Theoretical Analysis and Experimental Study of Underground Wireless Sensor Networks

中興工程顧問社
土木水利及軌道運輸研究中心
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Outline

1. Background
2. Theoretical Analysis
3. Experimental Study
4. Development of Advanced Underground WSN System

Background
簡歷

現職	
中興工程顧問社副研究員	
學歷	
• **2005/9 ~2011/6**	國立交通大學土木工程研究所博士(雙主修電機與控制工程研究所碩士)
• **2001/9 ~ 2003/6**	國立交通大學土木工程研究所碩士
• **2001/9 ~ 2003/6**	國立交通大學資訊管理研究所輔所
經歷	
• **2016/10~2017/10**	加州大學柏克萊分校土木工程系博士後訪問學者(Advisor: Professor K. Soga)
• **2011/8~2016/9**	中興工程顧問社副研究員
• **2009/7~2009/9**	日本東京大學短期研究

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Background
研究團隊與技術

Prof. Kenichi Soga

UNIVERSITY OF CAMBRIDGE

Cambridge Centre for Smart Infrastructure and Construction

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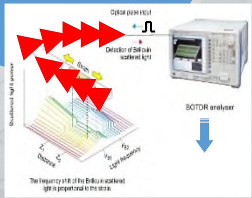
Civil and Environmental Engineering

地下無線感測網路

物聯網

先進光纖技術



關鍵技術

Prof. Thomas Denis O'Rourke

Cornell University
Bovay Lab

Full Scale Pipeline Experimental Lab

全美最大實尺寸地下管線實驗場

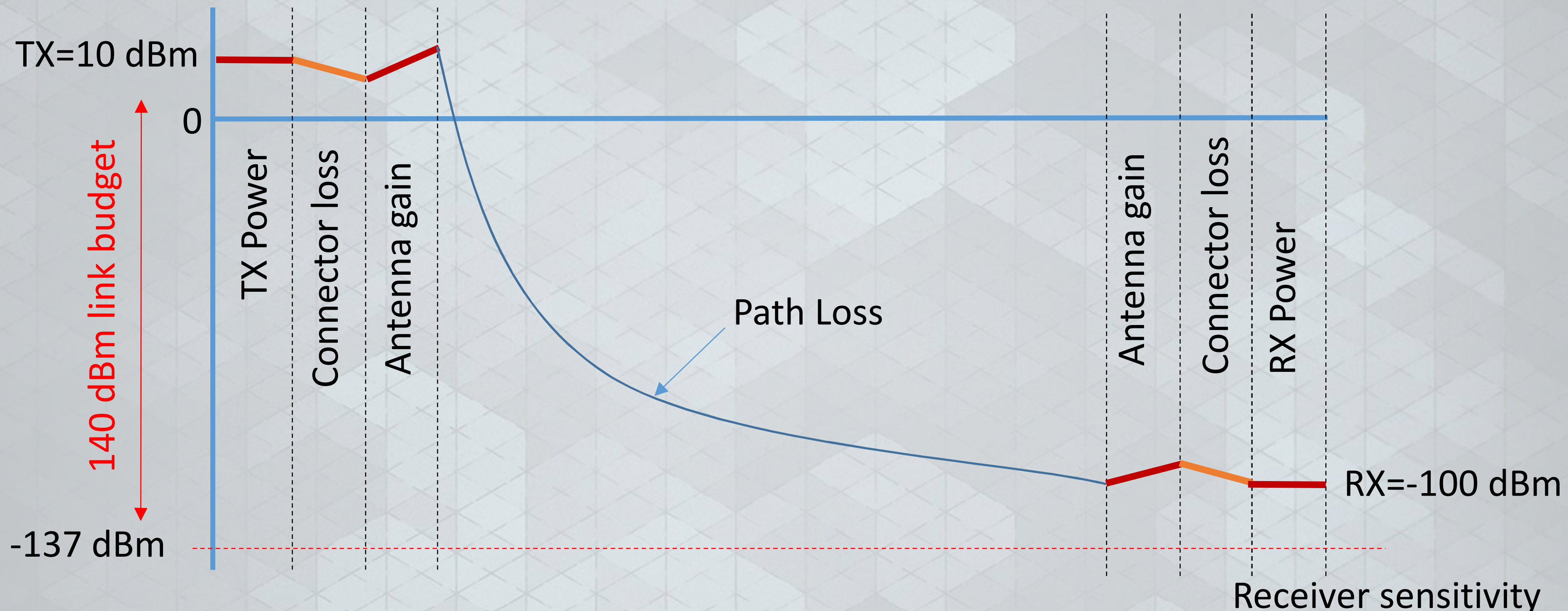
Background

研究目的

- Wireless transmission in the air can reach several kilometers.
- What is the transmission distance of the wireless transmission in the soil?
- What are the main factors that affect the wireless transmission in the soil?

Theoretical Analysis

Link budget(鏈接預算)



Theoretical Analysis

In Air Signal Propagation

Path loss (or path attenuation) is the reduction in power density (attenuation) of an electromagnetic wave as it propagates through space.

Pass loss model in free space

$$L_0 = 20\log\frac{4\pi d}{\lambda_0} = -147.6 + 20\log(d) + 20\log(f) \qquad (1)$$

where *d* is the distance between the transmitter and the receiver in meters, λ_0 is the wavelength in free space, and f (= $1/\lambda_0$) is the operating frequency in Hz.

Theoretical Analysis

In Air Signal Propagation

Theoretical maximum in free space

2.4 GHz, with 95.5 dBm link budget:

550 meters

915 MHz, with 151 dBm link budget:

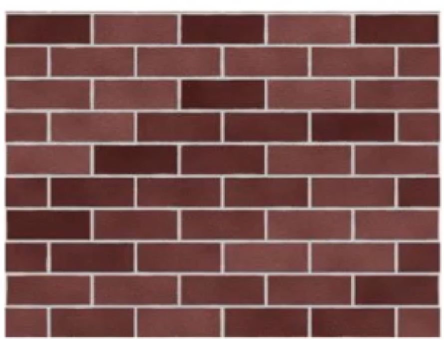
850,000 meters

Ref. https://pages.arm.com

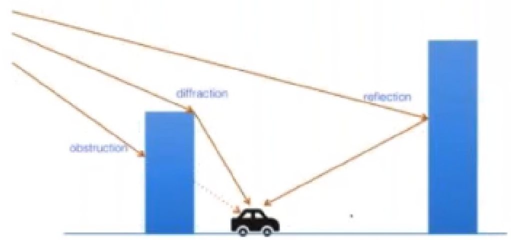
Theoretical Analysis

In Air Signal Propagation

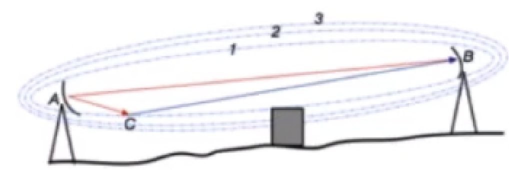
Unfortunately... we don't live in free space



Attenuation



Reflection and diffraction



Fresnel zone

Ref. https://pages.arm.com

Theoretical Analysis

In Soil Signal Propagation

When an EM wave propagates in soil, the path loss has two additional components:

$$L_s = L_\beta + L_\alpha \quad (2)$$

where L_β is the attenuation loss due to the difference of the wavelength of the signal in the soil, λ, compared to the wavelength in free space, λ_0; and L_α is the transmission loss caused by attenuation. L_β and L_α can be represented in *dB* as follows:

$$L_\beta = 154 - 20\log(f) + 20\log(\beta), \qquad L_\alpha = 8.69\alpha d \quad (3)$$

By combining Eqs. (1) to (3), the path loss of an EM wave in soil is as follows:

$$L_p = L_0 + L_s = 6.4 + 20\log(d) + 20\log(\beta) + 8.69\alpha d \quad (4)$$

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Theoretical Analysis

In Soil Signal Propagation

$$L_p = L_0 + L_s = 6.4 + 20\log(d) + 20\log(\beta) + 8.69\alpha d \quad (4)$$

The attenuation constant *α* and the phase shift constant *β* (i.e.) are given by the Peplinski principle, which governs the value of the complex propagation constant of the EM wave in soil.

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon'\varepsilon_0}{2}[\sqrt{1+(\frac{\varepsilon''}{\varepsilon'})^2} - 1]} \qquad \beta = \omega\sqrt{\frac{\mu\varepsilon'\varepsilon_0}{2}[\sqrt{1+(\frac{\varepsilon''}{\varepsilon'})^2} + 1]} \quad (5)$$

where $\omega = 2\pi f$ is the angular frequency

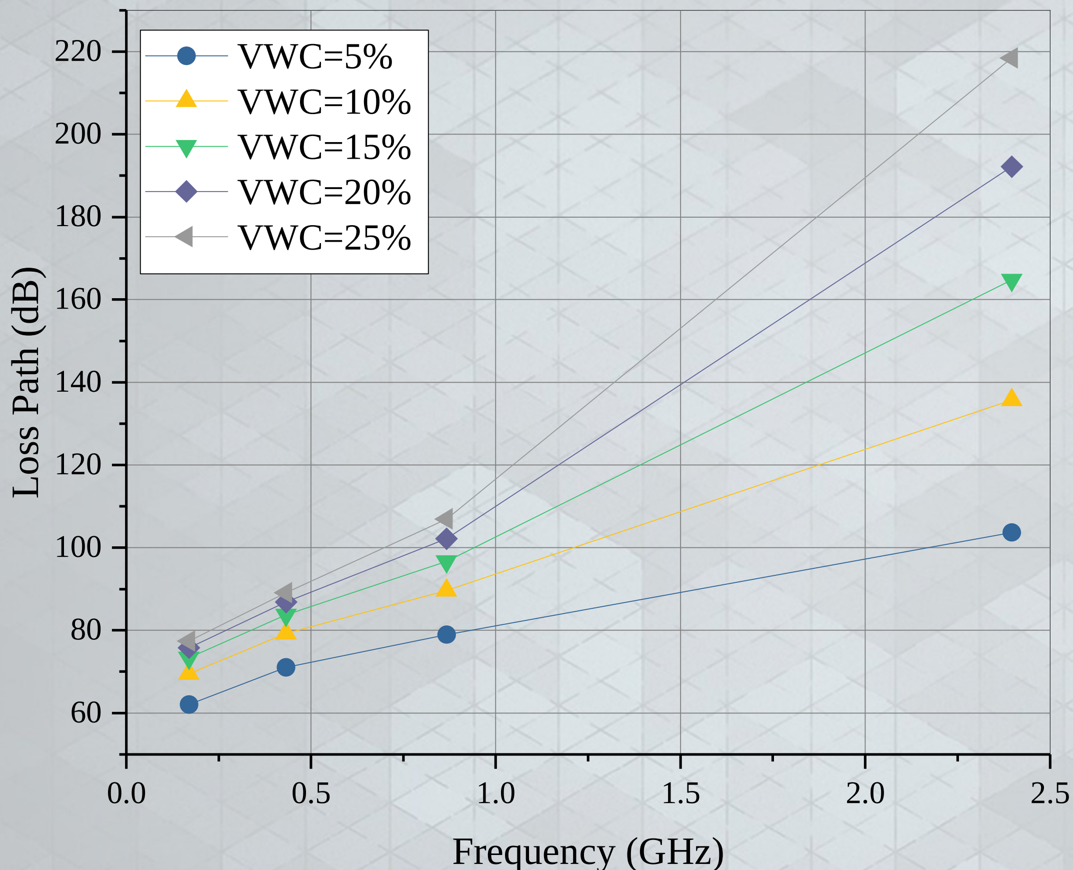
ε' and ε'' are the real and imaginary parts of the relative dielectric constant.

μ is the magnetic permeability of soil (i.e., 1.257×10^{-6} H/m);

ε_0 is the dielectric permittivity of free space (i.e., value of 8.85×10^{-12} F/m)

Theoretical Analysis

In Soil Signal Propagation



$$L_p = L_0 + L_s = 6.4 + 20\log(d) + 20\log(\beta) + 8.69\alpha d$$

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$$\alpha = \omega\sqrt{\frac{\mu\varepsilon'\varepsilon_0}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right]}$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon'\varepsilon_0}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} + 1\right]}$$

土壤含水量與無線頻率為影響土層內無線訊號傳輸的主因

Experimental Study

Experimental Study

Configuration of Test Hardware

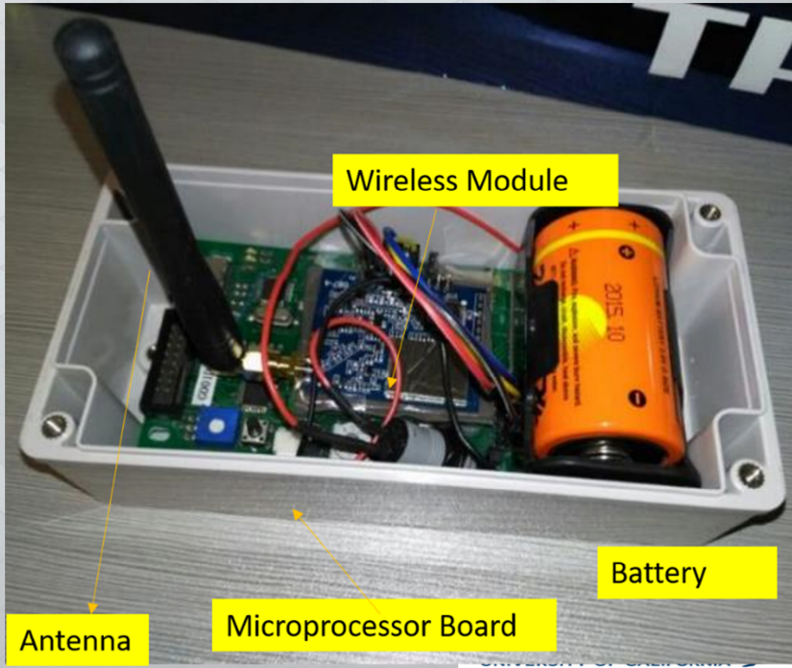
- Microprocessor Board: WISEN Atmel-Based Board
- Wireless Module: TI CC1120
- Battery: ER34615 3.6V 19AHr D Cell Battery
- Antenna: 1.5 dBi Dipole Antenna

Power Consumption of Wireless Node

Rx Power	Tx Power	Battery Capacity
60mA	290mA	19000mAH

Parameter of Wireless Module

Operation Frequency	Data Rate	RF Power	Antenna	Transmit Power	Receive Sensitivity
433MHz	9.6Kbps	26dBm	1.5dBi	26dBm (0.4W)	-125dBm



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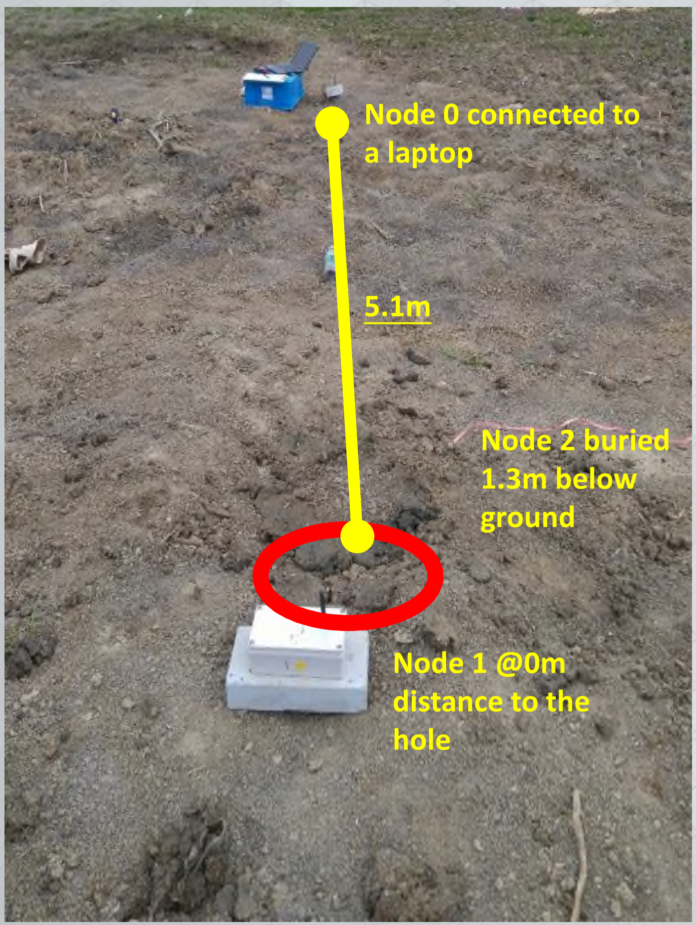
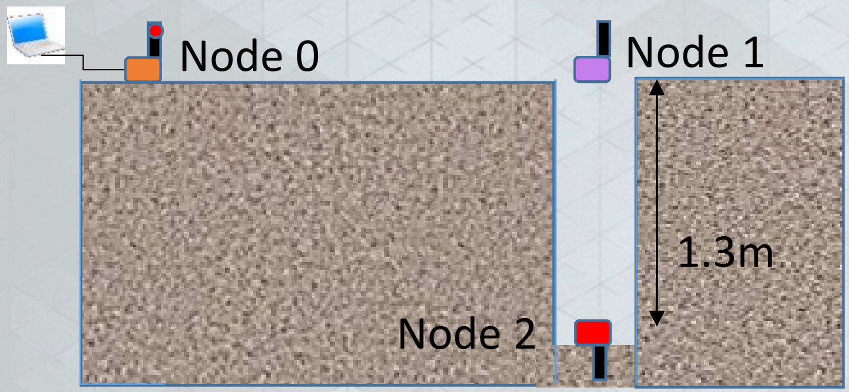
Experimental Study

Setup of Experiment



Experimental Study

Calibration Inspection Before Soil Burial

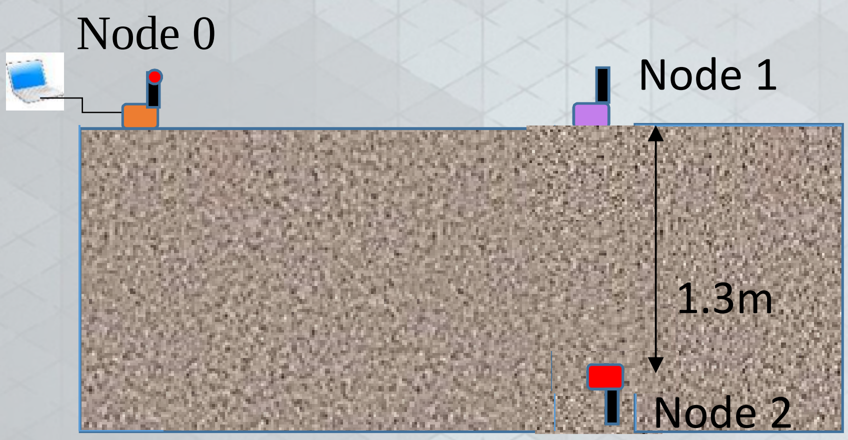


RSSI(21)	RSSI(12)	Packet Loss Rate(1-0)	Packet Loss Rate(2-1)
-42	-39	0%	0%

- Purpose: To Make sure the wireless node are working properly before buried.
- Evaluate Parameters: RSSI, Packet Loss Rate
  - RSSI: Received Signal Strength Index
  - Packet Loss Rate: Received packets/Sending packets

Experimental Study

Signal Strength vs. Filled Soil Depth

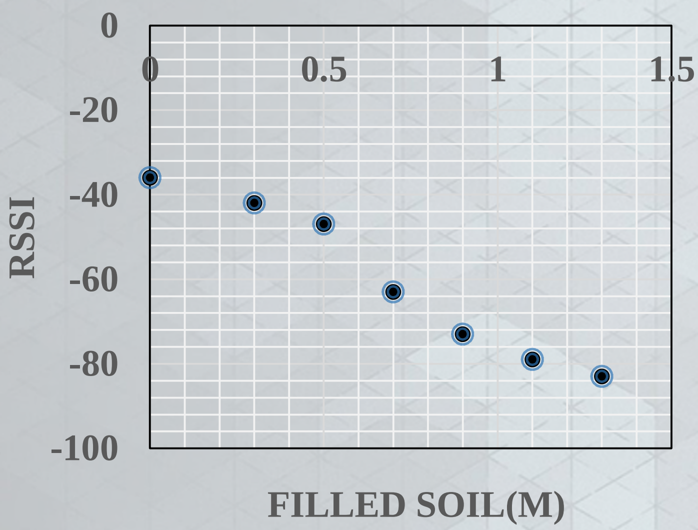


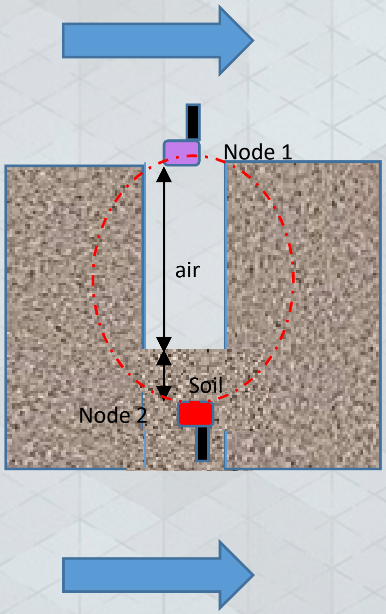
Filled Soil Depth	RSSI(21)	RSSI(12)	Packet Loss Rate(1-0)	Packet Loss Rate(2-1)
0	-36	-32	0.00%	4.16%
0.2	-42	-37	1.58%	2.41%
0.4	-47	-42	0.46%	1.86%
0.6	-63	-57	0.67%	0.00%
0.8	-73	-66	20.91%	0.82%
1	-79	-72	6.00%	16.98%
1.3	-83	-77	1.60%	1.63%

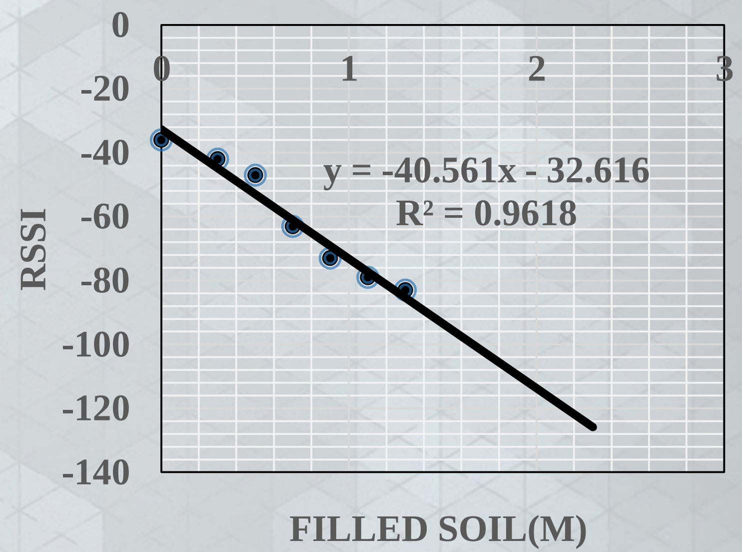
- Purpose: To see how the covered soil affect the wireless signal.
- Note: As the filled soil depth increases, the RSSI decreases.

Experimental Study

Signal Strength vs. Filled Soil Depth







- Note: Soil depth vs. RSSI plots have shown a good linear relationship.
- However, this result is caused by the combined effect of air and soil.

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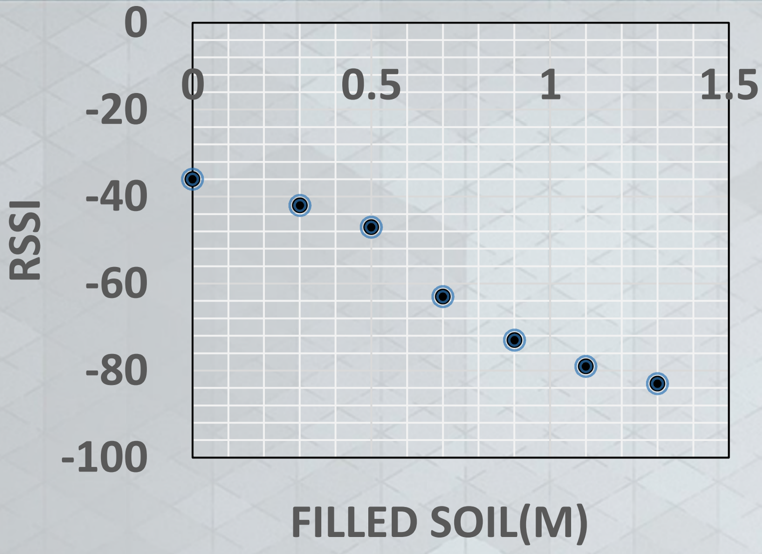
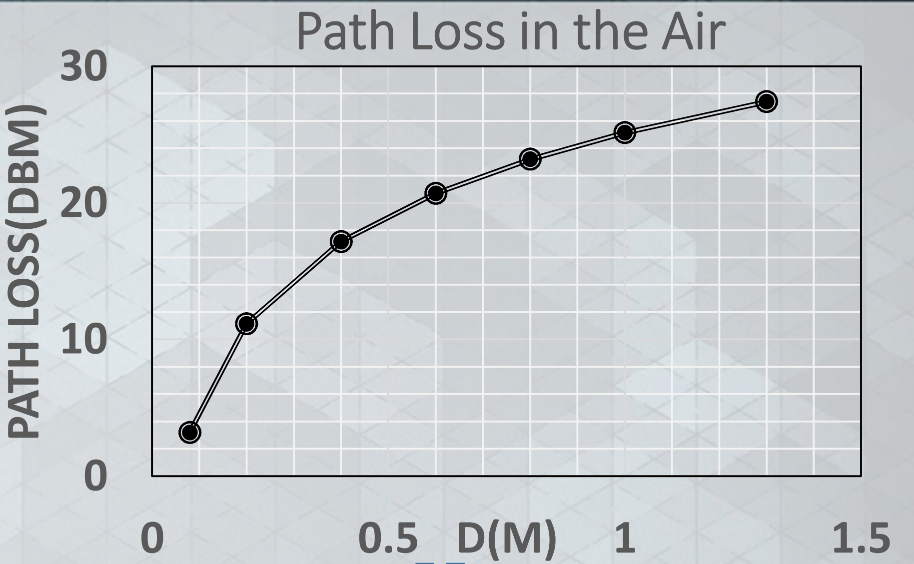
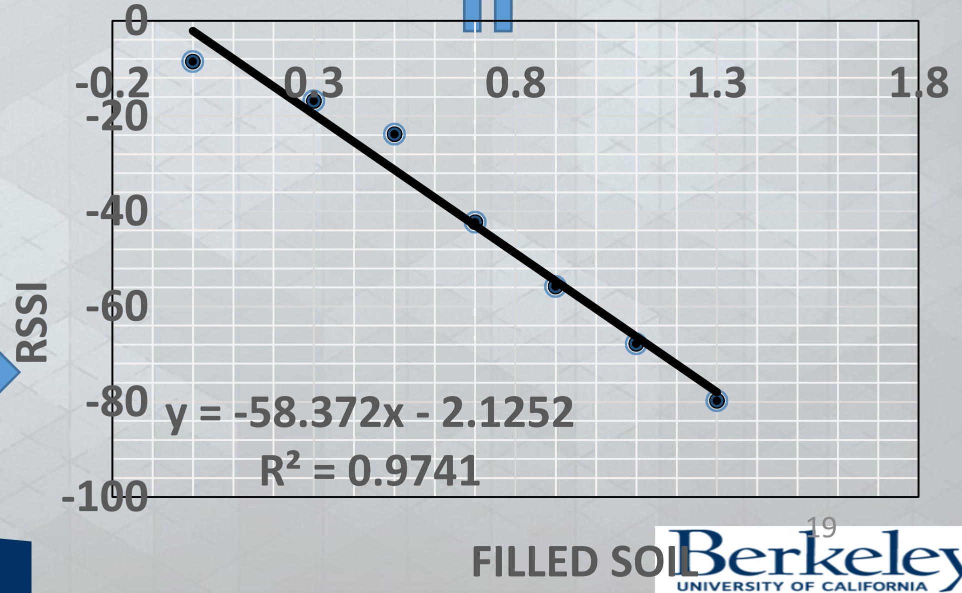
Experimental Study

Signal Strength vs. Filled Soil Depth







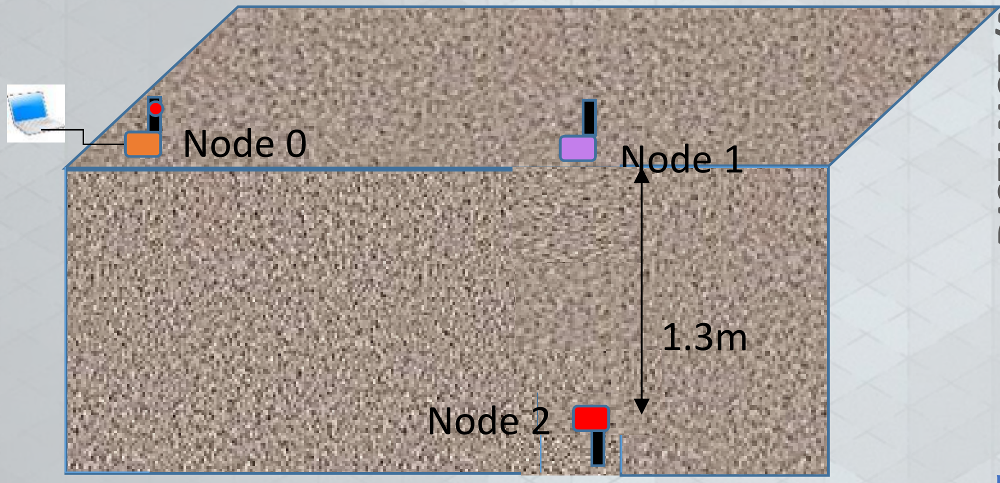
- Note: If the sensitivity of our receiver is 100dBm. We can use the regression equation to estimate the buried depth.

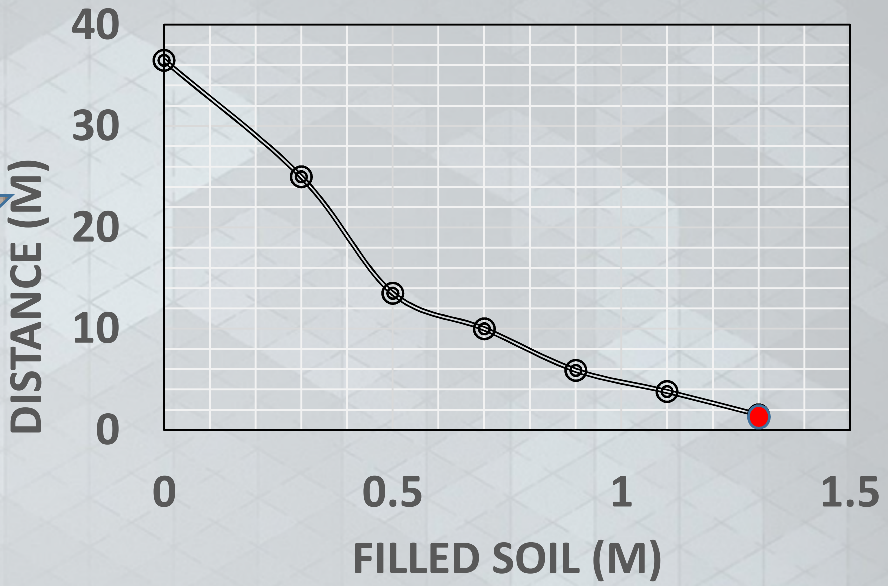
$-100dBm = -58.372x - 2.1252$

X=1.68m

Experimental Study

Max. Horizontal Distance Above Ground



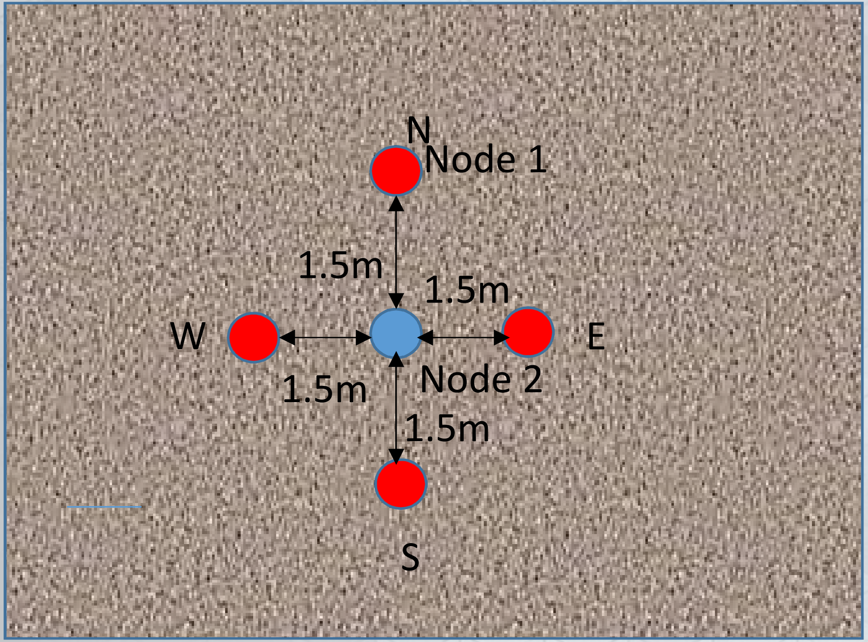


- Note: the measured distance is useful for horizontally positioning the first relay node above ground.

Filled Soil (m)	Distance (m)	RSSI21	RSSI12
1.3	1.5	-97	-98
1.1	3.8	-100	-98
0.9	5.9	-100	-97
0.7	10	-100	-99
0.5	13.5	-100	-98
0.3	25	-100	-99
0	36.5	-99	-95

Experimental Study

Directional Testing



Direction	RSSI(21)	RSSI(12)	Packet Loss Rate(1-0)	Packet Loss Rate(2-1)
N	-99	-91	0.00%	0.00%
S	-99	-91	2.29%	1.17%
E	-99	-91	1.53%	0.00%
W	-99	-95	1.67%	3.97%

- Note: This result conforms that the soil is uniform and the result of the electromagnetic wave propagating in the four directions are consistent.

Development of Advanced Underground WSN System

System Architecture and Features

Multi-Hop Underground Wireless Meshing

Remote Real-Time Visualization

Ultra low power design of Long Battery Life (2 Years+) when taking hourly reading

Cloud Computing

通訊(Communication) ⇨ LoRa物聯網+主動喚醒技術

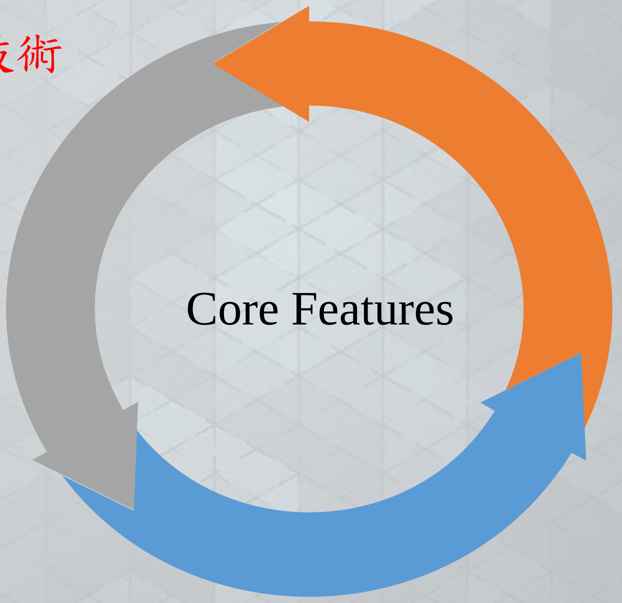
- Topology: meshing networks, e.g., tree, mesh, linear, star.
- No. of Hops: up to 10. Single hop penetration depth > 1.5m (of saturated water content).
- Sub-GHz ISM frequency, LoRa
- Wake up Communication

控制(Control) ⇨ 即時主動喚醒

- Remote sampling interval control.
- Real-time wake-up nodes.

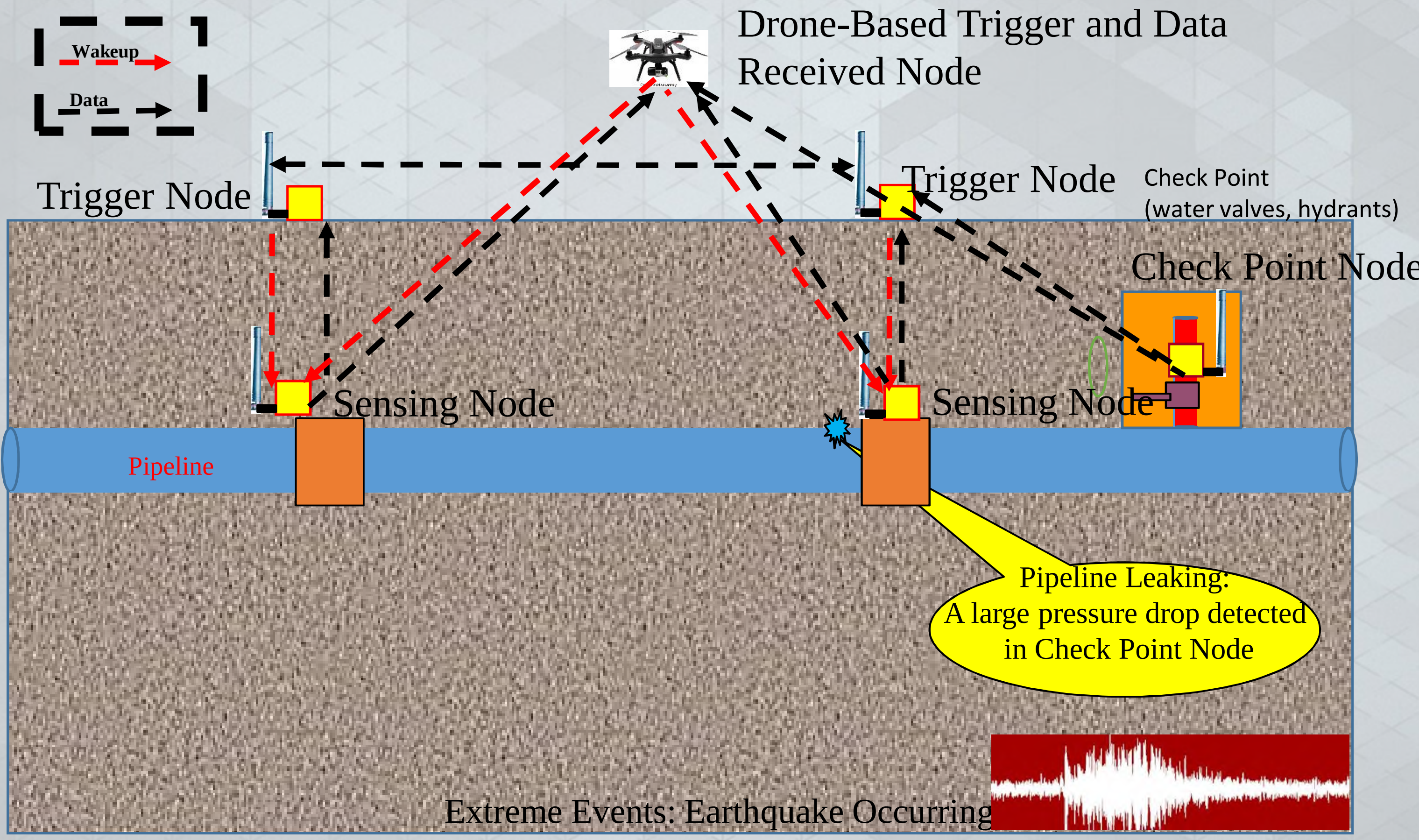
感測(Sensing) ⇨ 支援各式感測器

- Frequency domain reflectometry (FDR) soil moisture sensor.
- Smart Joint opening switch, vibration, temperature, etc.



Development of Advanced Underground WSN System

Application Scenario



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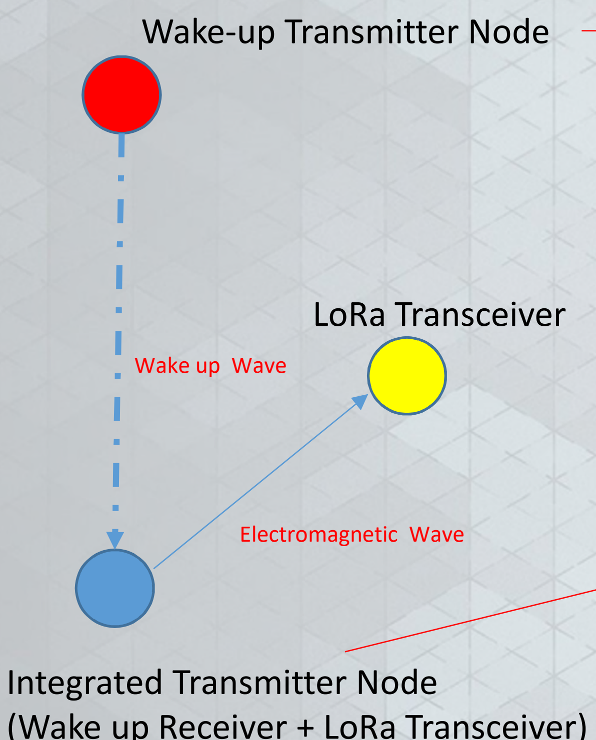
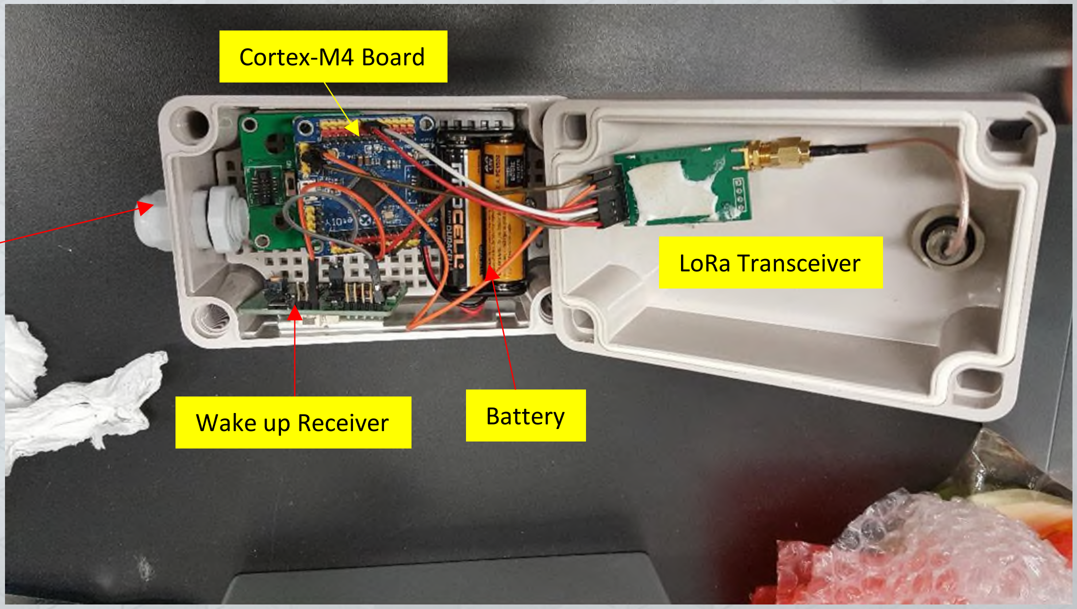
Prototype System





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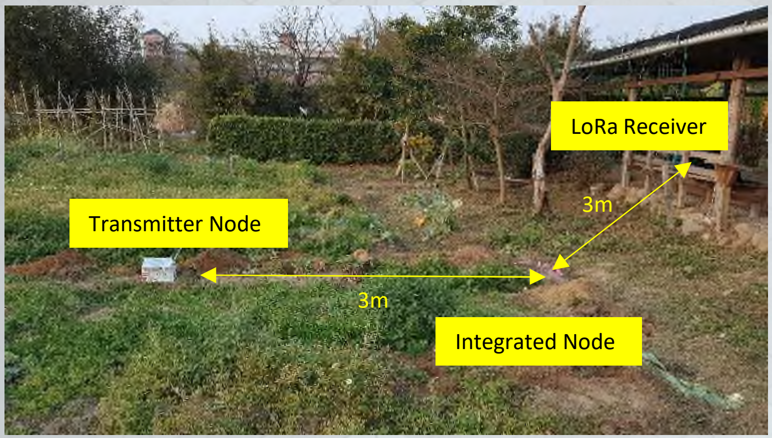
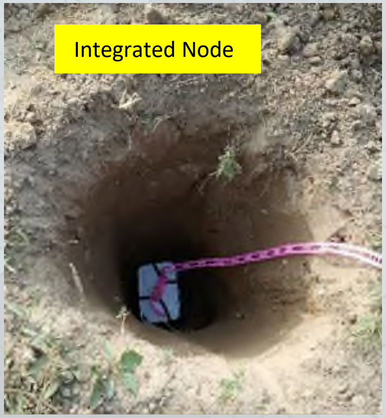
Development of Advanced Underground WSN System

Prototype Field Testing





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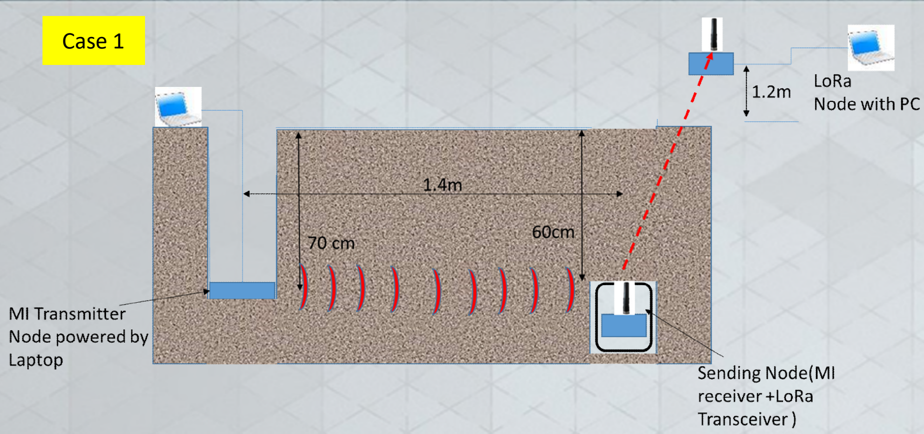
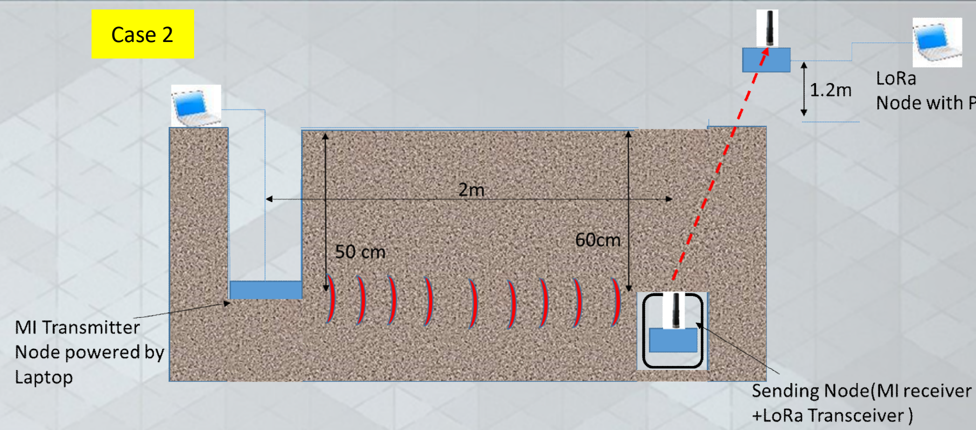
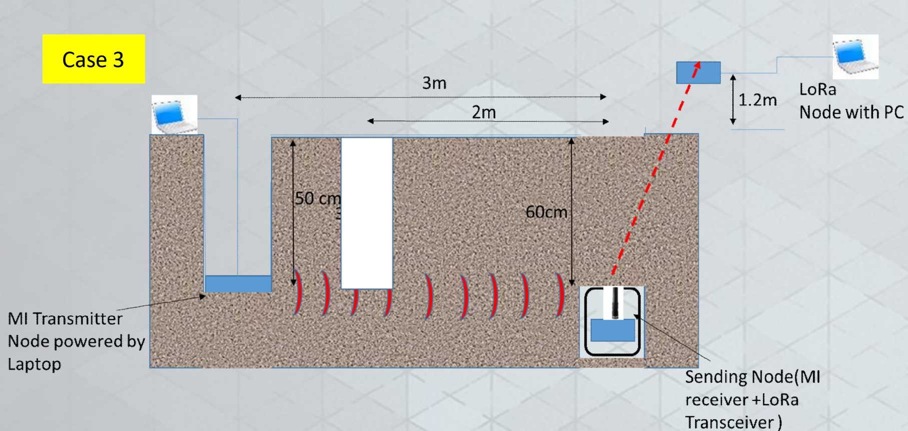
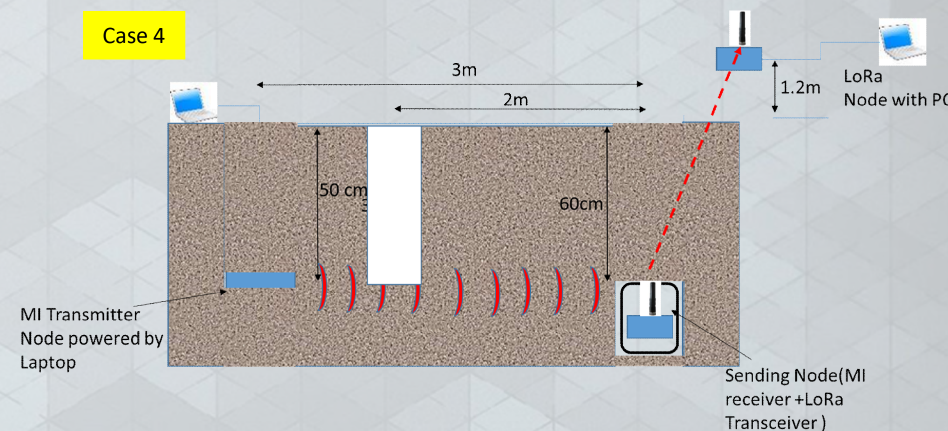
Prototype Field Testing









Case	Penetration Distance Between Transmitter Node and Integrated Transmitter Node	Packet Loss Rate	Remark
1	1.4m	<1%	
2	2m	<1%	
3	3m	<1%	
4	3m	<1%	Both transmitter node and sending node buried by the soil

Development of Advanced Underground WSN System

Full Scale Pipeline Performance Test During Large Ground Movements

Full Scale Pipeline Performance Test During Large Ground Movements

Testing New Sensing Technologies

- **Distributed fiber optic sensing**
  - Monitoring pipeline deformation continuously for many miles
- **Fiber brag grating sensors**
  - Monitoring pipeline joint movements

- **Leak detection sensor**
  - Monitoring water leakage from the pipe
- **Underground wireless sensor network**
  - Sending data wirelessly in the ground

本研究開發之系統

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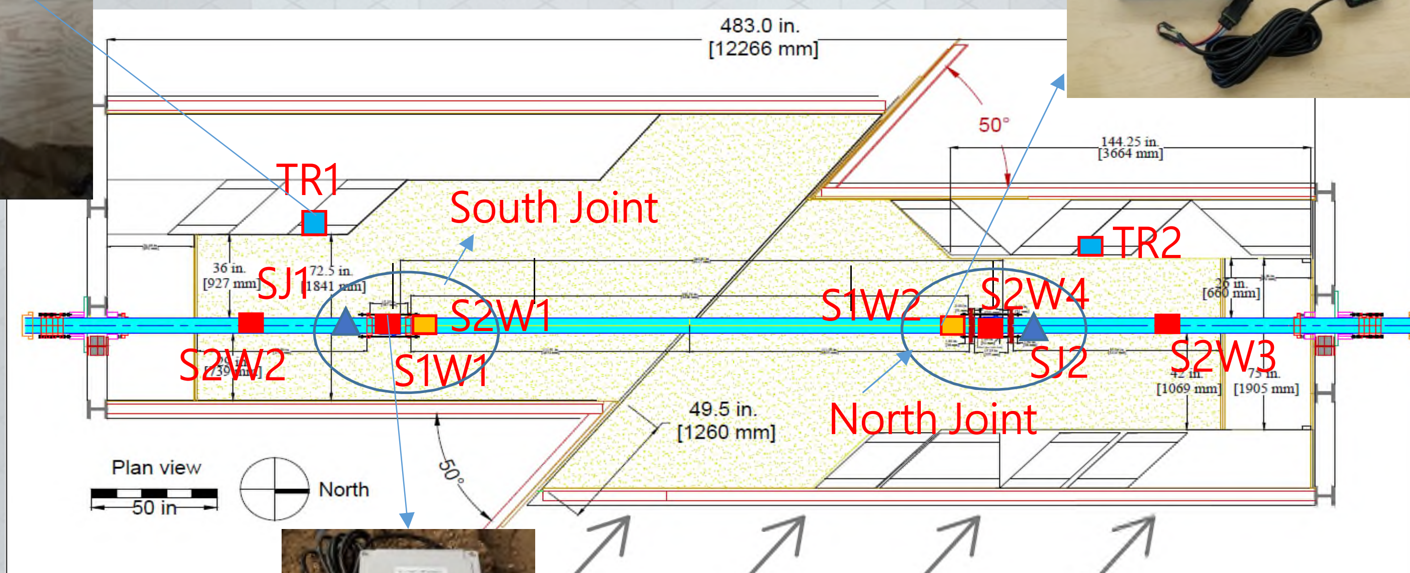
Development of Advanced Underground WSN System

Full Scale Pipeline Performance Test During Large Ground Movements

Deployment in Full-Scale Fault Rupture Test



- System 1:Sensing node,S1W1,S1W2
- System 1:Trigger node:TR1,TR2
- System 2:Sensing node,S2W1,S2W2, S2W3,S2W4 (WISEN System)
- Smart Joint Opening Switch Node:SJ1,SJ2

Development of Advanced Underground WSN System

Full Scale Pipeline Performance Test During Large Ground Movements

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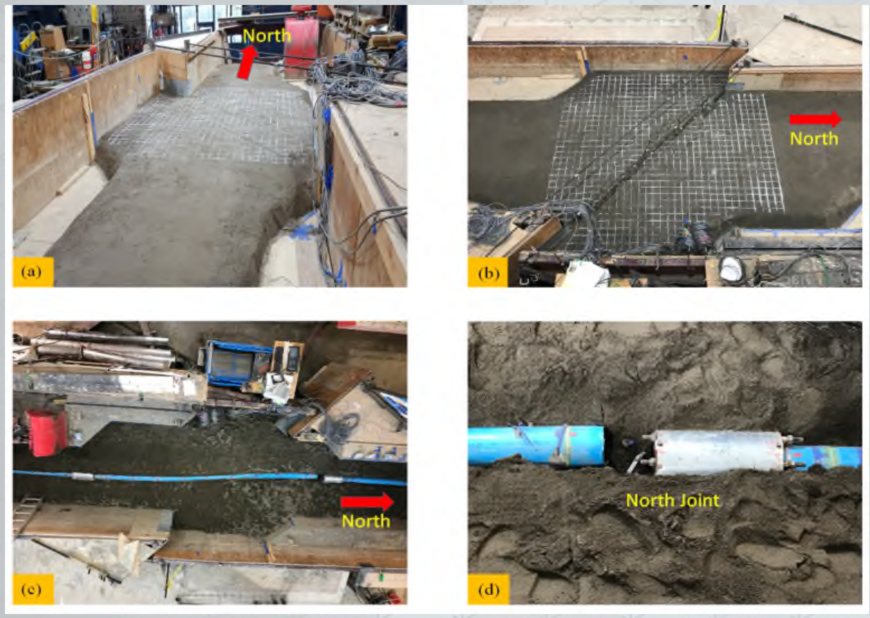
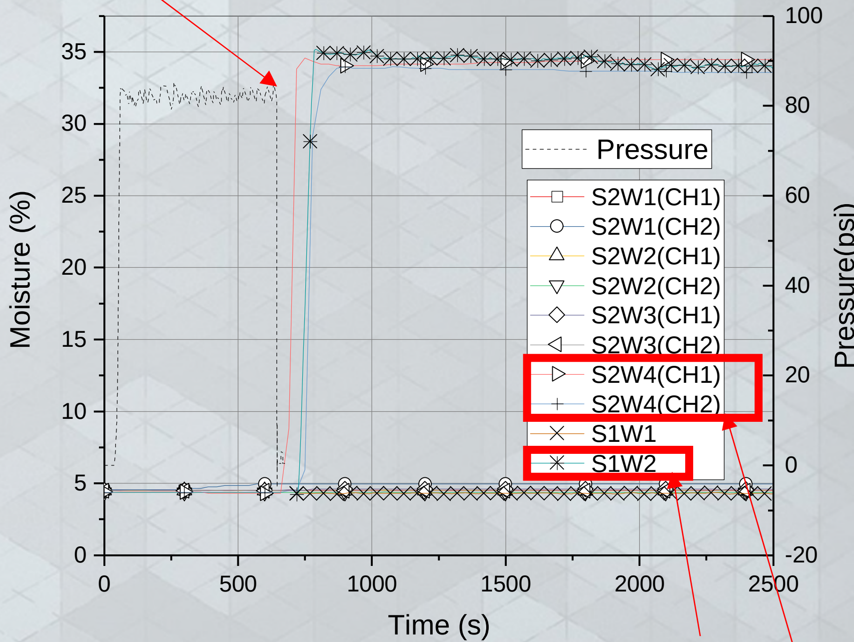
Development of Advanced Underground WSN System

Full Scale Pipeline Performance Test During Large Ground Movements

管線斷裂，水壓急降
但不知道斷裂的位置



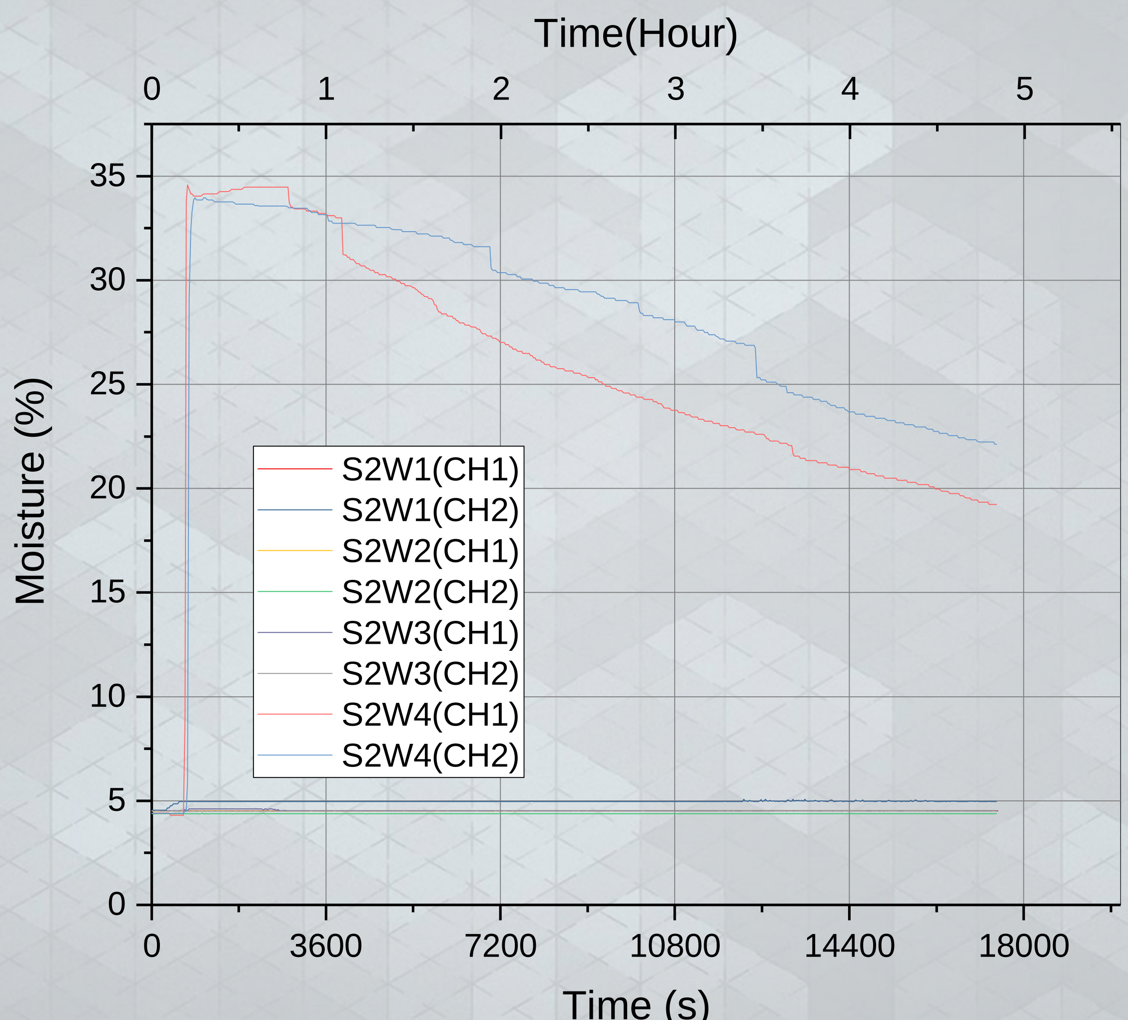
(a) Test Basin before Test; (b) Fault Rupture at Pipe Failure; (c) Pipe Excavated Following the Test ; (d) Ruptured Pipe at North Restraint



North Joint 周邊的感測節點偵測到土壤濕度上升
在移除管上覆土前提前確認了破壞的位置

Development of Advanced Underground WSN System

Full Scale Pipeline Performance Test During Large Ground Movements



Long-term Trend of Soil Moisture After Leakage

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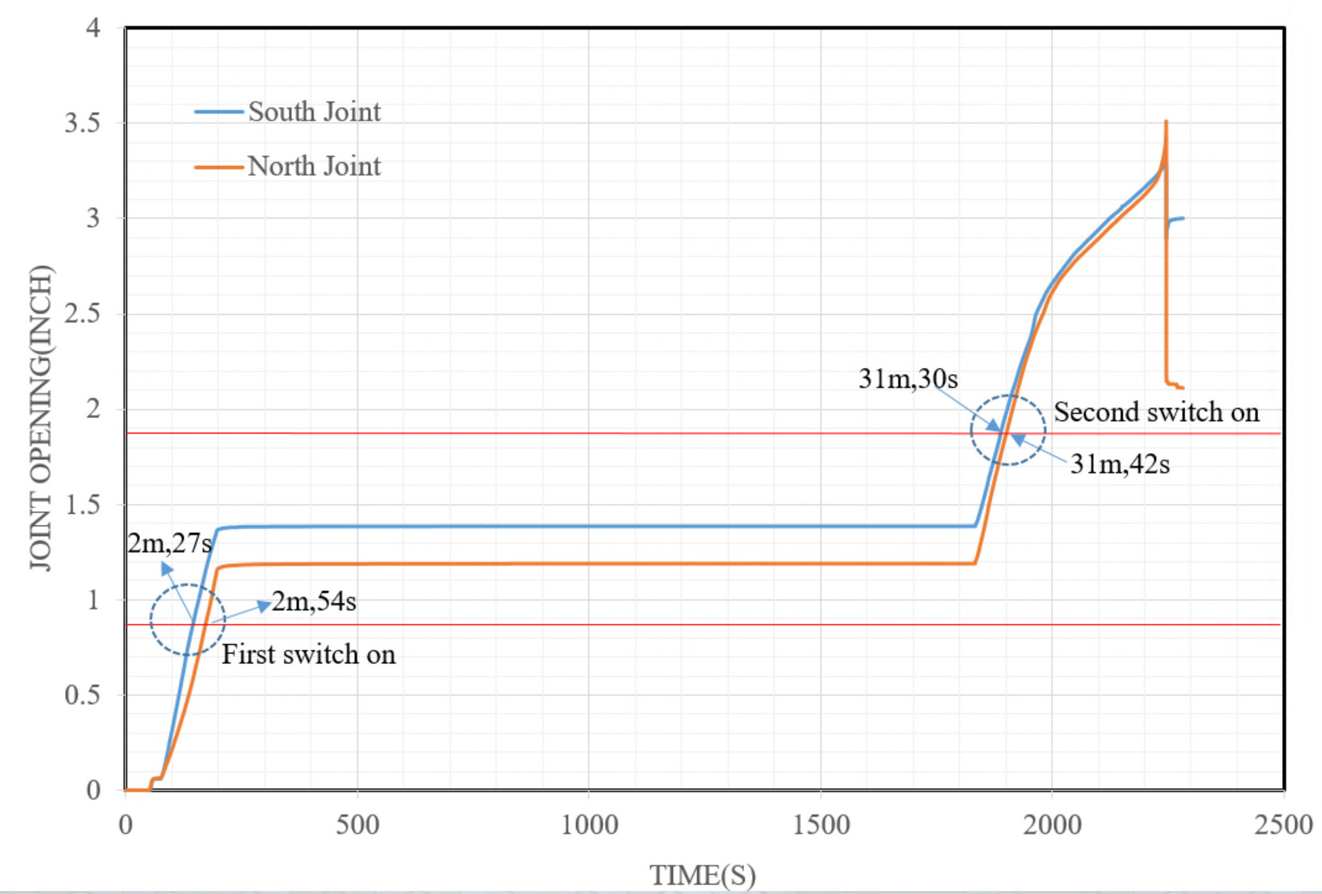
Full Scale Pipeline Performance Test During Large Ground Movements



Smart joint-opening detection time during the test

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感謝聆聽