Taking Soil to the Cloud: Advanced Wireless Underground Sensor Networks for Real-time Precision Agriculture

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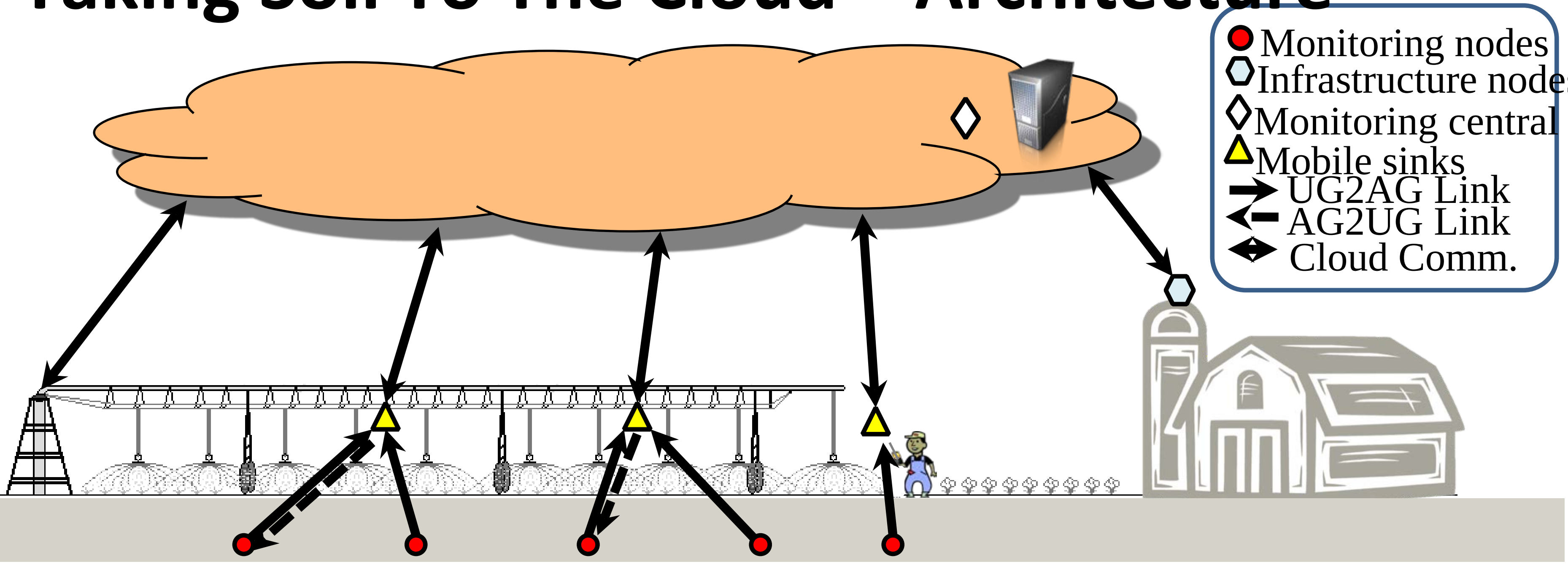
Overview

- Introduction
- Soil As Communication Medium
- Impulse Response Model of UG Channel
- Experiment Methodology
- Empirical Validations
- RMS Delay Spread and Coherence BW Statistics
- Conclusions

Introduction

[1] I.F. Ayildiz, and E.P. Stuntebeck, "Wireless Underground Sensor Networks: Research Challenges," Ad Hoc Networks Journal (Elsevier), vol. 4, no. 6, pp. 669-686, November 2006
[2] Z. Sun and I.F. Akyildiz. "Channel modeling and analysis for wireless networks in underground mines and road tunnels," IEEE Transactions on Communications, vol. 58, no. 6, pp. 1758–1768, June 2010.
[3] X. Dong, M. C. Vuran, and S. Irmak. "Autonomous Precision Agricultrue Through Integration of Wireless Underground Sensor Networks with Center Pivot Irrigation Systems". Ad Hoc Networks (Elsevier) (2012).
[4] I. F. Akyildiz, Z. Sun, and M. C. Vuran, "Signal propagation techniques for wireless underground communication networks," Physical Communication Journal (Elsevier), vol. 2, no. 3, pp. 167–183, Sept. 2009.

Taking Soil To The Cloud – Architecture

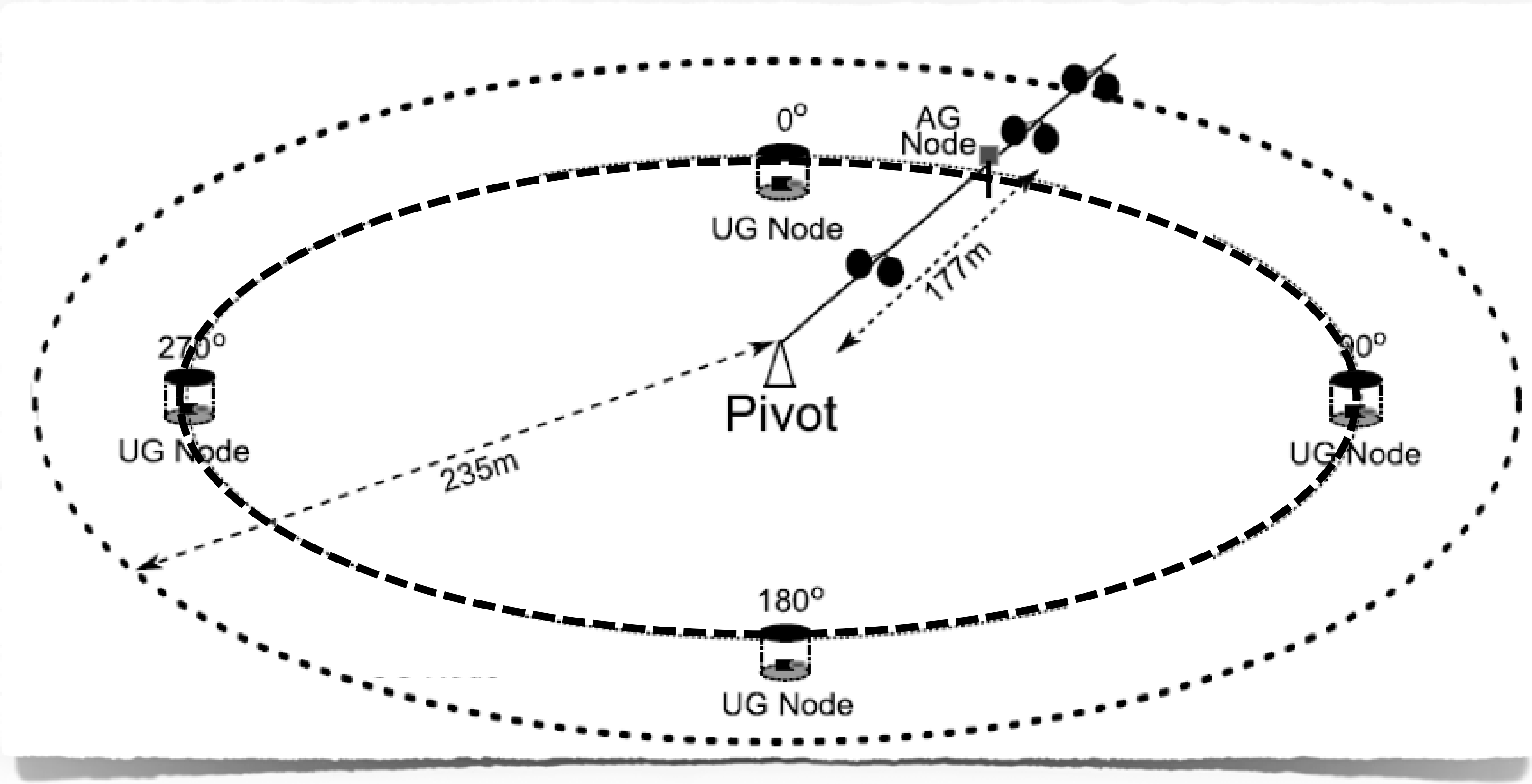


- On-board sensing capabilities (soil moisture, temperature, salinity,)
- Communication through soil
- Real-time information about soil and crop conditions
- Inter-connection of heterogeneous machinery and sensors
- Complete autonomy on the field

A. Salam and M.C. Vuran, ``Pulses in the Soil: Impulse Response Analysis of Wireless Underground Channel,'' in Proc. IEEE INFOCOM '16, San Francisco, CA, Apr. 2016

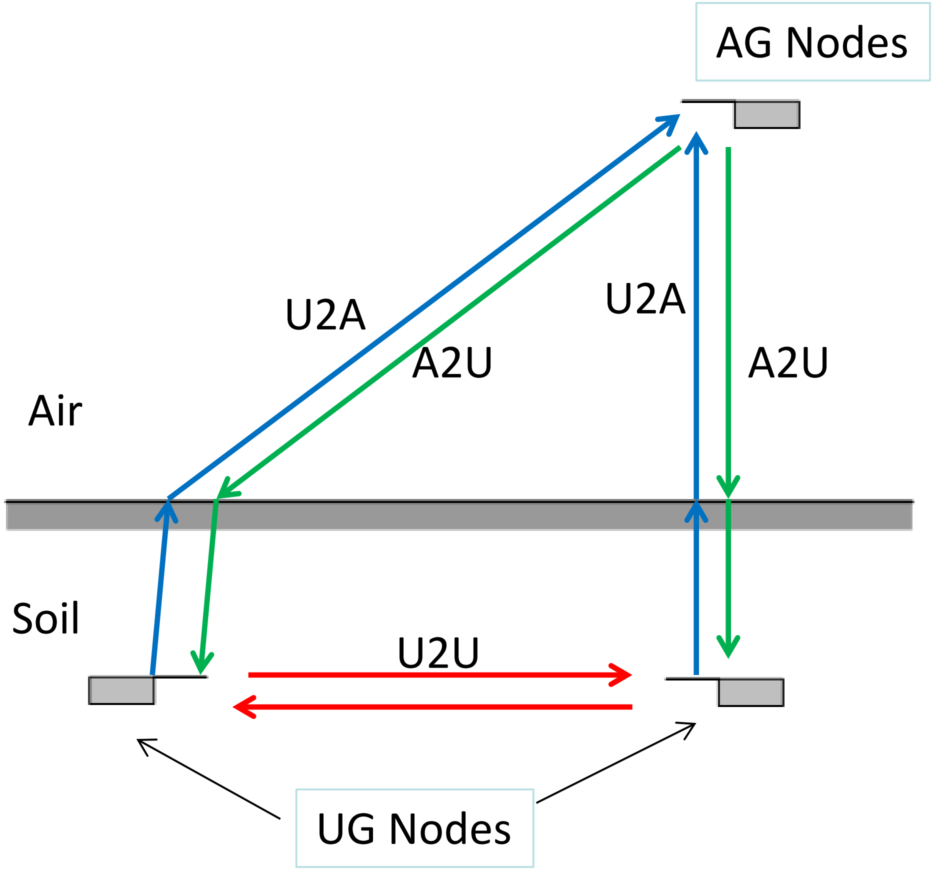
I. F. Akyildiz and E. P. Stuntebeck, "Wireless underground sensor networks: Research challenges," Ad Hoc Networks Journal (Elsevier), vol. 4, pp. 669–686, July 2006.

Center Pivot Integration



J. Tooker, X. Dong, M. C. Vuran, and S. Irmak, "Connecting Soil to the Cloud: A Wireless Underground Sensor Network Testbed," demo presentation in IEEE SECON '12, Seoul, Korea, June, 2012.

Wireless Underground Channel



[3] X. Dong and M. C. Vuran, "A Channel Model for Wireless Underground Sensor Networks Using Lateral Waves," in Proc. IEEE Globecom '11, Houston, TX, Dec. 2011.
[4] X. Dong, M. C. Vuran, and S. Irmak, "Autonomous Precision Agriculture Through Integration of Wireless Underground Sensor Networks with Center Pivot Irrigation Systems," accepted for publication in Ad Hoc Networks (Elsevier), 2013.

Underground Channel Modeling

- WUSN models based on the analysis of the EM field and Friis equations [5][6][7]
- Magnetic Induction (MI) based WUSNs [8][9]
- Lack of insight into channel statistics (RMS delay, coherence BW)
- No existing model captures effects of soil type and moisture on UG channel impulse response
- Important to design tailored UG communication solutions

[5] M. C. Vuran and Ian F. Akyildiz. “Channel model and analysis for wireless underground sensor networks in soil medium”. In: Physical Communication 3.4 (Dec. 2010), pp. 245–254.

[6] X. Dong and M. C. Vuran. “A Channel Model for Wireless Underground Sensor Networks Using Lateral Waves”. In: Proc. of IEEE Globecom ’11. Houston, TX, Dec. 2011.

[7] H. R. Bogena and et.al. “Potential of wireless sensor networks for measuring soil water content variability”. In: Vadose Zone Journal 9.4 (Nov. 2010), pp. 1002–1013.

[8] Z. Sun and I.F. Akyildiz. “Connectivity in Wireless Underground Sensor Networks”. In: Proc. of IEEE Communications Society Conference on Sensor Mesh and Ad Hoc Communications and Networks (SECON ’10). Boston, MA, 2010.

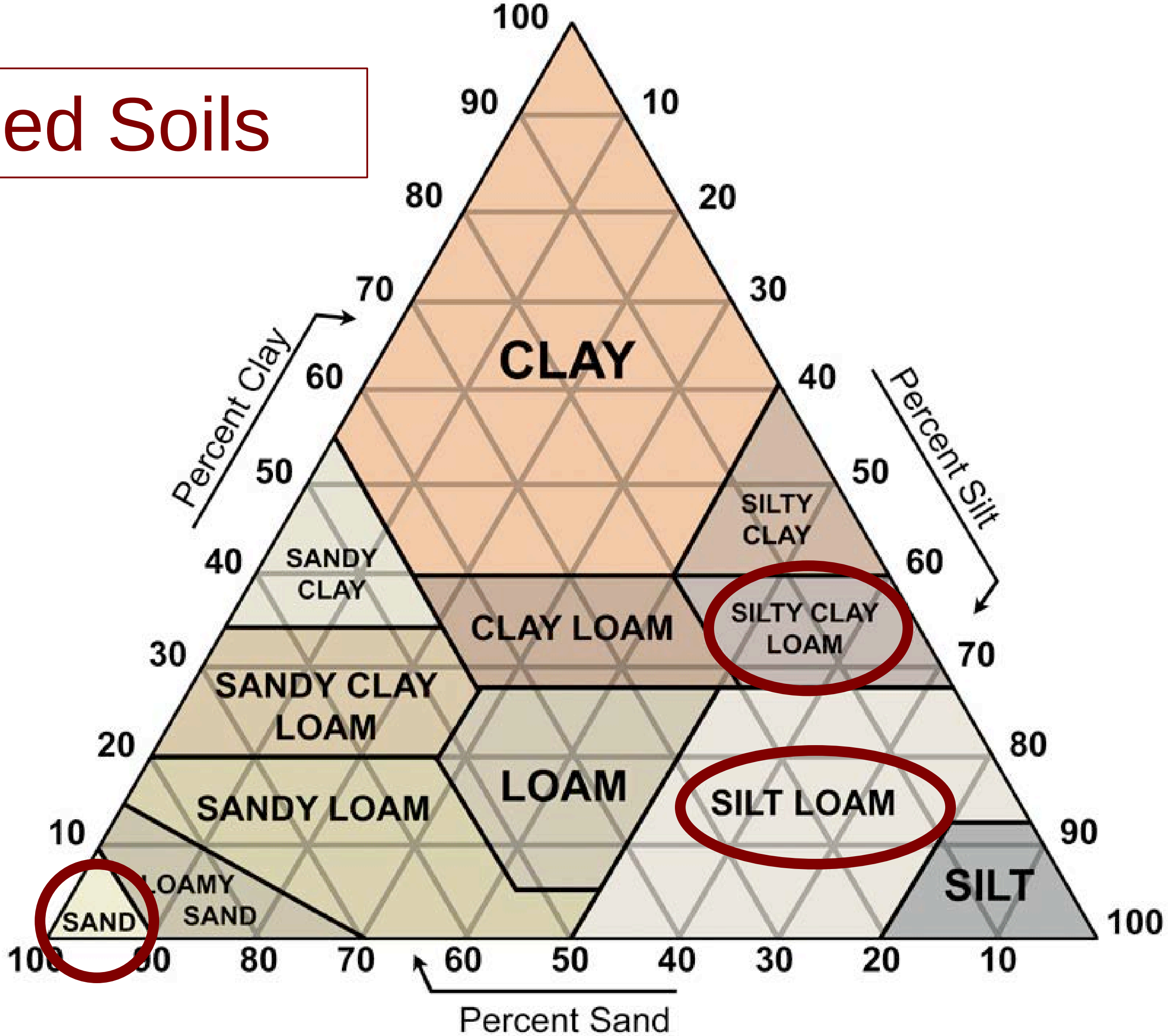
[9] A. Markham and Niki Trigoni. “Magneto-inductive Networked Rescue System (MINERS): Taking Sensor Networks Underground”. In: Proc. 11th ICPS. IPSN ’12. Beijing, China: ACM, 2012,

Soil As UG Communication Medium

- Soil Texture and Bulk Density
- Soil Moisture Variations
- Distance and Depth
- Frequency

Soil Texture and Bulk Density

Testbed Soils

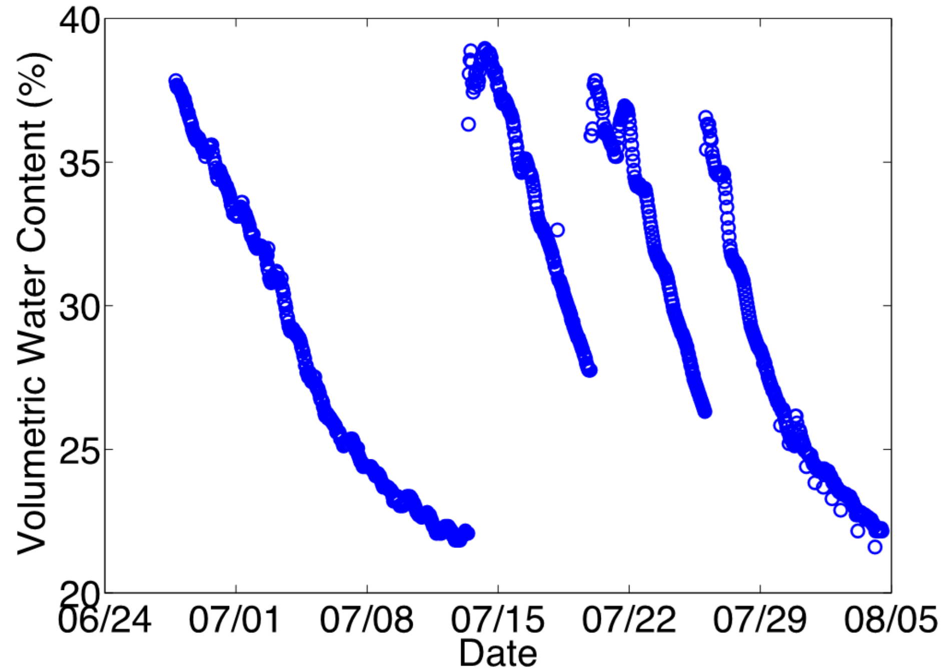


Soil Moisture Variations

- Complex permittivity of soil

$$\epsilon_s = \epsilon'_s - i\epsilon''_s$$

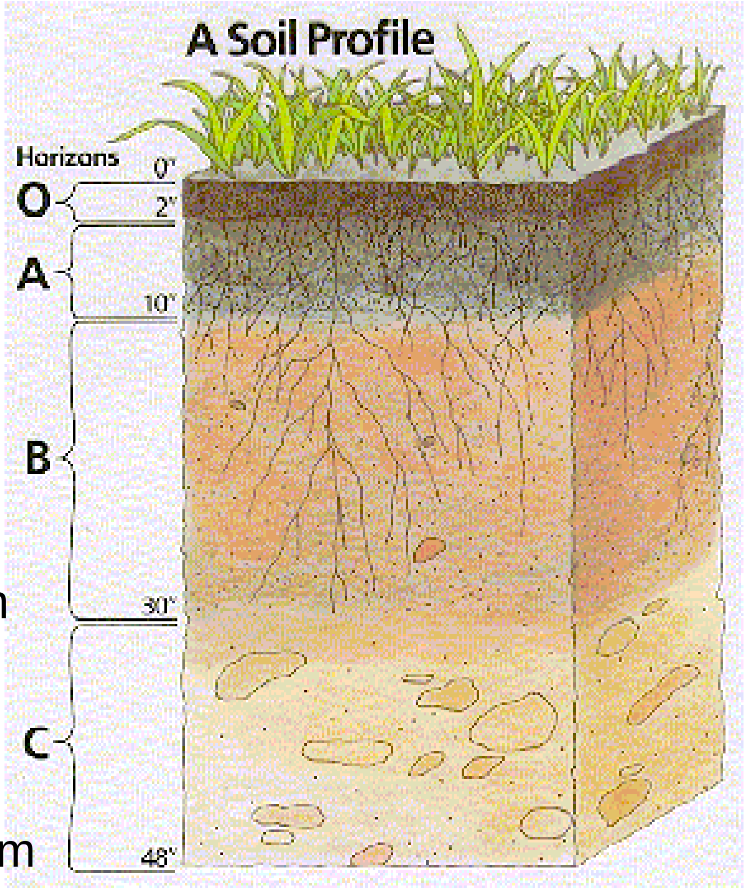
  - Diffusion attenuation
  - Water absorptior attenuation



- Permittivity variations over time and space

Distance and Depth

Sensors in WUSN applications are buried in Topsoil layer [10]



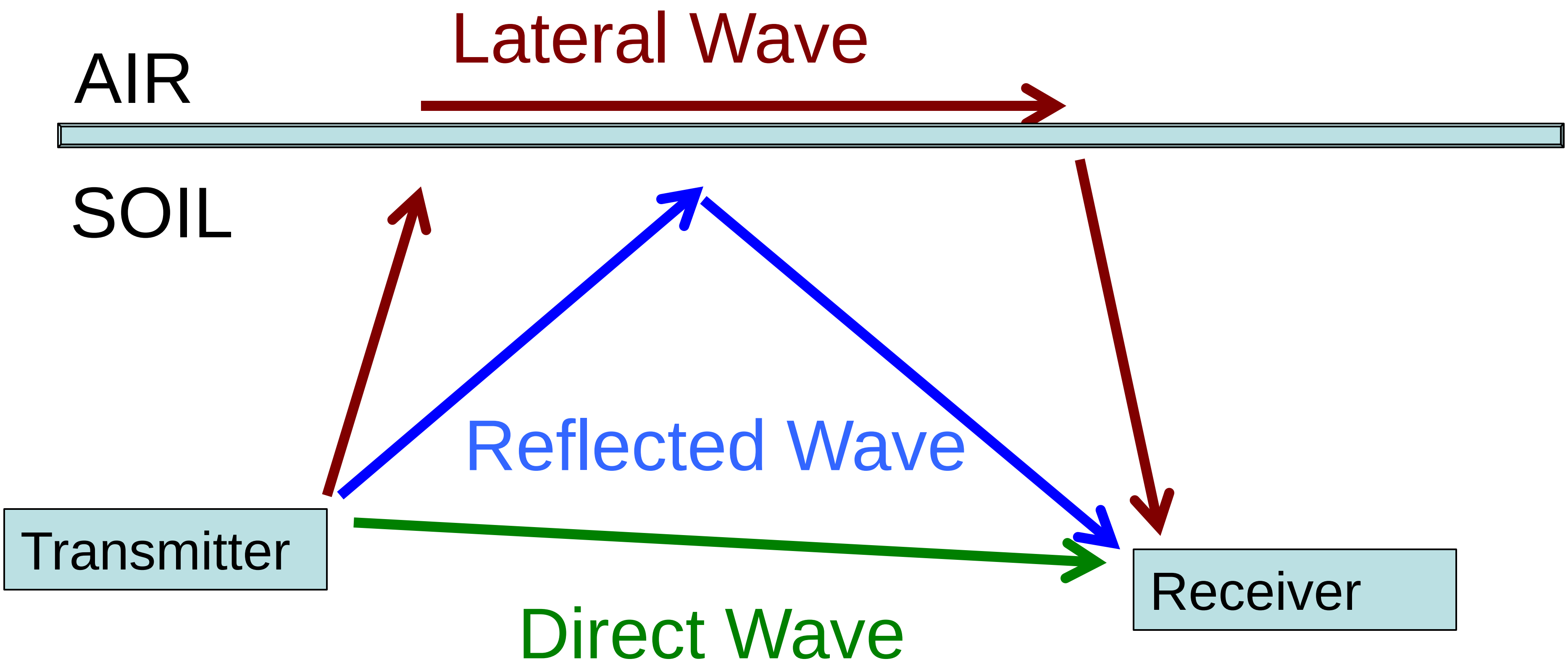
[10] A. R. Silva and M. C. Vuran. “Development of a Testbed for Wireless Underground Sensor Networks”. In: EURASIP Journal on Wireless Communications and Networking 2010 (2010).

Frequency Variations

- Frequency dependent path loss [11]
- Wave number in soil
- Channel capacity

[11] X.. Dong and M. C. Vuran. “Impacts of soil moisture on cognitive radio underground networks”. In: Proc. IEEE BlackSeaCom. Batumi, Georgia, July 2013.

EM Waves in Soil



[12] X. Dong and M. C. Vuran. “A Channel Model for Wireless Underground Sensor Networks Using Lateral Waves”. In: Proc. of IEEE Globecom ’11. Houston, TX, Dec. 2011.

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Impulse Response Model of UG Channel

$$h_{ug}(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l) + \sum_{d=0}^{D-1} \alpha_d \delta(t - \tau_d) + \sum_{r=0}^{R-1} \alpha_r \delta(t - \tau_r)$$

where

- L, D, and R are number of multipaths
- α_l, α_d, and α_r are complex channel gains
- τ_l, τ_d, and τ_r are delays associated with lateral, direct, and reflected waves, respectively

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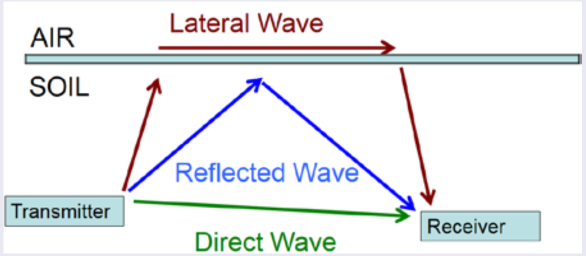
Impulse Response Model of UG Channel

Arrival time of each of the three components



$$\tau_d = (\delta_s / S) \quad (1)$$

$$\tau_r = 2 \times (\delta_s / S) \quad (2)$$

$$\tau_l = 2 \times (\delta_s / S) + (\delta_a / c) \quad (3)$$

where

- δ_s is distance travelled by wave in soil
- S is speed of wave in soil

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The Indoor Testbed

- Wooden Box
- Dimensions: 100" x36" x 48"
- 90 Cubic Feet of Soil

Drainage Pipes

Gravel

Soil Placement, Packing and Saturation

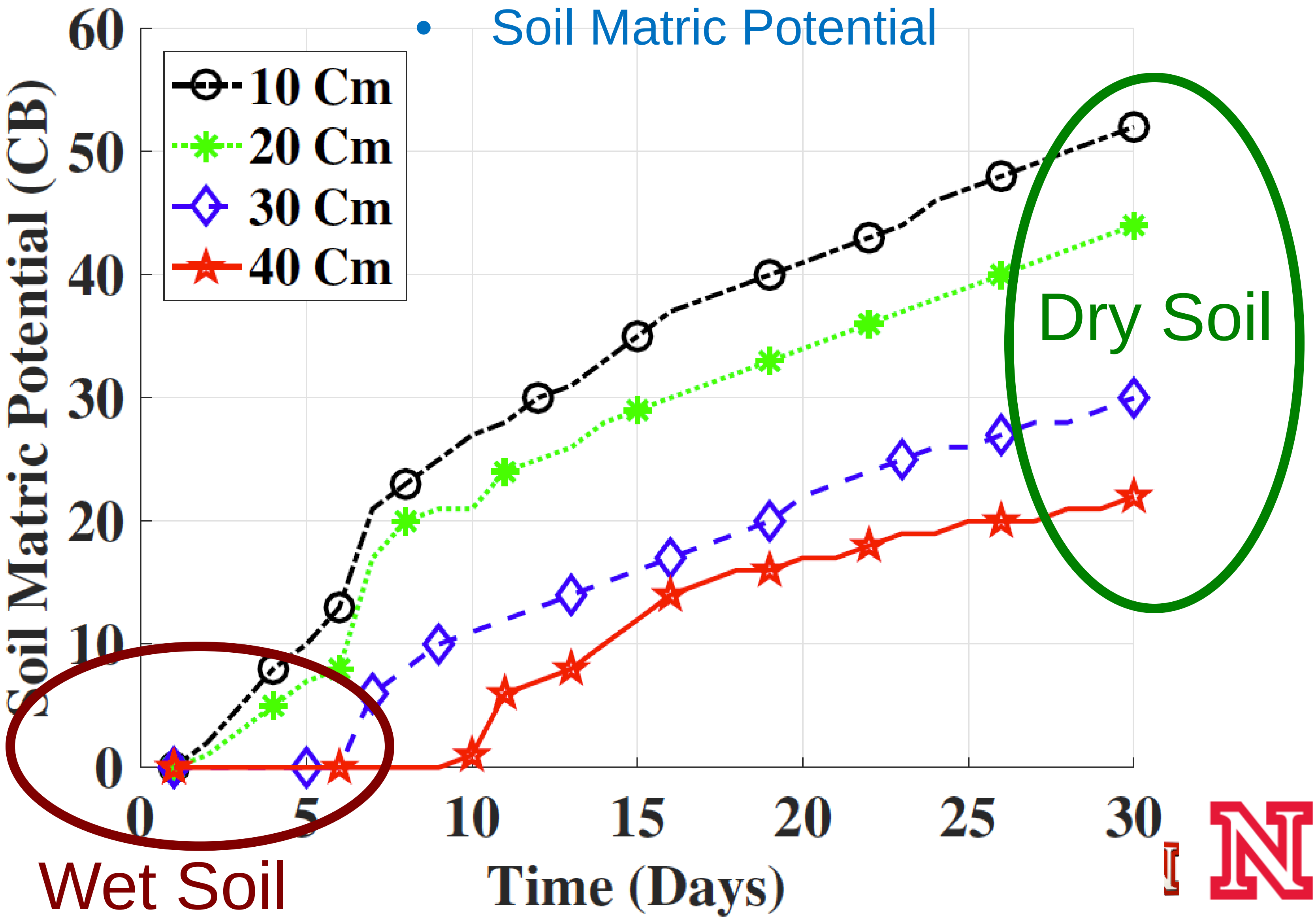
The Indoor Testbed

Antenna Placement

- Final outlook with watermark sensors and monitor
- Overhead drying lights

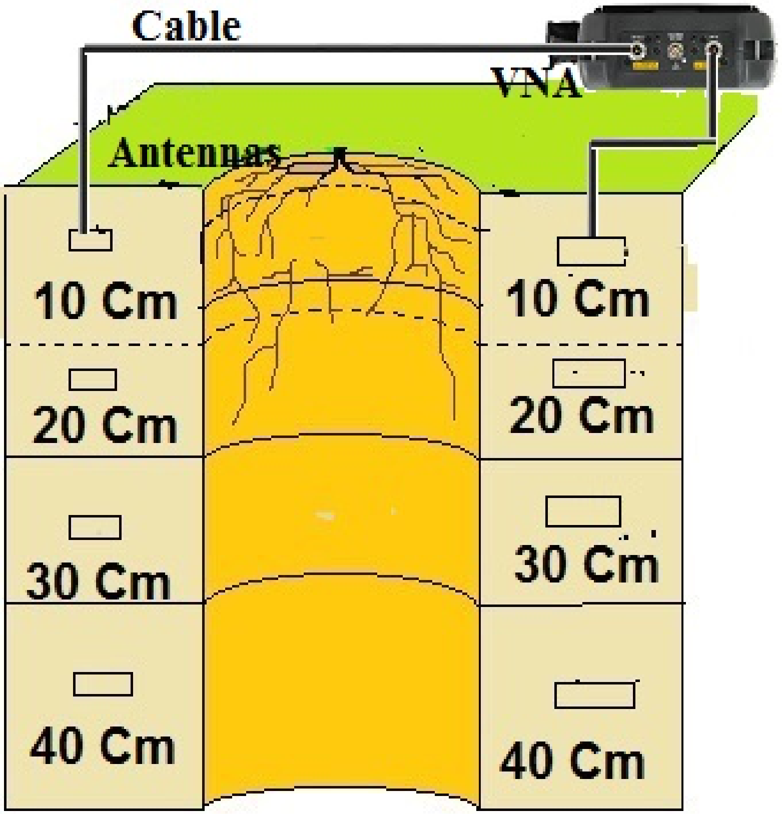
Soil Moisture in Indoor Testbed (Silt Loam)

- Matric forces (adsorption and capillarity)
- Soil Matric Potential



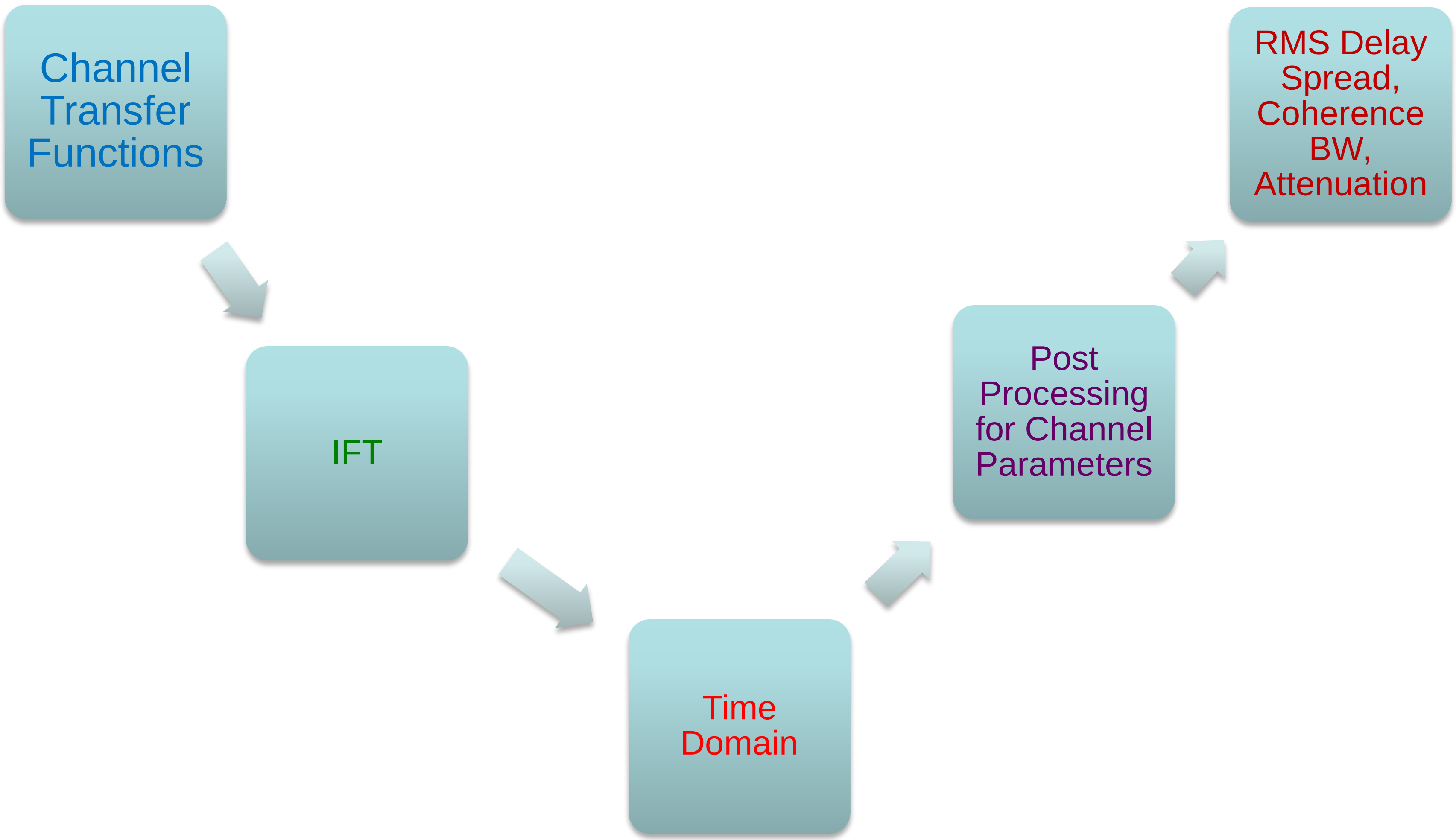
Antenna Layout

Indoor Testbed



Outdoor Testbed

VNA (Vector Network Analyser) Measurements



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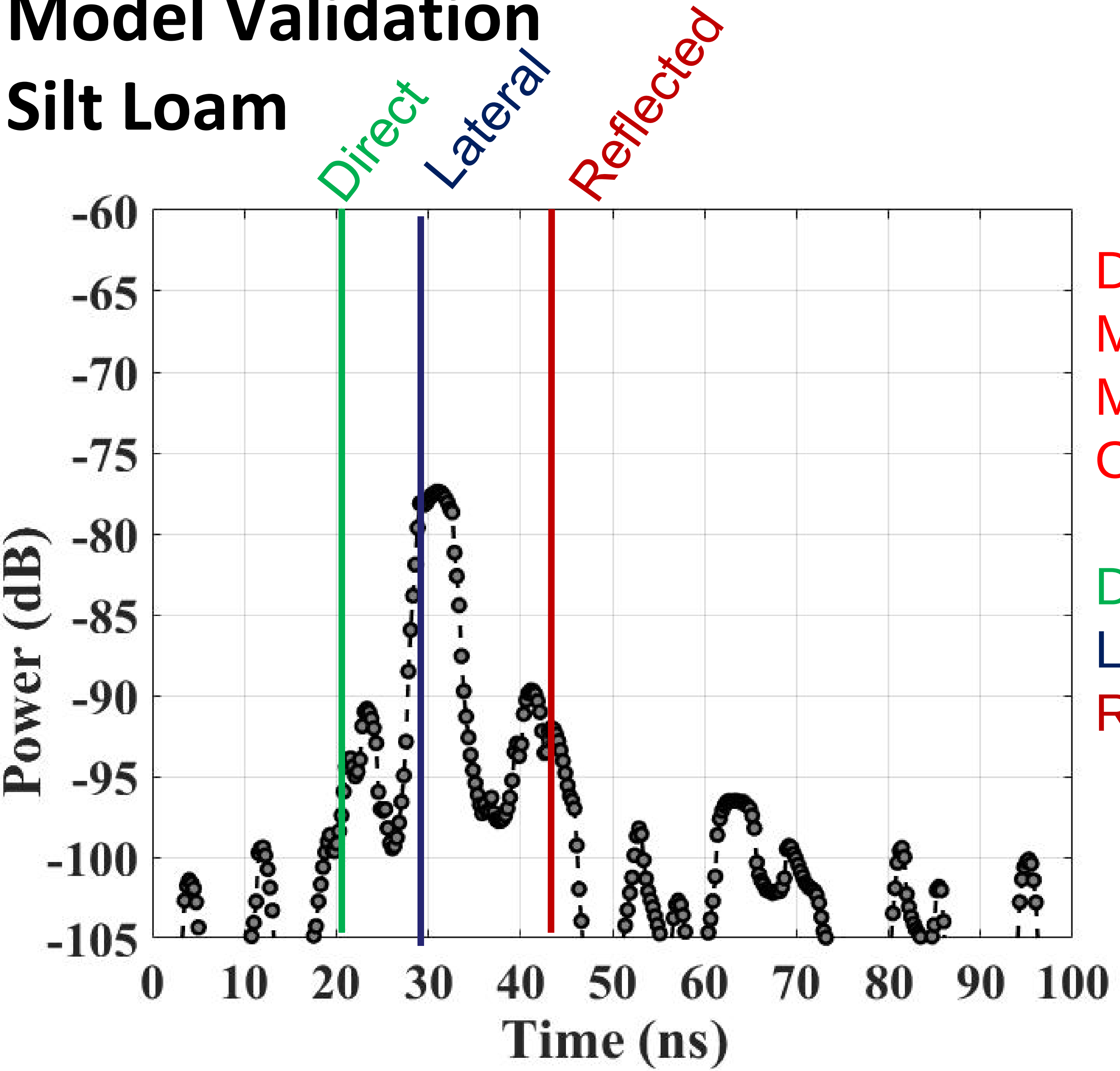
Model Validation

Silt Loam



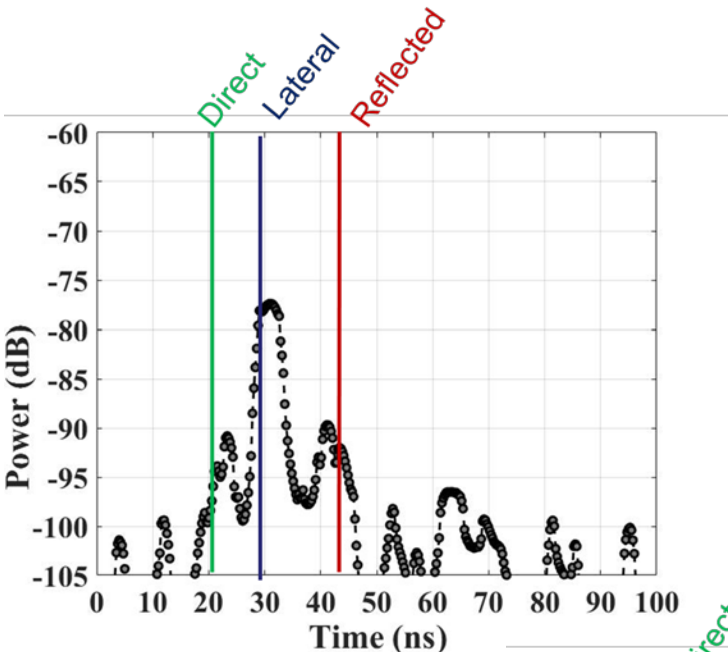
Difference of Measured and Modeled Components

DW: 10.2%

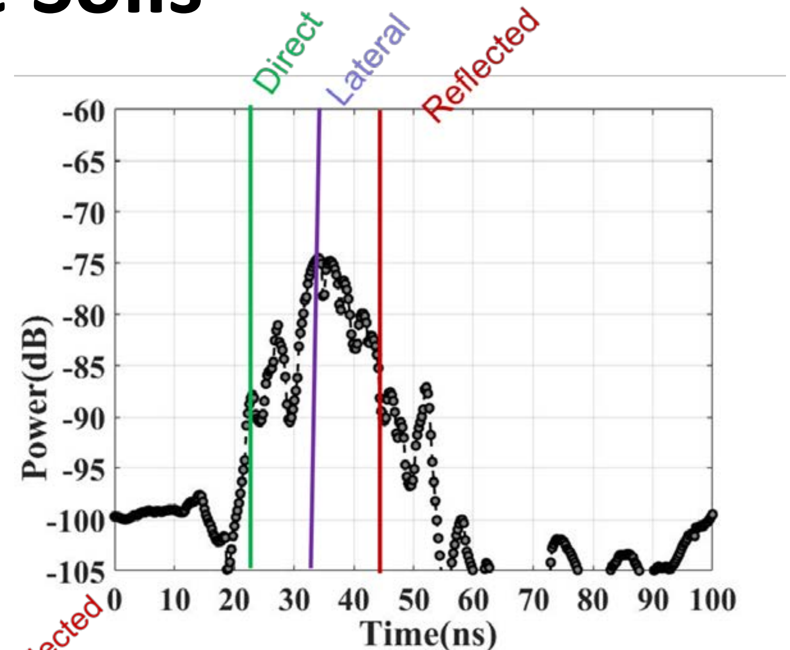
LW: 7.3%

RW: 7.5%

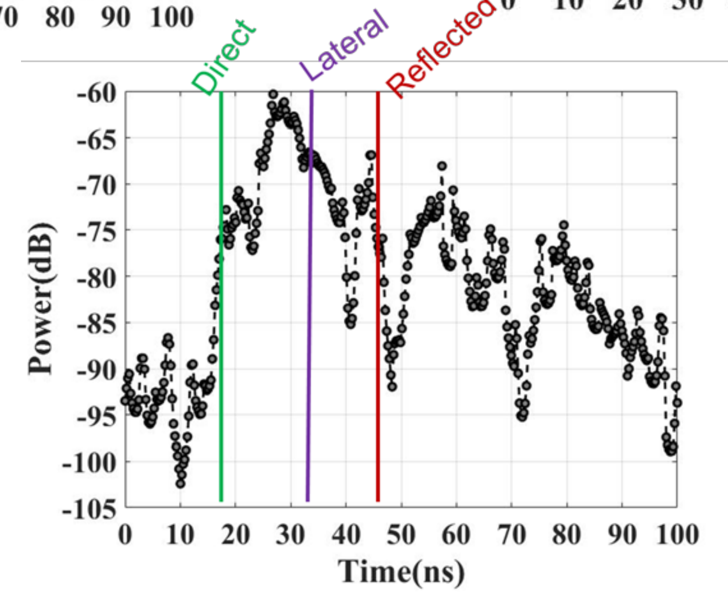
Model Validation – Three Soils



Silt Loam



Silty Clay Lom



Sandy Soil

Sandy soil has low attenuation

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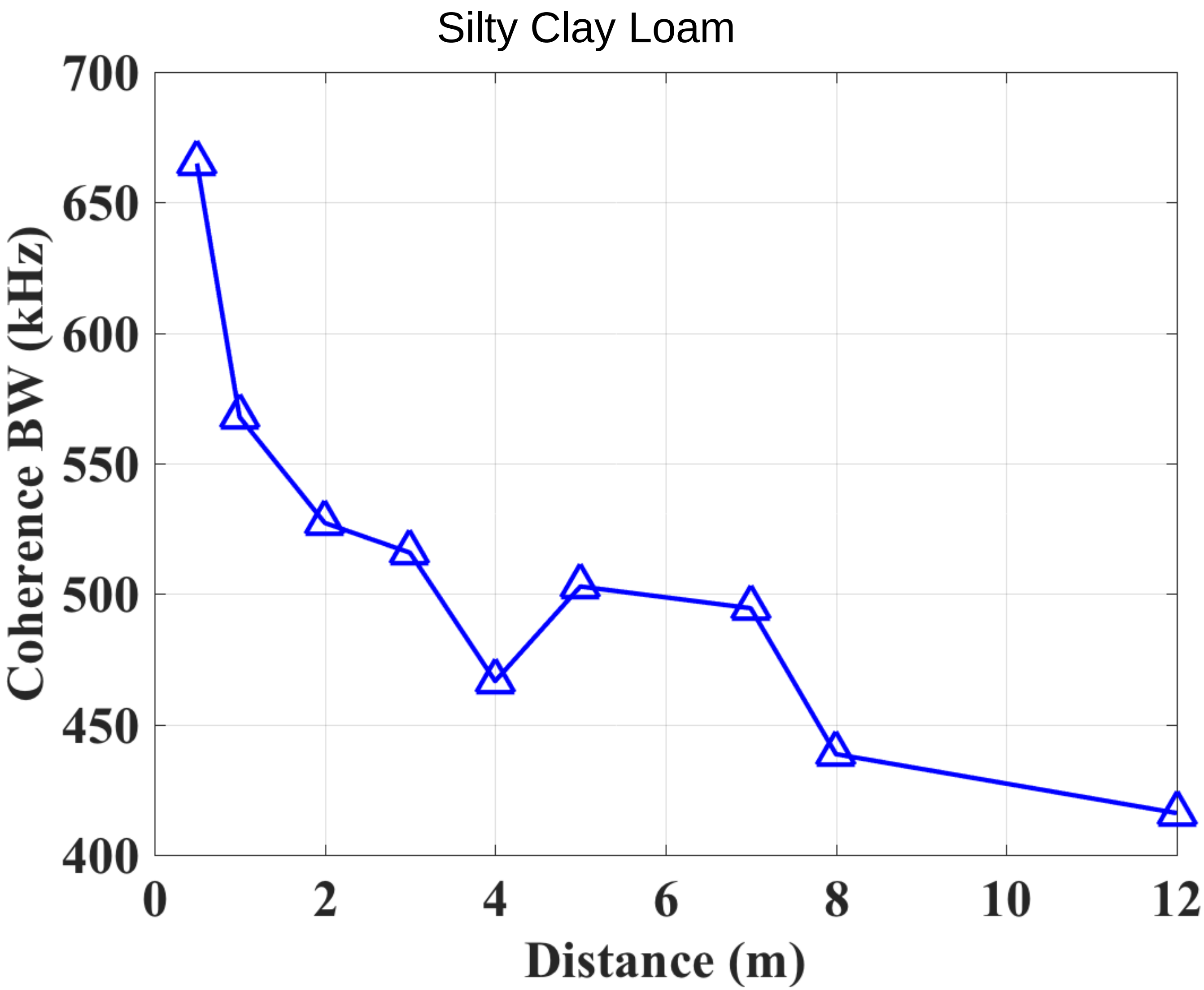
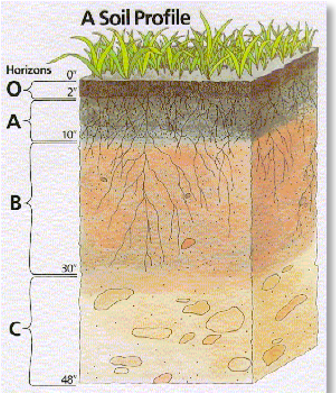
Coherence BW of the UG Channel

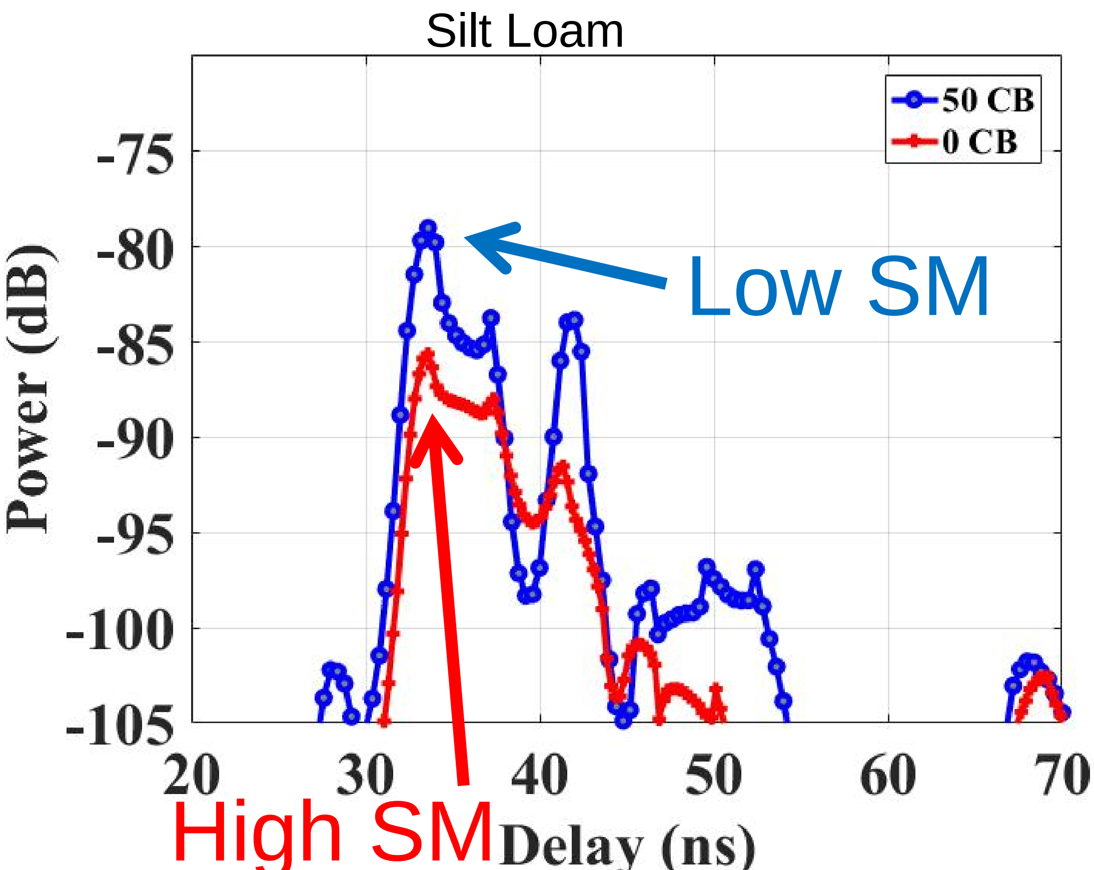
418 kHz as communication distance increases to 12m



Impact of Soil Moisture Variations

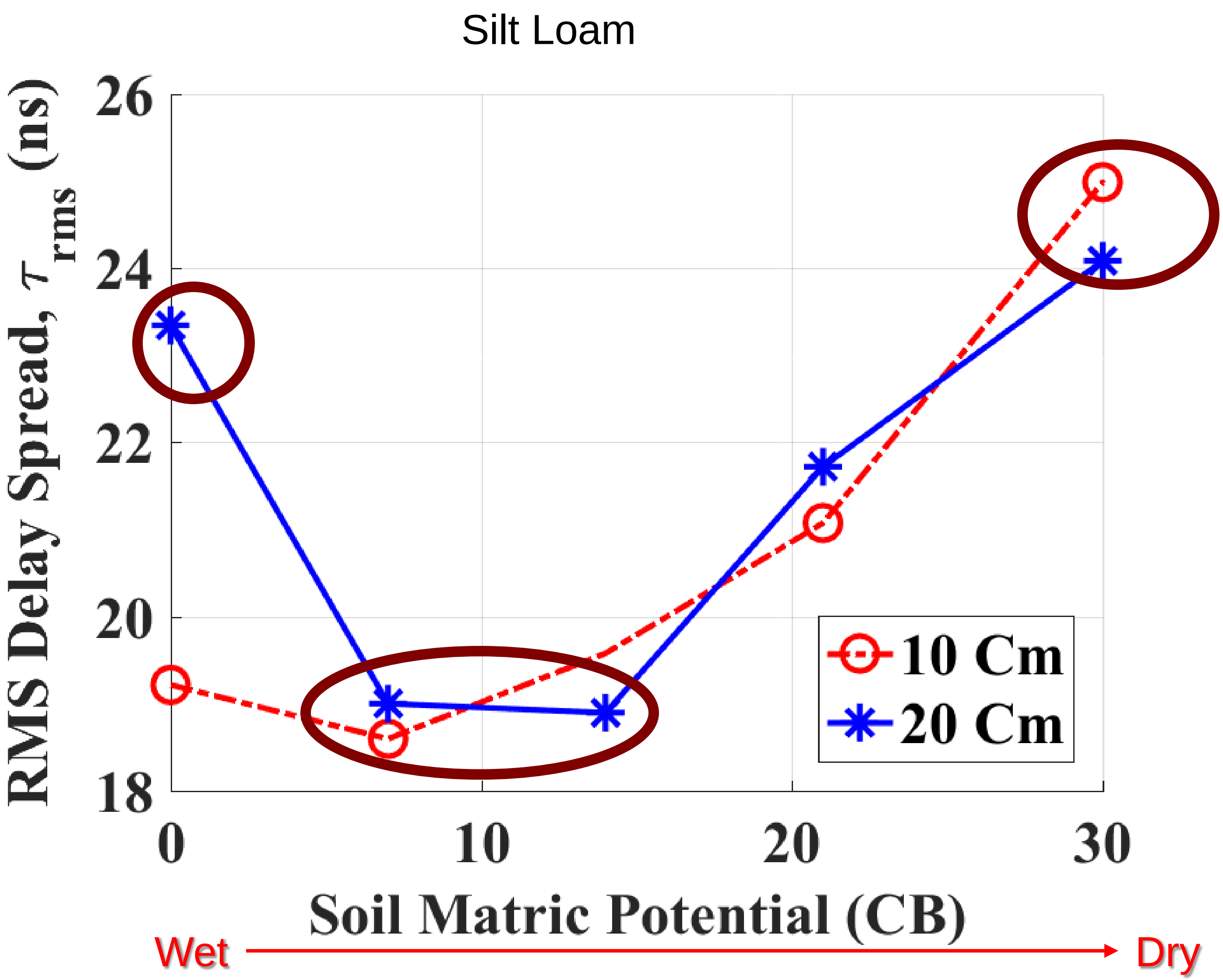


- Bound water and Free water
- Water contained in the first few particle layers of the soil
- Strongly held by soil particles
- Reduced effects of osmotic and matric forces [14]

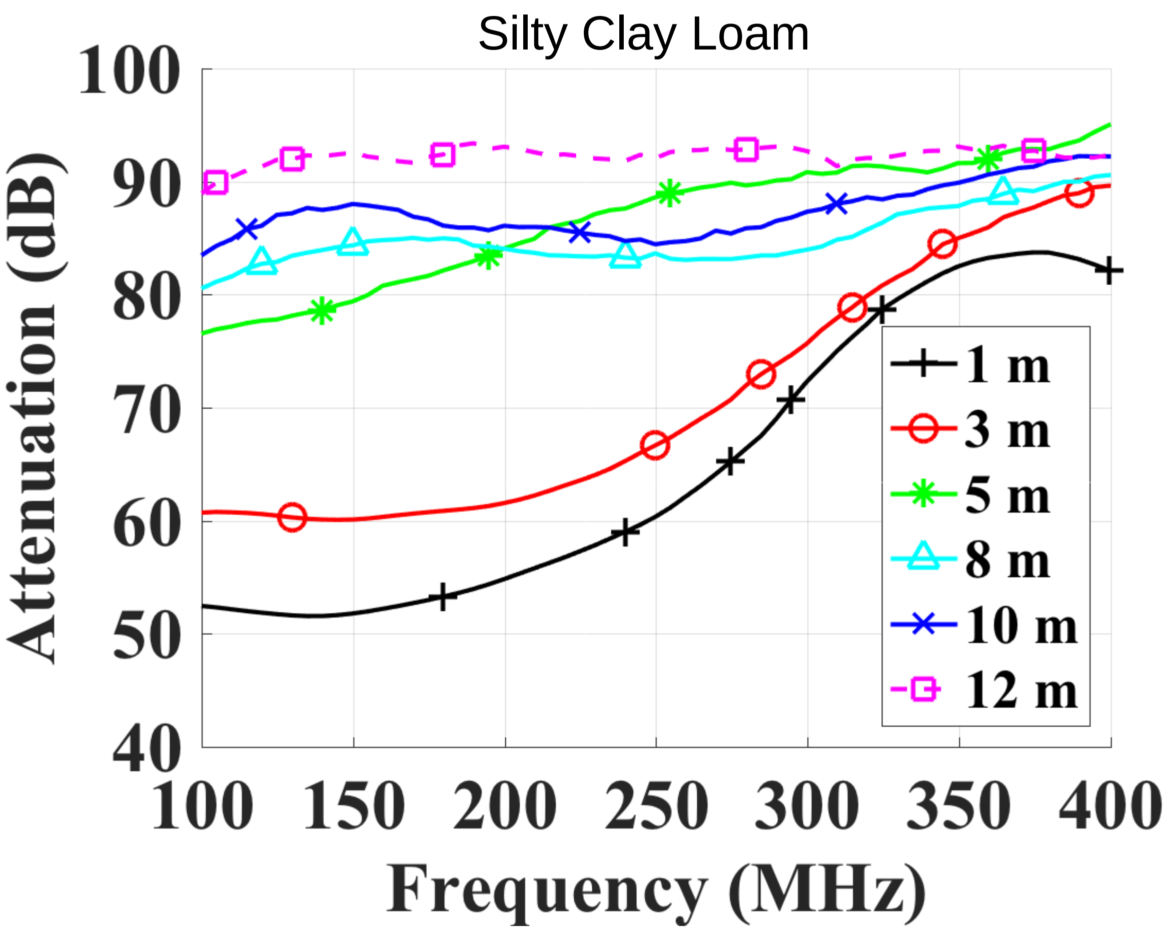


[13] H. D. Foth. Fundamentals of Soil Science. 8th ed. John Wiley and Sons, 1990.

Impact of Soil Moisture Variations



Attenuation With Frequency



- Higher frequencies suffer more attenuation
- Customized Deployment to the soil type and frequency range

Cognitive Radio Solutions

Adjust operation frequency,
modulation scheme,
and transmit power [14]

[14]. Dong and M. C. Vuran. "Impacts of soil moisture on cognitive radio underground networks". In: Proc. IEEE BlackSeaCom. Batumi, Georgia, July 2013.

Conclusion

Soil Type	Mean Excess Delay				RMS Delay Spread				Path Loss	
	Distance				Distance				Distance	
	50 cm		1 m		50 cm		1 m		**50 cm**	1 m
	mu	sig	mu	sig	mu	sig	mu	sig		
Silty Clay Loam	34.7	2.44	38.05	0.74	**25.67**	3.49	26.89	2.98	**49 dB**	52 dB
Silt Loam	34.66	1.07	37.12	1.00	**24.93**	1.64	25.10	1.77	**48 dB**	51 dB
Sandy Soil	34.13	1.90	37.87	27.89	**27.89**	2.76	29.54	1.66	**40 dB**	44 dB

Conclusion

$$h_{ug}(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t-\tau_l) + \sum_{d=0}^{D-1} \alpha_d \delta(t-\tau_d) + \sum_{r=0}^{R-1} \alpha_r \delta(t-\tau_r)$$

	Silty Clay Loam			Silt Loam			Sandy Soil		
	Distance			Distance			Distance		
	1 m			1 m			1 m		
	α	τ	N	α	τ	N	α	τ	N
Direct	-90	18-28	3	-103	15-23	2	-87	11-19	4
Lateral	-80	30-40	2	-82	26-43	3	-63	22-45	5
Reflected	-91	41-47	2	-94	47-59	4	-70	47-61	6

Questions



THANKS