Signals in the Soil

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Developments in Internet of Underground Things

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This book is dedicated to our families.

Preface

The farming sector is mainly responsible for the world's food needs; however, land degradation, contamination, poor agricultural techniques and practices, and urbanization are diminishing this resource. Therefore, given the rapidly increasing world's population, soil must be considered to be just as important as other natural resources like water and air. Soil has billions of organisms which initiate chemical, biological, and physical processes required for fiber and food production, growth of the plant, and removal of contaminants from water, hence, an integral component of an efficient farming ecosystem. Soil has many applications in human life: as a foundation of structures that cannot be supported by rocks, as a widely used material in the construction section, as a way to supply antibiotics to fight diseases, and as storage media for important gases (e.g. O_2, CO_2, and CH_3). Moreover, measures should be taken to prevent corrosion, soil movement, groundwater seepage, and other environmental effects to ensure that underground infrastructure (pipelines, tunnels, and basements) can function properly. The U.S. government spends billions of dollars to find and solve groundwater and soil contamination due to hazardous material, e.g., deliberate and accidental chemical spills, nuclear weapons production, pipeline ruptures, etc. Therefore, it is imperative to understand the soil ecosystems so that it can efficiently be used in meeting world's food demands. Moreover, this quote by Franklin D. Roosevelt *A nation that destroys its soils destroys itself* still holds true today.

Many credible national and international organizations like National Science Foundation (NSF), The Directorates for Engineering (ENG) and Geosciences (GEO), the Science and Technology Facilities Council (STFC) of United Kingdom Research and Innovation (UKRI), the Division of Integrative Organismal Systems in the Directorate for Biological Sciences (BIO/IOS), the Division of Computer and Network Systems in the Directorate for Computer and Information Science and Engineering (CISE/CNS) in collaboration with the US Department of Agriculture National Institute of Food and Agriculture (USDA NIFA), the Engineering and Physical Sciences Research Council (EPSRC), the Natural Environment Research Council (NERC), and the Biotechnology and Biological Sciences Research Council (BBSRC) encourage countries to do convergence and utilize underlying soil capabilities to their full extent using sensor and modeling systems. To that end, a collaborative effort from interdisciplinary researchers, scientific community, and funding agencies is required to develop advanced sensors, sensing systems, wireless communication systems, soil models, and cyber systems for complex problem-solving through education and outreach.

Lack of in-situ site-specific measurements of biological, chemical, and physical properties hinders the knowledge of dynamic soil changes. Currently, these properties are being measured by either laboratory methods using soil samples from the sites or soil models to predict soil states. However, these methods are based on limited data and unreliable assumptions. Therefore, it is important to develop sensing systems which provide advancement in detecting spatio-temporal dynamic soil changes. The sensor systems must have the capabilities to communicate wireless data being generated from the sensor, integrate with other available information, and generate analytics to observe spatial and temporal properties of managed and unmanaged soils. It is not possible to detect the soil health through signals, the term "healthy soil" has a proper definition. Therefore, it is important to integrate fundamental science and engineering knowledge to design a capable sensing system. To that end, skills from different departments, e.g., biological, atmospheric, hydrological, biogeochemical, geological sciences, and engineering are combined for assessment and monitoring of functional and sustainable soil. Furthermore, the sensor system will need advanced ground penetration, data transmission, dynamic modeling, data analytics, and visualization tools. The purpose of the research is to develop awareness and understanding about the soil so that it can be managed using new and innovative ways. It will also help in understanding the interaction between soil and the life (e.g., plants, microorganisms, etc.) supported by it.

Signals in the Soil adds new empirical and analytical results to the body of knowledge which enables researchers and industry professionals from the public and private sectors across the world to accelerate research on underground wireless communication, sensing, and networking technologies. It presents diverse and unique next-generation IoT applications in urban and rural areas. It is an excellent book for graduate students, academic researchers, and industry professionals, involved in communication, sensing, agriculture, and bio-systems research.

This book provides an understanding of the most recent developments in Signals in the Soil (SitS), from both the theoretical and practical perspectives. It identifies and discusses technical challenges and recent results related to improving wireless underground communications and sensing in Internet of Underground Things (IOUT). It covers both existing network technologies and those currently in development in three major areas of SitS: wireless underground communications, subsurface sensing, and antennas in the soil medium. It explores new applications of Internet of Underground Things in digital agriculture and urban underground infrastructure monitoring.

Signals in the Soil is an essential reference book for advanced students on courses in wireless underground communications and Internet of Things. It will also be of interest to researchers, communication engineers, system and network planners, technical managers, and other professionals in these fields. There is no book on the market that discusses wireless underground communications and Internet of Underground Things. Currently, this audience gets information about this topic from different sources (e.g., IEEE conferences, COMSOC tutorials, IEEE journals and transactions articles, and web forums). The purpose of this book is to transform information from these scattered sources into a comprehensive and easily accessible knowledge body.

Signals in the Soil is split into four parts: Physical Layer for Wireless Underground Communications, Underground Antenna, and Radio Interface Technologies; Novel Soil Sensing Techniques; Internet of Underground Things Advancements; Applications in Urban Underground Infrastructure Monitoring and Real-time Soil Monitoring and Irrigation Automation. It starts by introducing emerging technologies in wireless communications in the soil medium before moving on to cover propagation models, soil properties, and beyond; beamforming, antenna arrays, and MIMO; capacity and path loss analysis; empirical and statistical channel models in IOUT; underground antenna design; cross-layer and environment-aware protocol design and energy harvesting and power transfer, moving toward the applications in digital agriculture and urban underground infrastructure monitoring; and more. This valuable resource:

- Provides a comprehensive reference for all aspects of Signals in the Soil,
- Focuses on fundamental issues of wireless underground communication and subsurface sensing in an easy language that is understandable by a wide audience,
- Includes advanced treatment of IOUT custom applications of variable technologies in the field of digital agriculture and covers protocol design and energy harvesting,
- Features research developments and open research challenges in subsurface sensing,
- Provides a detailed set of path loss, antenna, and wireless underground channel measurements in novel indoor and field testbeds.

The intended audience for *Signals in the Soil: Developments in Internet of Underground Things* are graduate students, precision equipment technicians, academic researchers, field applicators, industry professionals and managers, dealerships, and digital agriculture sales specialists. There are many such individuals in academia and digital agriculture technology business, which is mostly targeted to the applications of technology in big and small agricultural fields. Moreover, the use of digital agriculture technology in diverse topographic and soil texture fields is also expanding. To effectively utilize enormous data being generated from the agricultural farms, this book has introduced technologies which are useful for data collection, design of decision tools, interpretation, and real-time decision-making in the field.

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August 2020 Usman Raza

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Dr. Abdul Salam is an Assistant Professor in the Department of Computer and Information Technology, Purdue University. He holds a Ph.D. from University of Nebraska–Lincoln. He is the Director of the Environmental Networking Technology Laboratory at Purdue University. He has also taught at the Bahauddin Zakariya University, Multan and Islamia University, Bahawalpur. He served in Pakistan Army for 9 years in a number of command, staff, and field roles. He held the principal position at the Army Public School and College, Thal Cantonment. He has won several awards including the ICCCN 2016 Best Student Paper Award, the Robert B. Daugherty Water for Food Institute Fellowship, the Gold Medal MS (CS) on securing first position in order of merit, and the 2016–2017 Outstanding Graduate Student Research Award from the University of Nebraska–Lincoln. He is the author of two books: Internet of Things for Sustainable Community Development and Signals in the Soil. He has published over 50 research articles in major journals and conferences. His recent research focuses on underground soil sensing, wireless communications, Internet of Underground Things in digital agriculture, sensor-guided irrigation systems, and vehicular communications. He has served as an Associate Editor for the IEEE GRSS Remote Sensing Code Library from 2016 to 2018. He serves as the Associate Editor of the Advanced Electromagnetics Journal and Array (Elsevier). Dr. Salam received his B.Sc. and M.S. degrees in computer science from Bahauddin Zakariya University, Multan, Pakistan, in 2001 and 2004, respectively, the M.S. degree in computer engineering from UET, Taxila, Pakistan, in 2012, and the Ph.D. degree in computer engineering from the Cyber-Physical Networking Laboratory, Department of Computer Science and Engineering, University of Nebraska–Lincoln, Lincoln, NE, USA.

Usman Raza is a Ph.D. student in computer and information technology at the Purdue University and a research assistant at Environmental Networking Technology Laboratory under the supervision of Dr. Abdul Salam. His research involves Internet of Underground Things, including the channel model, connectivity, and network protocols.