Tutorial

Managing Mobile Sensor Networks in an Underground Pipe

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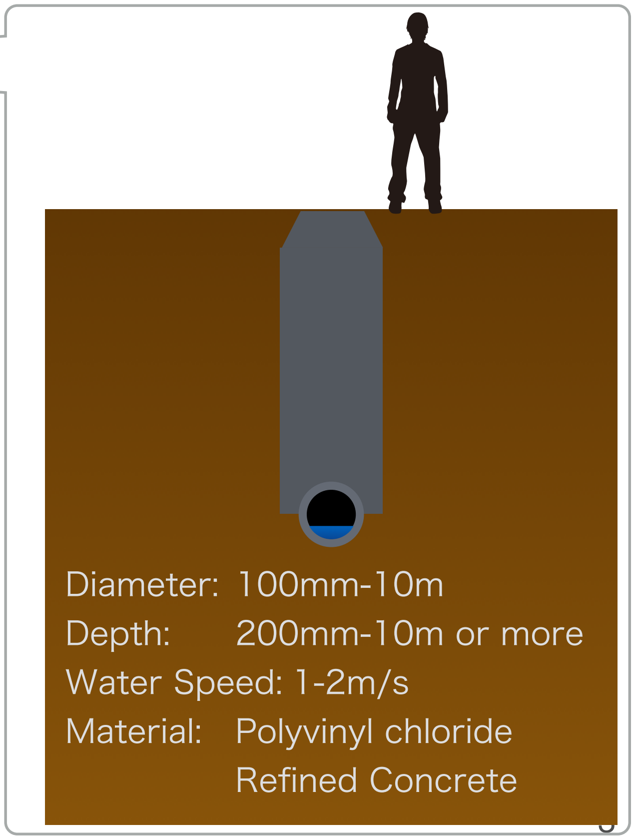
Agenda

- **Sewer Inspection Technologies**
  - Introduction of Drifting Sensor Network
- **Sensor Network Technologies for Underground Facilities / Pipes**
- **Wireless Communication in Underground Pipes**
  - Characteristics of Wireless Communication in Narrow Pipes
  - Our Experimentation in Narrow Sewer Pipes
- **Cooperative Protocol for Multiple Drifting Sensor Networks**
  - For reliably transferring large size sensor/camera data to access points
  - For saving battery power

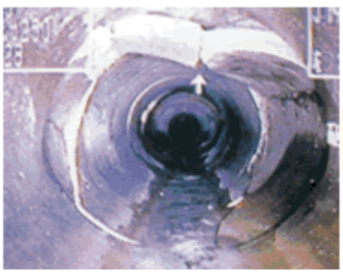
Underground Pipes

- **Sewer**
  - Sewage / Rain water / Mixed
  - Non-Pressured
- **Water Supply**
  - Pressured
- **Gas**
- **Trains / Cars**
- **Cables**



Aging Sewer Pipes

- **460,000km - Total length of sewer pipes in Japan**
- **Many pipes are buried in 1970's**
  - 10,000km pipes are over 50years old.
  - 10 year later -> 50% sewer pipes will be more than 30years old.
    - 30 years - Practical lifetime of reinforced concrete pipes.
- **About USD 110 Million/year for maintenance**
- **Cave-ins 3500/year（2013)**

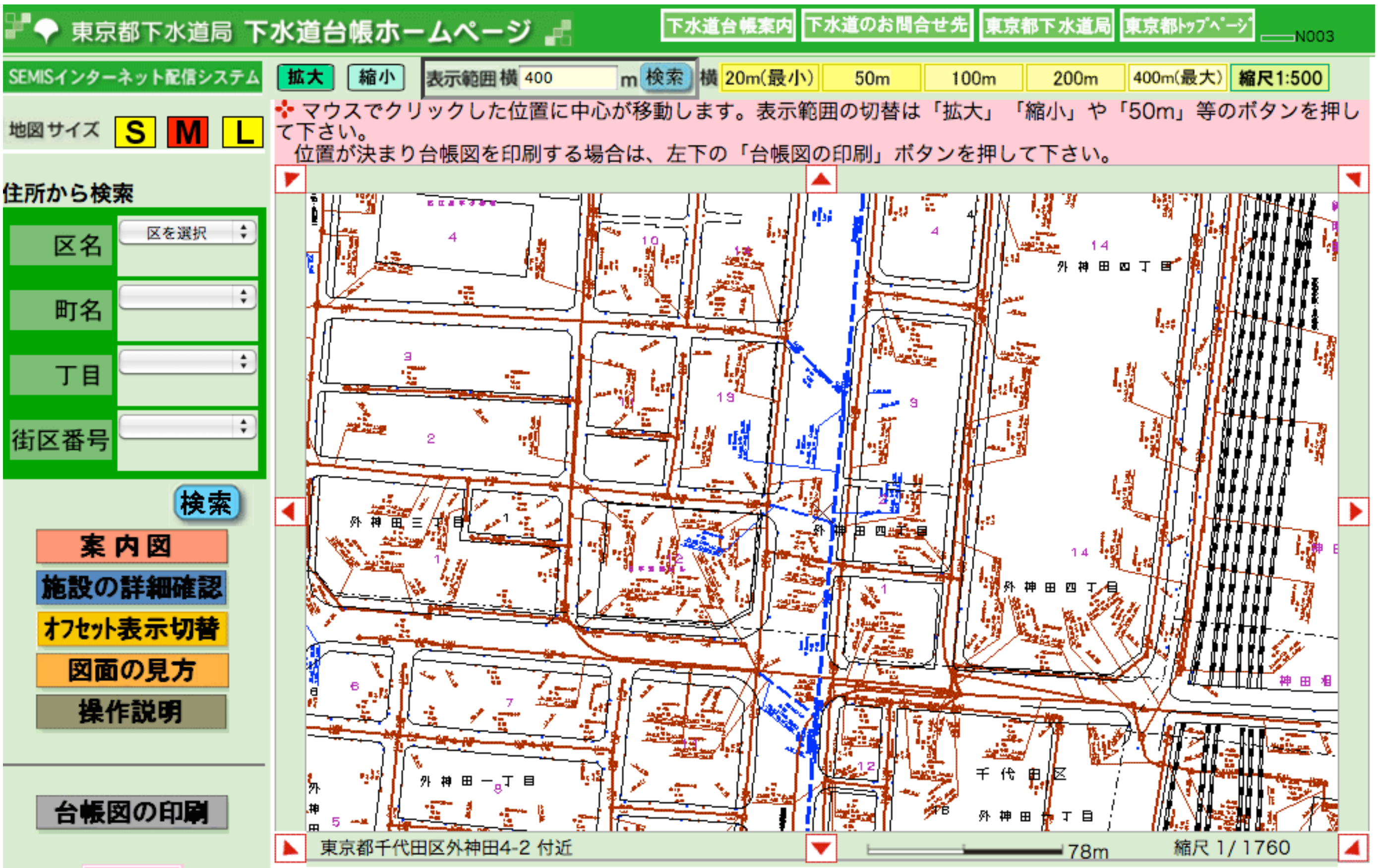

Inside of a collapsed pipe


Ginza


Takanawa

From Web page of Waterworks Bureau, Land, Infrastructure and Transportation Ministry of Japan
http://www.mlit.go.jp/crd/city/sewerage/yakuwari/kaitiku_koushin.html

Sewer Map: Kanda, Tokyo



http://www.gesuijoho.metro.tokyo.jp/semiswebsystem/SuperaPageWeb.aspx#

Sewer Inspection

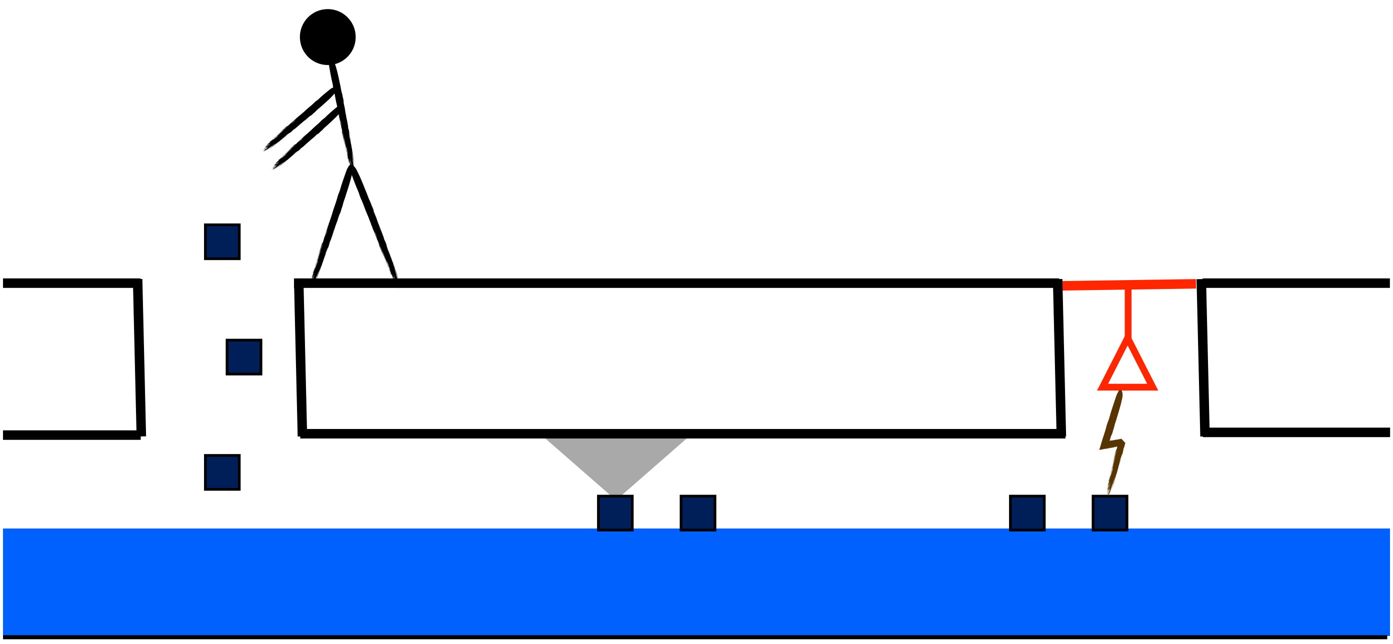
- **Needs much money, time, and human power**
- **Japanese law imposes an obligation of inspection of sewer pipes that reach their lifetime**
  - Most of local governments cannot afford it.
- **Conventional Sewer Inspection Techniques**
  - Robots (with cameras and sonars), Ships … wired Control
  - Human visual check (Danger!)
    … especially for large diameter pipes
  - Fiber Scopes

New Technologies

- **Effective Screening Techniques are needed**
  - For roughly checking wide areas in a short time
    - More than 1km/day
    - e.g. Detailed inspection with robot camera - 300m/day
- **Wired Remote controlled wheeled robot + wide-angle extraction camera**
- **Pipe-edge camera**
- **Unmanned ship + Action Cameras (e.g. GoPro)**
  - Still Needs Much Labor Cost and Time
- **Surface elastic wave**

Drifting Sensor Network for Sewer Inspection [Ishihara, 2012]

Save labor cost for sewer investigation using drifting sensors / cameras.



Sensor Network Technologies for Underground Facilities / Pipes

- **PIPENET [Stoianov, IPSN2007]**
  - Sensor Network for monitoring large diameter water transferring pipes.
  - Uses stationary sound sensors and vibration sensors
- **Underground Sensor Network [Akyildiz, AHN2006][Vuran, PCJ2010]**
  - For agriculture monitoring
  - Wireless communication with sub GHz radio, -100db in 3m, Very strong signal attenuation by soil (especially with higher water content)
- **Wireless Sensor Network in Coal Mines [Li, ISPN2007]**
  - Structure-Aware Self-Adaptive Sensor system (SASA)
  - Implementation with 27 MICA2 (868/916 MHz) sensor nodes at 3m-interval
- **Drifting Sensor Network for Sewer Inspection [Ishihara, 2012, etc.]**

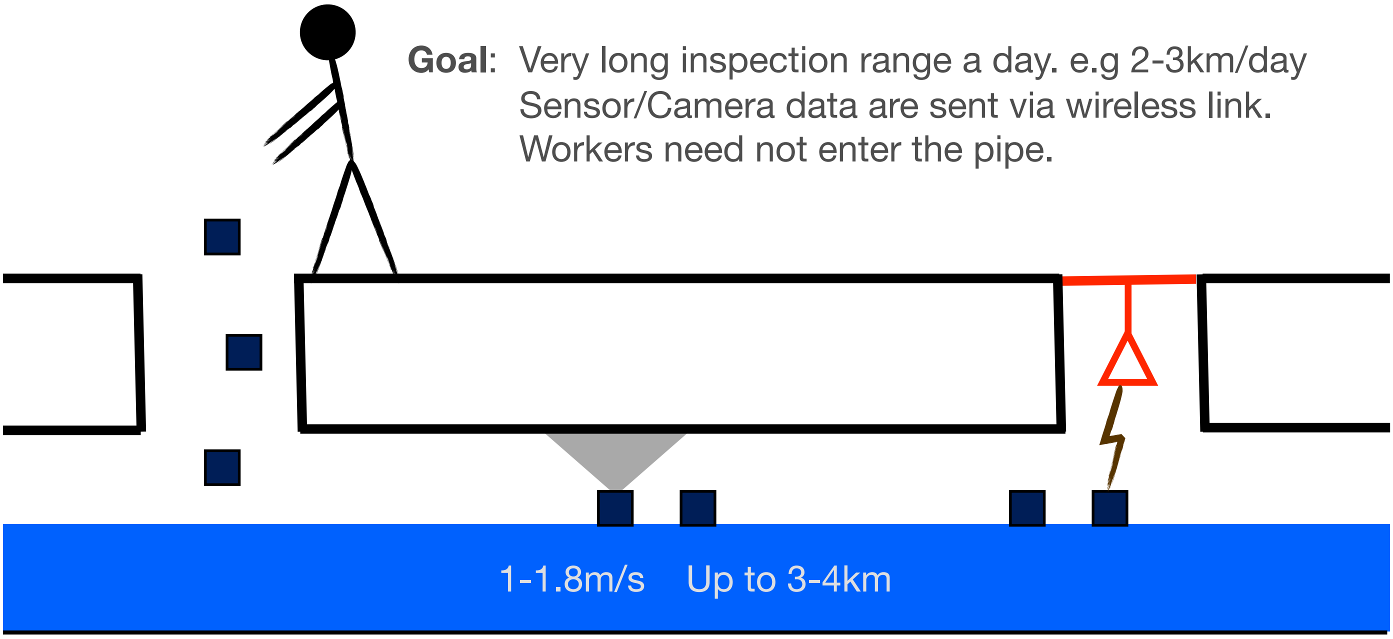
Related Work of Drifting Sensor Network

- **SewerSnort [Kim 09] (UCLA, UCI)**
  - Gas Sensor + IEEE802.15.4
    + Floating Tube
  - Estimates the position of the sensor using RSSI from AP
- **Floating Sensor Network (UCB)**
  - Monitors water current, water quality, etc.
  - 3G and IEEE802.15.4 (ZigBee) wireless interfaces

Drifting Sensor Network for Sewer Inspection [Ishihara, 2012]

Save labor cost for sewer investigation using drifting sensors / cameras.

Goal: Very long inspection range a day. e.g 2-3km/day
Sensor/Camera data are sent via wireless link.
Workers need not enter the pipe.



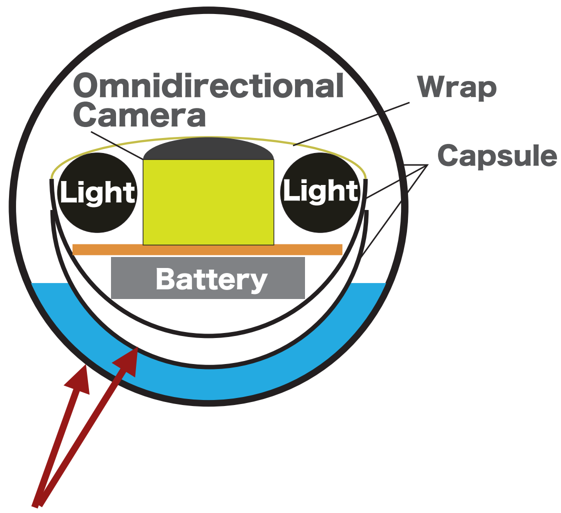
Issues for realizing drifting sensor network for sewer inspection

- **Sensors**
  - Gas sensors: H_2S, etc. … Expensive
  - **Cameras: Cheap and widely used in real sewer inspection**
  - Sound: Hard to use in drifting
- **Retrieving data**
  - No communication - Saving data on the memory card and retrieve it after the inspection
    - Workers cannot check/ monitor the progress of inspection
    - If the inspection range is long and sensing fails, the penalty is severe.
  - **Wireless communication:** Limited Communication Range
  - Wired communication: Annoying cables….

Chassis of the sensor/camera node

Joint work with Prof. Hiroaki Sawano (Aichi Institute of Technology, Japan)

- Light, Small, and Water Resistant
- Keeps the camera position
- Dual Capsule
- Battery for lights are placed at the bottom of the chassis
- Strong light: 4 lights
- Prevents reflection of light
- Wide view angle Omnidirectional camera Kodak SP360

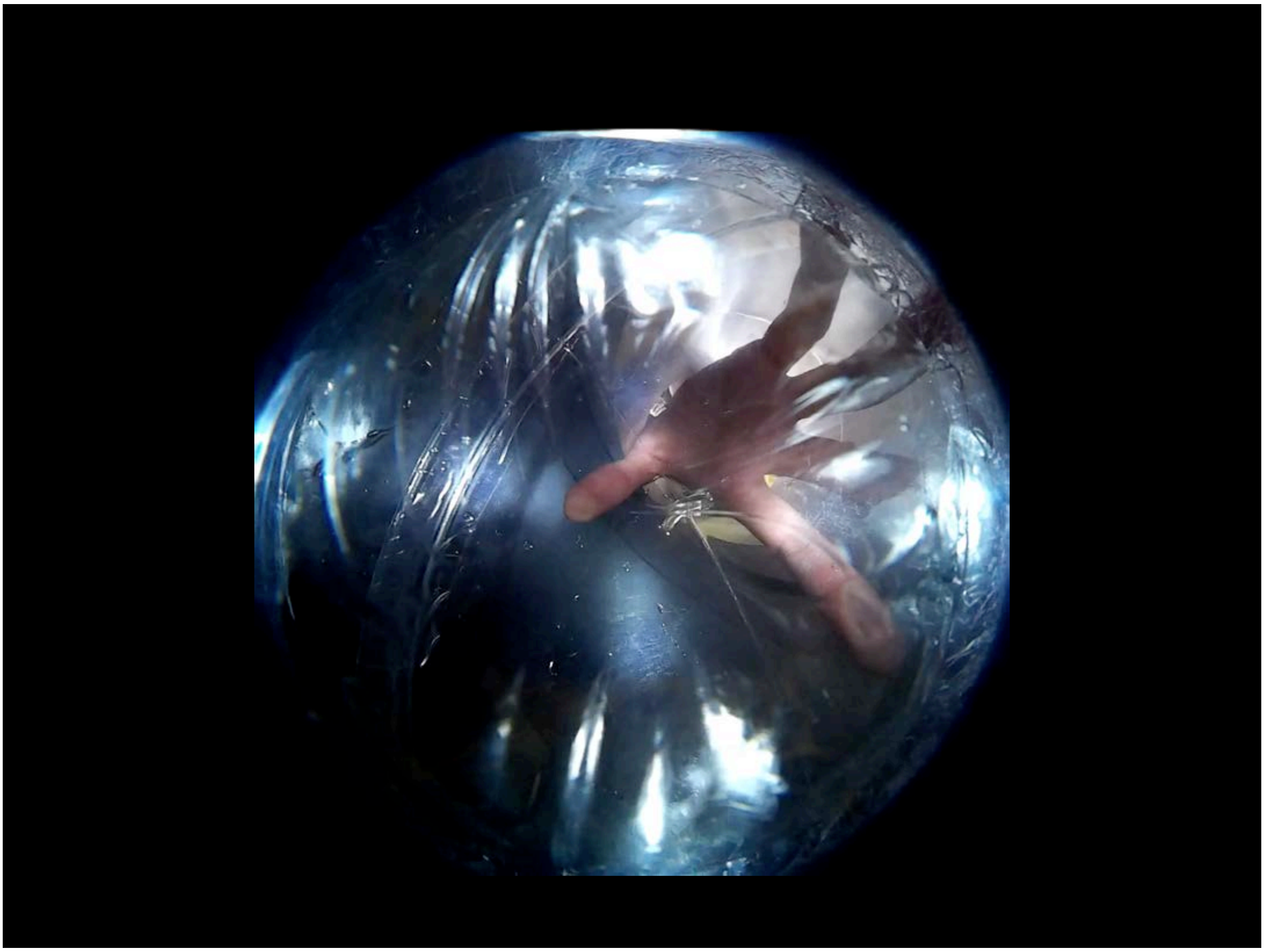


Capsules (Polyvinyl Chloride)

The first prototype Only camera and lights

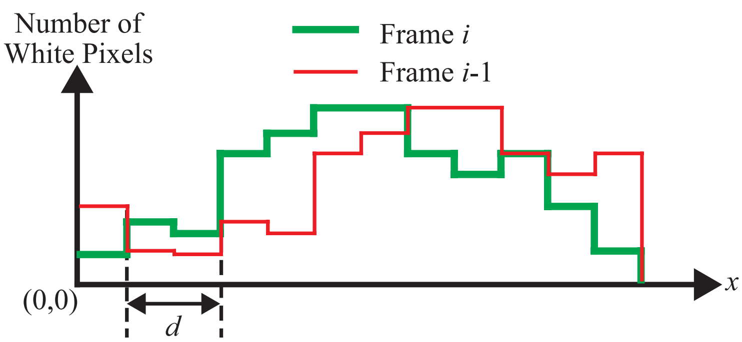
Candescent light bulb

LED bulb

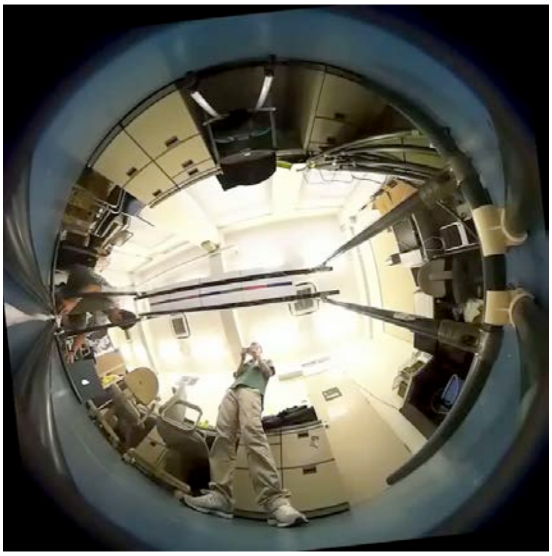


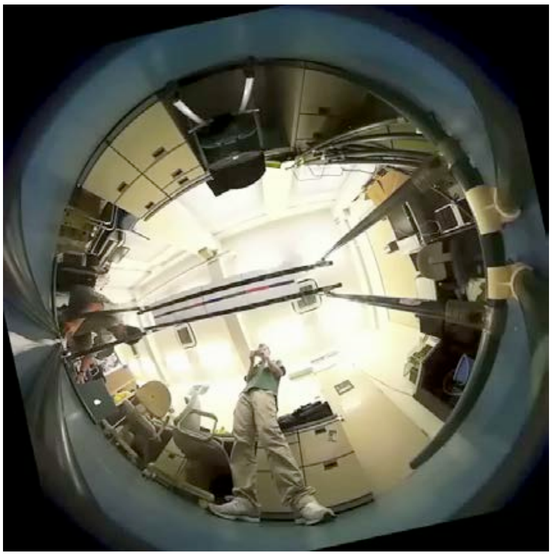
Compensation of rotation

- **By image processing, we compensated the horizontal rotation of the camera.**
  - Make a panorama-image of each frame, and binarize it
  - Make a histogram of the number of white-pixels at each X coordinate value
  - Matches the shape of the histogram of neighboring frames, and find the gap



Result of Compensation





Original video **After compensation**

1m/s Horizontal movement, 1deg/Frame rotation

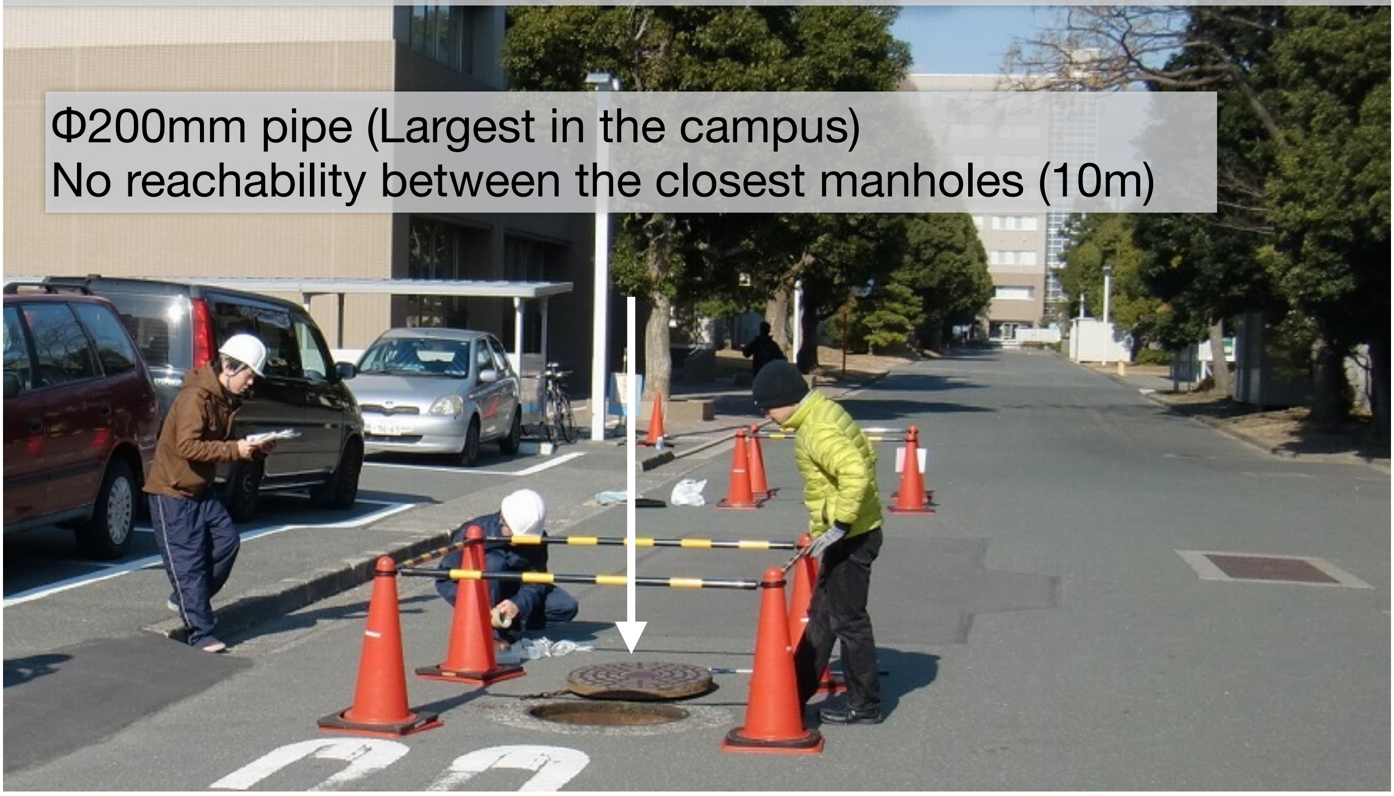
Wireless Communication in Underground Pipes

How long is the maximum communication range of off-the-shelf wireless devices in underground sewer pipes?

How to lengthen the range?

How to compensate the short communication range?

Experiment in a real sewer pipe in the campus



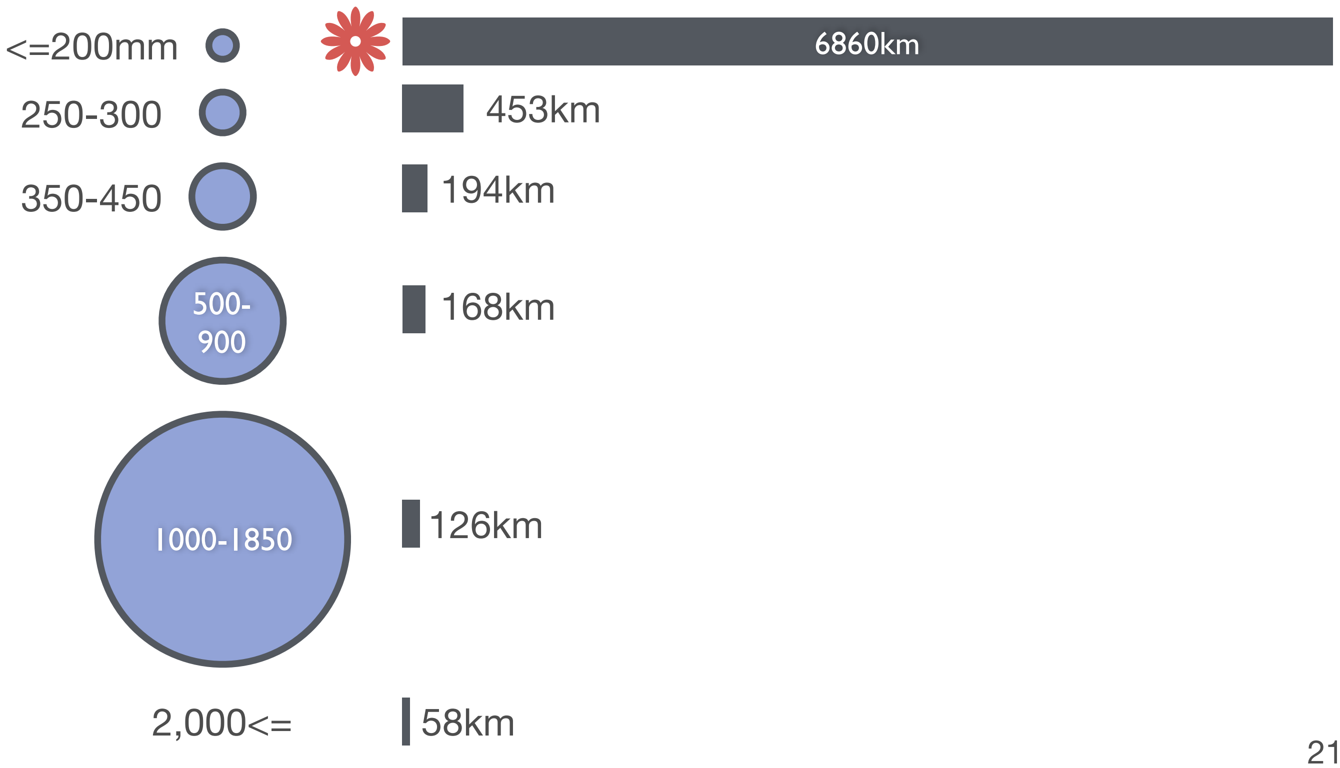
Devices used for measurement

Android Smartphone
IEEE 802.11g
100bytes / 500bytes 1s interval
Auto bitrate (5-54Mbps)

XBee Pro + Arduino UNO
IEEE 802.15.4
100bytes1s interval
Bitrate: 250kbps

Targeted Pipe Size

New sewer pipes' diameters in Japan, 2009



Relationship between received power and wireless communication range

- **To achieve sufficiently long wireless communication range, we should increase the received signal power.**

$$P_r = \frac{G_t G_r P_t}{L}$$ (Friis transmission equation)

P_t, P_r Transmission and received power L Path loss
G_t, G_r Transmitting and receiving antenna gain

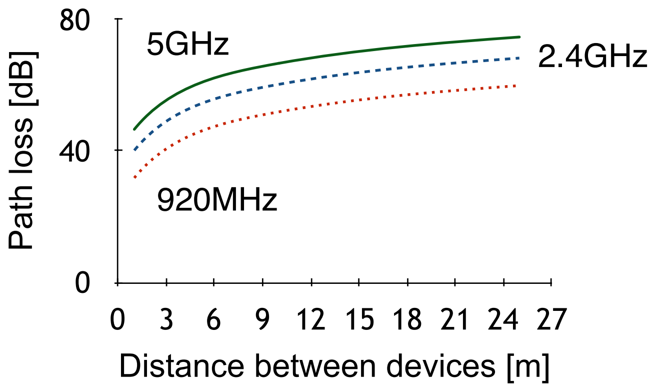
- **How to increase the received power?**
  - Increasing the transmission power
  - Increasing the transmitting and receiving antenna gain
  - Decreasing the path loss

Relationship between path loss and frequency band in free space

$$L = 20 \log_{10} \frac{4\pi d}{\lambda} \quad [\mathrm{dB}]$$

d : Distance between devices

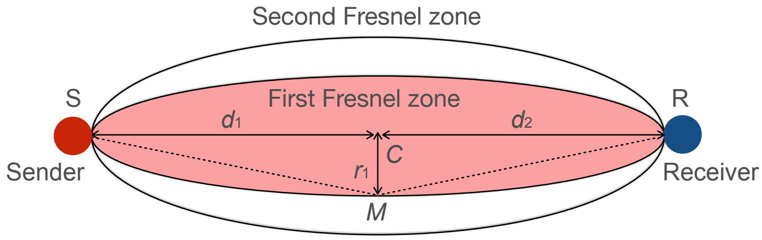
λ : Wavelength of radio signal



The path loss of low frequency radio is smaller than that of high frequency radio.

Relationship between Fresnel zone and frequency band

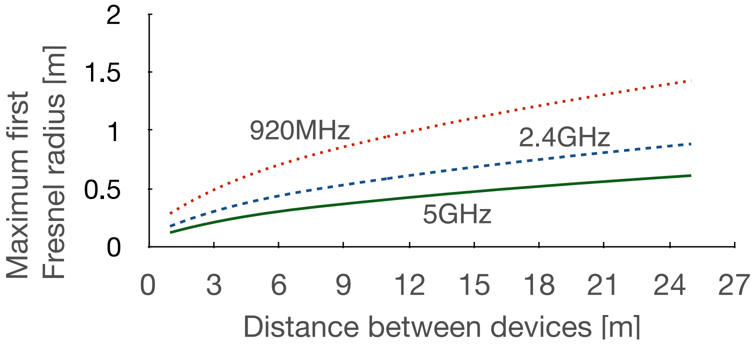
$$SM + MR - SR = \frac{n\lambda}{2}$$
$$(n = 1, 2, \ldots)$$



The first Fresnel zone of high frequency radio is smaller than that of low frequency radio.

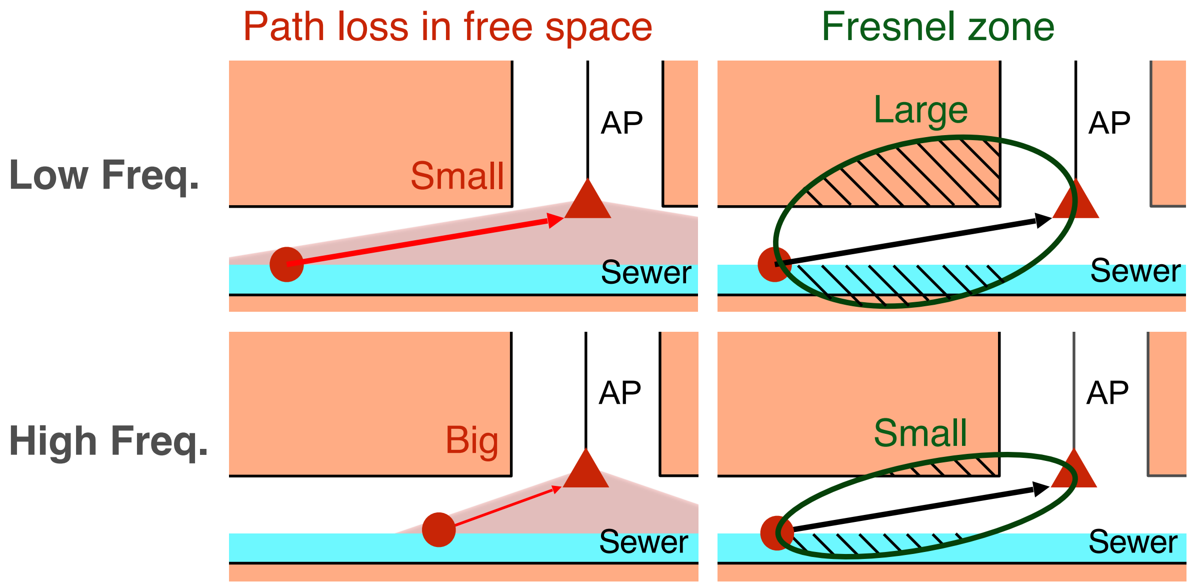
r : First fresnel zone radius

$$r = \sqrt{\lambda \frac{d_1 \, d_2}{d_1 + d_2}}$$



To ensure the line of sight for wireless communication,
60% of the first Fresnel zone radius should be free from obstacles.

Relationship between path loss and Fresnel zone



Trade off between the path loss and the Fresnel zone radius

➡ **We need to select suitable frequency based on wireless communication characteristics in sewer pipes.**

Measurement of wireless communication characteristics using an experimental pipe

The sender transmitted packets to the receiver.

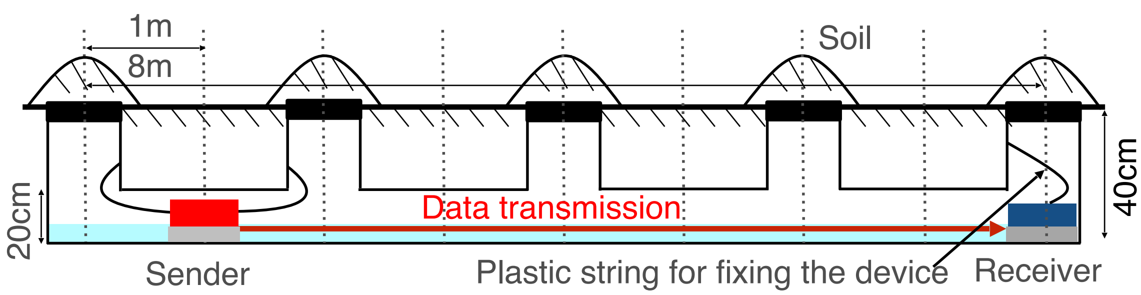
We measured the RSSI and the packet reception ratio.

Device

- Frequency: 920MHz (ARIB STD T-108)
  2.4GHz (IEEE802.15.4,11g)
  5GHz (IEEE802.11a)
- Data size: 100bytes
- Number of packet: 180
- Tx-interval: 1s
- Tx-power: 10dBm

Pipe

- Thickness of the pipe: 6.5mm
- Depth of water: 4cm



Making our own testbed

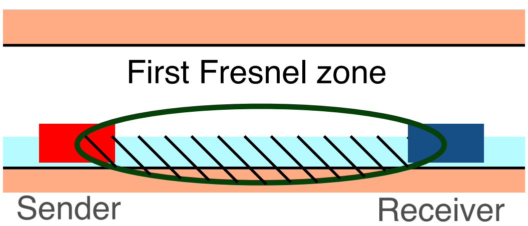
Experimental pipe after buried

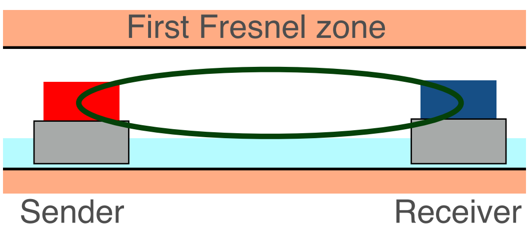
Device's position in an experimental pipe

To investigate the relationship between obstacles in first Fresnel zone and the wireless communication range, we changed the height of the device position.

At the bottom

At the center





Experiment Devices

920MHz

Arduino UNO
+Toho technology TMJ0914
(ARIB Std T108)

2.4GHz

Fujitsu
Arrows Me F-11D
Android Smartphone
(IEEE802.11g)

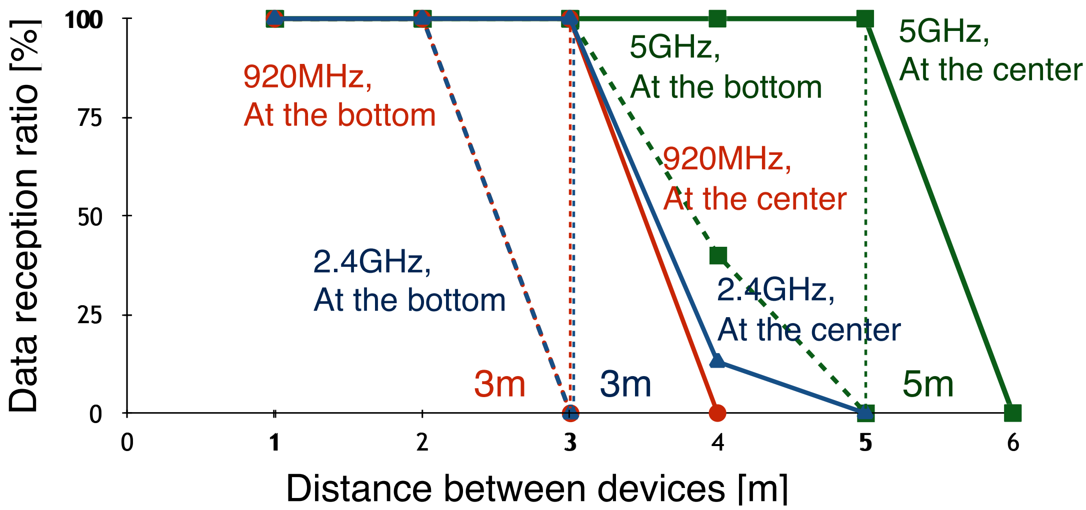
2.4GHz

Arduino UNO
+ Digi international Inc.
Xbee Pro
(IEEE 802.15.4)

2.4GHz, 5GHz

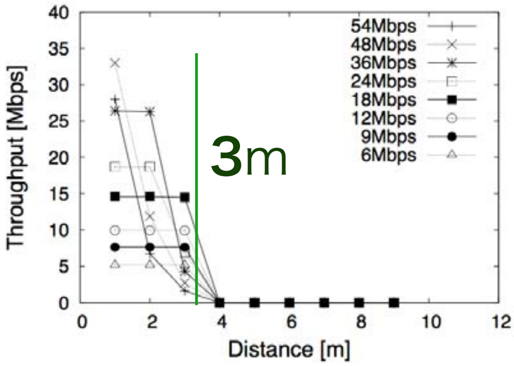
Raspberry Pi
+Planex comm.
GW-450D (USB dongle)
(IEEE802.11g, a)

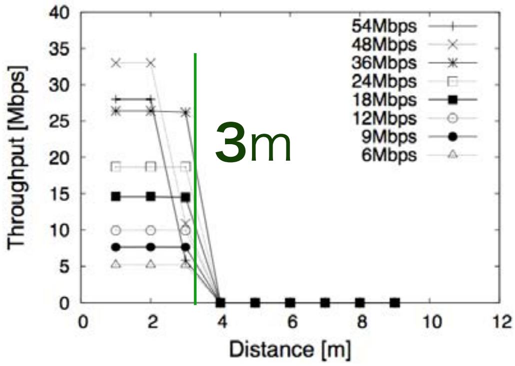
Data reception ratio (Omnidirectional antenna, Autorate)



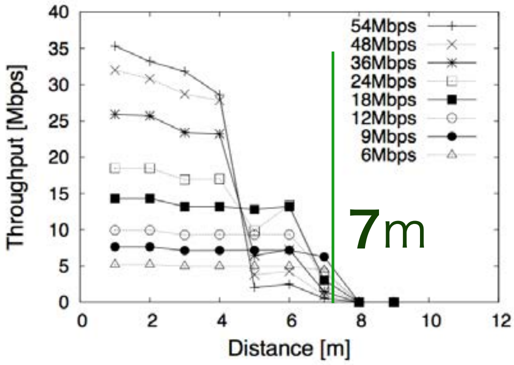
Measurement Results

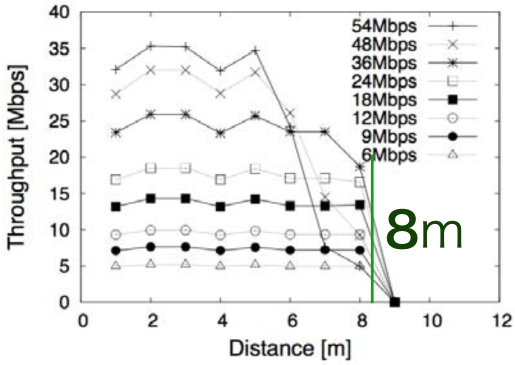
2.4GHz
(11g)





5GHz
(11a)



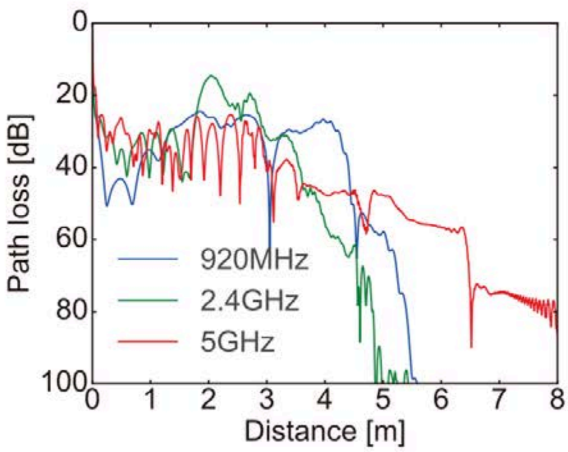


Antenna: on the bottom

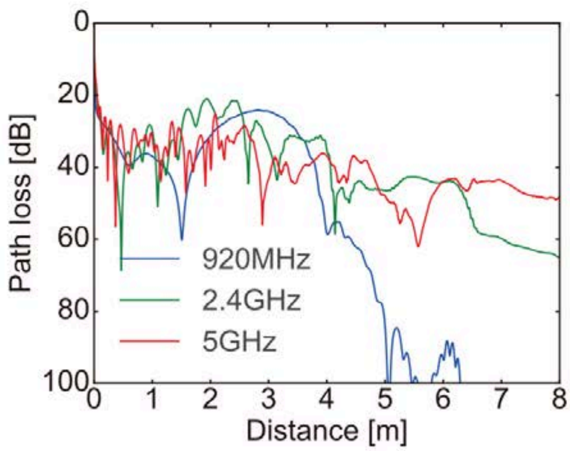
Antenna: center of the pipe

Simulation Results

- **FDTD Simulation results of radio propagation in a pipe without water surrounded by soil with 5mm x 5mm x 5mm-mesh.**



(a) Diameter=200mm



(b) Diameter=400mm

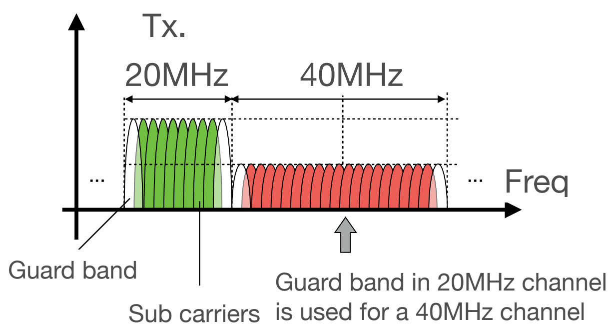
Increasing Data Transfer Size at APs

- **If the data transfer size is large,**
  - Distance between APs can be increased.
    -> Equipment cost is reduced
  - Reliability of video data transmission is increased
- **Using IEEE802.11n instead of IEEE802.11a**
  - **Channel bonding**
    [2 x 20MHz Channel -> 40MHz Channel]
  - MIMO
    Using multiple antennas for sending multiple streams on the same channel

Improving Data Transmission Speed by using wide bandwidth

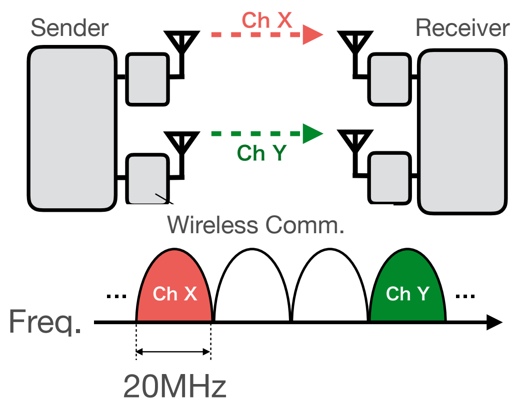
Using Channel Bonding

- Merges two neighboring 20MHz channel to a 40MHz channel
  - # of subcarriers of OFDM increases
    -> Higher data rate
- Tx. Power/MHz is kept.
  - Tx. Power/Subcarrier is reduced to 50% (-3dB)

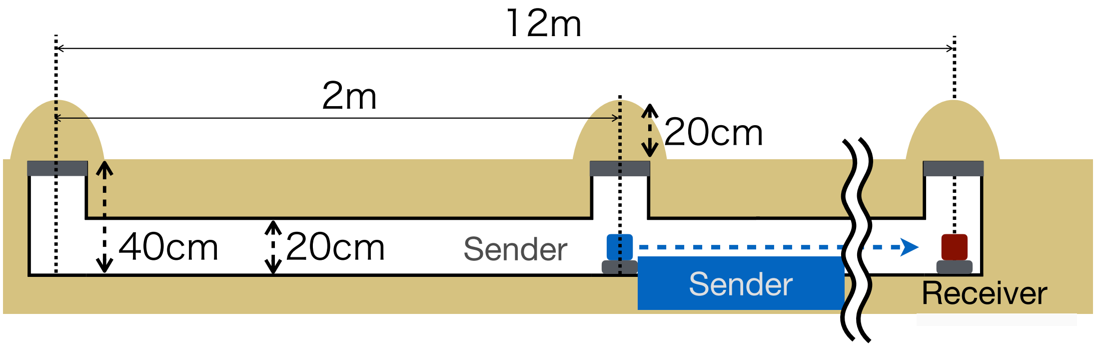


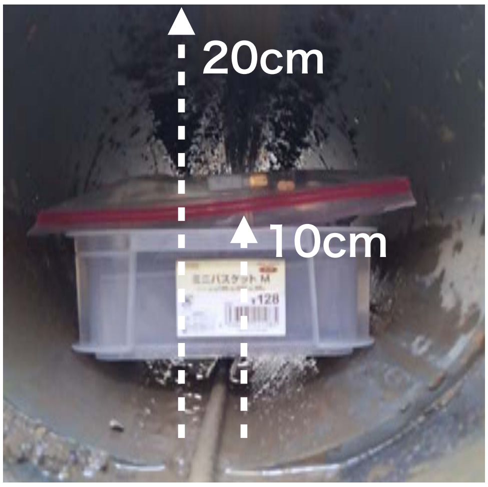
2CH Parallel Communication

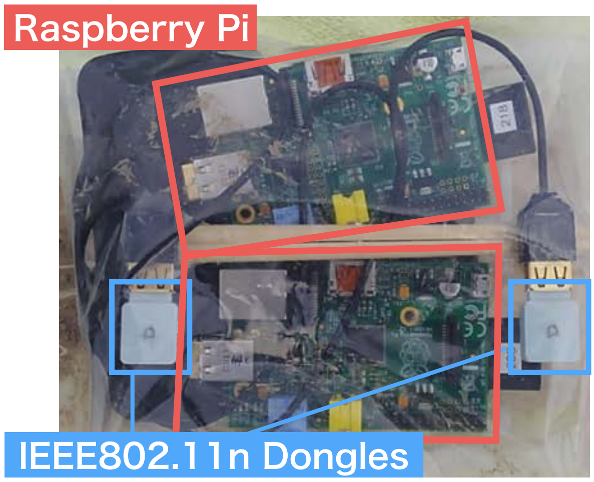
- Uses two comm. interfaces
- Assigns different channel to each interface
- Sends two different streams from the two interfaces



Experiment Setup

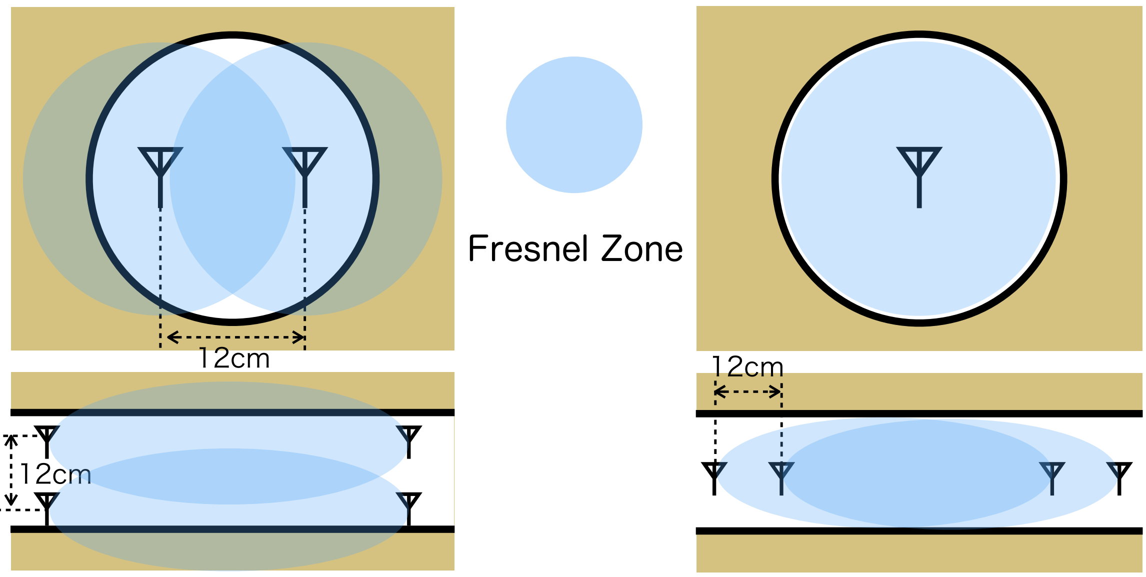






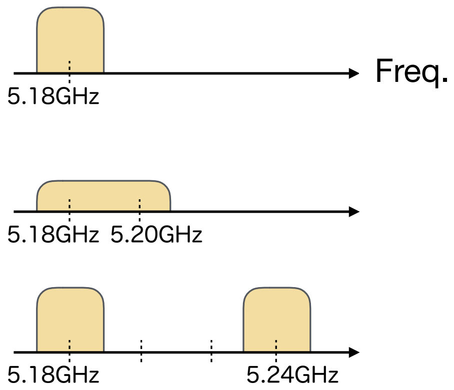
Placement of two antennas in a pipe

- Cross-Sectional Direction
- Axial Direction

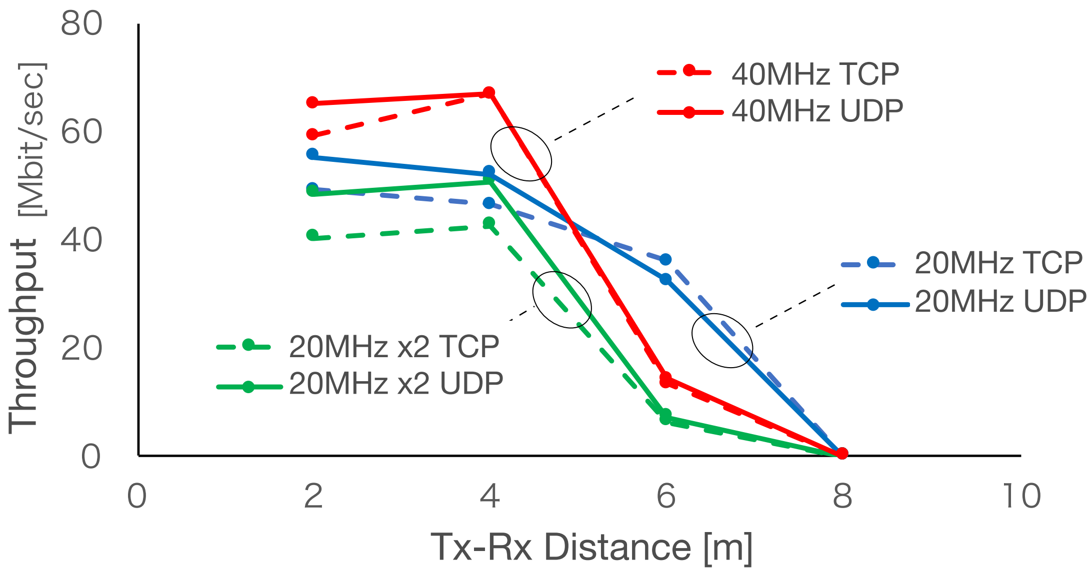


❖ Part of the Fresnel Zone is blocked by the soil

Experiment Setup

L1&L2 Standard	IEEE 802.11n
Radio Frequency	20MHz CH × 1 40MHz CH × 1 20MHz CH × 2 
Radio Interface	Planex GW-450D（MediaTek MT7610U）
Controller	Raspberry Pi Model B
Tx. Power	10mW/MHz
Data Rate	MCS7：65Mbps(20MHz), 135Mbps(40MHz) (64QAM Modula, Coding rate 5/6) MCS4：39Mbps(20MHz), 81Mbps(40MHz) (16QAM, Coding rate 3/4)

Experiment Result: Throughput



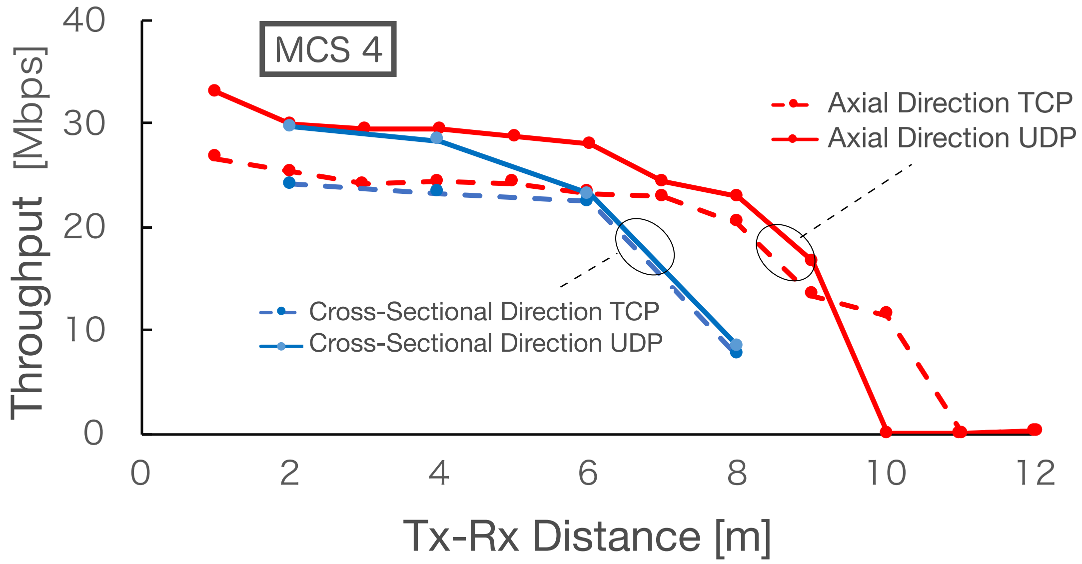
Channel Bonding

- Better throughput at <= 4m
- Throughput degraded at 6m.
  - Reason: Reduced Tx power/Sub channel

20MHz x 2
(Antenna: Cross-Sectional Placement)

- Throughput severely degraded at 6m
  - Blocked Fresnel Zone

Effect of Antenna Placement



- Almost the same Max. Throughput
- Axial Directional Placement achieves 2m longer Max. Communication Distance

Summary

Wireless Communication in Underground Sewer Pipes

- **Higher Frequency is better for Narrow Pipes**
  - For popular ϕ200mm PVC pipes
    5GHz is better than 2.4GHz and 920MHz
  - Fresnel zone is blocked by soil
- **Position of antennas in the pipe is important**
  - Antennas should be placed at the center of the space in the cross section of the pipe.
- **Using multiple antennas and multiple channels**
  - No positive experiment results so far.
- **Directional antenna works well**

Cooperative Protocol for Drifting Sensor Networks with Multiple Drifting Nodes

For reliably transferring large size sensor/camera data to access points

For saving battery power

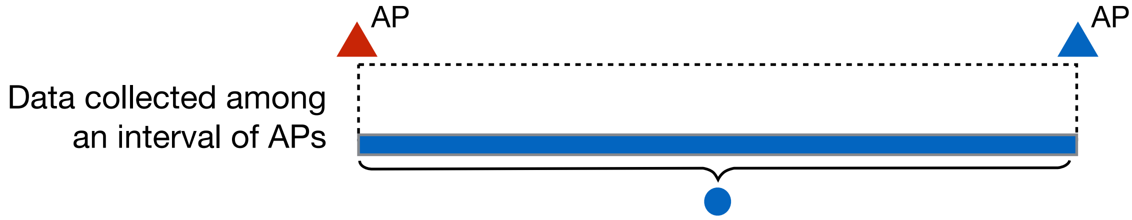
Strategies for transmitting large data in a sewer pipe

- **Increasing transmittable data size**
  - Increasing capacity of the link between a drifting camera node and an AP
    - Channel bonding
    - MIMO
  - Expanding communication range between a node and an AP
    - Multi-hop networking
    - High frequency band (e.g. 5GHz, 60GHz)

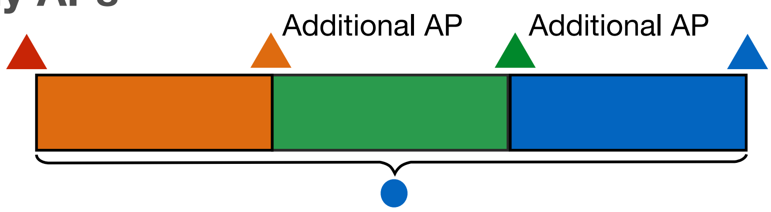
★ **Decreasing the data size which a drifting camera node transmits to an AP**

Schemes for decreasing the data size

Decreasing video quality

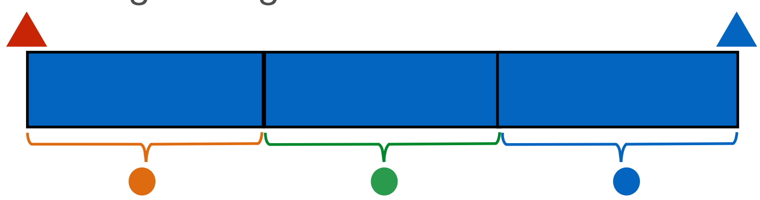


Deploying many APs

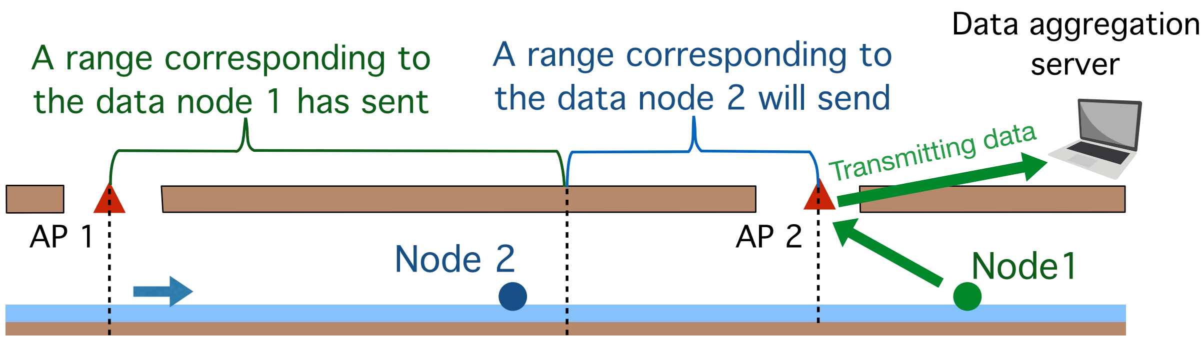


★ Using multiple drifting camera nodes

Drifting camera nodes share the workload to send video data of a section between two neighboring APs



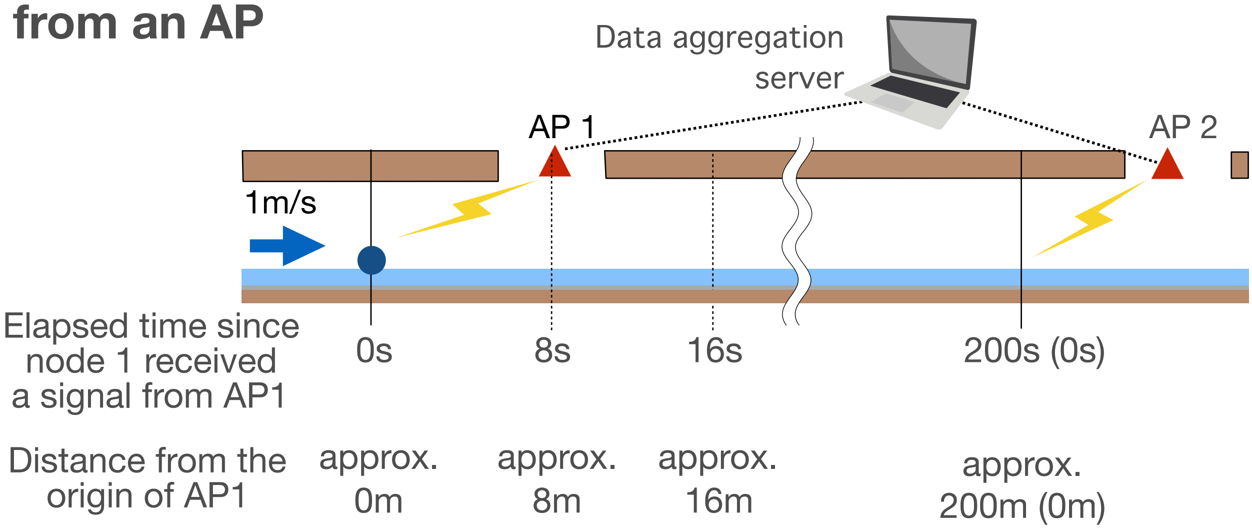
Issues in collecting data from multiple drifting camera nodes



- How does a node know the video data sent from other node?
  - How does a node detect its position (and where it recorded the video)?
- How do nodes avoid simultaneous transmissions near the same AP?

Estimating the position of a drifting camera node

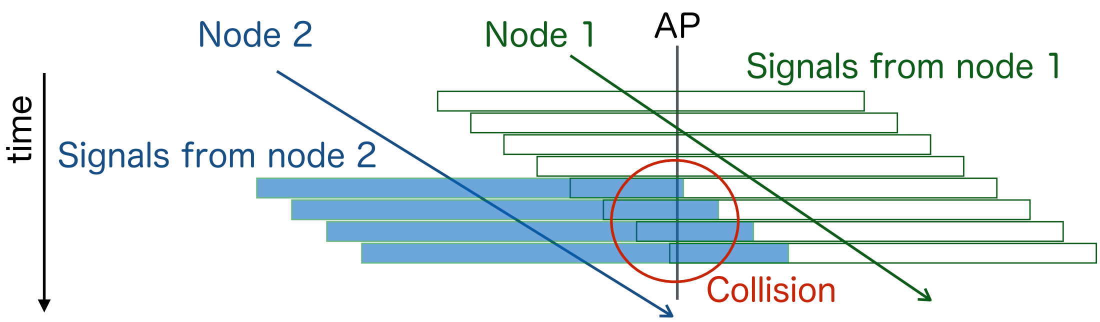
A drifting camera node estimates its position based on the elapsed time since it firstly received a signal from an AP



According to the elapsed time, the data aggregation server manages the video data it received from multiple camera nodes

Avoiding simultaneous transmissions

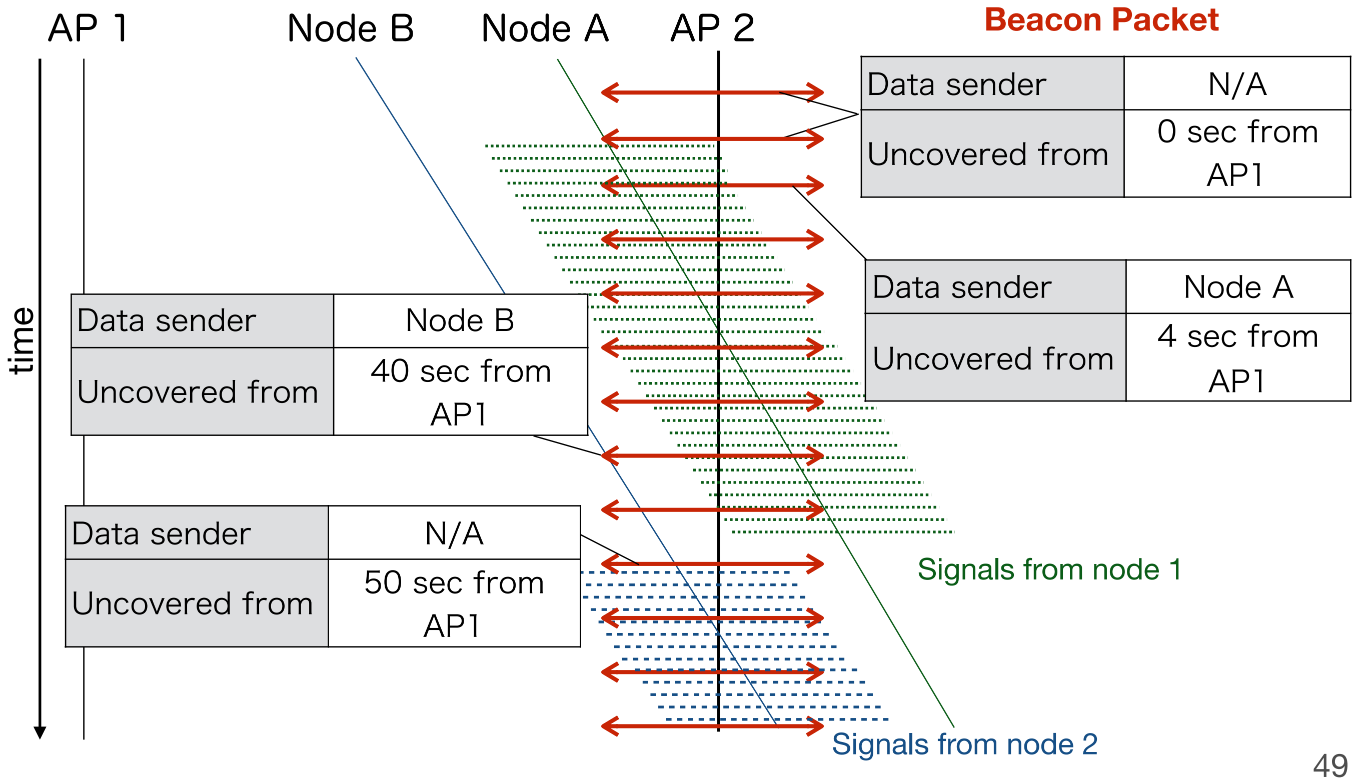
If a drifting camera node sends data anytime it has connectivity to an AP…



An AP notifies existence of a drifting camera node currently transmitting data by appending the node's ID to beacon packets

- Each drifting camera node transmits data if there is no node ID in a beacon packet it receives

Interaction between an AP and drifting camera nodes



How to Save Battery Power?

Here, we assume we use multiple small size sensor with very small battery and the data observed by them are sent to APs with a limited communication range.

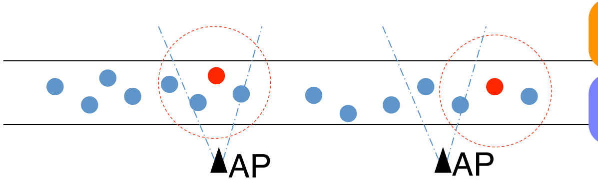
- **Turn off the sensor node**
  - Sensors
  - Communication Interface — Large Energy Consumption
- **When are they turned off?**
  - If the interface of a node is off when it passes by an AP, it fails to communicate with the AP.
  - No data will be forwarded to the AP!
  - We need to keep the connectivity between the AP and sensor nodes and save their battery power
  - If multiple sensor nodes are used, we can turn off some of those that work at the same place.

Basic Strategy

- **Leveraging a clustering algorithm for sensor networks**
  - A **cluster head** (or **active node**), one of nodes in the vicinity, works for **sensing** and **transferring data** obtained by the nodes in the vicinity to **APs**.
  - According to the **residual battery power**, a cluster is selected in a distributed manner.

Two well known distributed algorithms for selecting active nodes (CHs)

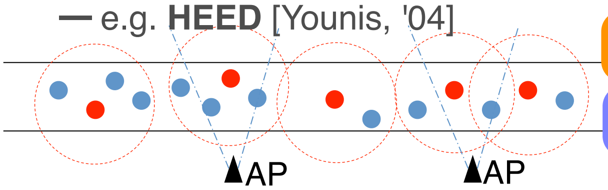
1. **Select CHs independently of the current connectivity between nodes according to a given probability.**
   - **LEACH** [Heinzelman, '00]



Pros. Longer node life time

Cons. Low connectivity to CH

2. **Select CHs so that every nodes can communicate with at least one CH.**
   — e.g. **HEED** [Younis, '04]



Pros. High connectivity to CH

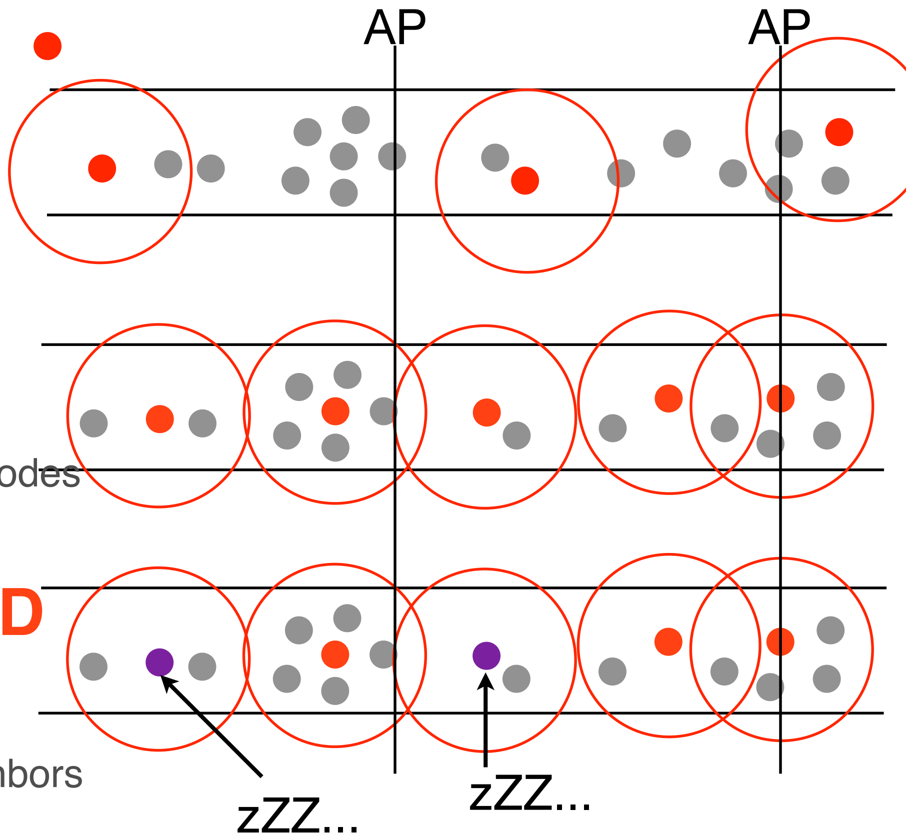
Cons. Shorter node life time

Comparison of 3 algorithms

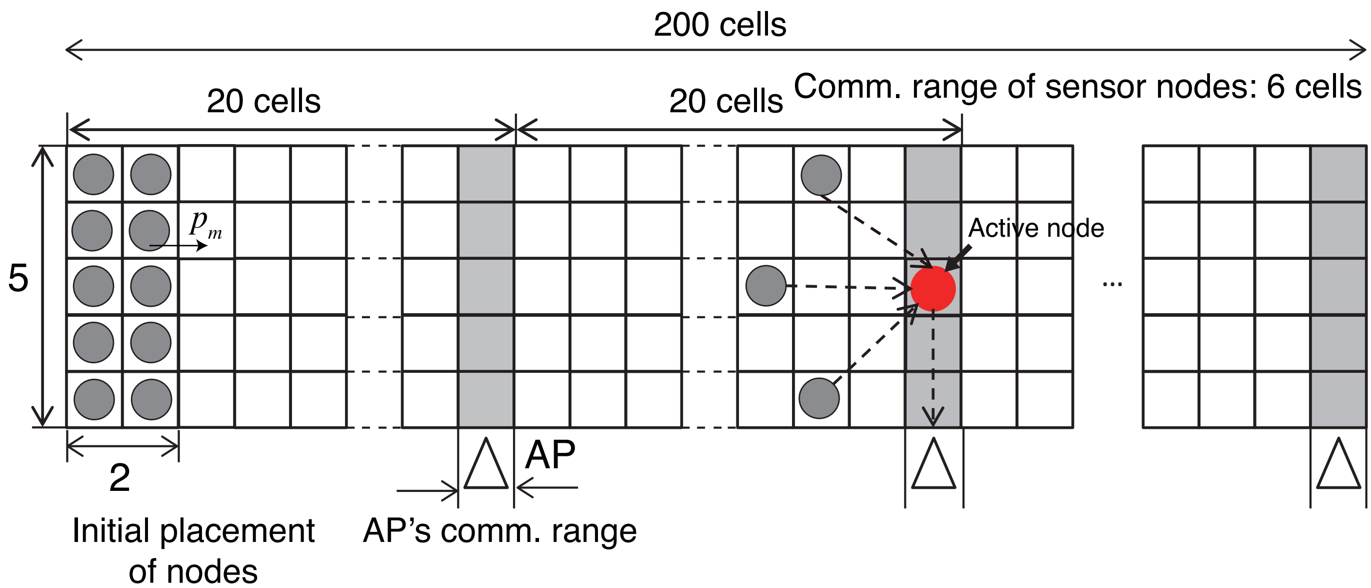
LEACH
# of CHs is const.

HEED
At least one CH
is reachable from every nodes

Our algorithm
Improved HEED
Even if a node is a CH,
it sometimes sleeps
according to the #of neighbors
to save energy



Simulation Model



Mobility model determines the movement of nodes from right side.

Model of node mobility on the water flow

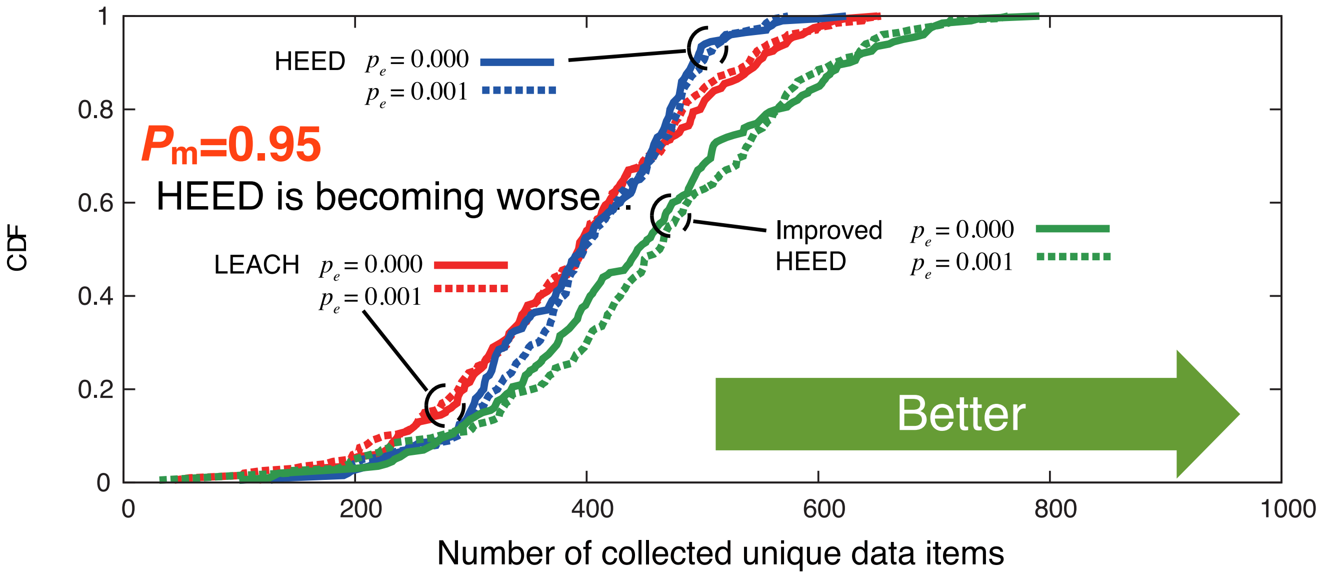
Each node moves to its right cell with probability p_m if the cell is empty.

P_m=1.0: All nodes move simultaneously: No spread

P_m < 1.0: Nodes spread widely

Simulation Results: # of data-collected locations

CDF of the number of data-collected areas obtained by 200 runs



- **Improved HEED can collect more data than HEED and LEACH**
- Pm=1.0 (All nodes move together) LEACH < HEED < Improved HEED
- Pm=0.95 (Nodes spread) LEACH=HEED < Improved HEED
  - Multiple clusters are made due to the spread of nodes.

Summary

Cooperative Protocol for Drifting Sensor Networks with Multiple Drifting Nodes

- **For reliably transferring large size sensor/camera data to access points**
  - Use multiple sensor/camera nodes to observe the same area
  - Transfer data from multiple nodes at different timing to APs.
  - Send the information of the area that is covered by the transferred sensor/vide data from APs to sensor/camera nodes.
- **For saving battery power**
  - Use multiple sensor nodes, turn on one of nodes in the vicinity based on a distributed clustering algorithm for sensor networks.
  - Select a cluster head according to the node density, residual battery power.
  - **Improved Heed:** Even if a node is selected as a cluster head, it sometimes sleep when the number of its neighbor is small.

Open issues

- **Localization**
  - Time elapsed after detecting an AP
  - Number of joints of pipes
  - Received signal strength
  - Kalman Filter and Rauch-Tung-Striebel (RTS) Smoother
- **Using higher frequency**
  - 60GHz
  - Free space optical (FSO) communication
- **Access point**
  - Communication between inside and outside of a manhole
  - Installation of the chassis and antennas

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