A Path Loss Model for Through the Soil Wireless Communications in Digital Agriculture

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***Abstract*—In this paper, a path loss model is developed to predict the impact of soil type, soil moisture, operation frequency, distance, and burial depth of sensors for through-the-soil wireless communications channel. The soil specific model is developed based on empirical measurements [1] in a testbed and field settings. The model can be used in different soils for a frequency range of $100MHz$ to $1GHz$. The standard deviation between measured and predicted path loss is from 4-$6dB$ in the silt loam, sandy, and silty clay loam soil types. The model leads to development of sensor-guided irrigation system in the field of digital agriculture [2].**

I. INTRODUCTION

Digital agriculture [2], [3], [4] is the an emerging field in which technology is used to effectively manage agriculture by understanding the temporal and spatial changes in soil, crop, production, and management through innovative techniques. In literature, the Hata-Okumura models are widely used for prediction and simulation of signal strength in cellular environments. Such empirical models don't exist in digital agriculture to predict path loss in through-the-soil wireless communications channel. The wireless communications in wireless underground channel is impacted by different factors [1] (e.g., soil type, soil moisture, operation frequency, transmitter-receiver distances, and burial depths). The prediction of path loss in through-the-soil communications is vital for digital agriculture sensing and communication system design. In this paper, a path loss model is developed to predict the impact of soil type, soil moisture, operation frequency, distance, and burial depth of sensors.

II. THE MODEL

The standard formula for the model is given as [1]:-

$$\begin{aligned} P_r(f,\delta,\phi,\rho,\nu) = \\ -58.8 - 20 \times log10(r1) - 20 \times log10(r2) - 20 \times log10(\delta) \\ +((\nu \times -10) + \gamma) \times 3 - \xi \times r1 - \xi \times r2 - \xi \times (\phi + \rho) \\ +F + K \end{aligned} \quad (1)$$

where f is the operation frequency, δ is distance between transmitter and receiver, ϕ and ρ are transmitter and receiver depths, respectively, ν is volumetric water content in percentage unit, $r1 = \sqrt{(\phi - \rho)^2 + \delta^2)}$, $r2 = \sqrt{(\phi + \rho)^2 + \delta^2}$, K is soil dependent constant, and F is frequency dependent constant. The γ and ξ, soil moisture and soil attenuation factor, respectively, are given in (3) and (5):

TABLE I
SOIL DEPENDANT CONSTANT.

Param	Silty Clay Loam	Sandy	Silt Loam
K	1	21	6

TABLE II
NUMERICAL VALUES OF FREQUENCY DEPENDANT CONSTANT FOR SILTY CLAY LOAM SOIL.

Frequency	$\delta < 1$ m	$\delta >= 1$ m
f <300 MHz	5	15
f >300 MHz f <600 MHz	-10	5
f >600 MHz	-25	1

$$\gamma = p1 * f^3 + p2 * f^2 + p3 * f + p4 \quad (2)$$

$$\begin{aligned} \text{where } p1 &= -1.6748e^{-26}, \\ p2 &= 3.8512e^{-17}, \\ p3 &= -3.6971e^{-08}, \\ p4 &= -4.9007, \end{aligned} \quad (3)$$

$$\xi = ((\nu * 10) * (p1 * f) + p2 + \nu) * 8.7 + (\nu * 20) \quad (4)$$

$$\begin{aligned} \text{where } p1 &= 4.1355e^{-10} \\ p2 &= 2.1161 \end{aligned} \quad (5)$$

and the path loss PL is given as:

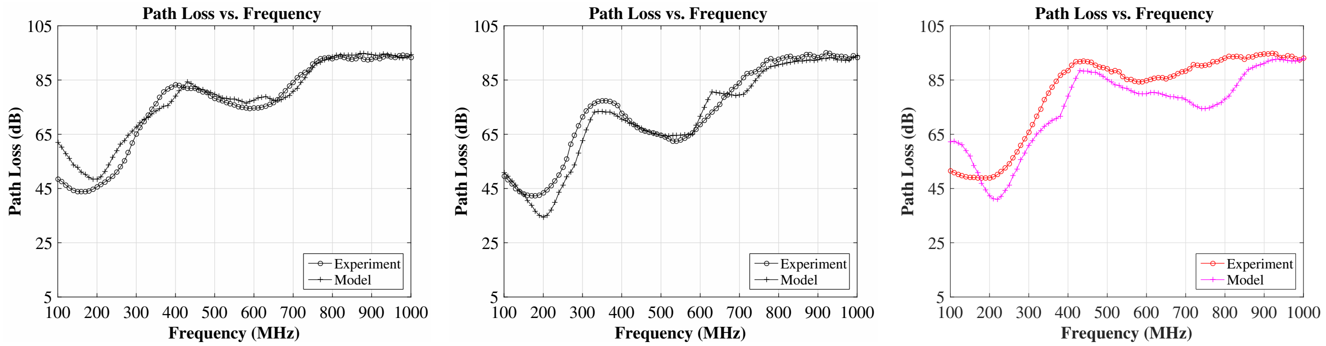
$$PL(f,\delta,\phi,\rho,\nu) = P_t + G_t + G_r - P_r(f,\delta,\phi,\rho,\nu) \quad (6)$$

where P_t is transmitted power, G_t is transmitter antenna gain, and G_r is receiver antenna gain. The values of soil dependent constants are given in Table I.

The frequency dependent constants for silty clay loam, sandy, and silt loam soil types are given in Table II, Table III, and Table IV, respectively.

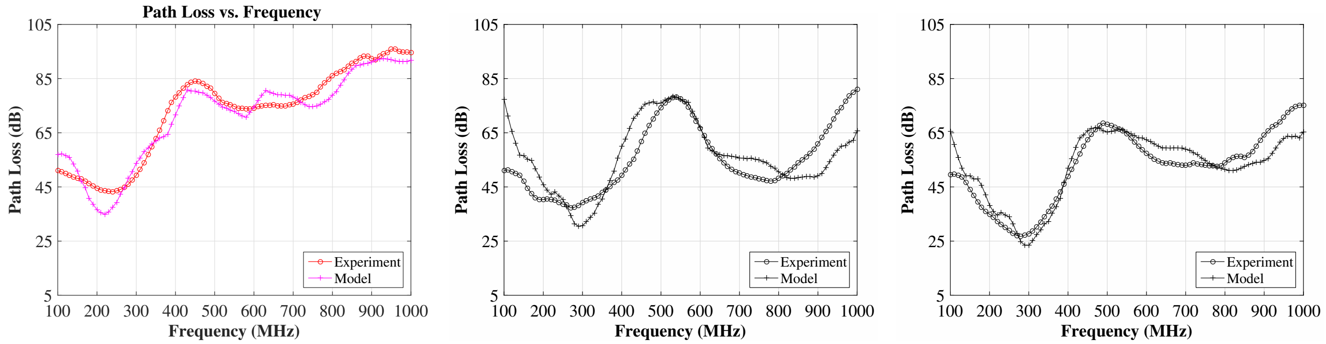
TABLE III
NUMERICAL VALUES OF FREQUENCY DEPENDANT CONSTANT FOR SANDY SOIL.

Frequency	$\delta < 1$ m	$\delta >= 1$ m
f <400 MHz	1	15
f >400 MHz f <600 MHz	-15	15
f >600 MHz	-15	1



(a) (b) (c)

Fig. 1. (a) The model comparison with measurement data in silty clay loam - 1m, (b) 50cm, (c) silt loam - 1m.



(a) (b) (c)

Fig. 2. (a) The model comparison with measurement data in silt loam - 50cm, (b) sandy soil - 1m, (c) sandy soil - 50cm.

TABLE IV
NUMERICAL VALUES OF FREQUENCY DEPENDANT CONSTANT FOR SILT LOAM SOIL.

Frequency	$\delta < 1$ m	$\delta >= 1$ m
f <400 MHz	1	15
f >400 MHz f <600 MHz	-15	1
f >600 MHz	-25	1

III. MODEL VALIDATION WITH EMPIRICAL DATA

The model is validated with the measurements data collected during an empirical campaign in a testbed and field settings [1]. The model comparison with measurement data in silt loam, sandy, and silty clay loam soil at $50cm$ and $1m$ distances are shown in Figs. 1 and 2. It can be observed that the path loss changes with change in the soil type. The sandy soil has $19dB$ less path loss as compared to the silt loam soil. The soil types rich in clay content exhibit higher prorogation path loss because of the higher water holding capacity [5]. Overall, the developed model has an excellent match with the empirical data with maximum prediction difference of $5dB$. It can also be observed that the path loss in through-the-soil wireless communications is high. A $50cm$ increase in the communications distance leads to $21dB$ increase in the propagation path loss due to complex permittivity of the soil [6]. The short communication range is a major challenge in development of in-soil communications system for digital agriculture field operation. Therefore, advanced signal processing techniques (e.g., moisture adaptive beamforming, multi-carrier) are needed for long-range communications in soil for sensor-guided variable-rate irrigation applications [2], [7].

IV. CONCLUSIONS

Based on an extensive set of measurements, a model has been developed to model the impact of different parameters on communications in silt loam, sandy, and silty clay loam soils. The model is useful to predict the propagation path loss in digital agriculture through-the-soil wireless communications channel. For in-soil system design, the model allows path loss prediction in various soil types, under different soil moisture levels without the need of conducting extensive measurements.

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