Wireless Ad hoc and Sensor Network Underground with Sensor Data in Real-Time

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***Abstract*— This paper describes an innovative approach using a wireless ad hoc and sensor network solution in a borehole telemetry system. This contribution is in line with the wireless network track of the conference with regards to channel modeling and characterization as well as wireless applications and services. The paper further validates the feasibility of achieving a reliable wireless communication network underground with real-time data acquisition with respect to the described borehole telemetry system.**

Keywords-Wireless communication; drilling; sensor node; tubes; underground

I. INTRODUCTION

The Intelligent Tube (ITUBE) Project, is an on-going project at the Center for Sensor Systems, University of Siegen. This is a borehole telemetry system where the objective is to obtain the latest information in real time on all relevant data during a drilling operation. This data is taken into account for faster complex decision-making processes, which affect the actual drilling (drilling, completion, intervention and process control). This is motivated by but not limited to the in situ soil mixing drilling process where quality and accurate vertical drilling is essential to save cost [8]. In connection with this soil mixing process, the pressure conditions at the nozzle exit and the temperature are of particular interest [7]. To ensure quality of work, pressure should be continuously monitored closely at the outlet to control the process, which is presently a challenge in the in situ soil mixing process [8]. During the drilling process, real-time information about the drill head progress is important, thus the need to cluster the essential sensors within the drill head to gather the relevant data to ensure the quality of the drilling process. For this to be achieved, a flexible, robust, fast and reliable communication structure needs to be put in place. Hence, in this paper, we analyze the feasibility of achieving such a reliable wireless communication underground for real-time data acquisition with regards to the borehole telemetry system.

Section II describes the proposed structure of the network nodes, as embedded in drill tubes, for communication. The succeeding section, Section III, explains the theoretical concept and the related work drawn from the works of [1][2] required to justify the feasibility of the approach. Section IV then shows MATlab simulations and analysis using the model equations described in the previous section. Finally, the last section, Section V, deals with open questions and future work.

II. PROPOSED NETWORK STRUCTURE

For data communication, as shown in Figure 1, the nodes are designed such that the radio transceivers are placed at the ends of each drill tube, therefore, enabling a closer proximity to each other (in this instance about 100mm to 300mm apart) within the ground, thereby, reducing the gap to be overcome by the signals. Within each tube, the end to end transceivers are connected to each other via a microcontroller and a power supply by cable to form a node as again shown in Figure 1. The microcontroller is programmed to enable for routing of data in the wireless ad hoc network setup. In accordance with the joining of the drill tubes into a strand during the drilling process, the individual wireless nodes will automatically form an ad hoc network strand irrespective of the order of the tubes. Sensor functionality is located in the drill head, which serves as a data source. The data collected in the drill-head sensor node is wirelessly sent to the next node located in the mechanically flanged pipe of the drill string. On the surface, the last node used in the drill string pipe connects with the base station communication interface outside of the drill string. The base station forms the interface to various system controls.

III. UNDERGROUND COMMUNICATION

This section focuses on the modeling and analysis of the underground communication to verify the feasibility of a reliable communication framework. For reliable communication between the nodes in the underground environment, the radio signals transmitted should be received independent of the prevailing conditions of the soil medium. This explains the close proximity of the transceiver modules to each other at adjoining ends of the tubes or pipes as described in the previous section.

A. Related Work

A modification of the Frii's Transmission Equation of the received signal strength, as described in [1], expressed in the logarithmic form is given as

$$P_r(dBm) = P_t(dBm) + G_r(dB) + G_t(dB) - L_0(dB) - L_m(dB) \quad , \qquad (1)$$

where $P_r(dBm)$: power at receiver, $P_t(dBm)$: power at transmitter, $G_r(dB)$: receiver gain, $G_t(dB)$: transmitter gain, $L_0(dB)$: path loss in free space, $L_m(dB)$: path loss in soil medium.

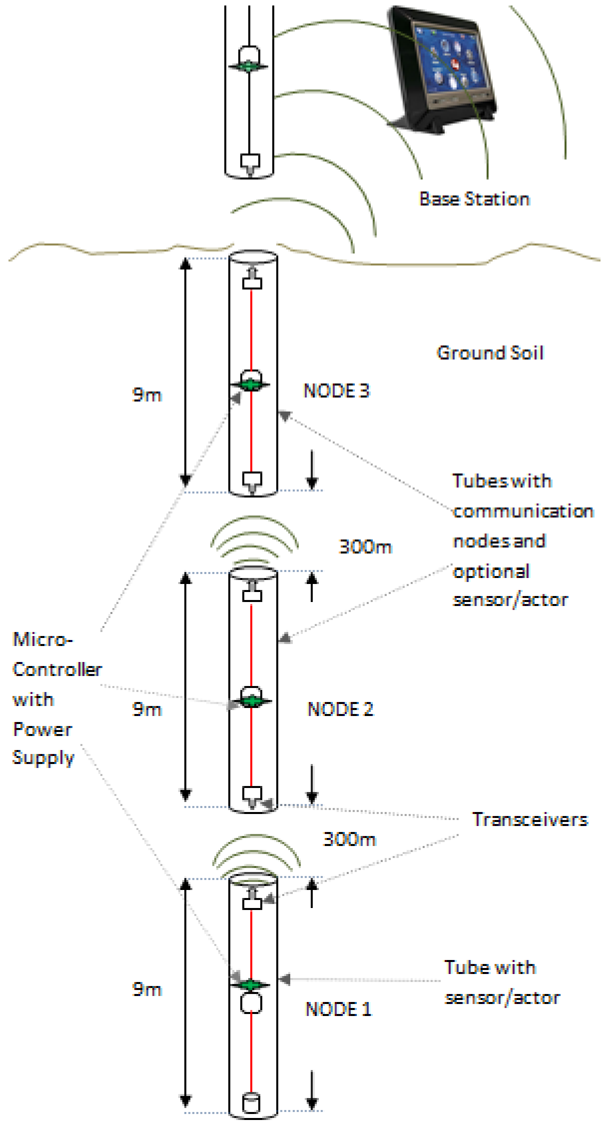

Figure 1. The schematic of the interconnecting drilling tubes with the integrated wireless ad hoc network. Each tube is a node, which consists of two transceivers, a micro-controller, and a power supply. The approximate distance between each tube is 300mm while each tube measures about 9m in length.

As observed in (1), this modified equation takes into account the path loss of the signal in the soil medium. The path loss is the reduction in power density (attenuation) of the radio signal as it propagates through a medium. Further deductions as described in [1], shows that the direct path loss considering both free space and the soil medium is given as

$$L_p = 6.4 + 20\log(d) + 20\log(\beta) + 8.69\alpha d, \quad (2)$$

$$L_p = L_0 + L_m\,. \quad (3)$$

where α and β represent the attenuation constant (1/m) and the phase shift constant (radian/m) respectively. These quantities depend on the dielectric permittivity of the medium through, which the signal passes as described also in [1]. It is represented as

$$\alpha = w\sqrt{\frac{\mu_o \epsilon_o \epsilon'}{2}\left[\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1\right]}\,, \quad (4)$$

$$\beta = w\sqrt{\frac{\mu_o \epsilon_o \epsilon'}{2}\left[\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2} + 1\right]}\,, \quad (5)$$

where ϵ' and ϵ'' represent the real and imaginary dielectric permittivity of the mixture of and water medium through, which signal transmission takes place. These quantities, according to Peplinski's principle [2], are represented as

$$\epsilon = \epsilon' + j\epsilon''$$

$$\epsilon' = 1.15\left[1 + \frac{\rho_b}{\rho_b}(\epsilon_s)^{\alpha'} + (m_v)^{\beta'}(\epsilon'_{fw})^{\alpha'} - (m_v)\right]^{\frac{1}{\alpha'}} - 0.68\,, \quad (6)$$

$$\epsilon'' = \left[(m_v)^{\beta''}(\epsilon''_{fw})^{\alpha'}\right]^{\frac{1}{\alpha'}}. \quad (7)$$

where α' represents an empirically determined constant, β' and β'' are also empirically determined constants depending on soil types given as

$$\alpha' = 0.65,$$

$$\beta' = 1.2748 - 0.519S - 0.152C\,, \quad (8)$$

$$\beta'' = 1.33797 - 0.603S - 0.166C\,. \quad (9)$$

where ϵ'_{fw} and ϵ''_{fw} represents the relative real and imaginary dielectric constant of water respectively, which are also given as

$$\epsilon'_{fw} = \epsilon_{w\infty} + \frac{\epsilon_{wo} - \epsilon_{w\infty}}{1+(2\pi f\tau_w)^2}, \quad (10)$$

$$\epsilon''_{fw} = \frac{2\pi f\tau_w(\epsilon_{wo} - \epsilon_{w\infty})}{1+(2\pi f\tau_w)^2} + \frac{\sigma_{eff}(\rho_s - \rho_b)}{2\pi\epsilon_o f\rho_s m_v}, \quad (11)$$

$$\sigma_{eff} = 0.0467 + 0.2204\rho_b - 0.4111S + 0.6614C\,. \quad (12)$$

where S: mass fraction of sand, C: mass fraction of clay, μ_o: magnetic permeability of free space, ϵ_o: permittivity of free space, m_v: volumetric water content of the soil, ϵ'_{fw} and ϵ''_{fw}

the real and imaginary parts of the relative dielectric constant of water, ϵ_{wo}: static dielectric constant of water, $\epsilon_{w\infty}$: high-frequency limit of ϵ'_{fw} , σ_{eff} : effective conductivity of water, f: operating frequency, τ_w: relaxation time of water, ρ_s : specific density of the solid soil particles, ρ_b : bulk density

B. Antenna Design

As the signals move through the soil medium there is a decrease in wavelength as compared to transmission through air [6]. This suggests the antenna should be designed for a higher frequency other than the given free space frequency of the transceiver modules (868MHz) or should have a wide bandwidth. From the above results the range of the resulting frequencies in the ground soil could be deduced using the following relation as again described in [1]

$$\lambda_n = \frac{2\pi}{\beta}, \quad \beta = w\sqrt{\frac{\mu_o \epsilon_o \epsilon'}{2}\left[\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2}+1\right]}, \qquad (13)$$

$$f_n = \frac{c}{\lambda}, \qquad (14)$$

where β is the phase shift constant, λ_n is the new wavelength in the ground soil, f_n represents the corresponding frequency and c is the speed of light in free space as described by (13)(14). From computational results, for a typical configuration setting, the theoretical new frequency in the ground soil is found to range from 1.7GHz to 1.9GHz. An integrated chip or ceramic antenna designed for such high frequencies is most appropriate for such underground wireless communication.

IV. FEASIBILITY OF COMMUNICATION

The model equations as described in the previous section were coded and simulated using MATLab software.

A. Matlab Simulations and Results

From the model equations, (2)-(12), in Section III, it is observed that the path loss depends on the frequency, distance between the transceiver nodes, clay soil content, sand soil content and the volumetric water content of the soil [3]. In conformance to the ITUBE project, the frequency of the radio module is fixed at 868MHz with a fixed maximum distance of approximately 300mm between any two adjoining transceiver nodes where wireless communication takes place. Using the above model equations, the range for the direct path loss as well as the power received at the receiver node (Received Signal Strength) was simulated with varying values of the parameters stated (clay content, sand content and water content) to determine the feasibility of the underground communication network in different soil conditions. These parameters are used to simulate a wide range of possible constituents of the ground soil since there is no much control over such ground soil characteristics on the field where the drilling takes place. The best case scenario with a Volumetric Water Content (VWC) of 1% is observed and compared to a worse situation of a VWC of 80%. VWC here is defined as the ratio of water contained in the soil to the total volume of the soil. The effect of the different proportions of clay to sand content in the soil on the path loss and consequently the Received Signal Strength Indicator (RSSI) is observed. RSSI is the measurement of the power present in the received radio signal.

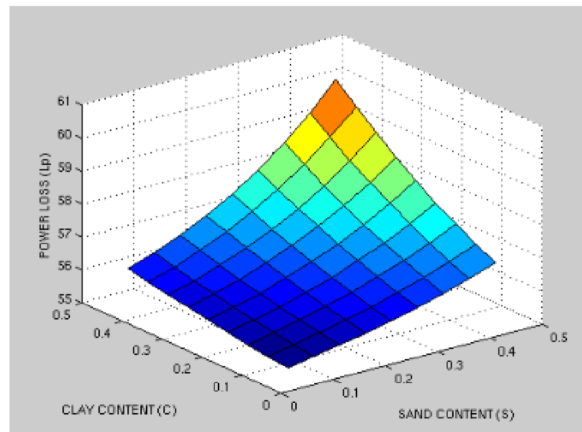

Figure 2. Path loss graph with volumetric water content (VWC) at 1% volume

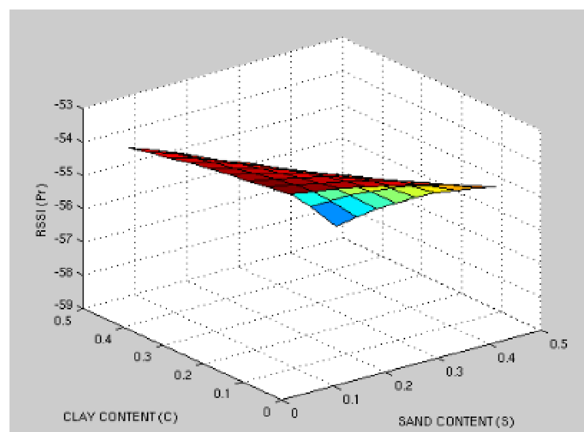

Figure 3. Received signal strength indicator graph with volumetric water content (VWC) at 1% volume

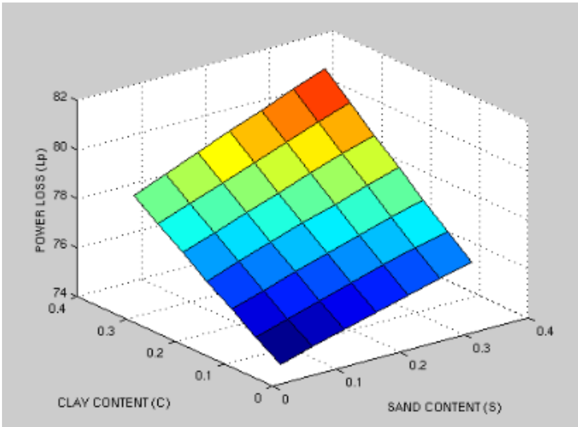

Figure 4. Power loss graph with volumetric water content (VWC) at 25% volume

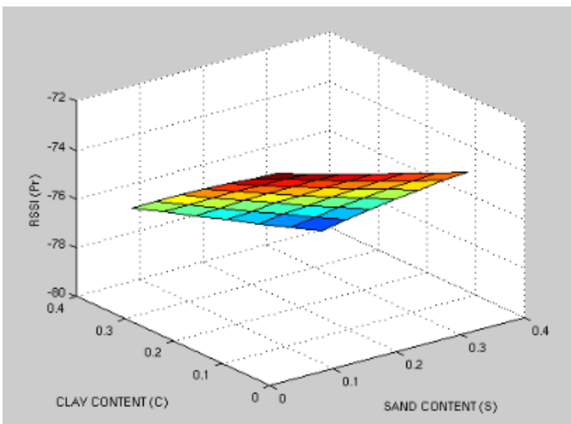

Figure 5. Received signal strength indicator graph with volumetric water content (VWC) at 25% volume

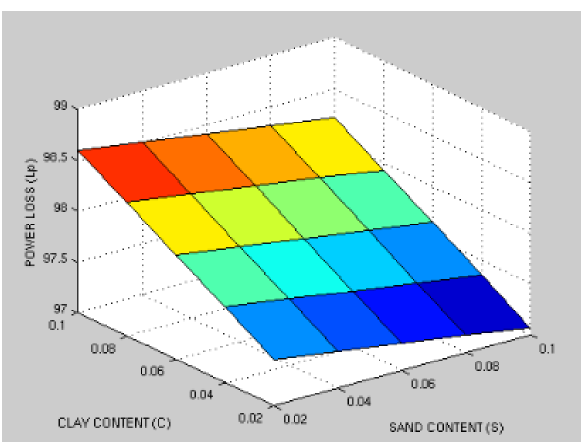

Figure 6. Power loss graph with volumetric water content (VWC) at 80% volume

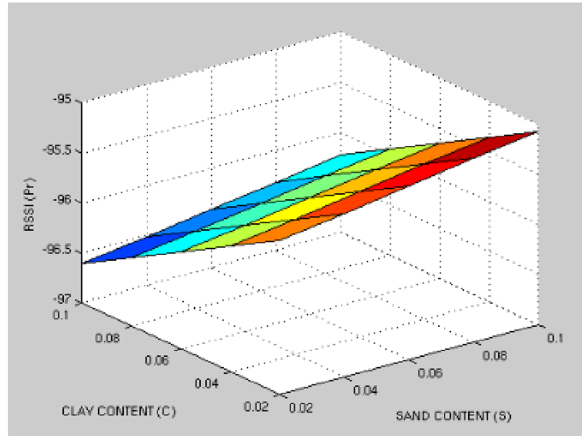

Figure 7. Received signal strength indicator graph with volumetric water content (VWC) at 80% volume

From the datasheet of the wireless transceiver module, AMB8420 [5], the minimum sensitivity of the receiver is -102dBm (-110dBm at 50Ω) and the output power of the transmitter is typically 2dBm (10dBm at 50Ω). From the results, as indicated in Figures 3, 5 and 7 above, the RSSI value in all cases falls within the RF sensitivity limit, thus indicating feasibility of the application given such conditions as described by the graphs. From the graphs, it can also be seen that the RSSI value at the receiver tends to decrease with increase in sand and clay content of the soil. This is more significant with the increase in the VWC of the soil. In Figure 2, the VWC is at 1%. This value is increased to 25%, as shown in Figure 4, and finally, to 80%, also as shown in Figure 6. With this trend, a steep increase in the path loss is observed. Consequently, the RSSI value is observed to fall from about -54.5dBm with 1% VWC to about -95.1dBm with 80% VWC, as shown in Figures 3 and 7, which does not exceed the threshold of -103dbm (the minimum receiver sensitivity). This observation establishes the feasibility of a reliable communication within the underground soil at the given fixed distance of 300mm and frequency of 868MHz.

V. CONCLUSION AND FUTURE WORK

From the analysis in the previous section, it is observed that for a frequency of 868MHz and a proximity gap of 300mm between transceiver modules, reliable communication underground is highly feasible under a wide range of possible soil conditions. However, on the work field, certain properties of the ground soil such as the chemical or salt content also have a significant effect on the dielectric characteristics of the soil [4]. Salty ground soil conditions tend to increase the path losses; therefore, decreasing the power at the receiver node (RSSI value) to a great extent [4]. Future work will include the possibility of transmission power control depending on the prevailing conditions of the soil as well as using cognitive radio techniques to enable automatic switching of transmission frequency to accommodate conditions in the ground soil.

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REFERENCES

[1] L. Li, M. C. Vuran, and I. F. Akyildiz, "Characteristics of Underground Channel for Wireless Underground Sensor Networks," Med-Hoc-Net '07, Corfu, Greece, pp. 92-99, June 13-15.

[2] N. R. Peplinski, F. T. Ulaby, and M. C. Dobson, "Dielectric Properties of Soils in the 0.3-1.3-GHz Range", IEEE Transactions on Geoscience and Remote Sensing, Vol. 33, No. 3, pp. 803-807, May 1995

[3] I. F. Akyildiz, Z. Sun, and M. C. Vuran, "Signal propagation techniques for wireless underground communication networks," Elsevier Journal, Physical Communication, pp. 167-183, 2009.

[4] R. J. Edwards, "RF Skin Depth in the Ground vs. Frequency for Given Soil Characteristics," Ground Systems, Tigertek Inc, 2010, http://www.smeter.net/grounds/rf-skin-depth-in-soil.php [Last Accessed: 18 July 2011].

[5] "AMB8420 Compact Low-Cost Radio Module 868MHz ISM Band," datasheet, Amber Wireless, 2009.

[6] A. R. Silva and Mehmet C. Vuran, "Communication with Aboveground Devices in Wireless Underground Sensor Networks: An Empirical Study," IEEE Communications Society, IEEE ICC, pp. 1-6, 2010.

[7] S. Kazemian and B. K. Haut, "Assessment of Stabilization Methods for Soft Soils by Admixtures," International Conference on Science and Social Research, Kuala Lumpur, Malaysia, pp. 118-121, 2010.

[8] R. D. Andrus and R M. Chung, "Ground Improvement Techniques for Liquefaction Remediation Near Existing Lifelines," U.S. Department of Commerce, National Institute of Standards and Technology, pp. 1-85, Ocotober 2005.

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