm in silty clay loam soil.

and by employing higher order modulation schemes. Symbol rate of the channel depends on delay spread of the underground channel leading to keep the rate less than or equal to the inverse of the delay spread in order to avoid inter symbol interference. These variations, which may occur within a short span of time due to external impacts such as rain or irrigation, causes the wireless underground channel to be frequency-selective. Due to these variations in channel impulse response, frequency response, and coherence bandwidth, underground communications exhibits inter-symbol interference (ISI). In general, to overcome ISI, multi-carrier modulation has generally been considered as favorable approach for signal transmission. Accordingly, signal bandwidth of each sub-channel can be kept below the coherence bandwidth of the channel. Hence considerable performance improvements and throughput gains can be made in an underground communication system.

Moreover, the coherence bandwidth of the underground channel also needs to be considered for system design. The coherence bandwidth statistics (for 90% signal correlation based on root mean square delay spread) are shown as a function of distance in Fig. 1(c). It can be observed that the coherence bandwidth ranges from 411 kHz to 678 kHz for distances up to 12 m. More details on the impulse response and coherence bandwidth statistics of the wireless underground channel can be found in [31]. The resulting small coherence bandwidth prohibits high data rate communication in underground channel using single carrier techniques. The dynamic and significant changes in coherent bandwidth, however, suggests that fixed-bandwidth operation, even with multi-carrier techniques may not be the best approach.

Given these spatio-temporal variations in soil moisture, RMS delay spread, and coherence bandwidth statistics at different burial depths and distances, it is desirable to find a design of underground communication system which have the potential and flexibility of adjustments in response to these soil dynamics. Above mentioned impairments could be overcome by designing a communication system which uses sub-channel based multi-carrier data communication approach in the underground channel. In this design, available system bandwidth is divided into sub-carriers and a small bandwidth

of system is occupied by each sub-carrier. The subcarrier bandwidth depends on the delay spread of the underground channel and needs to be in proportion to the delay spread of the channel in order to solve the issues caused by the delay spread impairments. However, an underground multi-carrier communication system designed on a fixed sub-carrier bandwidth may experience inter carrier interference (ICI) [11]. ICI is caused by time-varying coherence bandwidth channel statistics due to soil moisture variations. To mitigate ICI resulting from time-varying coherence and fixed subcarrier bandwidths, transmission parameters should be adjusted by setting bandwidth of subcarriers to the coherence bandwidth.

By using multi-carrier modulation, we have investigated the impacts of soil moisture and soil type on wireless underground channel by adapting coherence bandwidth changes intrinsic to soil moisture variations and hence adapting the system and subcarrier bandwidth accordingly. These factors have significant impact on the performance of data communications in the underground channel and should be considered for design of an efficient underground communication system.

To the best of our knowledge, this is the first work on the capacity of UG channel based on multi-carrier modulation and empirical channel parameters. These parameters include return loss, channel transfer function, and coherence bandwidth in different soil types. Results of capacity limits of UG channel highlight the potential of high data rate communication in UG channel and support the use of soil-based adaptation in the underground channel.

The rest of the paper is organized as follows: the related work is discussed in Section II. Measurement setup and experiment details are presented in Section III. UG capacity model by using multi-carrier modulation is given in Section IV. Results and factors affecting the UG channel capacity are discussed in Section V. Performance comparison of the proposed approach is given Section VI. We conclude in Section VII.

## II. RELATED WORK

Wireless communication in underground channel is an evolving field and extensive discussion of channel capacity does not exist in the literature. Capacity of underground



Fig. 2: The indoor testbed.

channel using magnetic induction (MI) techniques has been discussed in [22], [24], [26], [40], [41]. Magnetic induction techniques have several limitations. Signal strength decays with inverse cube factor and high data rates are not possible. Moreover, in MI, communication cannot take place if sender receiver coils are perpendicular to each other. Network architecture cannot scale due to very long wavelengths of the magnetic channel. Therefore, due to these limitations and its inability to communicate with above-ground devices, this approach cannot be readily implemented in I-OUTs.

Underwater communication [3], [27] has similarities with the wireless underground communication due to the challenged media. However, acoustic communication techniques are primarily used under water. This technique is impractical in underground due to vibration limitations. Acoustic propagation experiences low physical link quality and higher delays due to lower speed of sound. Bandwidth is distance dependent and only extremely low bandwidths are achieved. Moreover, other limitations, such as size and cost of acoustic equipment, and challenging deployment restrict the use of this approach in the wireless underground sensor networks.

Channel models for UG communication have been developed in [14], and [44] but empirical validations have not been performed. Proof-of-concept integration of wireless underground wireless sensor networks with precision agriculture cyber-physical systems (CPS) and center-pivot systems has been presented in [15], [36]. In [35], [33], empirical evaluations of underground channel are presented, however, antenna bandwidth was not considered. Capacity of single-carrier communication in the UG channel has been investigated in [13] but the analysis does not consider a practical modulation scheme and empirical validations have not been provided.

In [31], we have presented a detailed characterization of coherence bandwidth of the underground channel. The development in this paper builds upon the analysis in [31] to design an underground multicarrier communication system. To the best of our knowledge, this is the first work to analyze the capacity of multi-carrier modulation in the UG channel based on empirical measurements of channel transfer function, coherence bandwidth, and antenna return loss under three different soil types and various soil moisture conditions.

### III. EXPERIMENT METHODOLOGY

Capacity of UG channel is affected by soil texture, soil moisture, distance, and depth variations [13]. We present a detailed analysis of the impact of these factors on channel capacity by taking extensive measurements in an indoor and a field testbed with three distinct types of soils (silty clay loam, sandy soil, and silt loam) and under different soil moisture conditions. Thus, we have considered several possible scenarios with more than 1,500 measurements taken over a period of 10 months.

**Indoor Testbed:** The indoor testbed [31] was developed in a greenhouse, which provides ease of controlling soil moisture, replacement of soil, easy installation and replacement of non-functional equipment, and protection from weather.

Three sets of four dipole antennas are installed at the depths of 10 cm, 20 cm, 30 cm, and 40 cm. These sets are 50 cm apart from each other. Final outlook of the testbed with silt loam soil is shown in Fig. 2. Further details about testbed development can be found in [31].

Two different types of soils are used for conducting experiments in the indoor testbed: silt loam and sandy soil. Particle size distribution and classification of testbed soils is given in Table I. To investigate the effects of soil texture on underground communication, soils selected for use in the testbed have sand contents ranging from 13% to 86% and clay contents ranging from 3% to 32%.

**Outdoor Testbed:** To compare the results of indoor testbed experiments and evaluate the effect of distance, a testbed of dipole antennas has been prepared in an outdoor field in silty clay loam soil. Dipole antennas are buried in soil at a burial depth of 20 cm with distances from the first antenna as 50 cm to 12 m.

**Experiments:** Sensors in I-OUT applications are usually buried in topsoil and subsoil layers<sup>1</sup> [23], [34]. Therefore, for underground channel experiments, we have taken measurements for depths of 10 cm to 40 cm with transmitter-receiver (T-R) distances of 50 cm to 12 m. Near-field effects of underground antenna for frequency range used in these experiments are within the 30 cm region.

Frequency response and return loss of the channel are measured using a Agilent FieldFox N9923A Vector Network Analyzer (VNA). Use of VNA for channel measurements have been studied extensively in [5], [19], [20], [29], [32], [38].

The first set of experiments is conducted in the indoor testbed in silt loam soil. Return loss, channel transfer function, and impulse response measurements are recorded at T-R distances of 50 cm and 1 m, and for depths of 10 cm, 20 cm,

<sup>1</sup>Topsoil layer (root growth region) consists of top 1 Feet of soil and 2–4 Feet layer below the topsoil is subsoil.

TABLE I: Particle Size Distribution and Classification of Testbed Soils.

Textural Class	%Sand	%Silt	%Clay
Sandy Soil	86	11	3
Silt Loam	33	51	16
Silty Clay Loam	13	55	32

30 cm and 40 cm. The soil moisture range for these experiment is recorded in terms of matric potential values in the range of 0-50 CB, where greater matric potential values indicate lower soil moisture and zero matric potential represents near saturation condition. The second set of experiments is also conducted in the indoor testbed in sandy soil. Soil moisture range for these experiment is 0-250 CB. Return loss, channel transfer function, and impulse response measurements are taken at the same T-R distances and depths as the first set of experiments. The third set of experiments is conducted in the field testbed in silty clay loam soil. Return loss, channel transfer function, and impulse response measurements are taken at T-R distances of 50 cm to 12 m, and at a depth of 20 cm.

#### IV. CAPACITY MODEL

To evaluate the capacity of underground channel, we consider the bandwidth of sender-receiver antenna pair along with channel transfer function of UG channel, because channel capacity changes with bandwidth [28]. Bandwidth is determined from the return loss of antenna, which is a measure of the efficacy of power delivery from the transmission system to the antenna. Impedance mismatch gives rise to the return loss which is defined as [4]:

$$RL_{dB} = 20 \log_{10} \left| \frac{Z_s + Z_a}{Z_s - Z_a} \right|, \quad (1)$$

where  $Z_s$  and  $Z_a$  are the transmission line and antenna impedance, respectively.

The return loss of an antenna in three different soils at zero soil matric potential (saturated conditions) is shown in Fig. 3(a). The bandwidth of an antenna is traditionally calculated based on its return loss values below a threshold,  $\delta$ , value. In the literature,  $-10$  dB is generally used as the threshold value [4]. For the bandwidth analysis, we assume that the sender and receiver have the same return loss<sup>2</sup>. It is also assumed that the system is operating at the antenna resonant frequency, which maximizes the bandwidth [13]. Accordingly, the bandwidth of an underground system operating at the underground antenna resonant frequency is defined as [13]:

$$B_s = \begin{cases} 0 & \text{if } -R(f) > \delta, \\ 2(f - f_m) & \text{if } -R(f) \leq \delta \text{ and } f < f_r, \\ 2(f_M - f) & \text{if } -R(f) \leq \delta \text{ and } f \geq f_r, \end{cases} \quad (2)$$

where  $f_r$  is the resonant frequency,  $f_m$  and  $f_M$  are the lowest and highest frequency at which  $R(f) \leq \delta$ .

For multi-carrier modulation, the number of subcarriers can be calculated as the minimum number of subcarriers needed to avoid inter-symbol interference (ISI) based on the system bandwidth,  $B_s$ . Let  $B_{cb}$  denote the coherence bandwidth of underground channel<sup>3</sup>. Then, the number of subcarriers is

<sup>2</sup>Because of short distances and spatial homogeneity in soil, probability of major differences between sender and receiver return loss, and in resonant frequencies is very low.

<sup>3</sup>In our analysis of underground channel capacity we have used empirical coherence bandwidth values obtained from time domain impulse response measurements taken in field and testbed settings.

given as:

$$N_c = \left\lceil \frac{B_s}{B_{cb}} \right\rceil. \quad (3)$$

To express the UG channel capacity, we assume m-ary quadrature amplitude modulation (MQAM) for each carrier of multi-carrier transmission system because of its higher spectral efficiency [25].

Given a total number of subcarriers,  $N_c$ , and bandwidth of each subcarrier  $B_{cb}$ , the overall underground channel bit rate is given as:

$$R_{ug} = \sum_{i=1}^{N_c} r_i B_{cb}, \quad (4)$$

where  $r_i$  is the number of bits per symbol in each carrier.

At high SNR, the symbol-error probability,  $P_{sc_i}$ , for the  $i$ th carrier is given as [21]:

$$P_{sc_i} = K_{r_i} Q \left( \sqrt{\frac{3En}{(M_i - 1)N_0}} \right), \quad (5)$$

where the value of the constant  $K_{r_i}$  depends on the number of bits in each symbol and can take values in the range of  $2 \leq K_{r_i} < 4$ .

$$\sum_{i=1}^{N_c} \gamma_i \cdot P = P, \quad \gamma_i > 0. \quad (6)$$

The bit rate of the underground channel,  $R_{ug}$ , can be maximized by optimizing power allocation between all subcarriers based on a target probability of symbol error of each subcarrier,  $P_{sc}^* > P_{sc_i}$ ,  $\forall i$ , and a fixed power constraint,  $P$ .

In Fig. 3(b), empirical channel transfer functions at 50 cm and 1 m distances in sandy soil are shown. For multi-carrier transmission, the channel transfer function is approximated by a step (staircase) function  $|\widehat{H}(f)|^2$ , because for smaller  $B_{cb}$ , staircase function gives close approximation of channel transfer function  $|H(f)|^2$ . An approximation of channel transfer function through staircase function in sandy soil at transmitter receiver depth of 20 cm and distance of 50 cm is shown in Fig. 3(c). Then the overall bit rate is obtained by summing over all subcarriers [21]:

$$R_{ug} = \sum_{i=1}^{N_c} B_{cb} \log_2 \left\{ 1 + \frac{3\gamma_i P}{(N_0 B_{cb}) |\widehat{H}_i(f)|^2} \right\}, \quad (7)$$

where  $N_c$  is the number of subcarriers from (3),  $P$  is transmit power constraint, and  $\gamma_i$ 's are given such that:

The UG channel bit rate,  $R_{ug}$ , is maximized by optimizing the power distribution over all subcarriers. The solution to this optimization problem [30], [46] is similar to water filling of [10, chap. 9], [7]. Accordingly, the optimum power allocation,  $\gamma_i^*$ , is obtained by using a Lagrangian multiplier,  $\lambda$ , which leads to water-filling allocation [10]:

$$\gamma_i^* = \begin{cases} \lambda - \frac{1}{K_0 |H(f)_i|^2} & \text{if } \gamma_i > 0, \\ 0 & \text{otherwise,} \end{cases} \quad (8)$$

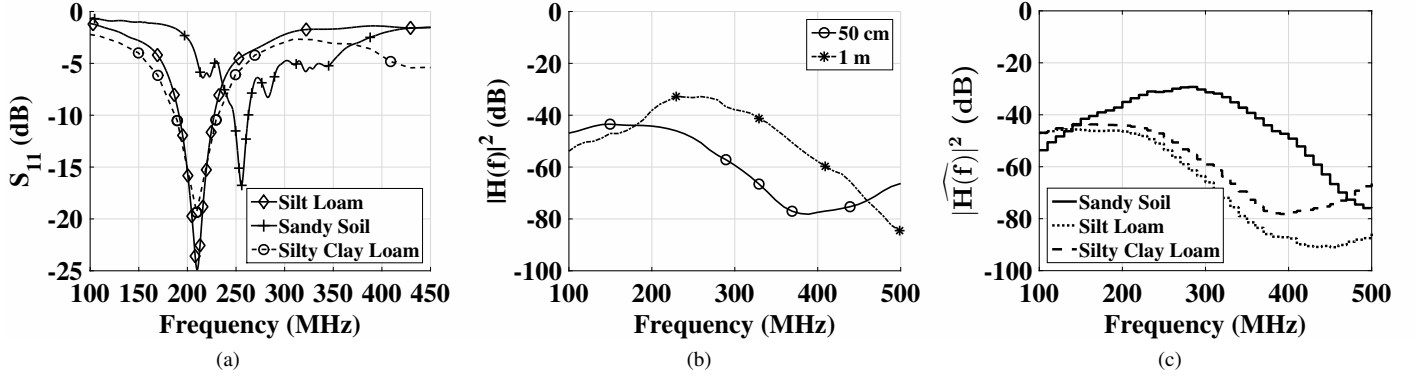


Fig. 3: (a) Return loss of the antenna at 0 CB soil matric potential, (b) Channel transfer function in sandy soil, (c) An approximation of channel transfer function through staircase function at transmitter receiver depth of 20 cm and distance of 50 cm.

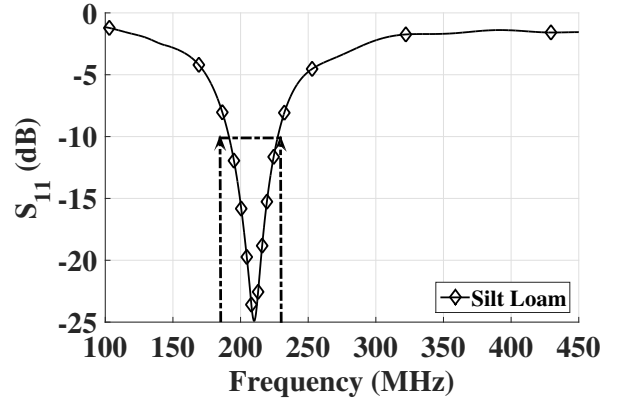
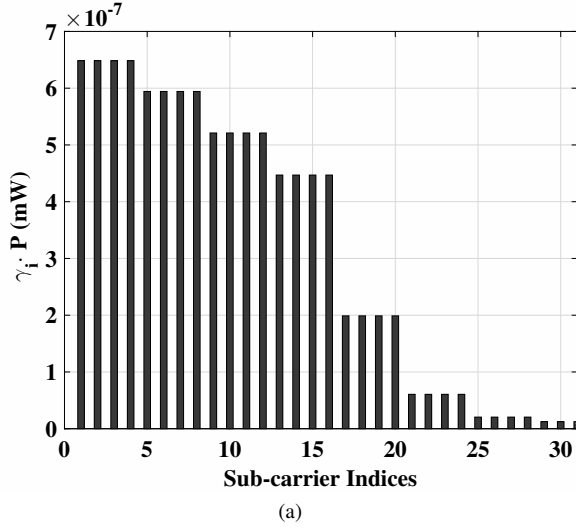


Fig. 5: The bandwidth of the antenna in silt loam.

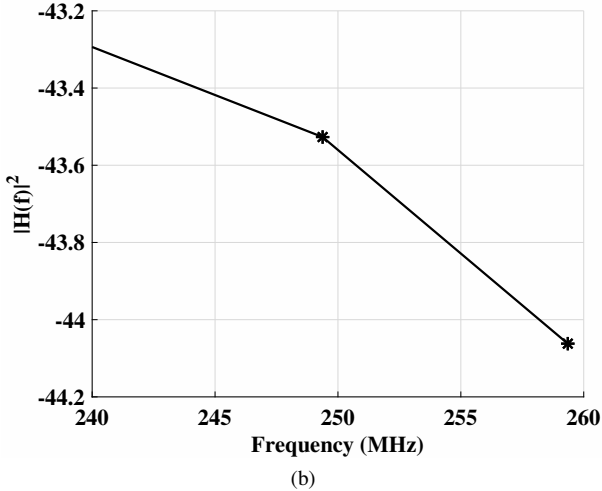


Fig. 4: (a)  $\gamma_i$ 's for channel frequency response in silt loam soil for T-R distance of 50 cm at 20 cm depth, (b) Corresponding channel transfer function.

where  $\sum_{i=1}^{N_c} \gamma_i^* = 1$ , and  $K_0 = 3P/(N_0[Q^{-1}[\cdot]]^2)$ . By jointly solving (6) and (8) the maximum bit rate is obtained as [21]:

$$R_{ug}^{\max} = \sum_{i=1}^{N_c} B_{cb} \cdot \log_2 \{ \lambda K_0 |H_i(f)|^2 \}, \quad (9)$$

where the maximization applies to the high-SNR cases. Thus, we denote this rate as *high-SNR optimal*.

A sub-optimal solution, of allocating equal power to subcarriers, has been shown to achieve capacity close to the optimal solution [8], [30]. To compare with (9), the underground bit rate of equal power allocation is given as:

$$R_{ug}^{eq} = \sum_{i=1}^{N_c} B_{cb} \log_2 \left\{ 1 + \frac{3P/N_c}{(N_0 B_{cb}) |H_i(f)|^2} \right\}, \quad (10)$$

which we denote as *equal power* in the following. In the next section, the results and impacts of different factors on the underground channel are discussed.

## V. RESULTS AND DISCUSSIONS

The performance of a communication system is generally evaluated under the probability of bit error rate constraints for a specified data rate and SNR values. However, transmission power is limited in underground nodes due to energy constraints to achieve longer operation periods [43]. Therefore, in wireless underground channel, it is useful to determine achievable data rate for a fixed BER and under low power transmission power requirements. By using (3), we have determined the minimum number of subcarriers required to avoid ISI based on coherence bandwidth analysis.

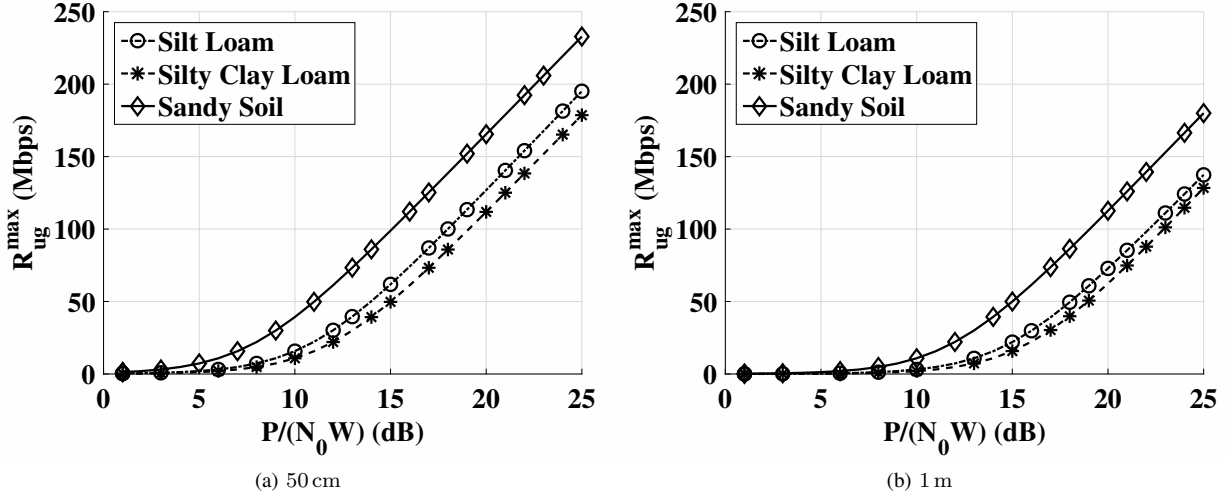


Fig. 6: Capacity in three different soils. Bandwidth is 20 MHz. Transmitter receiver depth of 20 cm and distance of: (a) 50 cm, where the number of subcarriers in the sandy, silty clay loam, and silt loam soils are 25, 25, and 24, respectively, (b) 1 m, where these are 27, 21, and 25, respectively.

In Fig. 4(a), high-SNR optimal  $\gamma_i \cdot P$  values are shown for a channel frequency response in sandy soil (Fig. 4(b)) for transmitter receiver distance of 50 cm at 20 cm depth. It can be observed that optimized power distribution closely follows the channel transfer function curve. To maximize the rate we have set  $K_{r_i}$  to 2 and  $P_{sc}^*$  to  $10^{-5}$ , with  $P/(N_0W)$  given.  $P/(N_0W)$  represents the signal-to-noise ratio (SNR).

In Fig. 5, an example of the bandwidth calculation of an antenna operating at resonant frequency in silt loam soil is shown for  $\delta = -10$  dB, where  $S_{11}$  is shown as a function of frequency. The minimum frequency,  $f_{min}$  is 191.2 MHz and the maximum frequency,  $f_{max}$  is 227.91 MHz, results in a bandwidth of 36.71 MHz.

In Section V-A, we present the effects of soil texture on the capacity of underground channel with measurements recorded in three different soil types. Impacts of soil moisture on UG channel capacity are discussed in Section V-B and the effects of underground T-R distance on the channel capacity are analyzed in Section V-C.

#### A. Soil Texture and Channel Capacity

In Figs. 6, multi-carrier capacity of UG channel in three different soil types is compared at distances of 50 cm and 1 m. At 50 cm, sandy soil has 30% higher capacity compared to silt loam and silty clay loam soil. The system bandwidth in all three soils is measured as 20 MHz. Capacity in sandy soil is 233 Mbps. In silt loam, 195 Mbps capacity is achieved, and in silty clay loam data rates up to 178 Mbps are possible. When the distance increases from 50 cm to 1 m, capacity in sandy soil decreases from 233 Mbps to 180 Mbps (22% decrease). Similarly in silt loam soil capacity has decreased from 195 Mbps to 137 Mbps (29% decrease) and in silty clay loam soil it has decreased from 178 to 129 Mbps (27% decrease).

In soil, electromagnetic waves experience attenuation, which varies with soil texture and bulk density [12]. Attenuation of EM waves in soil depends on the water holding capacity, because water absorbs electromagnetic waves incident

in the soil. Water holding capacity of fine-textured (silt-loam, silty clay loam) and medium-textured soils (fine sandy loam) is much higher, because of the small pore size (but, greater number of pores), as compared to coarse-textured (sandy, sandy loam, loamy sand) because of larger pore size (but less in number of pores) [16]. Therefore, the soils containing the highest clay contents exhibit higher attenuation. It can be observed from Fig. 6 that silty clay loam soil, which has the highest clay content as compared to sandy and silty clay loam soils, has the lowest capacity. Decrease in capacity at 1 m as compared to 50 cm can be attributed to increase in attenuation with distance. At 1 m, the number of required subcarriers is larger because of decrease in the coherence bandwidth with distance (Fig. 1(c)). Waves traveling in underground channel reach the receiver through different paths in soil and air with different permittivity and conductivity. These properties affect the speed of wave propagation in soil and air. Therefore, as the distance increases, the delay spread increases which leads to decrease in the coherence bandwidth.

#### B. Soil Moisture and Channel Capacity

Traditionally, parameters in a multi-carrier modulated system are optimized under a fixed system bandwidth constraint [9], [30], [45], [47]. However, fixing the system bandwidth to the worst-case scenario in UG communication (e.g., 20 MHz) can lead to significant performance loss as soil moisture decreases. On the other hand, when soil moisture increases, decreasing the system bandwidth under fixed transmit power constraint may lead to improvement in SNR which would compensate the increase in attenuation due to higher soil moisture.

In Figs. 7(a)-7(b), antenna (system) bandwidth, coherence (subcarrier) bandwidth, and the number of subcarriers are shown as a function of soil moisture (expressed as soil matric potential<sup>4</sup>) in silt loam soil. It can be observed that with

<sup>4</sup>Greater matric potential values indicate lower soil moisture and zero matric potential represents near saturation conditions.

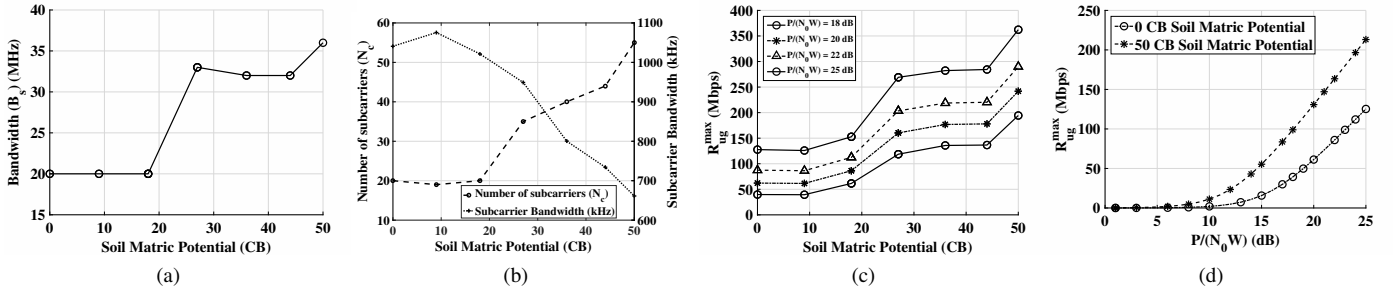


Fig. 7: Effects of change in soil moisture in silt loam soil: (a) System bandwidth with soil moisture, (b) Number of subcarriers with soil moisture, (c) Rate with soil moisture, (d) Capacity in sandy soil at transmitter receiver depth of 20 cm and distance of 50 cm.

decrease in soil moisture, antenna bandwidth increases from 20 MHz to 36 MHz (80% increase).

It can also be observed from Fig. 7(b) that coherence bandwidth decreases with decreasing soil moisture. By adjusting the sub-carrier bandwidth according to the coherence bandwidth of the channel, impacts of soil moisture on each carrier can be mitigated.

The number of subcarriers has increased from 20 to 55 when soil moisture changes from 0 CB to 50 CB.

From an implementation point of view, number of subcarriers has to be  $2^n$ . Moreover, hardware implementation of programmable FFT [17] can be used to adjust the bandwidth of each subcarrier under coherence bandwidth constraints. Accordingly, the number of subcarriers can be adjusted.

In Fig. 7(c), maximum rate in (9) is shown for silt loam soil as a function of soil moisture. It can be observed that for a  $P/(N_0W)$  value of 18 dB, rate increases from 39 Mbps to 194 Mbps, when soil moisture decreases from 10 CB to 50 CB. For a similar change in soil moisture at  $P/(N_0W) = 25$  dB, rate increases from 127 Mbps to 362 Mbps (185% increase). Similar results are observed for sandy soil as shown in Fig. 7(d), where for a decrease in soil moisture from 0 CB to 50 CB, capacity increases from 126 Mbps to 213 Mbps (69% increase). The significant gains highlight the potential of adaptive communication approaches where soil moisture is tightly integrated into communication parameters.

Absorption of electromagnetic waves by soil water content protrude additional attenuation along with diffusion attenuation. This phenomena results because effective permittivity of soil is a complex number. Water held by soil in its pore space can be classified into bound water and free water. Bound water is strongly contained because of the effects of osmotic and matric forces [16] acting on it and is held in top few particle layers. Effect of osmotic and matric forces is diminished in lower soil layers causing unrestrained movement of water. Bound water causes more absorption of electromagnetic waves because of its low infiltration as compared to unrestrained water which can infiltrate and drain easily. Variations in soil moisture leads to variations in permittivity of soil due to which wavelength in soil fluctuates causing more attenuation of waves. It is evident from Fig. 7(c) and Fig. 7(d), that low water absorption of EM waves with decrease in soil moisture has contributed to the increase in capacity in both sandy and silt loam soils.

### C. Distance and Channel Capacity

To analyze the effects of distance on channel capacity, we have conducted experiments in the field testbed in silty clay loam soil for antennas buried at 20 cm depth. In Fig. 8(a), change in the number of subcarriers ( $N_c$ ) as a function of distance is shown. For the empirical 20 MHz antenna bandwidth, when distance increases from 50 cm to 12 m, the coherence bandwidth decreases from 678 kHz to 411 kHz. Hence, number of subcarriers for a fixed system bandwidth increases from 30 to 49. The decrease in coherence bandwidth with distance can be explained by RMS delay spread variations with distance.

Effects of increasing T-R distance on channel capacity are shown in Fig. 8(b). In Fig. 8(b), it can be observed that rates up to 80 Mbps can be achieved up to distance of 12 m. Capacity increases further up to 124 Mbps for  $P/(N_0W)$  value of 25 dB. For higher values of  $P/(N_0W)$ , it can be observed that capacity can be as high as 200 Mbps.

Communication in the underground channel is mainly carried out by three electromagnetic waves [14]. First, the line-of-sight wave (direct wave), from transmitter to receiver, which goes through the soil. Second, the wave which is reflected from soil-air interface (reflected wave) and its path is also through the soil. Third, a wave which goes along the soil surface (lateral wave) and reaches the receiver. When distance is increased, the effects of the direct and reflected wave diminish and only the lateral wave contributes significantly to the received signal power at the receiver. With further increase in distance, the lateral wave attenuates, decreasing the maximum rate.

## VI. PERFORMANCE COMPARISONS

In Fig. 8(c), capacity under three different  $P_{sc}^*$  constraints in two soils (sandy soil and silty clay loam) is shown.  $P_{sc}^*$  values are changed from  $10^{-5}$  to  $10^{-3}$ . In sandy soil, when  $P_{sc}^*$  is increased to  $10^{-3}$ , rate increases from 233 Mbps to 248 Mbps (6 % increase). Similarly, in silty clay loam, rate has increased from 178 Mbps to 194 Mbps (9 % increase).

In Fig. 9(a), the high-SNR optimal rate in (9) is compared with equal power rate in (10) in the silty clay loam soil. It can be observed that for low  $P/(N_0W)$  values (i.e., less than 17 dB), equal power solution leads to slightly higher rates. However, for high  $P/(N_0W)$  values, as expected [30], [9],



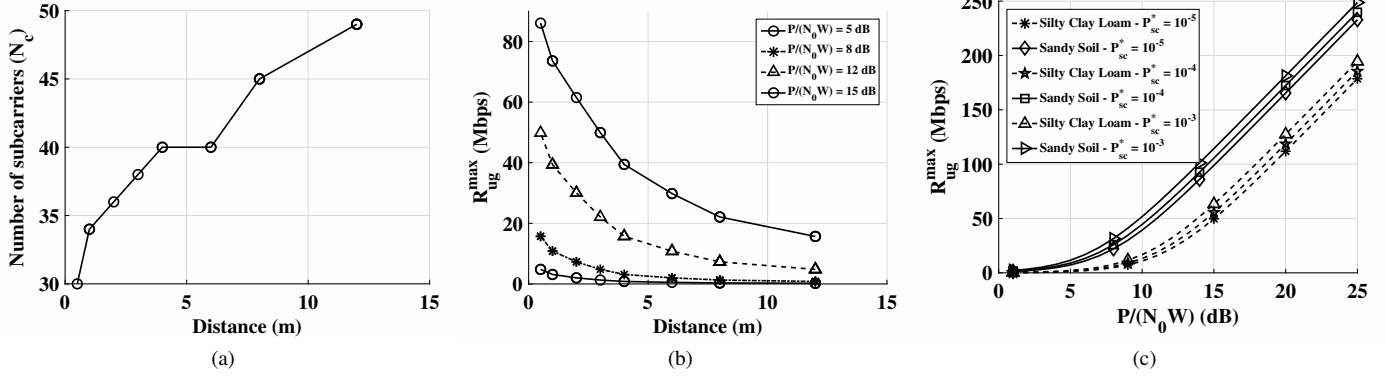


Fig. 8: Effects of distance on underground channel capacity in silty clay loam soil: (b) Change in number of subcarriers ( $N_c$ ) with distance for antenna bandwidth of 20 MHz and coherence bandwidth values shown in Fig. 1(c), (b) Rate with distance, (c) Capacity with different  $P_{sc}^*$  values in two different soils. Bandwidth is 20 MHz. Transmitter receiver depth of 20 cm and distance of 50 cm.

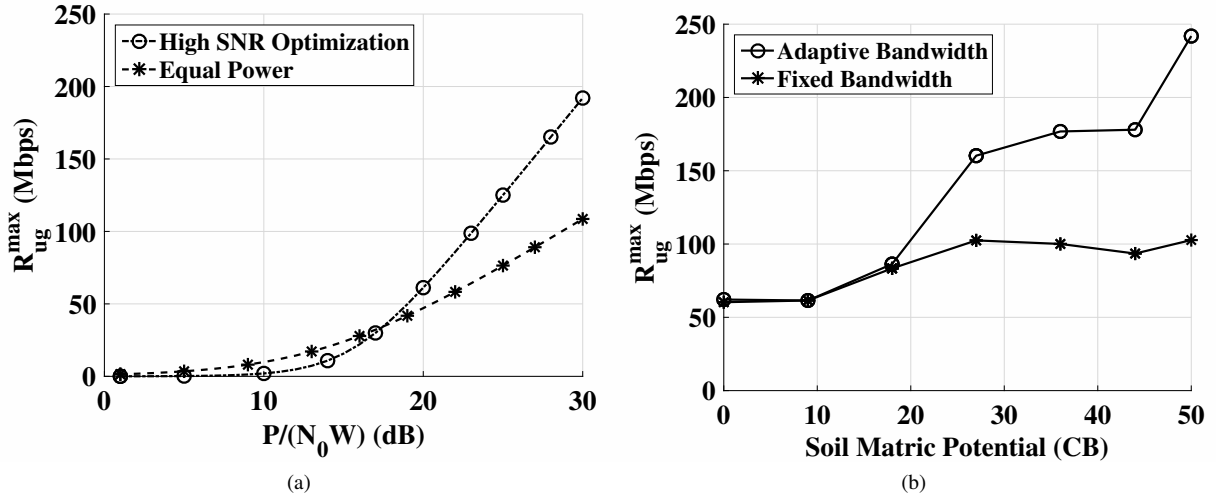


Fig. 9: (a) Comparison of higher SNR optimization with fixed power allocation in the silty clay loam soil. Transmitter receiver depth of 20 cm and distance of 1 m, (b) Comparison of fixed vs. adaptive system, and subcarrier bandwidth approaches with change in soil moisture in silt loam soil.

high-SNR optimal solution performs better. For a  $P/(N_0W)$  value of 25 dB, rate has increased from 76 Mbps to 125 Mbps (64% increase).

It is also of interest to compare the adaptive system and subcarrier bandwidth approach with fixed system and subcarrier bandwidth technique. This comparison with fixed system bandwidth (20 MHz), and fixed subcarrier bandwidth (411 kHz) is shown in Fig. 9(b). It can be observed that at 27 CB soil moisture, fixed bandwidth approach has capacity of 102 Mbps, whereas adaptive technique results in 56% higher capacity (161 Mbps). Similarly, this difference in capacity of both schemes is further increased at 50 CB soil moisture level where capacity of adaptive approach is 241 Mbps, and hence leads to 136% improvement in capacity.

## VII. CONCLUSIONS

In this paper, we provide an analysis of the multi-carrier modulation capacity in underground channel in different soils through extensive empirical channel transfer function, and antenna return loss measurements. Impacts of different soil types on channel capacity are investigated by conducting experiments in silt loam, sandy, and silty clay loam soils under

different soil moisture conditions. Results reveal that soil type, moisture, and T-R distances have an impact on the capacity of multi-carrier modulation in the underground channel. Accordingly, system performance can be enhanced by adjusting transmission parameters such as subcarrier bandwidth based on these changing environmental phenomena. Significant performance improvements can be made by using adaptive channel width [6], [8] and adaptive subcarrier bandwidth (ASB) [11], [37] techniques. Based on our findings and analysis in this paper, we can argue that an underground communication system using adaptive subcarrier bandwidth (ASB) approach is expected to enhance capacity of underground channel. This paves the way for adaptive communication approaches in the underground channel, where soil dynamics are tightly integrated with communication parameter selection.

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