Agricultural and Underground Communications and Sensing

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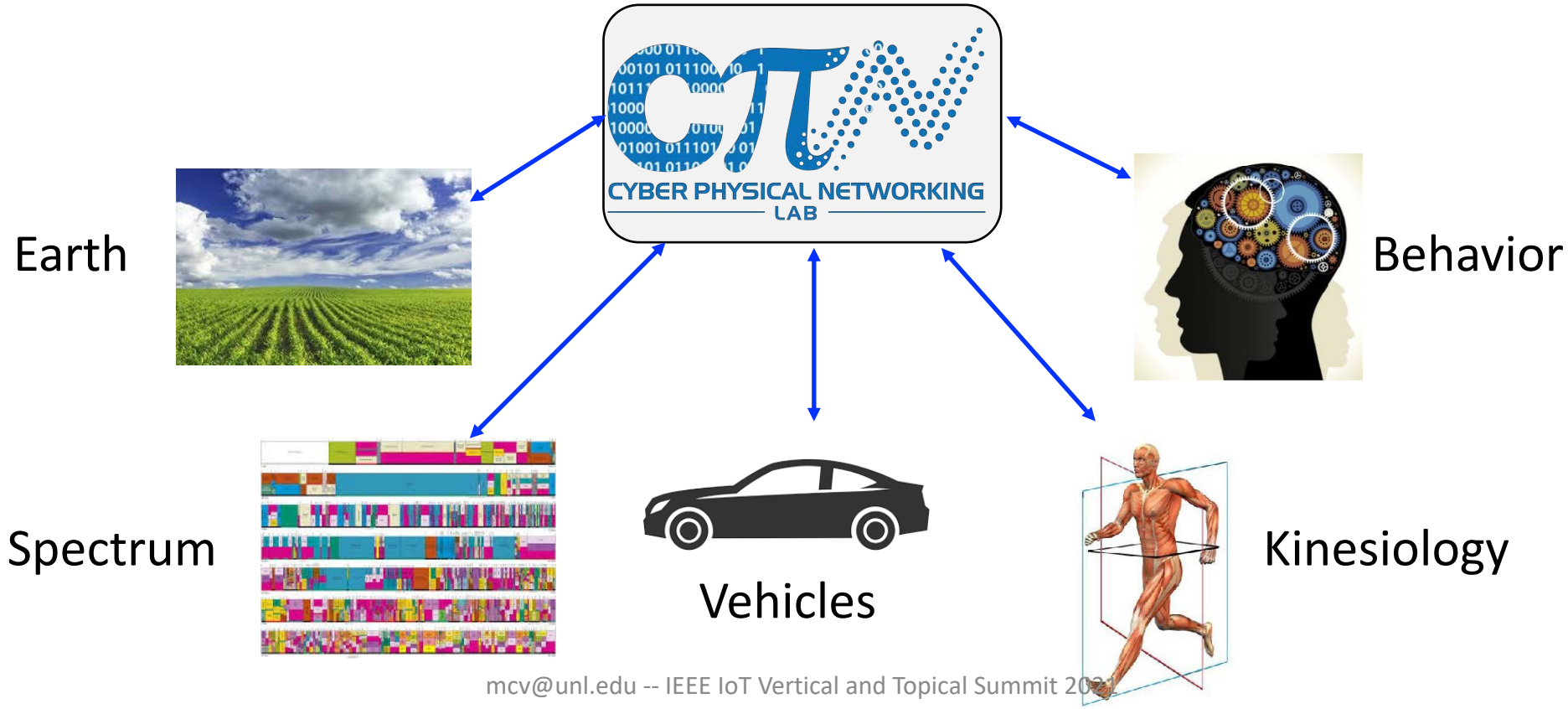
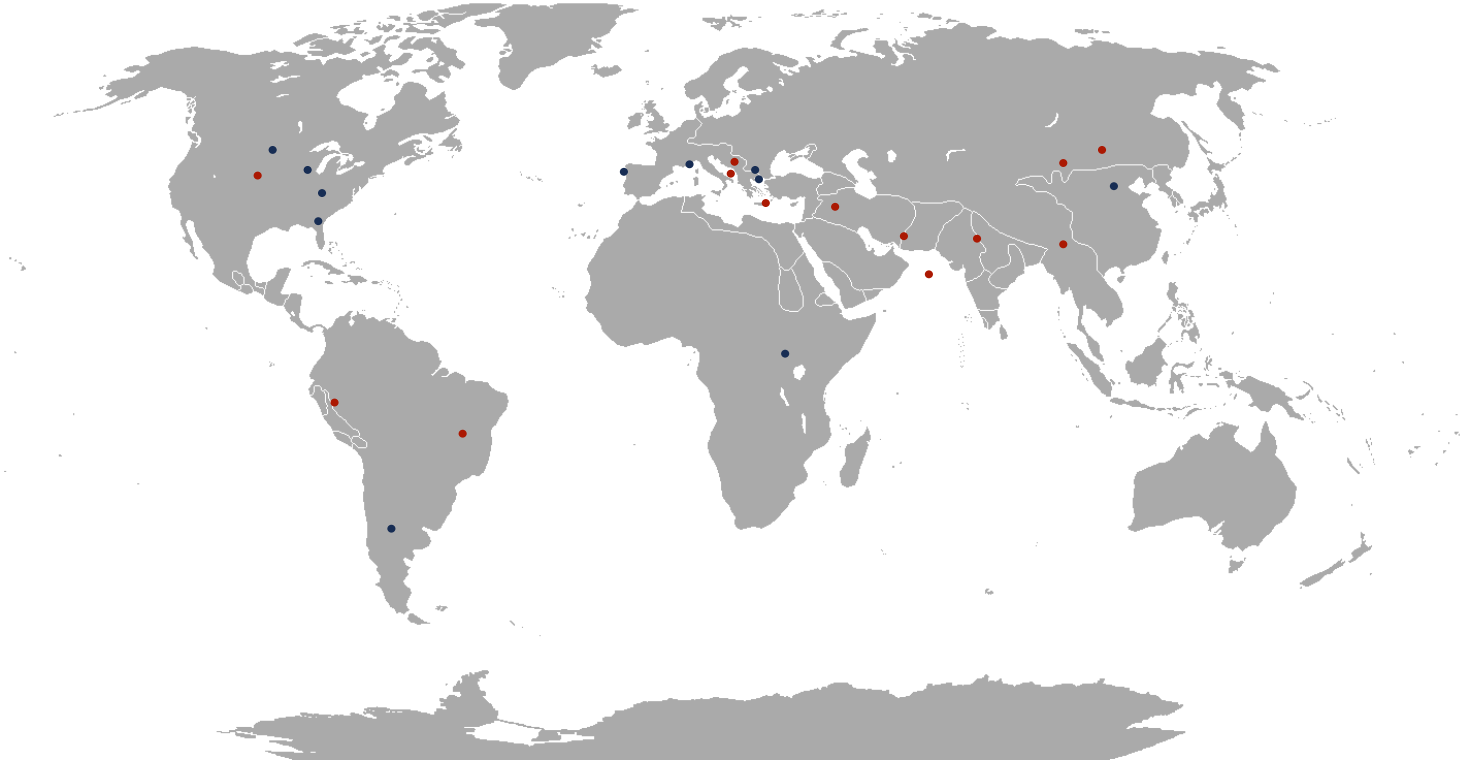
Happy *New* Year!

Cyber Physical Networking (CPN) Lab

- Wireless networks of systems that are aware of, can timely adapt to, and change their environment



Cyber-Physical Networking Lab



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HIGHLY CITED RESEARCHERS

...top 1% most cited for Computer Science" three years in a row

- > 60 publications
- > 18,000 citations

Today’s Agenda

- Rural Broadband and Agriculture
- Agricultural Internet of Things (Ag-IoT)
- Wireless Underground Communications
- Big Picture: Ag-IoT Data

Rural Broadband and Agriculture

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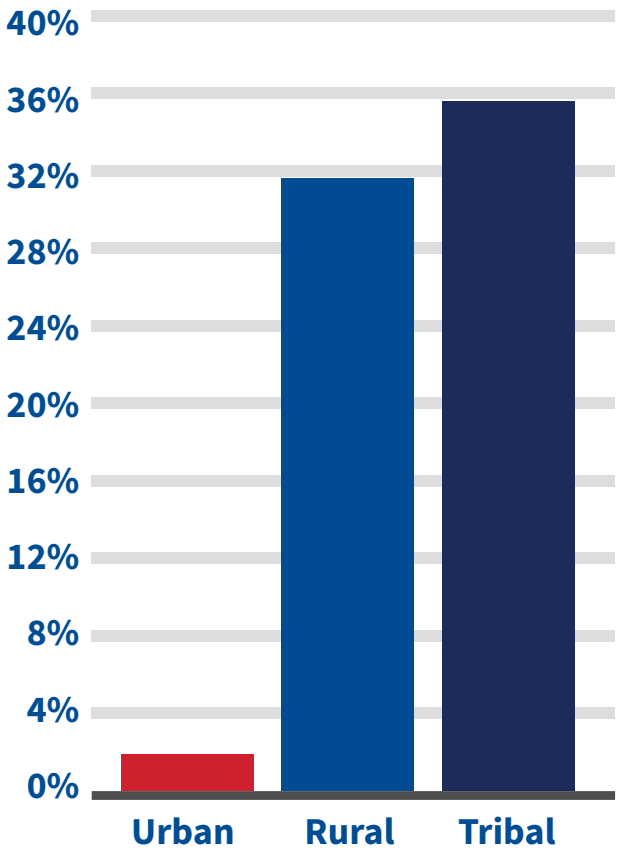
Rural Broadband

- *"A ma* S Natnl. Intelli
- *"Rura* *connecting rural* ce on Agricu
- USDA: $600M ReConnect Program
- FCC: $20B Rural Digital Opportunity Fund, $9B 5G Fund for Rural America

FIGURE 1: PERCENTAGE OF AMERICANS LACKING ACCESS TO FIXED TERRESTRIAL 25 MBPS/3 MBPS BROADBAND



2018 Broadband Deployment Report - based on 2016 data provided by Internet Service Providers

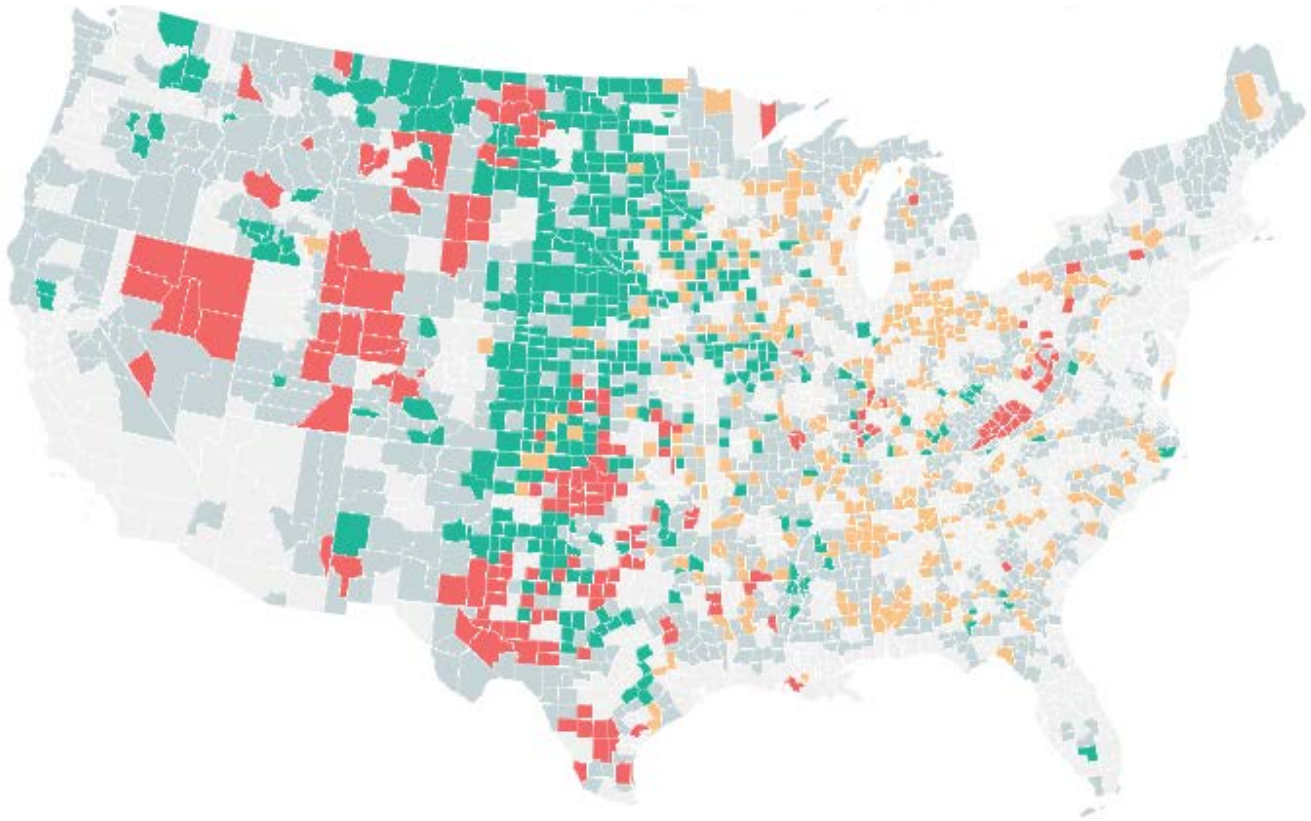
https://www.ntia.doc.gov/report/2019/american-broadband-initiative-milestones-report

Rural Economy

- Homes, fields, ranches, factories
  - Majority of Midwest is Ag-driven
- Can Agricultural IoT (Ag-IoT) become one of the economic drivers?

FIGURE 1

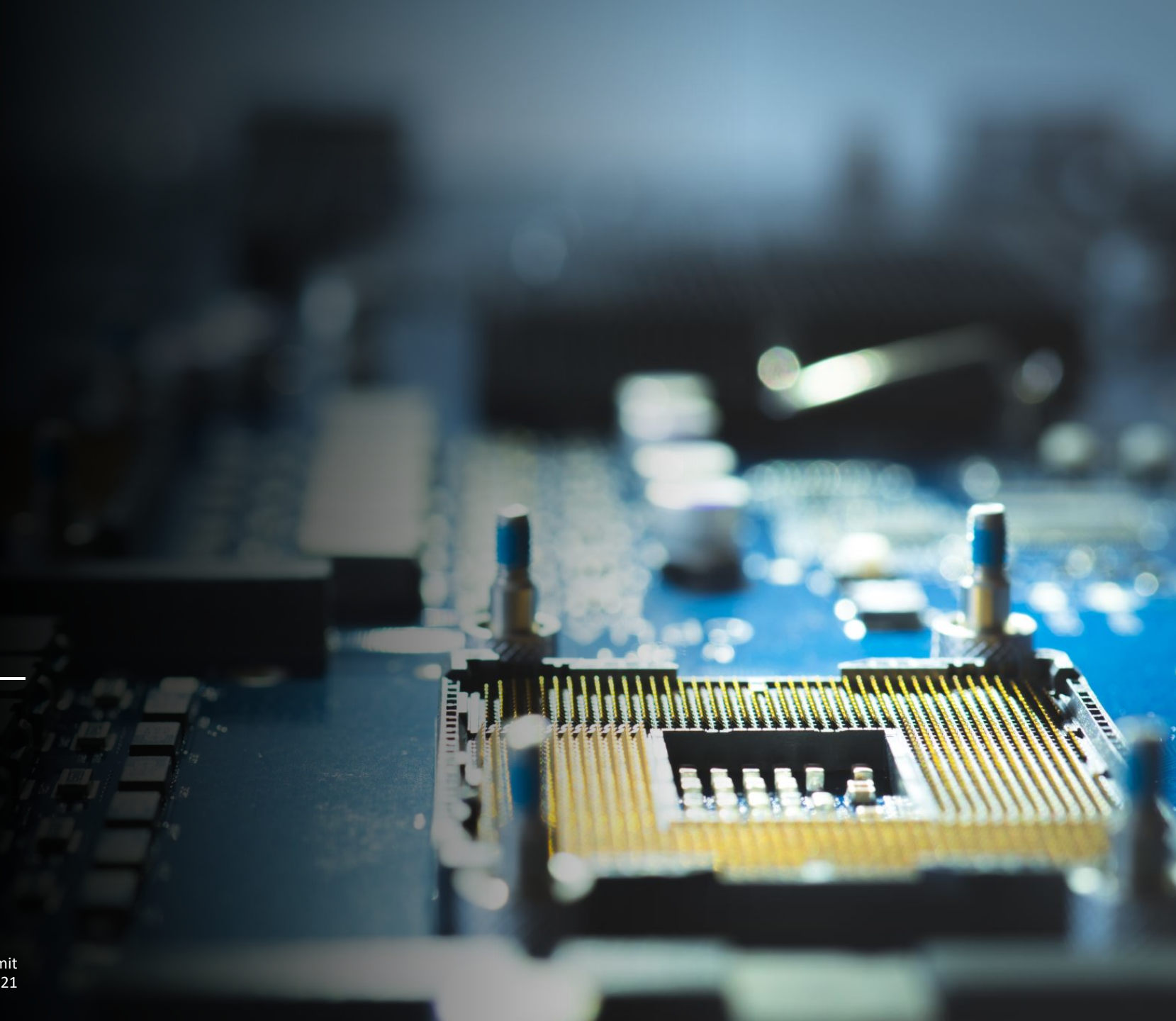
Nonmetro counties where the primary industry—agriculture, manufacturing, or mining—exceeds 25 percent of employment or 15 percent of earnings



Note: Counties not shaded are metropolitan counties in which the primary industry is not agriculture, manufacturing, or mining, or where those industries account for less than 25 percent employment and 15 percent of earnings.
Source: Economic Research Service, "Atlas of Rural and Small-Town America," available at https://www.ers.usda.gov/data-products/atlas-of-rural-and-small-town-america/ (last accessed June 2019).

CAP

Agricultural Internet of Things



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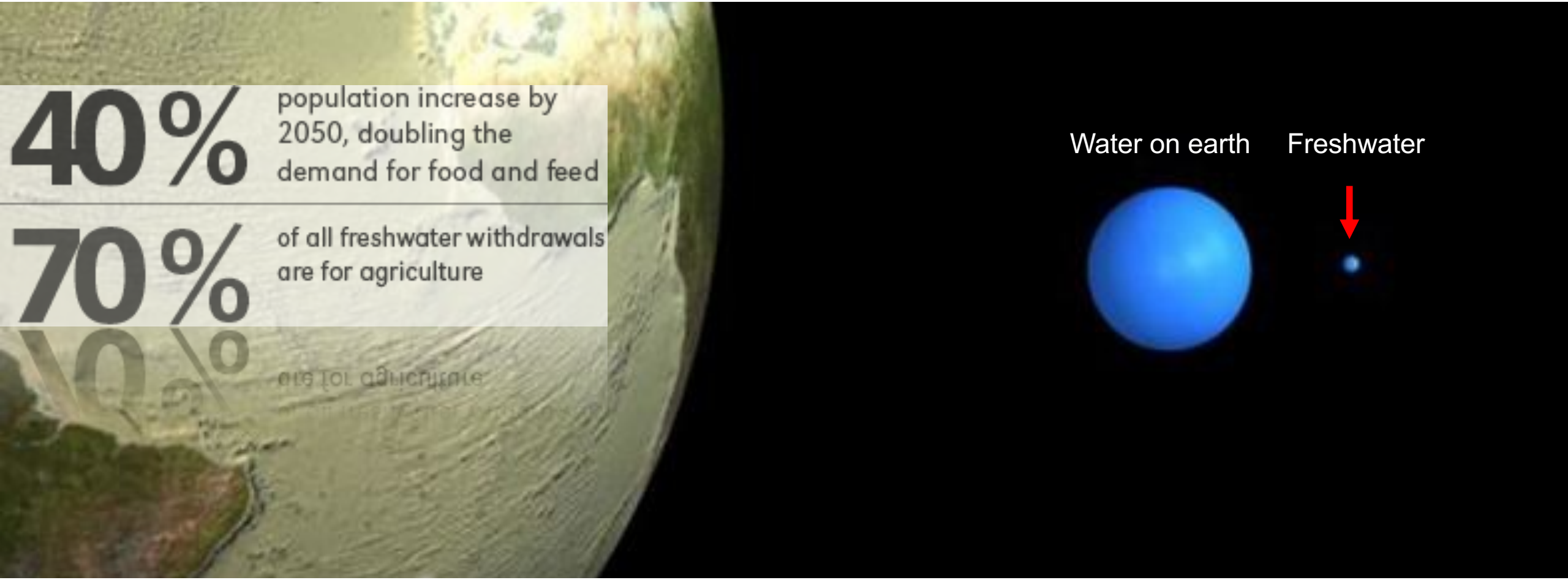
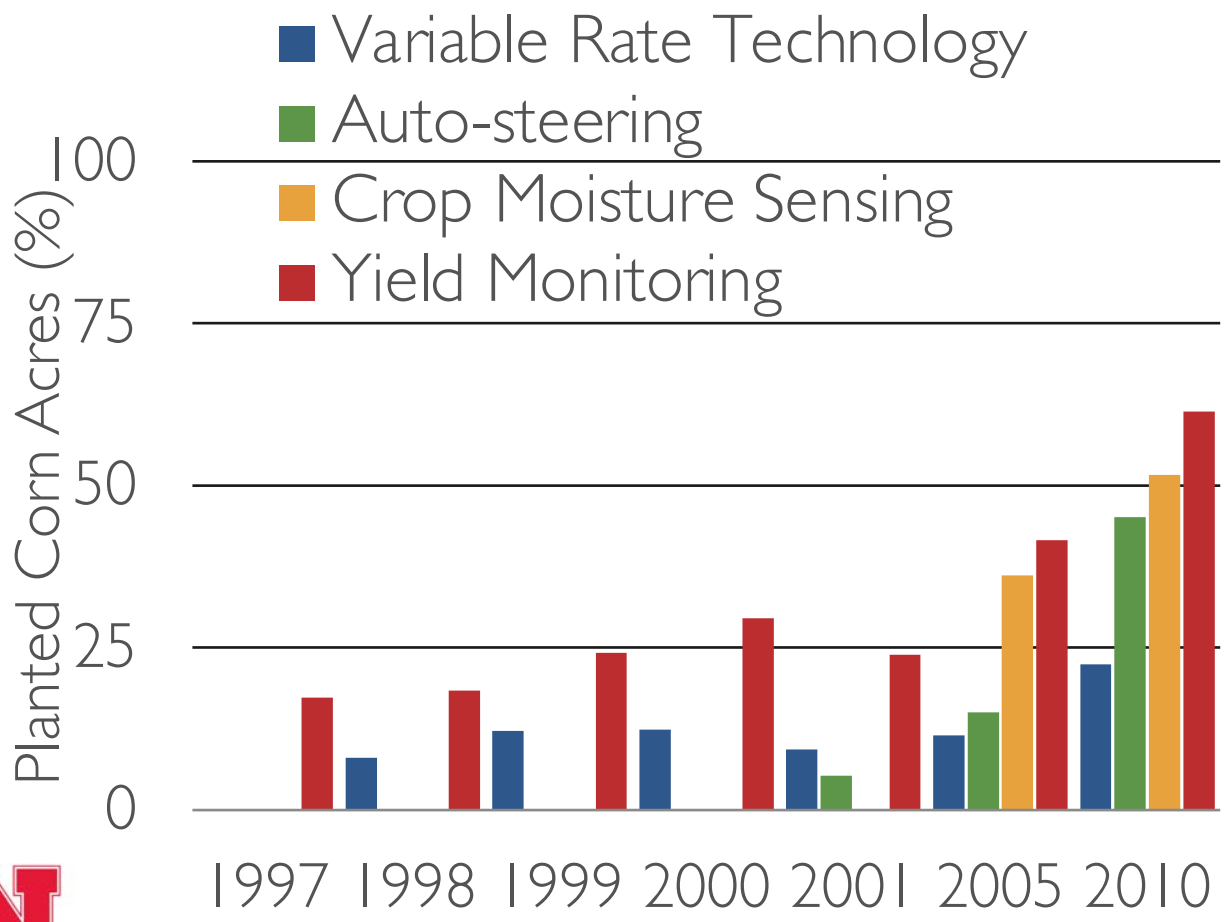
The Problem: Water Scarcity

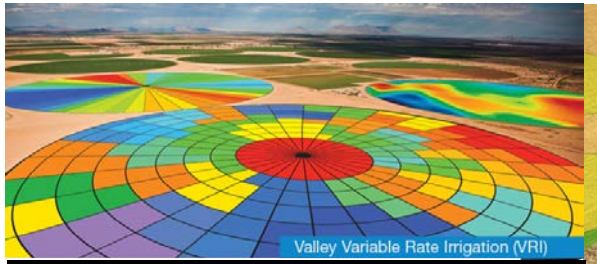


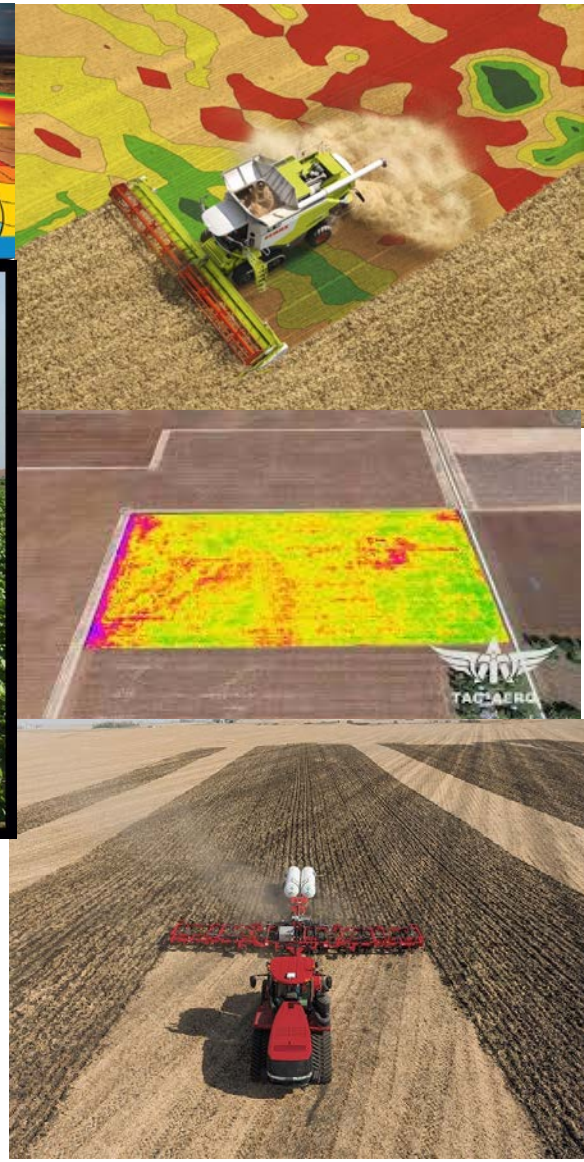
Need more crop for drop!

Source: USGS

Precision Agriculture







Source: USDA

Tillage

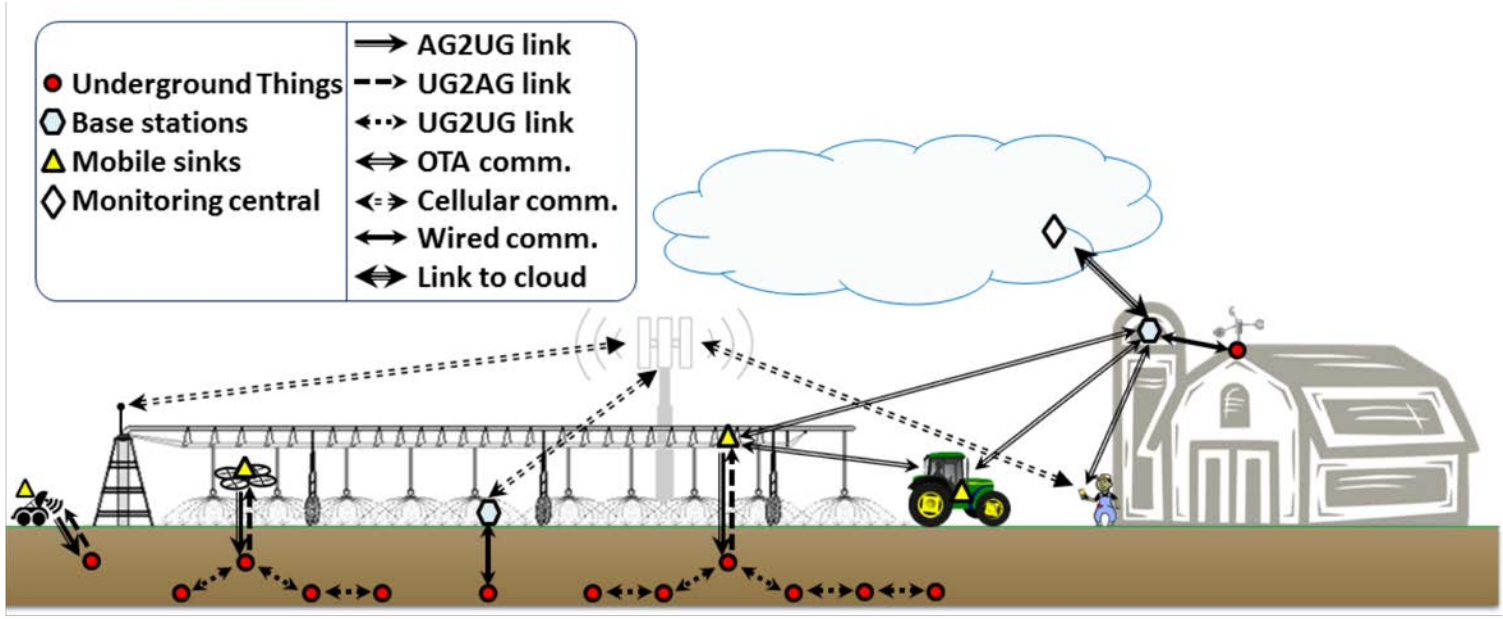
Precision Agriculture

- Seeding - type of soil, climate, economy, draught, etc.
- Fertilization - leeching, weather
- Irrigation - evapotranspiration, weather, soil moisture
- Harvesting - crop state, soil state, weather
- Distribution - demand, crop type, weather

Agricultural Internet of Things (Ag-IoT)

A. Silva, M. C. Vuran, S. Irmak, ``Internet of underground things in precision agriculture: Architecture and technology aspects ,'' Ad Hoc Networks Journal, v. 81, pp. 160-173, Dec. 2018.

- Autonomous devices that
  - collect any relevant information about the Earth
  - interconnected with communication and networking solutions
  - facilitate *sending the information out of fields* to the growers and decision mechanisms
- On-board sensing capabilities (soil moisture, temperature, salinity)
- Real-time information about soil and crop conditions
- Inter-connection of heterogeneous machinery and sensors
- Complete autonomy on the field



Agricultural Internet of Things (Ag-IoT)

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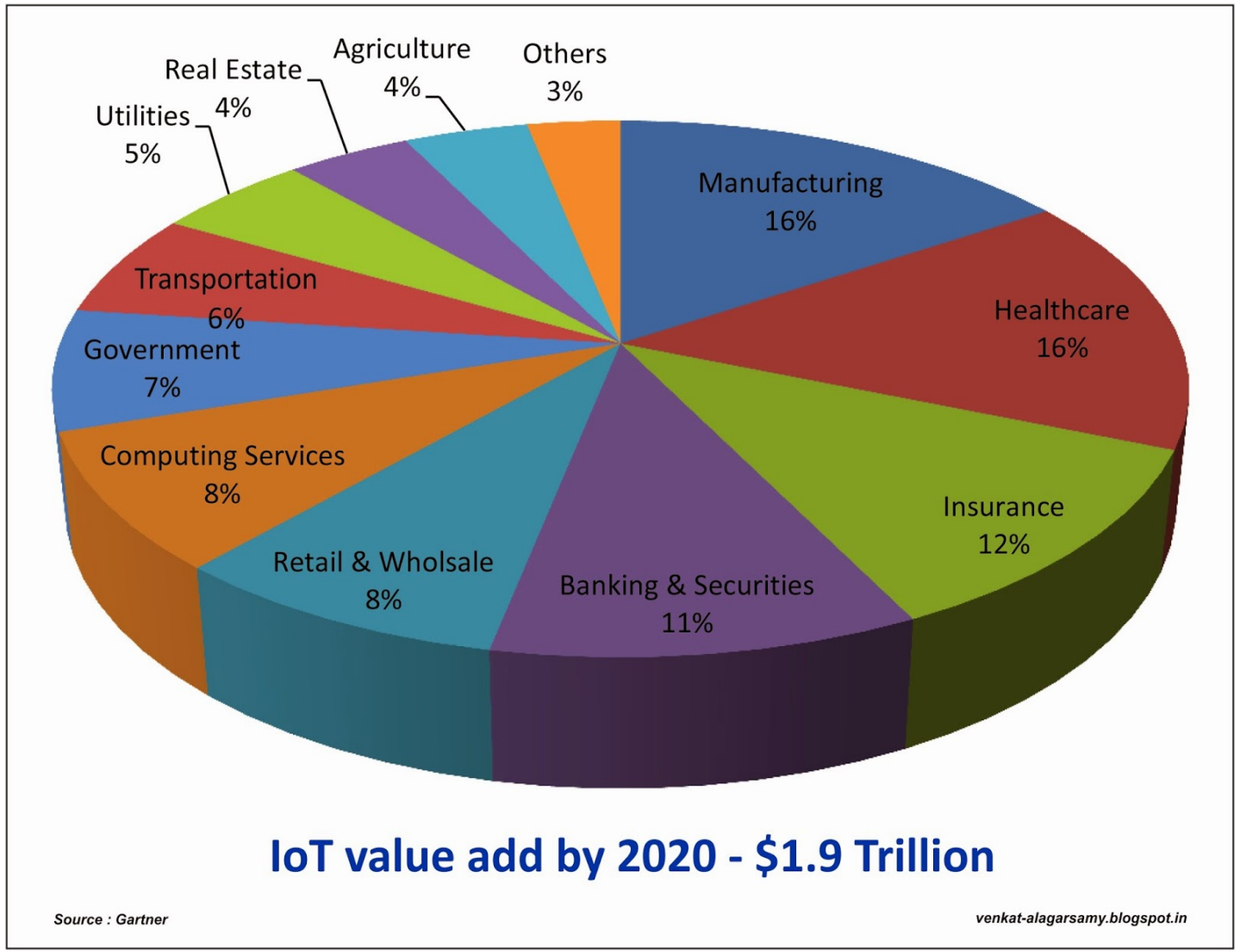
- In-situ sensing
- Wireless communication in challenging environments
- Inter-connection of field machinery, sensors, radios, and edge/fog/cloud
- Real-time Decision Making
- Mobility

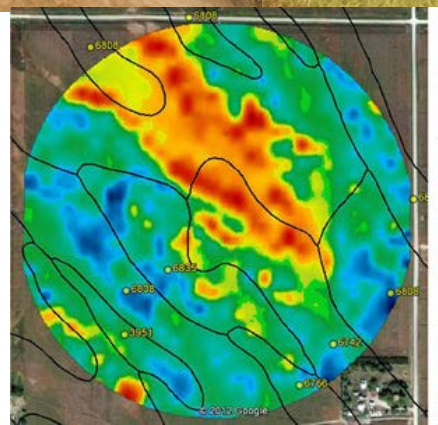
Where is Ag-IoT?

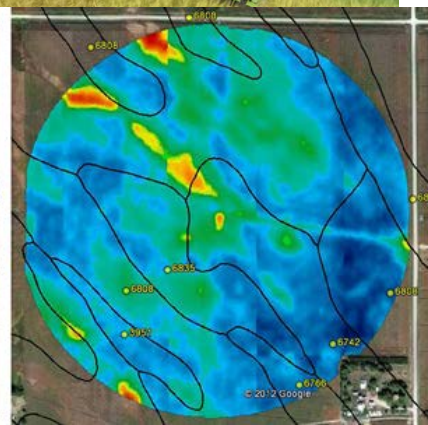


Sensing in Precision Agriculture

A. Silva, M. C. Vuran, S. Irmak, ``Internet of underground things in precision agriculture: Architecture and technology aspects ,'' Ad Hoc Networks Journal, v. 81, pp. 160-173, 2018.

- Soil moisture
  - Gravimetric sampling, resistive, capacitive, ground penetrating radar (GPR), neutron scattering probes, time-domain reflectometry (TDR), frequency-domain reflectometry (FDR), Gamma ray attenuation
- Other soil physical properties
  - Organic meter, acidity (pH), soil composition, nutrients (Mg, P, OM, Ca, K, Ca)
- Yield monitoring
- Electrical conductivity
- Weather and environment sensing
- Remote sensing (soil moisture, yield, texture, nutrients)
- Other PA techniques (precision planting, geolocation, GIS, soil sampling, drone sensing, auto-steering, VRT)





Wireless Connectivity for Ag-IoT

A. Silva, M. C. Vuran, S. Irmak, ``Internet of underground things in precision agriculture: Architecture and technology aspects ,'' Ad Hoc Networks Journal, v. 81, pp. 160-173, Dec. 2018.

- Wireless underground (UG) communications
  - Electromagnetic, magnetic induction, and acoustic
- Lower power wide area networks (LPWAN)
  - LoRaWAN, Sifgox, On-Ramp/Ingenu, EC-GSM-IoT
- Wireless LAN (WLAN)
  - Bluetooth, ZigBee, Thread, WiFi
- Cellular
  - LTE, NB-IoT,

Wireless Connectivity for Ag-IoT

- Today, you can go to BestBuy, buy a WiFi box, and connect all your devices
- Not in a field
- Wireless for Ag-IoT
  - Basic research for rural and ag. fields
  - Accessible rural experimental platforms
  - Standardization for rural broadband

Wireless Underground Communications

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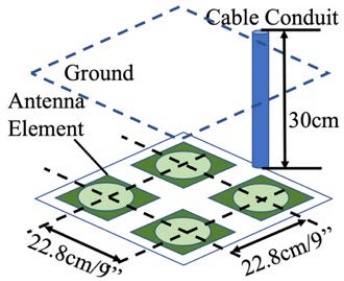
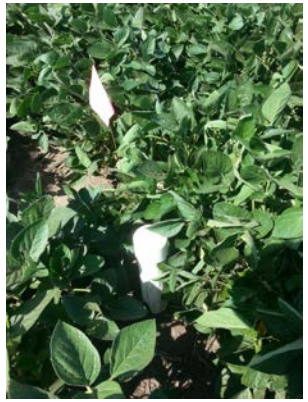
Wireless (Over-The-Air)
Now you see me…

- Obstruction in the field
- Deployment after seeding, removal before harvest
- A short window for vendors to deploy and remove (1,000s of fields within 1-2 weeks)
- Single point-of-failure
- Theft, natural elements, maintenance
- $$$
- Limited adoption (6% of irrigated farms)
- Main reasons: Connectivity and OTA wireless technology

Wireless Underground
Now you see me… Now you don't…

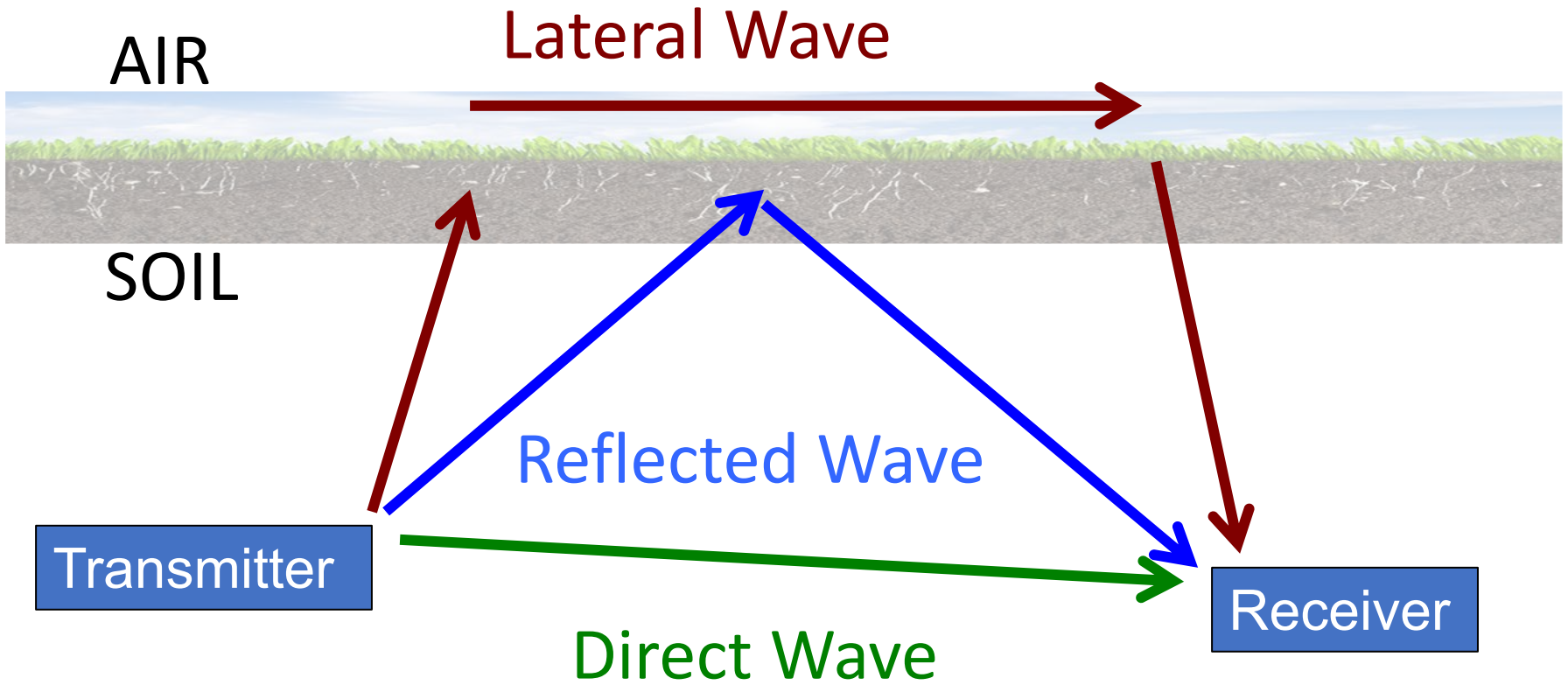
- Enter wireless underground
- Unobstructed operation
- Multi-year operation
- Multi-sensor deployment
- Natural protection from theft, maintenance
- $
- Increased adoption
- Major player for rural connectivity demand





Impulse Response of the Wireless Underground Channel

A. Silva, M. C. Vuran, S. Irmak, ``A Statistical Impulse Response Model Based on Empirical Characterization of Wireless Underground Channels,'' IEEE Transactions on Wireless Communications, v. 19, no. 9, pp. 5966-5981, Sept. 2020.



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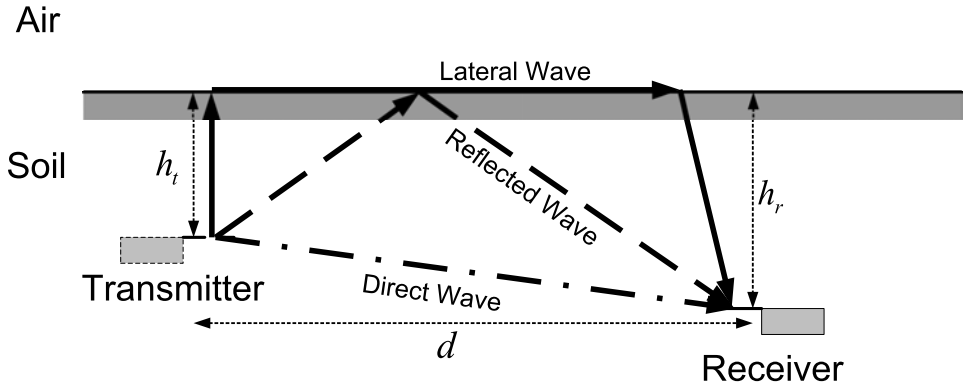
# of multipaths

$$\mathrm{h}(t) = \sum_{p=0}^{P-1} \alpha_p \delta(t - \tau_p)$$

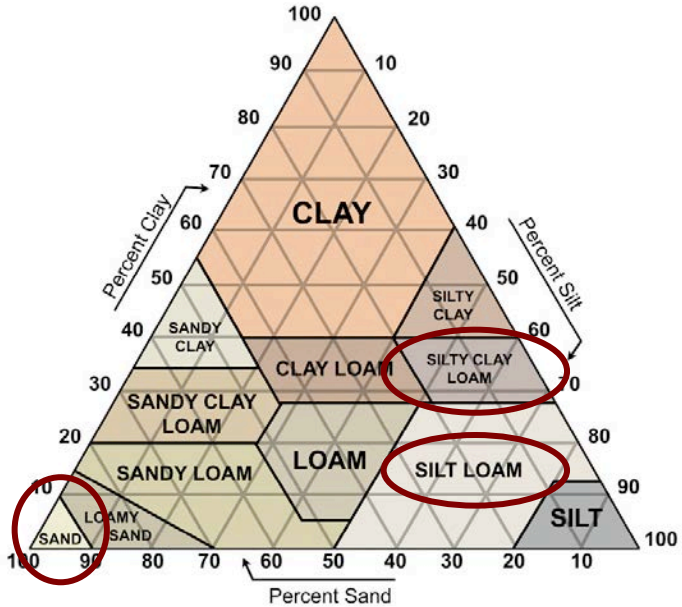
path delay

path gain



$$\mathrm{h_{ug}}(t) = \sum_{i=0}^{L-1} \alpha_{\mathrm{l},i} \delta(t - \tau_{\mathrm{l},i}) + \sum_{j=0}^{D-1} \alpha_{\mathrm{d},j} \delta(t - \tau_{\mathrm{d},j}) + \sum_{k=0}^{R-1} \alpha_{\mathrm{r},k} \delta(t - \tau_{\mathrm{r},k})$$

- Mean access delay
- RMS delay spread
- Coherence bandwidth



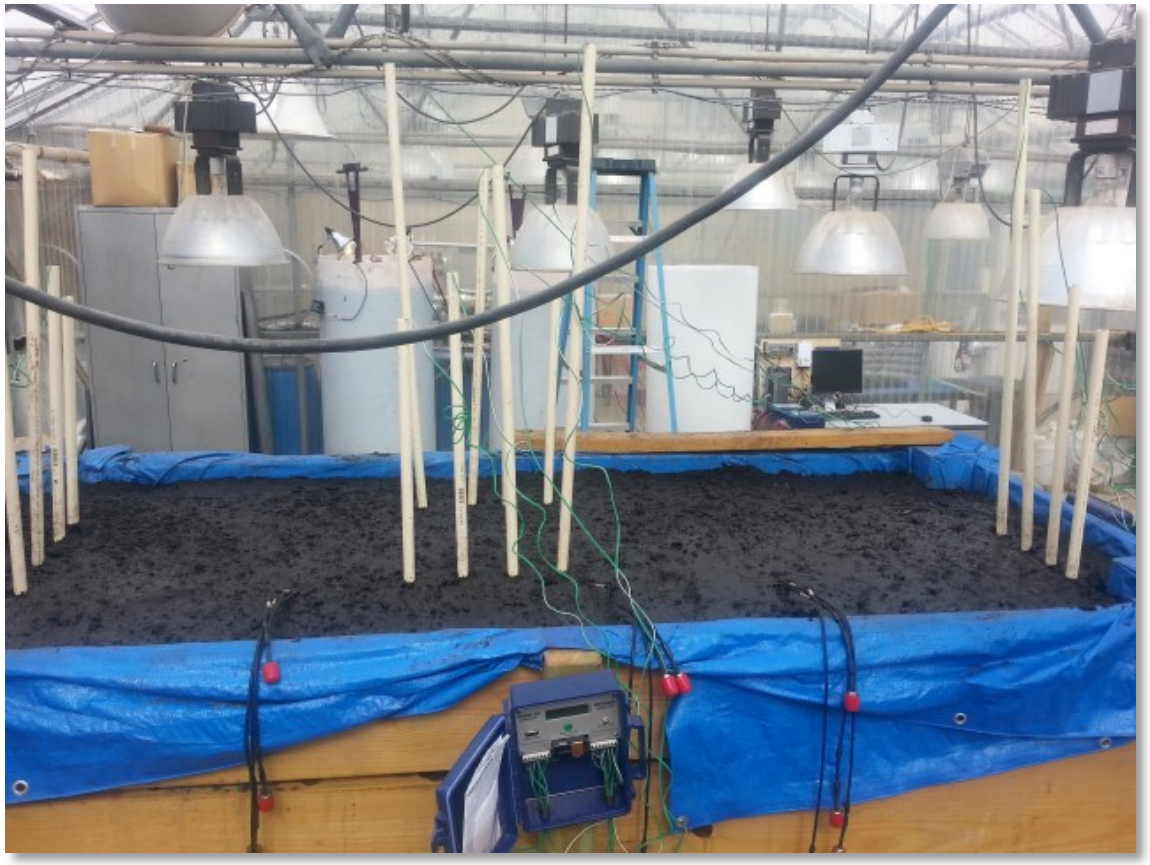
Indoor Testbed

Sandbox
Dimensions: 100" x36" x 48"
90 Cubic Feet of Soil

Gravel

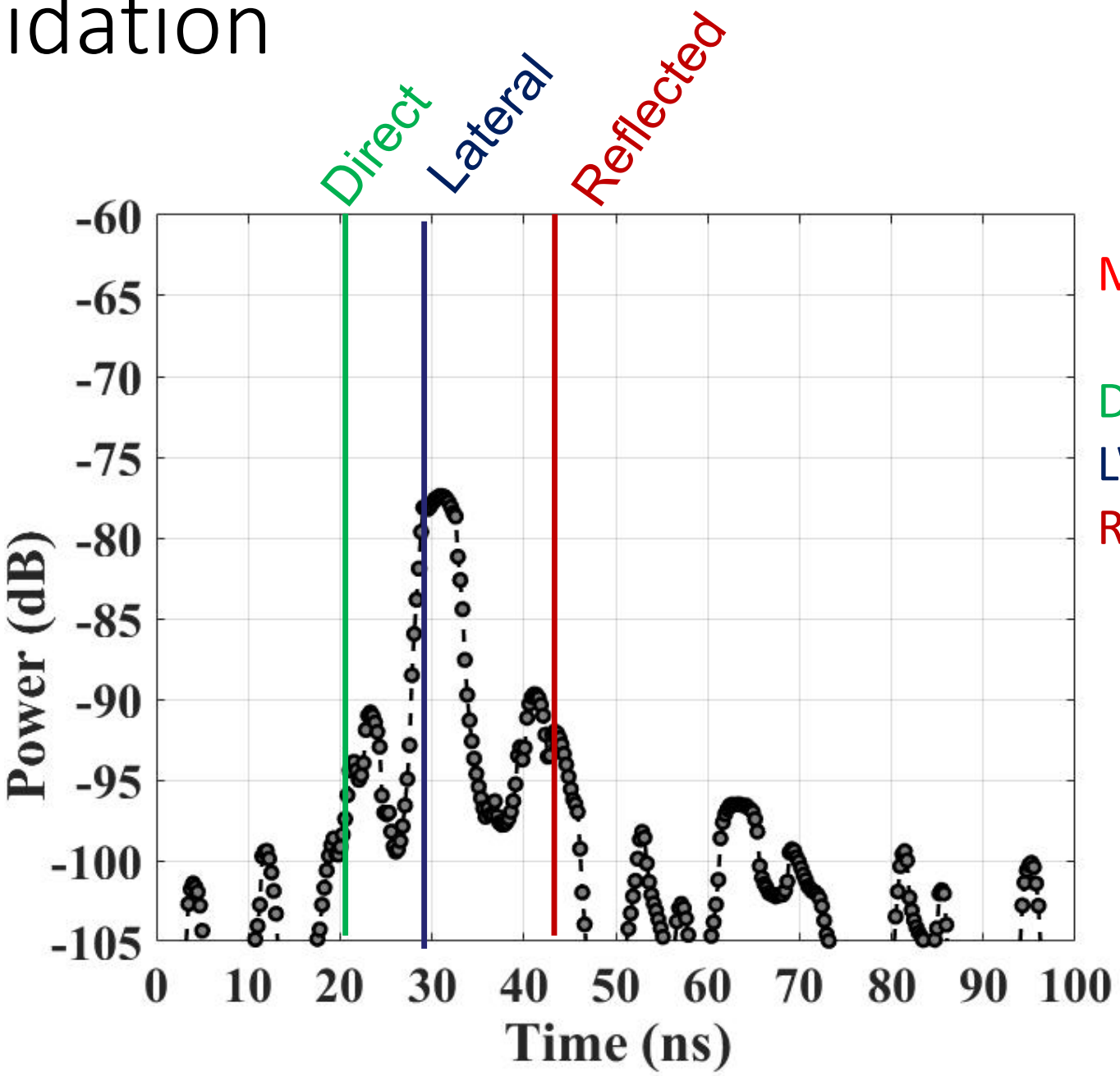
Soil Placement, Packing and Saturation

Indoor Testbed



Outdoor Testbed

Model Validation
Silt Loam



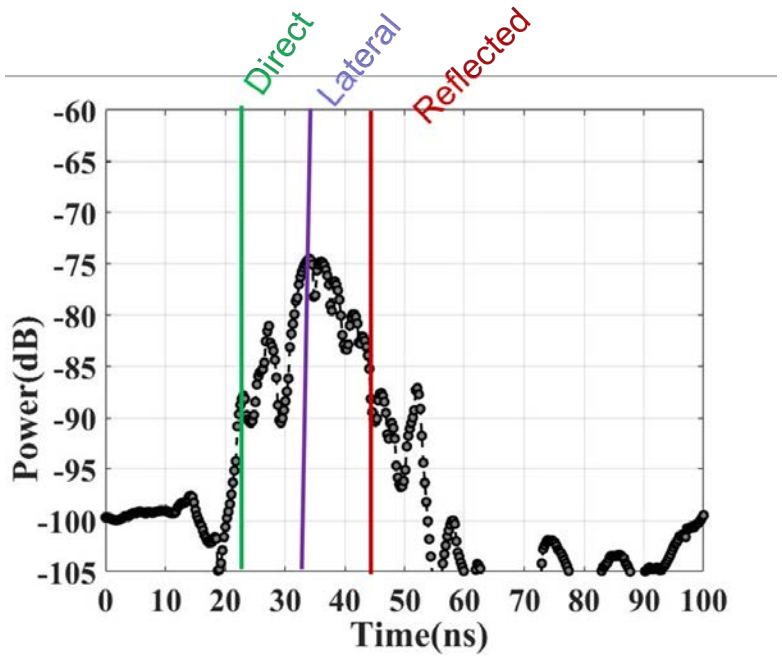
Model deviation:

DW: 10.2%

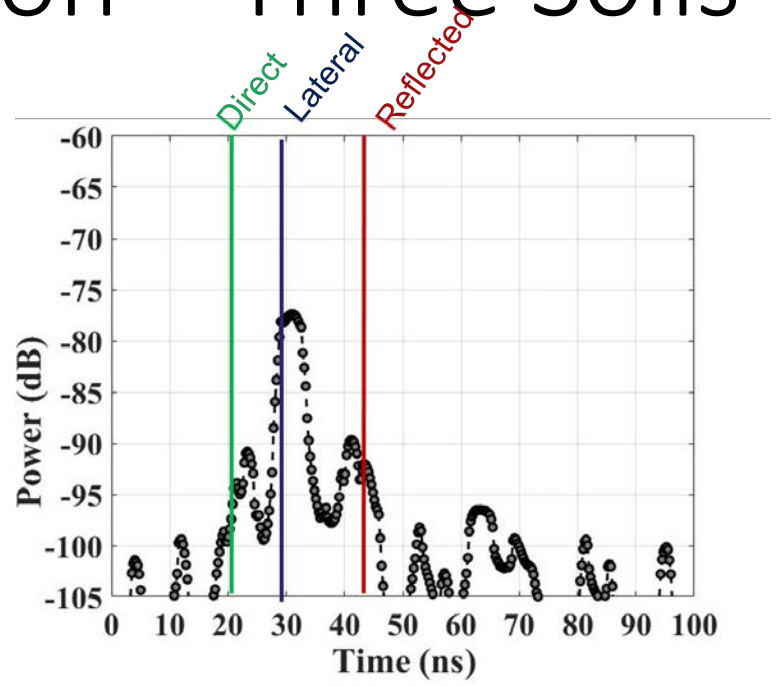
LW: 7.3%

RW: 7.5%

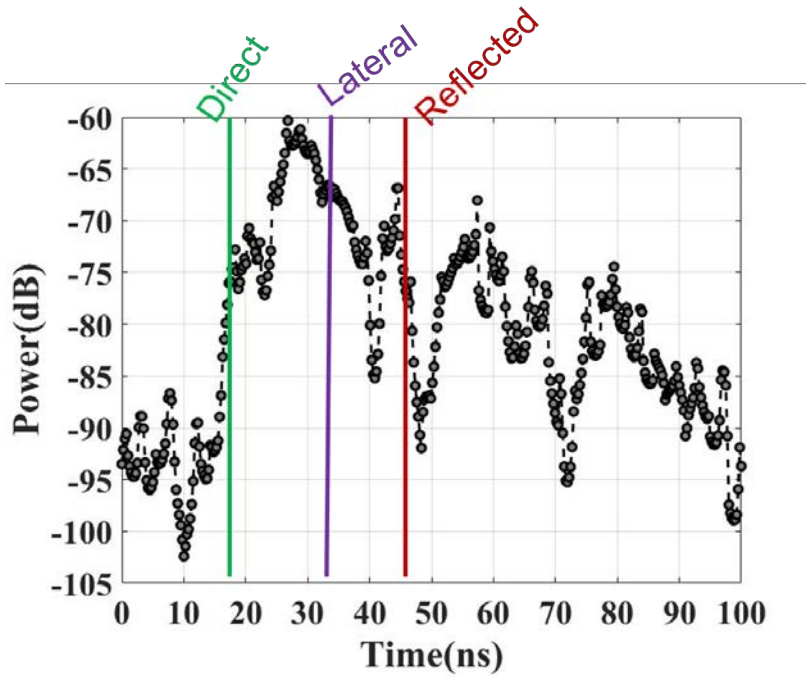
Model Validation – Three Soils



Silty Clay Loam



Silt Loam



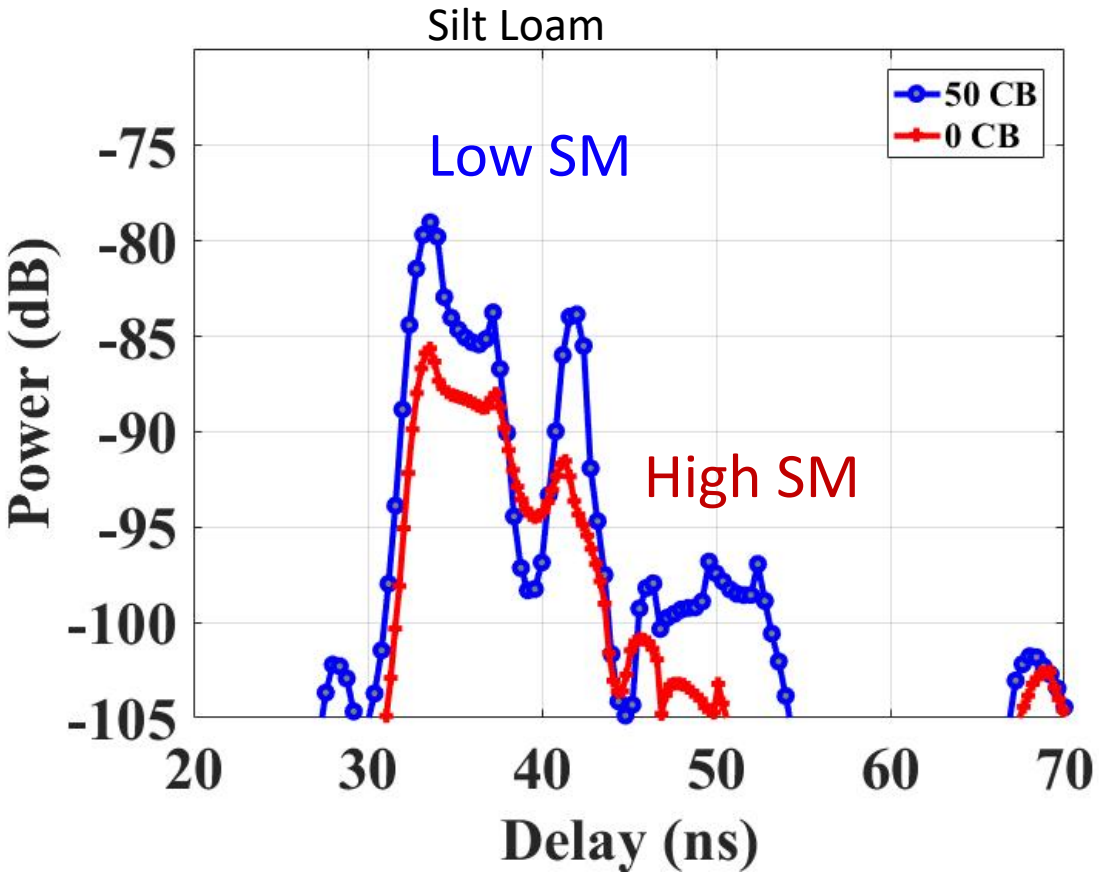
Sandy Soil

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
	μ	σ	μ	σ	μ	σ	μ	σ		
Silty Clay Loam	34.77	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	0.80	27.89	2.76	29.54	1.66	40 dB	44 dB

Sandy soil has low attenuation

Impact of Soil Moisture (SM) Variations

- Water contained in the first few particle layers of the soil
- Strongly held by soil particles
- Reduced effects of osmotic and matric forces



Statistical Model

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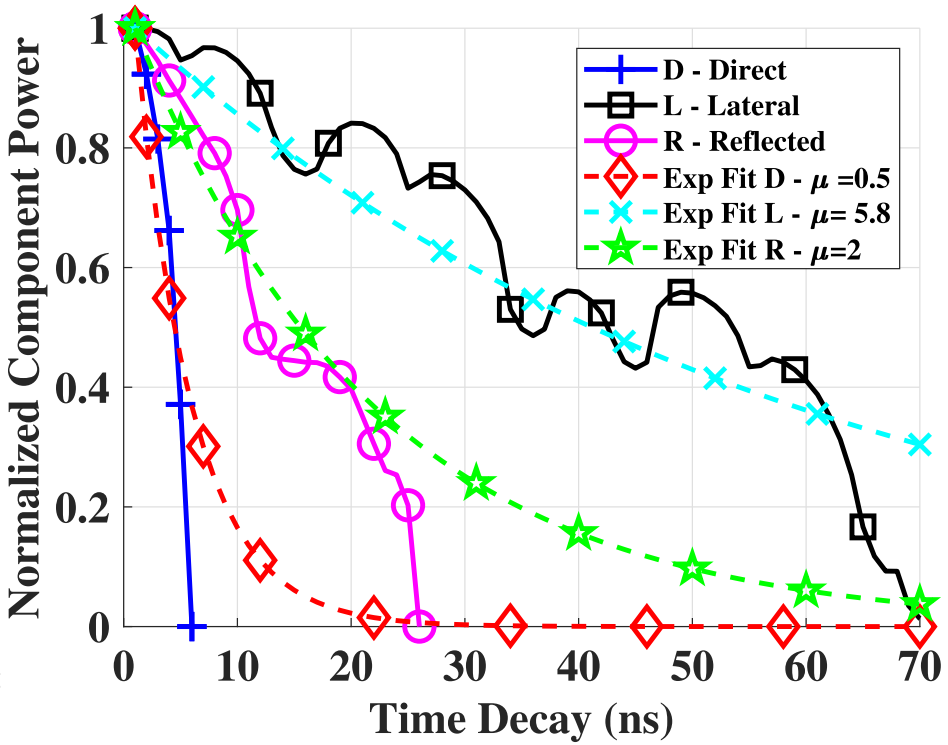
$$\mathrm{h_{ug}}(t) = \sum_{i=0}^{L-1} \alpha_{\mathrm{l},i}\delta(t-\tau_{\mathrm{l},i}) + \sum_{j=0}^{D-1} \alpha_{\mathrm{d},j}\delta(t-\tau_{\mathrm{d},j}) + \sum_{k=0}^{R-1} \alpha_{\mathrm{r},k}\delta(t-\tau_{\mathrm{r},k})$$

$$\alpha_{\mathrm{l},i} = \alpha_{\mathrm{l},0}e^{-(\tau_{\mathrm{l},i}-\tau_{\mathrm{l},0})/\gamma_{\mathrm{L}}} \ \forall\ 0 < i < L,$$
$$\alpha_{\mathrm{d},j} = \alpha_{\mathrm{d},0}e^{-(\tau_{\mathrm{d},j}-\tau_{\mathrm{d},0})/\gamma_{\mathrm{D}}} \ \forall\ 0 < j < D,$$
$$\alpha_{\mathrm{r},k} = \alpha_{\mathrm{r},0}e^{-(\tau_{\mathrm{r},k}-\tau_{\mathrm{r},0})/\gamma_{\mathrm{R}}} \ \forall\ 0 < k < R,$$

- Statistical path gain model for each path
  - Multipath components between each major path (L, D, R) are statistically independent
  - Multipaths within each major path are correlated
  - Phases arrive at the receiver with a uniform distribution
- Modeled as decaying exponentials



Tailored UG Communication Solutions

- 3-wave model -> UG channel diversity reception to combine multipaths [1]
- Lateral wave -> UG antenna array design and UG beamforming to increase range [2]
- Dynamic coherent bandwidth -> Adaptive UG multi-carrier modulation to increase data rates [3]
- Dynamic Permittivity of soil -> Underground antenna [4]

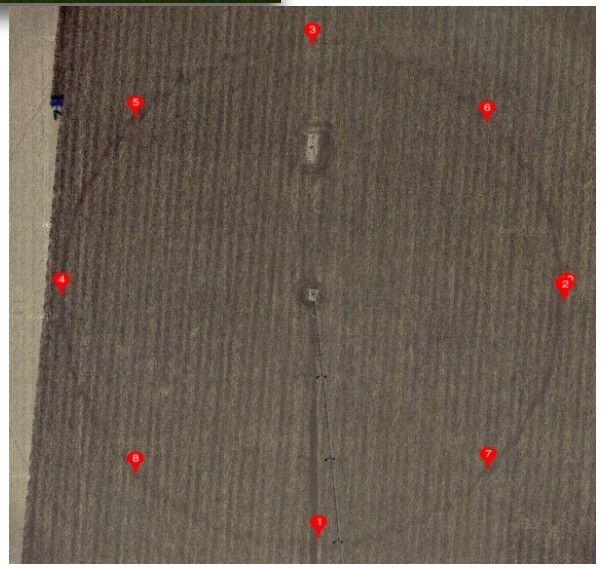
[1] A. Salam, M. C. Vuran, ``Wireless Underground Channel Diversity Reception With Multiple Antennas for Internet of Underground Things,'' in Proc. IEEE ICC '17, May 2017.
[2] A. Salam, M. C. Vuran, ``Smart Underground Antenna Arrays: A Soil Moisture Adaptive Beamforming Approach,'' in Proc. IEEE INFOCOM '17, Atlanta, GA, May 2017.
[3] A. Salam and M. C. Vuran, ``Impacts of Soil Type and Moisture on the Capacity of Multi-Carrier Modulation in Wireless Underground Communications,'' in Proc. ICCCN '16, Waikoloa, Hawaii, Aug. 2016. (Best Student Paper Award).
[4] M. C. Vuran, X. Dong, D. Anthony, ``Antenna for wireless underground communication,'' U.S. Patent US 9532118 B2, Dec. 2016.

I-OUT - Center Pivot - Cloud Integration

X. Dong, M. C. Vuran, and S. Irmak, "Autonomous Precision Agriculture Through Integration of Wireless Underground Sensor Networks with Center Pivot Irrigation Systems," Ad Hoc Networks Journal, vol. 11, no. 7, pp. 1975-1987, Sept. 2013.

2011-2013

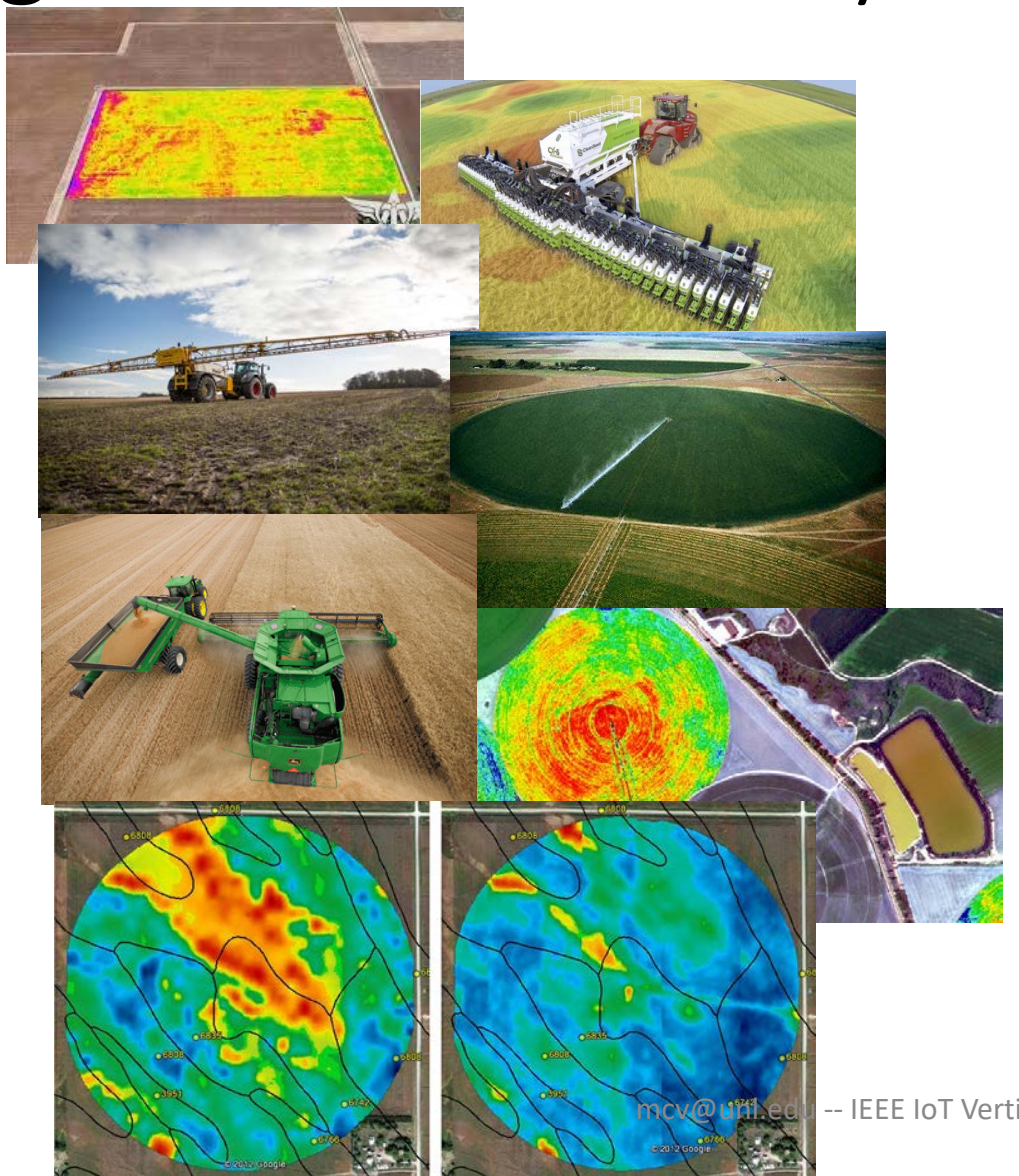
2014



2015-2019

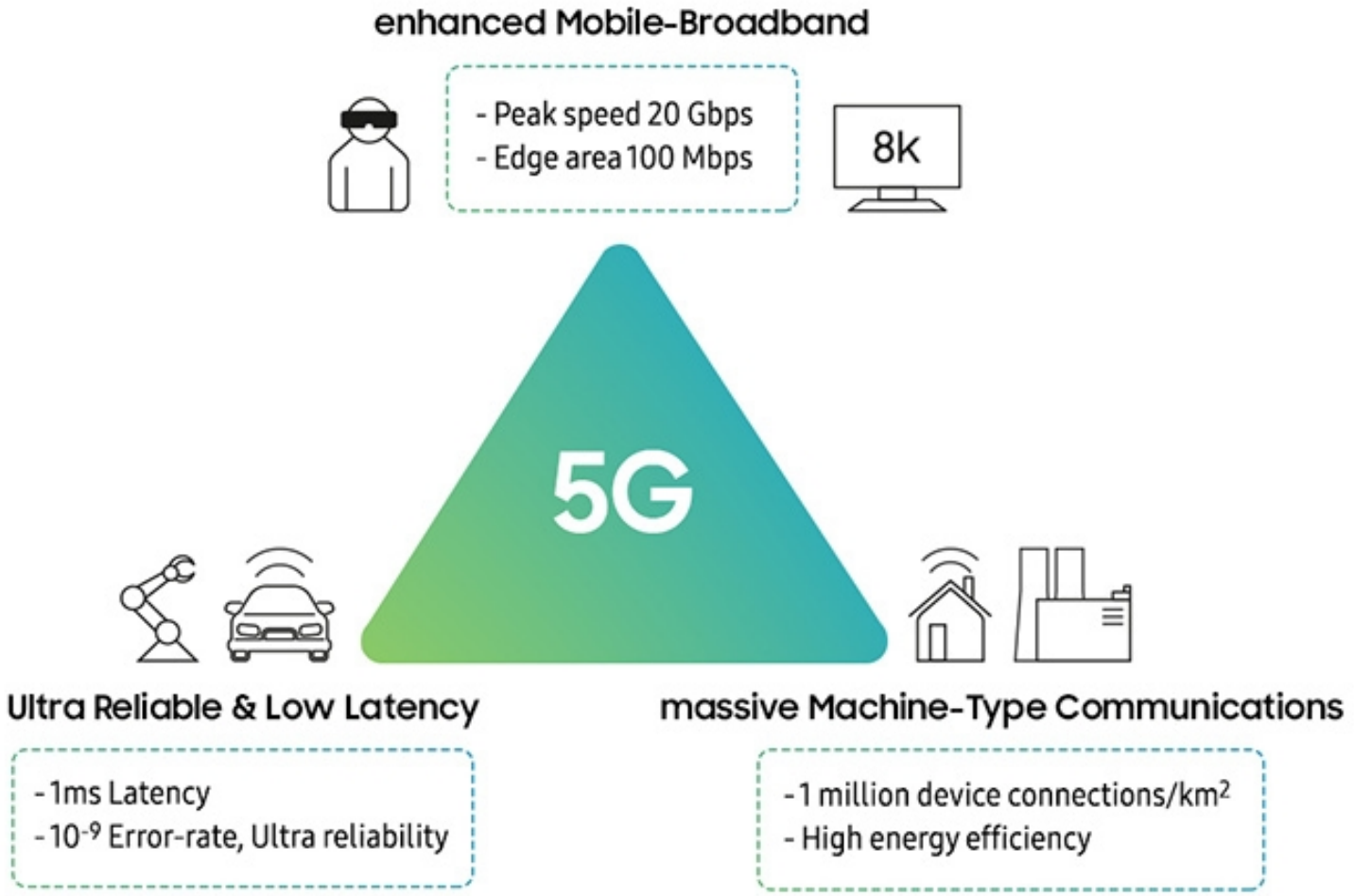
Big Picture: Ag-IoT Data

Ag-IoT Data - Variety

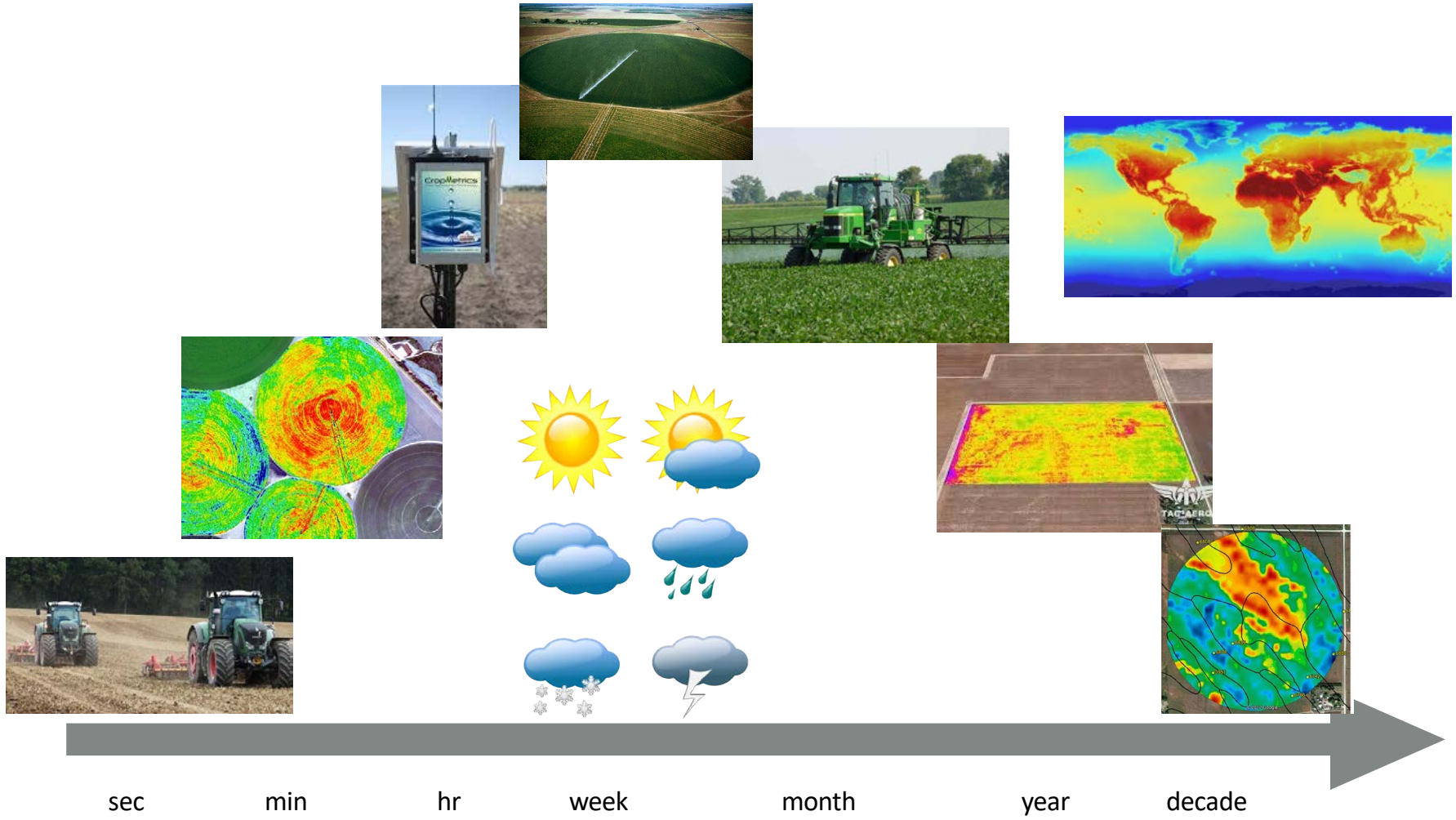


Ag-IoT Data - Volume

- Collection
  - 5G for Ag?
  - Connectivity, bandwidth
- Training
  - Lack of past data
  - Privacy, sharing, fusion
  - Every farm is different (?)
- Domain knowledge



Ag-IoT Data - Velocity



Ag-IoT Data - Veracity

- Does what I see represent what is happening down there?
  - Data validation: Pedigree and provenance
  - Model accuracy
  - Standardization
- Privacy & Security
  - Wireless
  - Databases
  - Sharing and decision making
- User trust
  - "I know my field better than anyone else!"
- Information → Decision & Action

Ag-IoT Data Who is the user?

AG Service Providers

PureSense

AquaCheck SOIL MOISTURE MANAGEMENT

AquaSpy

Gov. Agencies (NRD, Power)

Upper Republican Natural Resources District

Protecting Lives. Protecting Property. Protecting the Future.

UPPER BIG BLUE NRD "CONSERVATION IS THE NATURE OF OUR BUSINESS"

your energy partner OPPD Omaha Public Power District

LES Lincoln Electric System

VALLEY Precision Irrigation Made Easy

Reinke MORE RIGHT THAN RAIN

Center Pivot Companies

Sentek technologies

IRROMETER

AG Sensor Manufactures

Sprint

verizon wireless

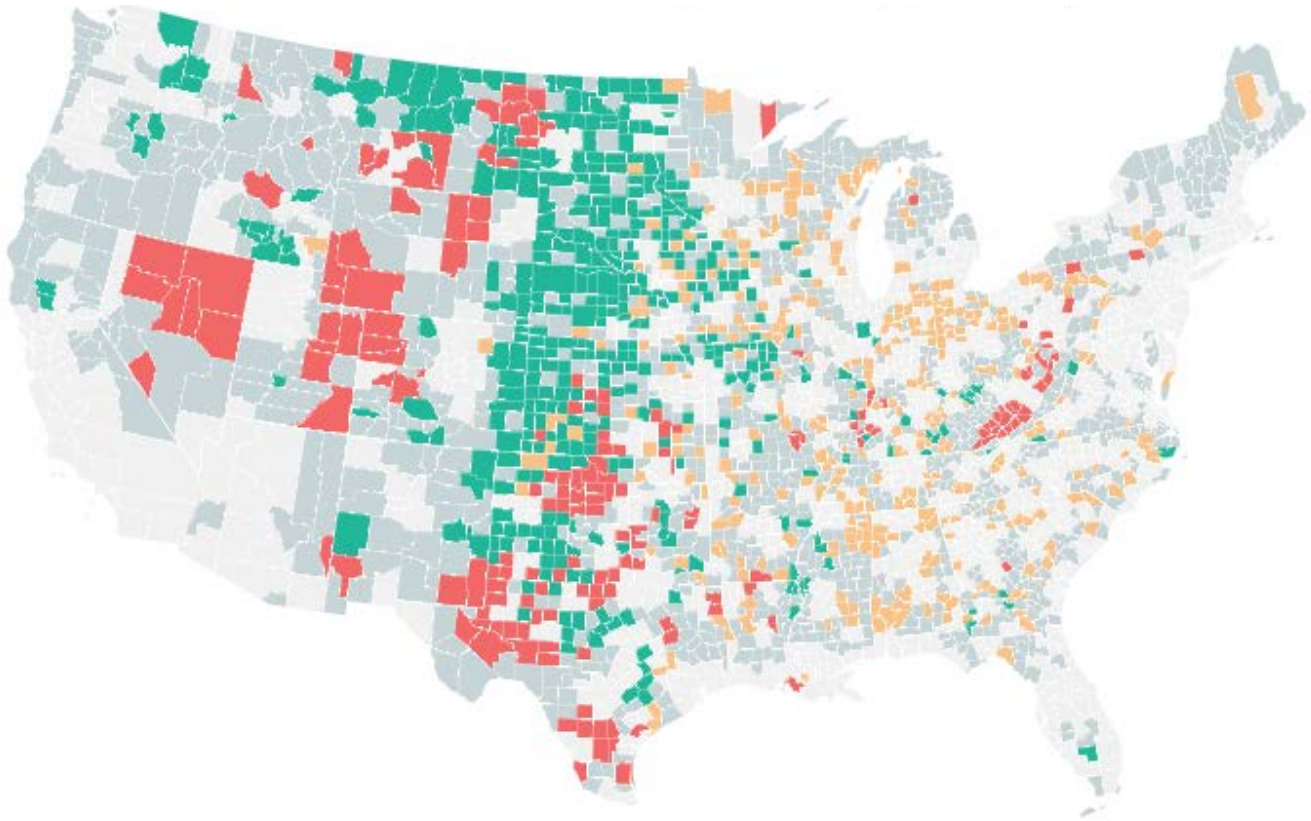
Cellular Service Providers

Rural Economy

- Homes, fields, ranches, factories
  - Majority of Midwest is Ag-driven
- Can Agricultural IoT (Ag-IoT) become one of the economic drivers?

FIGURE 1

Nonmetro counties where the primary industry—agriculture, manufacturing, or mining—exceeds 25 percent of employment or 15 percent of earnings



Note: Counties not shaded are metropolitan counties in which the primary industry is not agriculture, manufacturing, or mining, or where those industries account for less than 25 percent employment and 15 percent of earnings.
Source: Economic Research Service, "Atlas of Rural and Small-Town America," available at https://www.ers.usda.gov/data-products/atlas-of-rural-and-small-town-america/ (last accessed June 2019).

CAP

Thank You

Prof. Suat Irmak
Agnelo Silva, Dr. Xin Dong, Dr. Abdul Salam, Rigoberto Wong, Baofeng Zhou

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Further Reading

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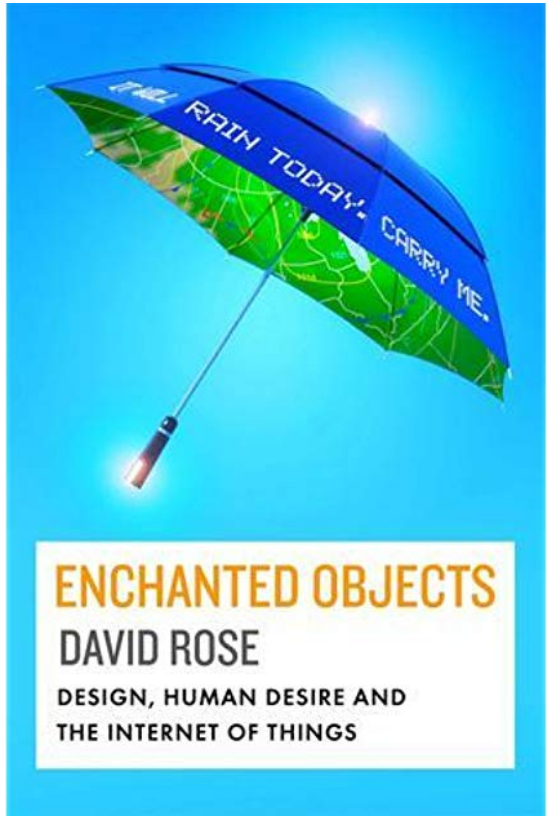
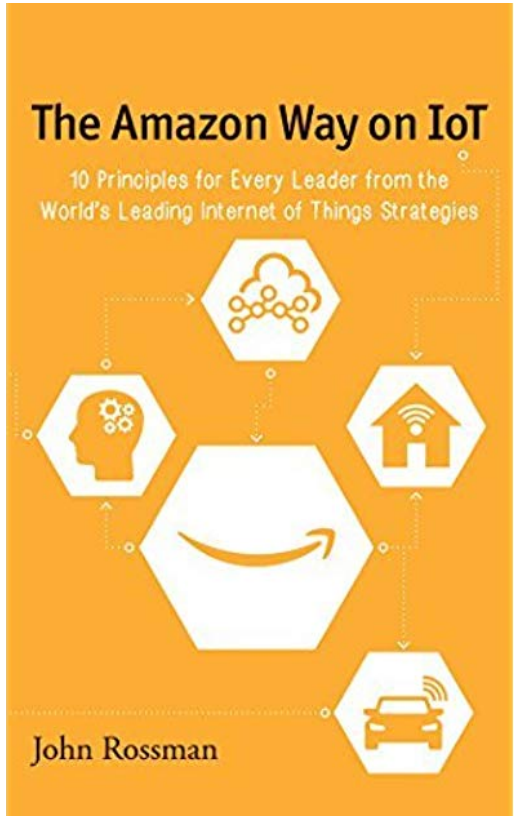
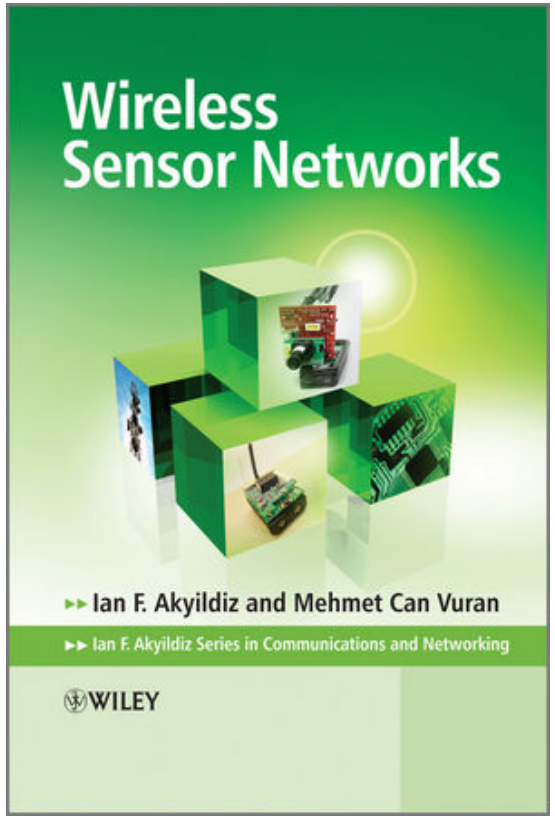
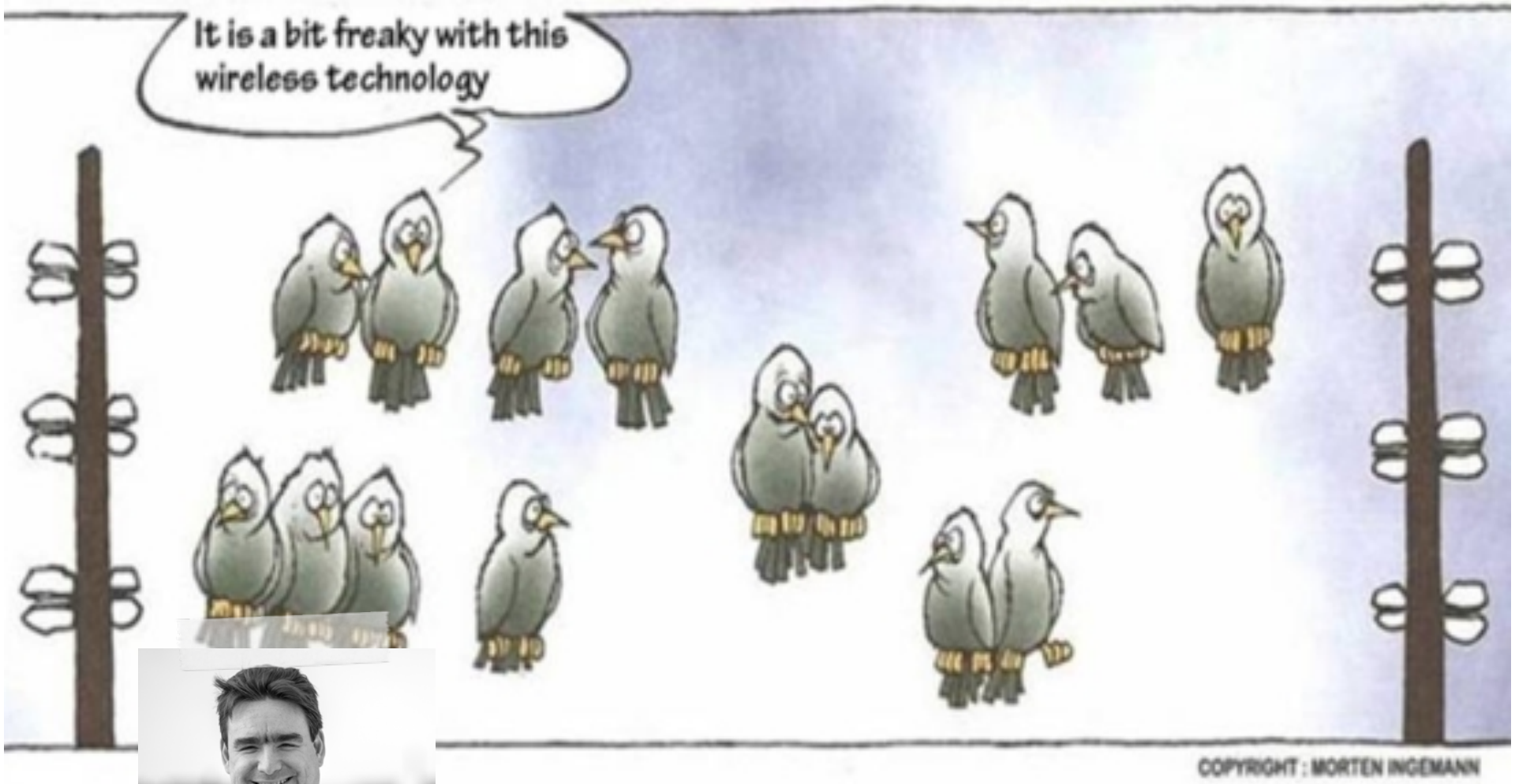






QUESTIONS?



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