# The Radio Field as a Sensor - a Segmentation Based Soil Moisture Sensing Approach

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Abstract---Soil moisture sensing is important for many different monitoring applications. Especially for a dam monitoring system, soil moisture is one of the most safety-critical parameters. The coverage area of spot based soil moisture sensors is very limited and they mostly provide insignificant benefits, if the area of interest is not largely known. The developed Soil Moisture Sensing system uses the radio field as a sensor and covers a larger area with minimum invasion, even at locations difficult to reach. The radio field between buried nodes provides information about the channel conditions allowing assessments to be made of the soil characteristics within the communication channel. Long Range packet radio modules, originate from the Internet of Things, ensure a robust communication with a high receiver sensitivity enabling an application as Wireless Underground Sensors. In this paper, the sensing system is used for a long-term evaluation of the soil moisture at the airside of the Bever dam near to Wuppertal in Germany. It is shown that the measured Received Signal Strength Indicator variation of the underground communication link quality enables a classification of precipitation events. Further, the experimental setup of a sensor field in the laboratory performs a segmentation based soil moisture sensing and visualizes the moisture with a higher resolution. This concept is transferred to the Long Range approach while ensuring a reasonable trade-off between evaluation accuracy and battery lifetime.

#### I. INTRODUCTION

Internet of Underground Things (IoUT) is an emerging field of research enabling robust and long range wireless communication of sensors at the subsurface region of the soil [1]. In contrast to traditional spot based soil moisture sensors, a solution to significantly increase the coverage area is a multidimensional Soil Moisture Sensing (SoMoS) system, which is able to detect soil moisture changes via the radio field by measuring the variation of the Receive Signal Strength Indicator (RSSI) of an underground communication link between two IoUT devices. The basic operating principle of the SoMoS system was developed by the authors in a previous work [2]. To improve the performance of soil moisture detection and evaluation in the sensor field with many different communication links, a visualization concept to localize soil moisture with a higher resolution is necessary. In medical imaging techniques, cross-sectional images of threedimensional structures are generated by a large number of signals emitted. Similarly, Radio Tomographic Imaging (RTI) can be used to detect and even classify moving objects within a room [3]. In both cases, absorption characteristics are used to detect spatial structures. For this purpose, the observed volume

is split into numerous small-sized spatial segments, hereinafter named as voxel. If the connection of a communication link is described by the propagation of electromagnetic waves, a link can be understood as a series of several space segments. In this paper, an approach is presented according to which the principle described above is applied to the experimental setup for moisture detection (see Fig. 1).



Fig. 1. Segmentation based soil moisture sensing approach.

The paper is organized as follows: The related work is discussed in Section II. Section III introduces the fundamental underground radio transmission and attenuation model by using Peplinski's principle [4] to define and analyze an underground communication link in theory. The channel model is used to dimension the experimental setup and to validate the results. Section IV shows the segmentation based approach of the developed SoMoS system to detect soil moisture in the laboratory more efficiently. In Section V, results of a first long-term soil moisture evaluation at the Bever dam near to Wuppertal in Germany are described. In Section VI, the segmentation based visualization concept of the laboratory is transferred to a concept for the field test. Finally, the conclusion is provided in Section VII.

## II. RELATED WORK

Internet of Things (IoT) devices have reached the underground. Equipped with several sensors and small batteries, they are used for many different monitoring applications [5], [6], [7]. Commonly, Wireless Underground Sensors (WUS) still perform measurements locally at the place of burying and transmit the data to other near sensors or relays at the surface. Therefore, the authors in [8] try to enable high data rates for long range wireless underground communication links with a three antenna design by evaluating the spatial modularity of direct, lateral, and reflected components of the underground channel.

The authors in [9] use Magnetic Induction (MI) as an alternative solution for underground communication to localize objects. However, MI based WUSN have some significant limitations. MI is designed to be mostly resistant against changing channel conditions like varying soil moisture. Further, sender and receiver cannot be perpendicular to each other so that a communication to the surface is not possible.

In contrast, current research, which considers soil moisture detection via the radio field, focusses on ZigBee at 2.4 GHz [10] or Ultra-Wideband (UWB) at 4 GHz [11]. Due to the high path loss in the frequency range above 1 GHz, only short communication ranges are possible. To the best of the authors' knowledge, SoMoS is the first system using LoRa in the 433 MHz range to detect and evaluate soil moisture via the radio field.

# III. UNDERGROUND RADIO TRANSMISSION AND ATTENUATION MODEL

The receive power  $P_r$  [dBm] of a wireless underground channel is affected by an additional path loss  $L_s$  [dB]

$$P_r = P_t + G_r + G_t - L_0 - L_s,$$
 (1)

which is depending on the soil medium [12].  $P_t$  [dBm] is the transmit power,  $G_{t,r}$  [dBi] the transmitter and receiver antenna gains  $L_0$  [dB] the free space path loss. Generally,  $L_s$  consists of two components,  $L_{\alpha}$  [dB] and  $L_{\beta}$  [dB], and is calculated by

$$L_s = L_\alpha + L_\beta,\tag{2}$$

where  $L_{\alpha}$  considers the additional signal attenuation and  $L_{\beta}$  considers the delay difference of the signal.

$$L_{\alpha} = 8.69\alpha d \tag{3}$$

$$L_{\beta} = 154 - 20log(f) + 20log(\beta)$$
 (4)

Thereby,  $\alpha$  [m<sup>-1</sup>] is the attenuation constant, d [m] is the distance between sender and receiver, f [Hz] is the operating frequency and  $\beta$  [m<sup>-1</sup>] is the phase shifting constant. The overall signal attenuation  $L_p$  in soil can be calculated as

$$L_p = 6.4 + 20 \log(d) + 20 \log(\beta) + 8.69 \alpha d.$$
 (5)

 $\alpha$  and  $\beta$  depend on the dielectric properties of soil, which can be calculated by

$$\epsilon = \epsilon' - j\epsilon'',\tag{6}$$

where  $\epsilon'$  is the dielectric constant and  $\epsilon''$  is the dielectric loss factor of the soil. Peplinski introduced a principle [4] to determine the dielectric soil properties in the frequency range of 0.3 to 1.3 GHz by using a simple linear adjustment

$$\epsilon' = 1.15\epsilon'_m - 0.68\tag{7}$$

with

$$\epsilon'_m = \left(1 + \frac{\rho_b}{\rho_s} (\epsilon_s)^{\alpha'} + (m_v)^{\beta'} (\epsilon'_{fw})^{\alpha'} - m_v\right)^{1/\alpha'}, \quad (8)$$

$$\epsilon_s = (1.01 + 0.44\rho_s)^2 - 0.062,\tag{9}$$

$$B' = 1.2748 - 0.519S - 0.152C \tag{10}$$

and

$$\epsilon'' = \left( (m_v)^{\beta''} (\epsilon''_{fw})^{\alpha'} \right)^{1/\alpha'}, \qquad (11)$$

$$\beta'' = 1.33797 - 0.603S - 0.166C \tag{12}$$

where  $\rho_b$  [g/cm<sup>3</sup>] is the bulk density of the soil,  $\rho_s$  [g/cm<sup>3</sup>] is the specific density of the solid soil particles,  $m_v$  is the moisture in soil, calculated as Volumetric Water Content (VWC),  $\alpha'$  is an empirically determined constant [4],  $\epsilon_s$  is the relative permittivity of the solid soil,  $\beta'$  and  $\beta''$  are soil-type dependent and empirically determined constants [4], S and C are the mass fractions of sand and clay,  $\epsilon'_{fw}$  and  $\epsilon''_{fw}$  are the real and imaginary parts of the relative dielectric constant of free water, which are given by

$$\epsilon'_{fw} = \epsilon_{w\infty} + \frac{\epsilon_{w0} - \epsilon_{w\infty}}{1 + (2\pi f \tau_w)^2} \tag{13}$$

$$\epsilon_{fw}^{\prime\prime} = \frac{2\pi f \tau_w (\epsilon_{w0} - \epsilon_{w\infty})}{1 + (2\pi f \tau_w)^2} + \frac{\sigma_{\text{eff}}}{2\pi \epsilon_0 f} \frac{(\rho_s - \rho_b)}{\rho_s m_v}, \qquad (14)$$

respectively.  $\epsilon_{w0}$  is the static dielectric constant of water,  $\epsilon_{w\infty}$  is the high-frequency limit of  $\epsilon'_{fw}$ , f [Hz] is the operating frequency,  $\tau_w$  is the relaxation time of water,  $\epsilon_0 = 8.854 \cdot 10^{-12}$  [F·m<sup>-1</sup>] is the permittivity constant of free space,  $\sigma_{\rm eff}$  [S·m<sup>-1</sup>] is the effective conductivity depending on soil texture, which is given by

$$\sigma_{\rm eff} = 0.0467 + 0.2204\rho_b - 0.4111S + 0.6614C.$$
(15)

Finally, the attenuation constant  $\alpha$  and the phase shifting constant  $\beta$  can be calculated with

$$\alpha = \omega \sqrt{\frac{\mu \epsilon'}{2} \left( \sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right)}$$
(16)

$$\beta = \omega \sqrt{\frac{\mu \epsilon'}{2} \left( \sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} + 1 \right)},$$
 (17)

where  $\mu$  [H·m<sup>-1</sup>] is the magnetic permeability,  $\omega = 2\pi f$  is the angular frequency,  $\epsilon'$  is the dielectric constant and  $\epsilon''$  is the dielectric loss factor of the soil as given in (7) and (11), respectively.

Fig. 2 shows the path loss  $L_p$  of an average topsoil for different distances d and typical IoT frequencies f at two different VWCs, 5% and 50%, respectively. The higher the operating frequency, the higher the influence of rising VWC. Therefore, 433 MHz is chosen for the experimental setups in the laboratory and in the field. Assuming a lowest receiver sensitivity of -140 dBm [13] and a transmit power of +10 dBm for the LoRa based SoMoS setup, a VWC dependent communication range of up to 9.5 m is possible.



Fig. 2. Analytically determined path loss vs. distance and frequency at two different volumetric water contents.

# IV. SEGMENTATION BASED SOIL MOISTURE SENSING SYSTEM IN THE LABORATORY

By using [2] as a basis, the laboratory setup has been extended to enable a segmentation based moisture sensing. Since eight SoMoS transceivers are deployed in the laboratory, N(N-1)/2 bidirectional communication links are provided, so that with N = 8 transceivers 56 RSSI values can be evaluated in maximum (see Fig. 3).  $M^2$  voxels (here M = 3) of the same size are assigned to each of the four cubes, so that an MxM voxel matrix per cube is available.



Fig. 3. Eight SoMoS transceivers around a 2x2 cube matrix filled with sand. 9 voxels are assigned to each cube.

Each transmission path is characterized by a Fresnel zone. The Fresnel zone describes the area between transmitting and receiving antennas in which the majority of transmission power is transferred. The shape of the Fresnel zone depends on the wavelength  $\lambda$  and the distance d between sender and receiver. In free space, this model is used to estimate additional attenuation by obstacles. In the further sections, it is assumed that Fresnel zones can also be used for modeling the spatial propagation of electromagnetic waves in underground

communication. To the wavelength of electromagnetic waves in a medium applies

$$\lambda = \frac{\lambda_0}{\sqrt{\mu_r \epsilon_r}} \tag{18}$$

where  $\mu_r$  is the magnetic permeability and  $\epsilon_r$  is the relative permittivity of the medium. As described in [12],  $\epsilon_r$  of sand increases with rising moisture content. Further, a threedimensional propagation is projected onto a two-dimensional field. The Fresnel zone has the form of an ellipse in the two-dimensional plane with a maximum width of  $\sqrt{\lambda d}$ . With increasing moisture, the width of the Fresnel zone is therefore reduced. In the next step, all paths are determined for each voxel that propagate within it. The spatial match between ellipse and voxel is determined by the midpoint of the voxel. If this is within the ellipse, the associated path is relevant for the voxel in the analysis. The arithmetic mean of the RSSI of all paths selected by this method can be used to evaluate the attenuating effect of this voxel. If the variation at a previous point in time  $t_0$  is considered, changes of the VWC within a close meshed network can be determined. The RSSI change at time t can be used as a parameter for the detection of a precipitation event. In addition, the standard deviation (STDEV) of the RSSI of each voxel is determined over a fixed period of time. This reflects the dispersion of measured RSSI values. It is evident that a high dispersion of the values is the result of a reaction to an event.



Fig. 4. Segmentation based soil moisture sensing. 1.5 liters of water were added to Cube 1 at the top left.

In the following, this evaluation method has been used to analyze a precipitation event. At the beginning of the measurement series, 1.5 liters of water were added to the cube at the top left (Cube 1). Fig. 4 shows the STDEV of the resulting RSSI values of all voxels immediately after the addition of water, calculated over a period of one hour. Fig. 3 clearly shows that the outer four voxels are not well covered by the radio field, so they will not be considered during the evaluation. The average standard deviation of all voxels in this period is 0.67 dB. The maximum dispersion occurs for a voxel within Cube 1 with a value of 1.15 dB. For each cube, an average standard deviation can be calculated by means of all  $M^2$  assigned voxels. This is 1.10 dB for Cube 1, 0.54 dB for Cube 2, 0.41 dB for Cube 3 and 0.61 dB for Cube 4. After that, the signal attenuation caused by moisture is measured in a quasi-stationary test environment. During the measurement, the VWC increases to  $\approx 27\%$  within Cube 1, which is monitored with a reference sensor. All other cubes contain dry sand ( $\approx 5\%$  VWC). Compared to the initial state without moisture in Cube 1, an additional RSSI attenuation of 7.58 dB can be determined. According to the WUSN channel model introduced in Section III, an additional attenuation of 8.17 dB is expected due to the additional moisture. The difference between experimentally and analytically determined additional path loss is therefore only 0.59 dB (see Fig. 5).



Fig. 5. Comparison of experimentally and analytically determined attenuation due to the added water in Cube 1.

These evaluation results show that a precipitation event can clearly be detected on the basis of fluctuations in average reception levels. However, certain voxels not belonging to Cube 1 are also subject to higher fluctuations. This can be explained by the fact that some paths leading over Cube 1 are included in the calculation. Furthermore, a voxel-based calculation leads to results that approximately match the channel model presented in Section III. These paths are attenuated by the influence of soil moisture. Filtering the measurements may eliminate these inaccuracies. In further research work, the method presented here has been used to classify precipitation events according to their intensity.

# V. EVALUATION OF THE SOIL MOISTURE SENSING SYSTEM IN A REAL DAM SCENARIO

As presented in [2], the SoMoS system was already used to detect soil moisture after a manually produced precipitation event to a single communication link within the sensor field. The same SoMoS system configuration will now be used to detect soil moisture in a real dam scenario. Therefore, a sensor field consisting of nine sensors has been installed airside the Bever dam near to Wuppertal, Germany (see Fig. 6). Horizontal and vertical distance between the nodes is 3 m, so that an area of 36 m<sup>2</sup> is covered by the sensor field. The burial depth is 0.5 m and the burial direction is perpendicular to the surface. The distance between surface and the top of the node antenna is 0.18 m and the soil consists of topsoil.

LoRa packet radio is chosen as a robust communication technology with a high receiver sensitivity. Due to the spread spectrum signal modulation technique, a signal reception even



Fig. 6. Sensor field installation scheme at airside of the Bever dam near to Wuppertal, Germany.

below the noise floor is possible [13]. To maximize the communication range of the radio module, the lowest possible frequency band of 433 MHz is used. The radio module is mounted on an Adafruit Feather 32u4 development board [14]. During active radio listening, the power consumption is about 40 mA, during transmission with +20 dBm about 120 mA and during full sleep about 0.3 mA. Due to legal requirements, the transmit power is limited to +10 dBm (10 mW). The resulting sensor is small in size and can easily be installed with minimum invasion. Equipped with a 3000 mAh battery, the sensor is independent of power supply. To be resistant to soil, moisture and humidity, the sensor is placed in a waterproof acrylic glass cylinder (Ø 0.1 m). In the developed sensor field, one of the SoMoS nodes is configured as gateway to continuously listen to the communication channel and measure the RSSI of node packets. To enable an USB power supply of the gateway, it will positioned at the top edge of the sensor field. Fig. 7 shows the communication topology. The maximal distance between gateway and nodes is 6.7 m.



Fig. 7. Side view of the field installation at the Bever dam with one gateway and eight nodes before burying.

To save battery, each node enters the full sleep mode for 900 s after successful transmission. After waking up, it requests channel access and transmits packets in a predefined period of time if access was granted. If the channel is occupied by another node, it calculates a random back-off time between 60 and 300 s, enters the full sleep mode for this time again and requests channel access afterwards. The advantage of this state machine is that the system is very robust due to low complexity and no synchronization is needed for the nodes.

In a long-term evaluation over 78 days (see Fig. 8), the sensor field was affected by random precipitation events, which has been used to analyze and evaluate the SoMoS system. At



Fig. 8. Long-term evaluation of SoMoS Node 4 buried in the middle of the sensor field. The daily sums of precipitation (bottom), measured RSSI (top) and RSSI standard deviation (center) are visualized for 78 days.

the bottom of Fig. 8, the daily sum of precipitation at the dam for the measuring period between August and October 2017 is shown. There were several precipitation events, some with light (0-2  $1/m^2/day$ ), some with moderate (2-15  $1/m^2/day$ ) and some with heavy rain (>15  $1/m^2/day$ ). At the top of Fig. 8, the measured RSSI of SoMoS Node 4 buried in the middle of the sensor field is visualized, the daily standard deviation of the RSSI below. The RSSI varies from -96 dBm to -142 dBm, the standard deviation significantly increases at most of the precipitation events. The measurement results of the other nodes correlate similarly. To classify the dependency between RSSI and precipitation of the complete sensor field, Fig. 9 shows the standard deviation divided into three precipitation categories with light, moderate and heavy rain.



Fig. 9. Measured RSSI standard deviation of the complete sensor field divided into three precipitation categories.

No or light rain leads to an average RSSI standard deviation of 1.29 dB, moderate rain to 2.67 dB and heavy rain to 4.84 dB. Due to the slow seepage velocity and precipitation events significantly longer than one day and also other signal influences, which are neglected here, not every RSSI variation can be clearly assigned to an increasing soil moisture. Nonetheless, 79 % of all precipitation events can be correctly detected and assigned to the right category.

# VI. CONCEPT FOR SOIL MOISTURE SENSING IN THE FIELD WITH INCREASED RESOLUTION

As shown in the previous section, the LoRa based SoMoS system is able to detect soil moisture. But due to the star

topology from nodes to gateway, the amount of communication links for the soil moisture sensing is limited. Therefore, a concept for the SoMoS system has been developed to maximize the amount of available communication links, which leads to an increased resolution of soil moisture localization. For the considered sensor field with 9 transceivers at the Bever dam, the amount of 8 unidirectional communication links is increased to 36 bidirectional communication links with 72 measurable RSSI values by adapting the soil moisture sensing process to a rotating gateway approach (see Fig. 10).



Fig. 10. Rotating gateway concept to increase soil moisture detection resolution in the field.

Every 900 s, the gateway generates a small packet, hereinafter named as token, which will consecutively be passed through the sensor field by the nodes (Round Robin). Each node has to be awake to receive and measure the RSSI value of the received token, even though it was not the destination. When the token reaches the gateway again, each node has measured 8 RSSI values of each communication link, which will then be collected by the gateway.

The significantly extended awake period of each node obviously results in a decreased battery lifetime. To minimize the lifetime loss, the nodes have to synchronize to the 900 s token interval as accurately as possible to maximize the sleep period in between. The main challenge is caused by the clock deviation of the local oscillators of each node, which is constant within one system, but differs from other clock drifts. For a target sleep time of 900 s, this drift resulted in a maximal observed time deviation of 70 s, in which the node woke up too early or too late. Therefore, each node measures the time interval between two tokens in local oscillator cycles to calibrate itself, which minimizes the waiting time for the first token sent by the gateway. Reversely, this maximizes the sleep time and battery lifetime of each node. Fig. 11 visualizes the measured waiting time for the first token of six nodes, a-c with and d-f without calibration, respectively.



Fig. 11. SoMoS nodes w/o (d-f) and w/ calibration (a-c) to minimize waiting time for first token.

Node a, c and d initially woke up too late and missed the first token. In this case and without calibration (like Node d), sleep mode would never be possible. Node e and f woke up sufficiently early but wasting battery lifetime each round. Now, node a-c incrementally calibrating itself and after 6.5 hours, the lowest possible waiting time of about 0.75 s was reached. Assuming a maximum deviation of 70 s, the calibration increases the expected lifetime by 45% to 360 days, which is quite sufficient for a long-term evaluation of the segmentation based concept in a field test.

Summarized, the extended SoMoS system provides a reasonable trade-off between evaluation accuracy and battery lifetime. Due to the maximal amount of communication links, the observed volume can now be split into numerous voxels like the laboratory setup to enable soil moisture sensing with a significantly increased resolution, which is required for an RTI approach. This will be analyzed in a further step of research.

#### VII. CONCLUSION

In this paper, the authors implement and evaluate a segmentation based Soil Moisture Sensing approach in the laboratory to increase the localization accuracy and visualization resolution of moisture in an underground material under test while using the radio field as a sensor. To dimension the field test and validate the measurement results, an underground radio transmission and attenuation model is developed. Before transferring this segmentation based approach to a concept for Soil Moisture Sensing in the field to increase the resolution of moisture visualization, it is shown that the system basically is able to detect soil moisture under real conditions at the airside of the Bever dam near to Wuppertal in Germany. The longterm evaluation over 78 days shows a high correlation between measured Receive Signal Strength Indicator and precipitation events. In future work, additional weather dependent parameters like temperature and seasons as well as cross-correlations of the measurement values between neighbored nodes will be analyzed to improve the sensing performance, preferably by a machine-learning approach.

### ACKNOWLEDGMENT

Part of the work on this paper has been supported by the German TaMIS project, which is part of the nationwide geotechnology research program funded by the German Federal Ministry of Education and Research (BMBF) (03G0854A) and by Deutsche Forschungsgemeinschaft (DFG) within the Collaborative Research Center SFB 876 "Providing Information by Resource-Constrained Analysis", project A4.

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