PULSES IN THE SAND: LONG RANGE AND HIGH DATA RATE COMMUNICATION TECHNIQUES FOR NEXT GENERATION WIRELESS UNDERGROUND NETWORKS

by

Abdul Salam

A DISSERTATION

Presented to the Faculty of
The Graduate College at the University of Nebraska
In Partial Fulfilment of Requirements
For the Degree of Doctor of Philosophy

Major: Engineering

Under the Supervision of Mehmet Can Vuran

Lincoln, Nebraska
August, 2018
PULSES IN THE SAND: LONG RANGE AND HIGH DATA RATE COMMUNICATION TECHNIQUES FOR NEXT GENERATION WIRELESS UNDERGROUND NETWORKS

Abdul Salam, Ph.D.
University of Nebraska, 2018

Adviser: Mehmet Can Vuran

The recent emergence of Internet of Underground Things (IOUT) in many areas including environment and infrastructure monitoring, border patrol, transportation, and precision agriculture, underscores the importance of wireless underground (UG) communications. Yet, existing solutions are limited by relatively short communication distances and low data rates that prohibit widespread adoption. Extending the communication ranges and increasing data rates in wireless UG communications faces unique challenges because of the interactions between soil and communication components: (1) antenna properties, such as resonance frequency and antenna bandwidth, depend on soil type and varies with changes in soil parameters (e.g., soil moisture). Therefore, an antenna designed for over-the-air communication is no longer matched to the transceiver when buried in soil, and the system bandwidth, which is limited by antenna bandwidth varies in time. (2) Delay spread of the UG channel, which determines its coherence bandwidth, is a time-variant function of the soil parameters. Accordingly, the channel bandwidth varies significantly with physical changes in the environment. (3) The soil-air interface results in fluctuations in both antenna performance and EM wave propagation, which should be considered in system design. Consequently, next generation wireless UG communication solutions should be tailored to deployment parameters such as soil composition and depth while being
robust to variations in environmental parameters.

In this dissertation, the UG channel is characterized and environment-aware, cross-layer communication solutions are developed to achieve high data rate, long range communications. Moreover, applications to agriculture and smart lighting are illustrated. The impulse response of the wireless UG channel is captured and analyzed through extensive experiments. Based on this analysis, multi-carrier modulation and wireless underground channel diversity reception schemes have been developed. Furthermore, based on UG antenna analysis, soil moisture adaptive beamforming using underground antenna arrays is also designed. A wide variety of applications can potentially utilize UG communication solutions with diverse requirements. Among these, smart agriculture solutions that highlight long range and high data rate aspects of UG communications are considered to evaluate the developed solutions. The findings of this research are also evaluated using computational electromagnetics simulations.
DEDICATION

To Dr. Mehmet C. Vuran,

as George Bernard Shaw said, "Some men see things as they are and ask "Why?" Others dream things that never were and ask "Why not..."

Indeed, Dr. Vuran has a humble home in "Why not..."!
ACKNOWLEDGMENTS

I am highly excited and glad to express my heartfelt gratitude to many people who made this dissertation possible.

I am exceedingly thankful to my advisor and teacher, Dr. Mehmet Can Vuran who encouraged me to work in the area of wireless underground communications. No words can ever fully express my gratitude for his great mentorship. It has been an honor being his student. I am very grateful to have been trained by him. His encouragement has been a great inspiration to achieve excellence. He has not only guided me for the research work in this area, but also gave me the excellent guidance and support that has helped me to secure a faculty position at the Purdue University. I am indebted to Dr. Vuran for everything that I have learnt from him.

I whole heartedly thank Dr. Suat Irmak for his tremendous guidance and support during the design and development of the greenhouse indoor testbed and UNL’s South Central Agricultural Laboratory (SCAL) experiments. I am very grateful to him for sharing invaluable scientific expertise and for providing access to these great facilities. This dissertation and the prior work completed at the Internet of Underground Things (IOUT) testbed at Irmak Research Laboratory advanced center pivot irrigation system at SCAL would not have being possible without his support.

I would like to thank Dr. Byrav Ramamurthy for being on my dissertation committee. His invaluable comments have helped me to greatly improve this dissertation. His expertise in next-generation Internet architectures and protocols, design of optical WDM networks; and LAN, MAN and WAN architectures have been a great inspiration for me.

My cordial thanks also extend to Dr. Christos Argyropoulos for sharing his expertise in antenna theory and design. I really enjoyed his electromagnetic theory classes
and working with him. I would also like to thank Dr. Hongfeng Yu for his constant support throughout the dissertation writing.

I am also grateful to my colleagues at the Cyber-Physical Networking Lab for their support. I am especially thankful to Dr. Samil Temel who benefited me with his company during his post-doctoral pursuit at University of Nebrasaka-Lincoln; and also to Dr. Xin Dong, Mohammad Mosiur Rahman Lunar, and Rigoberto Wong for their friendship and support. Time passes, things change, but memories will always stay where they are, in the heart!

This acknowledgment section would not be complete without a heartfelt gratitude to Umbreen, Alizay, Anzalna, and Naba, who have stood by me, through all my hard times, particularly, through the process of leaving my homeland Pakistan to pursue my doctoral education at Nebraska. It is due to their love and prayers, I have the chance to complete this dissertation.

All praise be to Allah, the Sustainer of the creation; and peace be upon His servants whom He has chosen. May Allah sent his salutations on Prophet Muhammad and his family, as He sent salutations on the Ibrahim and his family. By Whose bounty all pious deeds are completed. I ask Him, for beneficial knowledge, good sustenance, and good deeds that are acceptable. Indeed, there is no power and no strength except with Him.
GRANT INFORMATION

This work is partially supported by a NSF CAREER award (CNS-0953900), NSF CNS-1423379, NSF CNS-1247941, CNS-1619285, and a NSF Cyber-Innovation for Sustainability Science and Engineering (CyberSEES) grant (DBI-1331895).
# Table of Contents

1 Introduction 6

1.1 Internet of Underground Things 8

1.1.1 Introduction 8

1.1.2 IOUT Architecture 10

1.2 Challenges in IOUT Communications 14

1.3 Research Objectives and Solutions 19

1.3.1 Impulse Response Analysis of Wireless Underground Channel 20

1.3.2 A Statistical Model of Wireless Underground Channel 20

1.3.3 Impacts of Soil Type and Moisture on the Capacity of Multi-Carrier Modulation in Internet of Underground Things 21

1.3.4 Soil Moisture Adaptive Beamforming 21

1.3.5 Wireless Underground Channel Diversity Reception With Multiple Antennas 22

1.3.6 Underground Dipole Antennas for Communications in Internet of Underground Things 23

1.3.7 \textit{In Situ} Real-Time Permittivity Estimation and Soil Moisture Sensing using Wireless Underground Communications 23

1.4 Thesis Organization 24

2 Related Work 26
3 Underground Communication Testbeds and Experiments

3.1 Background ......................................................... 37

3.2 Experimental Setup .............................................. 39

3.2.1 The Indoor Testbed ............................................. 39

3.2.2 The Field Testbed .............................................. 42

3.2.3 UG Software-Defined Radio (SDR) Testbed ............... 43

3.2.4 Soil Moisture Logging ........................................... 43

3.3 Measurement Techniques and Experiments Description .... 44

3.3.1 Measurement Methods ........................................... 44

3.3.1.1 Path Loss Measurements .................................. 44

3.3.1.2 Return Loss Measurements ................................ 45

3.3.1.3 Power Delay Profile (PDP) Measurements .............. 46

3.3.2 Measurement Campaign ......................................... 46

3.3.2.1 Sandy Soil Experiments .................................. 47

3.3.2.2 Silty Clay Experiments .................................... 47

3.3.2.3 Silt Loam Experiments .................................... 47

3.3.2.4 Underground-to-aboveground (UG2AG) Channel Experiments ............................................. 47

3.3.2.5 UG SDR Experiments ....................................... 48

3.3.2.6 Planar Antenna Experiments .............................. 48

3.4 Experimental Results ............................................. 49

3.4.1 Return Loss Measurements .................................... 49

3.4.2 Channel Transfer Function Measurements .................. 54

3.4.3 Power Delay Profile Measurements .......................... 62

3.4.4 UG2AG Channel Measurements Results .................... 66

3.5 Conclusion ......................................................... 68
4 Impulse Response Analysis of Wireless Underground Channel

4.1 Motivation ................................................................. 71
4.2 Related Work .............................................................. 72
4.3 Impulse Response of UG channel ........................................ 74
4.4 Measurement Sites and Procedures ...................................... 76
  4.4.1 Measurement Procedure .............................................. 76
4.5 Analysis and Results ..................................................... 78
  4.5.1 Characterization of UG Channel Impulse Response .............. 78
    4.5.1.1 Statistics of Mean Excess Delay ......................... 79
    4.5.1.2 Analysis of RMS Delay Spread .......................... 79
    4.5.1.3 Soil Moisture Variations ................................. 82
    4.5.1.4 Soil Type ................................................ 83
    4.5.1.5 Distance and Depth .................................... 85
    4.5.1.6 Operation Frequency .................................... 86
4.5.2 Model Parameters and Experimental Verifications .............. 86
4.6 WUSN Communication System Design ................................ 88
  4.6.1 Underground Beamforming ....................................... 88
  4.6.2 Underground OFDM ............................................. 89
4.7 Conclusion .................................................................. 90

5 A Statistical Model of Wireless Underground Channel .............. 91

5.1 Motivation .................................................................. 91
5.2 Related Work ................................................................ 94
5.3 The Statistical Model ................................................... 95
5.4 Model Evaluation ........................................................ 101
5.5 Empirical Validation .................................................... 102
6 Impacts of Soil Type and Moisture on the Capacity of Multi-
Carrier Modulation in Internet of Underground Things 105
6.1 Motivation .......................................................... 106
6.2 Related Work ....................................................... 110
6.3 Experiment Methodology .......................................... 111
6.4 Capacity Model ..................................................... 113
6.5 Results and Discussions ............................................ 118
   6.5.1 Soil Texture and Channel Capacity ......................... 120
   6.5.2 Soil Moisture and Channel Capacity ....................... 121
   6.5.3 Distance and Channel Capacity ............................. 123
6.6 Performance Comparisons ......................................... 125
6.7 Conclusions ....................................................... 125

7 Smart Underground Antenna Arrays: A Soil Moisture Adaptive
Beamforming Approach .................................................. 127
7.1 Motivation .......................................................... 128
7.2 Related Work ....................................................... 131
7.3 Channel Model for SMABF ......................................... 132
7.4 Challenges in Underground Beamforming ....................... 134
7.5 Analysis of Single Array Element in Soil ....................... 135
   7.5.1 Comparison of In-Soil and OTA Array Element .......... 135
   7.5.2 Element Impedance in Soil ................................. 136
7.6 Design of SMABF Array ............................................ 137
   7.6.1 Array Layout and Element Positioning .................... 138
   7.6.2 UG2AG Communication Beam Pattern ..................... 139
7.6.3 UG2UG Communication Beam Pattern .......................... 141
7.6.4 SMABF Directivity Maximization ................................. 142
7.6.5 SMABF Element Thinning Through Virtual Arrays .................. 143
7.6.6 Feedback Control ............................................. 144
7.6.7 Adaptive SMABF Element Weighting ............................. 146
7.7 Results ........................................................................ 147
7.8 SMABF Implementation ............................................... 160
7.9 Conclusions ................................................................... 162

8 Wireless Underground Channel Diversity Reception with Multiple
Antennas for Internet of Underground Things ............................. 163
8.1 Motivation .................................................................... 164
8.2 Related Work ............................................................. 165
8.3 Background ................................................................. 166
8.4 System Models ............................................................. 168
  8.4.1 UG 3W-Rake Receiver .............................................. 169
  8.4.2 LDR Receiver Design ................................................ 171
8.5 Performance Analysis .................................................... 173
  8.5.1 Coherent Detection .................................................. 174
  8.5.2 Experimental Evaluation ............................................ 175
    8.5.2.1 Setup ......................................................... 175
    8.5.2.2 Empirical Results ............................................ 176
  8.5.3 Performance of Equalization in the UG Channel ................. 176
  8.5.4 Differential Detection .............................................. 179
  8.5.5 3W-Rake Performance in UG Channel ............................ 180
  8.5.6 LDR Performance Analysis ........................................ 181
8.5.7 LDR Implementation ........................................ 182
8.6 Conclusions ......................................................... 183

9 Underground Dipole Antennas for Communications in Internet of Underground Things ........................................ 184
9.1 Motivation .......................................................... 185
9.2 Related Work ...................................................... 187
9.3 System Model ...................................................... 191
  9.3.1 Terminal Impedance of Underground Dipole Antenna as a Function of Soil Properties ........................................ 191
  9.3.2 Resonant Frequency of UG Dipole Antenna .................. 196
  9.3.3 UG Antenna Bandwidth ........................................ 196
9.4 Underground Dipole Antenna Simulations and Experiment Setup .... 197
9.5 Model Validation .................................................. 199
  9.5.1 Comparison of Theoretical, Simulated, and Measurement Results 199
  9.5.2 Analysis of Impact of Operation Frequency .................. 205
9.6 Underground Wideband Antenna Design .......................... 209
  9.6.1 Radiation Pattern for Underground Communications ........... 210
  9.6.2 The Return Loss .............................................. 211
  9.6.3 Communication Results ....................................... 211
9.7 Conclusions ....................................................... 214

10 Di-Sense: In Situ Real-Time Permittivity Estimation and Soil Moisture Sensing using Wireless Underground Communications 215
10.1 Motivation ........................................................ 216
10.2 Related Work ..................................................... 218
10.3 System Models .................................................... 221
10.3.1 Di-Sense Permittivity Estimation ......................... 222
10.3.2 Di-Sense Soil Moisture Sensing ......................... 225
10.4 Model Validation Techniques ................................. 226
10.5 Empirical Setup ............................................. 228
  10.5.1 Experiment Methodology ................................. 228
  10.5.2 PDP Measurements ..................................... 229
10.6 Performance Analysis, Model Validation, and Error Analysis .. 230
  10.6.1 Path Loss in Wireless Underground Communications .. 230
  10.6.2 Model Validation ..................................... 233
  10.6.3 Model Error Analysis .................................. 234
  10.6.4 Di-Sense Transfer Functions ............................ 236
10.7 Di-Sense Applications ....................................... 237
10.8 Conclusions .................................................. 237

11 Conclusions and Future Work .................................. 238
  11.1 Research Contributions .................................... 238
  11.2 Future Research Directions ............................... 239
    11.2.1 Integration of IOUT with Cloud ..................... 239
    11.2.2 Big Data in Precision Agriculture ................... 240
    11.2.3 Soil Moisture Adaptive Multi-Carrier Protocol Design 241

A Appendices ....................................................... 242
  A.1 Derivation of Optimal Angle ................................ 242
  A.2 Wavenumber in Soil ........................................ 244
  A.3 Speed of Wave in Soil ..................................... 244
  A.4 Periodogram Method of Power Spectrum Density .......... 245
  A.5 Semi-Empirical Dielectric Mixing Model ................... 246
B Publications 248

Bibliography 250
Appendix B

Publications

The work of this research has yielded the following major publications.


• A. Salam, and M. C. Vuran, “Impacts of Soil Type and Moisture on the Capacity of Multi-Carrier Modulation in Internet of Underground Things”, in Proc. of the 25th International Conference on Computer Communication and Networks (ICCCN 2016), Waikoloa, Hawaii, USA, Aug 2016 (Best Student Paper Award).


Bibliography


[24] “Smos,” www.esa.int/Our_Activities/Observing_the_Earth/SMOS.


[124] S. Kisseleff, I. F. Akyildiz, and W. H. Gerstacker, “Magnetic induction based simultaneous wireless information and power transfer for single information and


