F.L. Lewis
Moncrief-O’Donnell Endowed Chair
Head, Controls & Sensors Group

Automation & Robotics Research Institute (ARRI)
The University of Texas at Arlington

Wireless Sensor Networks

Talk available online at
http://ARRI.uta.edu/acs
Wireless Sensor Networks

2006 Conferences on Cybernetics & Intelligent Systems (CIS) and Robotics, Automation, & Mechatronics (RAM)

Invited by I-Ming Chen
Wireless Sensor Networks

Data Acquisition Network
- Machine Monitoring
- Animal Monitoring
- Ship Monitoring
- BST (Base Station Controller, Preprocessing)
- Wireless Sensor

Data Distribution Network
- Roving Human Monitor
- PDA
- Online Monitoring
- Printer
- Wireless Data Collection Networks
- Wi-Fi 802.11 2.4GHz
- BlueTooth
- Cellular Network, -CDMA, GSM
- Wireland (Ethernet WLAN, Optical)
- Online monitoring
- Server
- Notebook
- Cellular Phone
- PC
- Management Center (Database large storage, analysis)

Any where, any time to access
Applications

- Wide area monitoring for personnel / vehicles
- Secure area intrusion monitoring and denial
- Environmental monitoring
  - animal habitats
  - migration
  - forest fires
  - natural disasters
- Subsea monitoring
- Environmental toxin detection
- Building monitoring
  - Integrity after earthquakes and tornadoes
- Urban area environmental monitoring
  - sensors on buildings
  - sensors in taxis or buses
- Vehicle traffic monitoring & control
  - sensors on roadways and traffic lights
  - sensors on vehicles
- Remote site power substation monitoring
- Remote site patient medical monitoring
- Smart home
- Inventory management

Metrics / QoS

- Latency (delay)
- Energy efficiency
- Accuracy
- Fault-tolerance
- Scalability
- Security
Wireless CBM Research Areas

• Sensor Technology
  MEMS?

• Node Technology
  DSP
  Power
  RF link

• Remote Access Terminals
  Wireless PDA, Wireless Laptop
  Cellphone, Internet

• Data management
  Sensor data storage
  DSP
  Data Access

• Fault & Diagnostic Decision-Making

• Alarming

• COTS Wireless Sensors
  Berkeley Crossbow
  Microstrain

• Wireless Networks
  Cellular network
  WLAN
  Other short range RF networks
  Multiple linked networks
Deploy

Self-Organize
Communication
Localization
Form clusters

Random vs.
Structured topology

Coverage

Operate

1. Program Missions
2. Accomplish Missions

Monitoring
continuous event-based query

Reconfigure

Post-deployment
Redeployment of new nodes
Fault recovery

Mobility
user / observer
sensors
phenomena / target

Changing Topology
mobile nodes
event occurrence
mobile target / phenomena
changing user queries/interests

node failure
deploy additional nodes

Changing Topology

Agent interactions
Bayesian, Uncertainty, Dempster-Shafer, and Utility Theory

FSM

Requirements

Event/ Context

Change/Modify

Sensor states

Actions

Applications

Algorithms and Techniques

Sensors
Principal Problems in Army Communications

Paul Baran, Rand Corp.
Which Technology?

Cellular Technologies
- 2G Systems
- 2.5G Systems
- 3G Systems

Wireless LAN Technology
- 2.4 GHz Wireless LAN
- 5 GHz Wireless LAN
- Ad-hoc Mode
- Infrastructure Mode

Other Short-range Technologies
- Home RF
- Bluetooth
- IrDA
- IEEE 802.11

Long Range Technologies
- Cordless Telephony (cellphone)
- Internet

IEEE 1451 Standard for Smart Sensor Networks
Frequency Bands for WSN

The Industrial, Scientific and medical (ISM) radio bands were originally reserved internationally for non-commercial use of RF EM fields for industrial, scientific and medical purposes. In recent years they have been used for license free communications applications such as sensor networks and bluetooth.

The bands generally used for WSN in ISM are:

- 433MHz
- 933 MHz
- 2.4 GHz
- 5.8 GHz
Network Topology

**Uniform** - for placed sensors -
e.g. environmental monitoring

**Random** - for deployed sensors -
e.g. secure area monitoring

Self Healing Net – Dual Ring
Fig. 2--The Spider Web Communications Network
Network Topology

Centralized, Decentralized, Distributed

Paul Baran, Rand Corp.

Neighbor Connectivity and Redundancy

FIG. 1 - Centralized, Decentralized and Distributed Networks

FIG. 2 - Definition of Redundancy Level
Connectivity and Number of Links

Number of links increases exponentially

Figure 4—Number of Links as a Function of Number of Terminal Stations: The Necessity for Switching in a Communications Network
The Problem of Complexity

Communication Protocols in a network must be restricted and organized to avoid Complexity problems

Think of the military chain of command

e.g. in Manufacturing
The general job shop allows part flows between all machines
The Flow Line allows part flows only along specific Paths

We have shown that the job shop is NP-complete
but the reentrant flow line is of polynomial complexity
Historical Development and Standards

**Ethernet.** The Ethernet was developed in the mid 1970’s by Xerox, DEC, and Intel, and was standardized in 1979. The Institute of Electrical and Electronics Engineers (IEEE) released the official Ethernet standard IEEE 802.3 in 1983. The Fast Ethernet operates at ten times the speed of the regular Ethernet, and was officially adopted in 1995. It introduces new features such as full-duplex operation and auto-negotiation. Both these standards use IEEE 802.3 variable-length frames having between 64 and 1514-byte packets.

**Token Ring.** In 1984 IBM introduced the 4Mbit/s token ring network. The system was of high quality and robust, but its cost caused it to fall behind the Ethernet in popularity. IEEE standardized the token ring with the IEEE 802.5 specification. The Fiber Distributed Data Interface (FDDI) specifies a 100Mbit/s token-passing, dual-ring LAN that uses fiber optic cable. It was developed by the American National Standards Institute (ANSI) in the mid 1980s, and its speed far exceeded current capabilities of both Ethernet and IEEE 802.5.

**Gigabit Ethernet.** The Gigabit Ethernet Alliance was founded in 1996, and the Gigabit Ethernet standards were ratified in 1999, specifying a physical layer that uses a mixture of technologies from the original Ethernet and fiber optic cable technologies from FDDI.
**Client-Server** networks became popular in the late 1980’s with the replacement of large mainframe computers by networks of personal computers. Application programs for distributed computing environments are essentially divided into two parts: the client or front end, and the server or back end. The user’s PC is the client and more powerful server machines interface to the network.

**Peer-to-Peer networking** architectures have all machines with equivalent capabilities and responsibilities. There is no server, and computers connect to each other, usually using a bus topology, to share files, printers, Internet access, and other resources.

**Peer-to-Peer Computing** is a significant next evolutionary step over P2P networking. Here, computing tasks are split between multiple computers, with the result being assembled for further consumption. P2P computing has sparked a revolution for the Internet Age and has obtained considerable success in a very short time. The Napster MP3 music file sharing application went live in September 1999, and attracted more than 20 million users by mid 2000.
**802.11 Wireless Local Area Network.** IEEE ratified the IEEE 802.11 specification in 1997 as a standard for WLAN. Current versions of 802.11 (i.e. 802.11b) support transmission up to 11Mbit/s. WiFi, as it is known, is useful for fast and easy networking of PCs, printers, and other devices in a local environment, e.g. the home. Current PCs and laptops as purchased have the hardware to support WiFi. Purchasing and installing a WiFi router and receivers is within the budget and capability of home PC enthusiasts.
Bluetooth was initiated in 1998 and standardized by the IEEE as Wireless Personal Area Network (WPAN) specification IEEE 802.15. Bluetooth is a short range RF technology aimed at facilitating communication of electronic devices between each other and with the Internet, allowing for data synchronization that is transparent to the user. Supported devices include PCs, laptops, printers, joysticks, keyboards, mice, cell phones, PDAs, and consumer products. Mobile devices are also supported. Discovery protocols allow new devices to be hooked up easily to the network. Bluetooth uses the unlicensed 2.4 GHz band and can transmit data up to 1Mbit/s, can penetrate solid non-metal barriers, and has a nominal range of 10m that can be extended to 100m. A master station can service up to 7 simultaneous slave links. Forming a network of these networks, e.g. a piconet, can allow one master to service up to 200 slaves.

Currently, Bluetooth development kits can be purchased from a variety of suppliers, but the systems generally require a great deal of time, effort, and knowledge for programming and debugging. Forming piconets has not yet been streamlined and is unduly difficult.

Home RF was initiated in 1998 and has similar goals to Bluetooth for WPAN. Its goal is shared data/voice transmission. It interfaces with the Internet as well as the Public Switched Telephone Network. It uses the 2.4 GHz band and has a range of 50 m, suitable for home and yard. A maximum of 127 nodes can be accommodated in a single network. IrDA is a WPAN technology that has a short-range, narrow-transmission-angle beam suitable for aiming and selective reception of signals.
A catalyst for the standardisation of communications protocols and the functions of a protocol layer.
Cross-layer design

e.g. Integrate navigation, communication, congestion control, and sensing
**IEEE 1451 Standard for Smart Sensor Networks**

**Objective of IEEE 1451 - Smart Transducer Interface Standard.**
To make it easier for transducer manufacturers to develop smart devices and to interface those devices to networks, systems, and instruments by incorporating existing and emerging sensor- and networking technologies.

**History of IEEE-1451**
In September 1993, the National Institute of Standards and Technology (NIST) and the Institute of Electrical and Electronics Engineers (IEEE)'s Technical Committee on Sensor Technology of the Instrumentation and Measurement Society co-sponsored a meeting and set up four working groups -

- P1451.1 Defining a common object model for smart transducers along with interface specifications for the components of the model.
- P1451.2 Defining a smart transducer interface module (STIM), a transducer electronic data sheet (TEDS), and a digital interface to access the data.
- P1451.3 working group aims at defining a digital communication interface for distributed multidrop systems.
- P1451.4 Defining a mixed-mode communication protocol for smart transducers.
- The working groups created the concept of **smart sensors** to control networks interoperability and to ease the connectivity of sensors and actuators into a device or field network.
IEE 1451 Standard for Smart Sensor Networks

Concept of Smart Sensor
contains functions in addition to those needed for accurate presentation of the measurand
IEEE 1451 Standard for Smart Sensor Networks
<table>
<thead>
<tr>
<th>Measurements for Wireless Sensor Networks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurand</strong></td>
</tr>
<tr>
<td><strong>Physical Properties</strong></td>
</tr>
<tr>
<td>Pressure</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>Humidity</td>
</tr>
<tr>
<td>Flow</td>
</tr>
<tr>
<td><strong>Motion Properties</strong></td>
</tr>
<tr>
<td>Position</td>
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<tr>
<td>Velocity</td>
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<td>Angular velocity</td>
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<tr>
<td>Acceleration</td>
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<tr>
<td><strong>Contact Properties</strong></td>
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<tr>
<td>Strain</td>
</tr>
<tr>
<td>Force</td>
</tr>
<tr>
<td>Torque</td>
</tr>
<tr>
<td>Slip</td>
</tr>
<tr>
<td>Vibration</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Presence</strong></td>
</tr>
<tr>
<td>Tactile/contact</td>
</tr>
<tr>
<td>Proximity</td>
</tr>
<tr>
<td>Distance/Range</td>
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<tr>
<td>Motion</td>
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<tr>
<td><strong>Biochemical</strong></td>
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<tr>
<td>Biochemical agents</td>
</tr>
<tr>
<td><strong>Identification</strong></td>
</tr>
<tr>
<td>Personal features</td>
</tr>
<tr>
<td>Personal ID</td>
</tr>
</tbody>
</table>
Xbow wireless sensor boards

- Temperature, ambient light, acoustic sensors, accelerometer, and magnetometer, (can get GPS)
- Each node is endowed with a microcontroller, programmable with a C-based operating system
- Cricket motes have ultrasound rangefinders
- 433 or 933 MHz ISM band

Environmental Monitoring & Secure Area Denial
WSN for Machinery Monitoring - Diagnostics & Prognostics

Microstrain, Inc., Wireless Sensors

http://www.microstrain.com/index.cfm

RFID node
Signal Conditioning

Temperature compensation

Low pass filter for noise rejection

Analog LPF

\[ H(s) = \frac{k a}{s + a} \]

Digital LPF

\[ \hat{s}_k = K \frac{z + 1}{z - \alpha} s_k \]

Difference equation

\[ \hat{s}_{k+1} = \alpha s_k + K(s_{k+1} + s_k) \]

Filtered velocity

\[ v_{k+1} = \alpha v_k + K(s_{k+1} - s_k) \]

Wheatstone Bridge

Changes in R converted to changes in V

Improved sensitivity

DSP - Kalman Filter

\[ \hat{x}_{k+1} = A(I - KH)\hat{x}_k + Bu_k + AKz_k \]
User Interface, Monitoring, & Decision Assistance

Wireless Access over the Internet

LabVIEW Real-time Signaling & Processing

CBM Database and real time Monitoring

PDA access Failure Data from anytime and anywhere
ARRI Distributed Intelligence & Autonomy Lab
DIAL

Small mobile Sensor-Dan Popa
Unattended Ground Sensors

Testbed containing MICA2 network (circle), Cricket network (triangle), Sentry robots, Garcia Robots & ARRI-bots
DEC for WSN

Mission result: False fire alarm

Robot 1 goes to sensor 2

Sensor 1 output: alarm

Robot 1 picks sensor 2

Robot 2 follows robot 1

Sensor 3 measurement

Sensor 4 measurement

Robot 1 places sensor 2

Sensor 2 measurement

Robot 1 goes to sensor 1

Robot 2 smoke detection

Programmable Missions
### Fast Programming of Missions

#### Table I- Mission 1 - Task sequence

<table>
<thead>
<tr>
<th>Task</th>
<th>notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input 1</td>
<td>$u^1$</td>
<td>$UGS1$ launches chemical alert</td>
</tr>
<tr>
<td>Task 1</td>
<td>$S4m^1$</td>
<td>$UGS4$ takes measurement</td>
</tr>
<tr>
<td>Task 2</td>
<td>$S5m^1$</td>
<td>$UGS5$ takes measurement</td>
</tr>
<tr>
<td>Task 3</td>
<td>$R1gS2^1$</td>
<td>$R1$ goes to $UGS2$</td>
</tr>
<tr>
<td>Task 4</td>
<td>$R2gA^1$</td>
<td>$R2$ goes to location A</td>
</tr>
<tr>
<td>Task 5</td>
<td>$R1rS2^1$</td>
<td>$R1$ retrieves $UGS2$</td>
</tr>
<tr>
<td>Task 6</td>
<td>$R1lis^1$</td>
<td>$R1$ listens for interrupts</td>
</tr>
<tr>
<td>Task 7</td>
<td>$R1gS1^1$</td>
<td>$R1$ goes to $UGS1$</td>
</tr>
<tr>
<td>Task 8</td>
<td>$R2m^1$</td>
<td>$R2$ takes measurement</td>
</tr>
<tr>
<td>Task 9</td>
<td>$R1dS2^1$</td>
<td>$R1$ deploys $UGS2$</td>
</tr>
<tr>
<td>Task 10</td>
<td>$R1m^1$</td>
<td>$R1$ takes measurement</td>
</tr>
<tr>
<td>Task 11</td>
<td>$S2m^1$</td>
<td>$S2$ takes measurement</td>
</tr>
<tr>
<td>output</td>
<td>$y^1$</td>
<td>Mission 1 completed</td>
</tr>
</tbody>
</table>

#### Table II- Mission 2 - Task sequence

<table>
<thead>
<tr>
<th>Mission 2</th>
<th>notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>$u^2$</td>
<td>$UGS3$ batteries are low</td>
</tr>
<tr>
<td>Task 1</td>
<td>$S1m^2$</td>
<td>$UGS1$ takes measurement</td>
</tr>
<tr>
<td>Task 2</td>
<td>$R1gS3^2$</td>
<td>$R1$ goes to $UGS3$</td>
</tr>
<tr>
<td>Task 3</td>
<td>$R1cS3^2$</td>
<td>$R1$ charges $UGS3$</td>
</tr>
<tr>
<td>Task 4</td>
<td>$S3m^2$</td>
<td>$UGS3$ takes measurement</td>
</tr>
<tr>
<td>Task 5</td>
<td>$R1dC^2$</td>
<td>$R1$ docks the charger</td>
</tr>
<tr>
<td>output</td>
<td>$y^2$</td>
<td>Mission 2 completed</td>
</tr>
</tbody>
</table>
Supervisory Control of Mobile Wireless Sensor Networks

Deadlock avoidance policy
Program Missions- Selection of matrices
Node Deployment & Failure- Modify \( F_r \)
Select Resources- Priority modification of \( F_r \)

Performance Measures

NEX TASK LOGIC:
\[ \bar{x} = F_v \bar{y} + F_r \bar{r} + F_u \bar{u} + F_{\text{sub}} \bar{u}_d \]
\[ v_x = S_y x \]

RESOURCE RESET LOGIC:
\[ r_s = S_y x \]

MISSION COMPLETE LOGIC:
\[ y = S_y x \]

Discrete Event Supervisory Controller - US Patent

- Fast programming of multiple missions
- Real-time event response
- Dynamic assignment of shared resources

无线传感器网

传感器读数事件
任务执行
资源可用
任务命令
资源重置命令

目标或事件输入

LabVIEW用户界面
WSN Issues

- Limited
  - Range
  - Power
  - Processing power / memory
  - Cost

- Large number of nodes
- Prone to failures
- Easy to be compromised
- Changing topology
- Lack of global ID

- Disseminate
  - Sensor data
  - Information
  - User Interest

- Sensor Management Protocol (SMP)
  - Attribute-based naming
  - Location-based addressing
  - Data-centric routing
  - User broadcast interest

Figure courtesy Akyildiniz, Su, et al. 2002
Network layer

Routing
- Minimum energy
- Minimum hop
- Max. min power available

Interest dissemination
- Responsive action
- Event detection

Routing

Data fusion

Interest dissemination
- Responsive action
- Event detection

Routing
- Minimum energy
- Minimum hop
- Max. min power available

Data fusion

Interest dissemination
- Responsive action
- Event detection

Routing
- Minimum energy
- Minimum hop
- Max. min power available

Data fusion

Sensor Protocols for Information via Negotiation

Akyildiz, Su, et al. 2002
Hierarchical Routing Allows Multicast – Efficient Routing

- **source node**
- **destination**
- **group leader**

1. Source to leader
2. Leader to destination

**Standard peer-to-peer routing**

- 5 links
- 18 links
- **23 links total**

**Multicast routing**

- 7 links
- 8 links
- **15 links total**

Election of cluster heads
- Event-based
- Application-based
- LEACH

Taken from Chen et al. (2000)
Node Relative Positioning & Localization

Ad hoc network- scattered nodes
Nodes must self organize

Calibrated network-
Each node knows its relative position

TDMA frame for both communication protocols and relative positioning
Integrating new nodes into relative positioning grid

a. Two nodes- define x & y axes

b. 3 node closed kinematic chain- compute \((x_3, y_3)\)

One can write the relative location in frame \(O\) of the new point 3 in two ways. The triangle shown in the figure is a closed kinematic chain of the sort studied in [Liu and Lewis 1993, 1994]. The solution is obtained by requiring that the two maps \(T_{13}\) and \(T_{123}\) be exact at point 3.

Kinematics transformation

\[
A_i = \begin{bmatrix} R_i & p_i \\ 0 & 1 \end{bmatrix}
\]

Recursive closed-kinematic chain procedure for integrating new nodes
Adaptive Sampling with Mobile Sensor Nodes

Dan Popa, Sreenath, Mysorewala, F.L. Lewis
ICCA Budapest 2005

Mobile node dynamics
\[ x_{k+1} = x_k + h(x_k, u_k) + w_k \quad E[w_k w_k^T] = Q_k \]

Mobile node position measurement
\[ y_k = f(x_k) + \xi_k \quad E[\xi_k \xi_k^T] = R_k \]

Distributed field measurement model
\[ z_k = g(x_k, a_k) + v_k \]

Sum of Gaussian model
\[ z_k = a_o + a_1 g_1(x_k) + \ldots + a_m g_m(x_k) \quad \text{(RBF neural network)} \]

A. Estimation of Field Without Localization Uncertainty
\[ A_{k+1} = A_k \quad z_k = G_k A_k + v_k, \quad G_k = \begin{pmatrix} \ldots & g_1(X_k) & \ldots & g_m(X_k) \end{pmatrix} \quad E[v_k v_k^T] = R \]
\[ A_o \sim (\tilde{A}_o, P_{A_o}), P_o = P_{A_o} \]
\[ P_{k+1}^{-1} = P_k^{-1} + G_{k+1}^T R^{-1} G_{k+1}, \]
\[ \hat{A}_{k+1} = A_k + P_{k+1} G_{k+1}^T R^{-1} (Z_{k+1} - G_{k+1} A_k). \]

B. Estimation of Field With Localization Uncertainty
\[
\begin{pmatrix} X_{k+1} \\ \hat{A}_{k+1} \end{pmatrix} = \begin{pmatrix} X_k \\ A_k \end{pmatrix} + \begin{pmatrix} I_3 \\ 0 \end{pmatrix} U_k + \begin{pmatrix} W_k \\ 0 \end{pmatrix} = \begin{pmatrix} X_k \\ A_k \end{pmatrix} + BU_k + \mathcal{G}_k,
\]
\[
\begin{pmatrix} Y_k \\ Z_k \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} X_k \\ \hat{A}_k \end{pmatrix} \end{pmatrix} + \begin{pmatrix} \xi_k \\ v_k \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} X_k \\ \hat{A}_k \end{pmatrix} \end{pmatrix} + \lambda_k,
\]
\[
P_{k+1}^{-1} = P_k^{-1} + G_{k+1}^T R^{-1} G_{k+1},
\]
\[
\hat{X}_{k+1} = \begin{pmatrix} X_k \\ \hat{A}_k \end{pmatrix}, \quad \hat{X}_{k+1} = \begin{pmatrix} X_k \\ \hat{A}_k \end{pmatrix} + BU_k,
\]
\[
P_{k+1} = \begin{pmatrix} X_{k+1} \\ \hat{A}_{k+1} \end{pmatrix} = \begin{pmatrix} X_{k+1} \\ \hat{A}_{k+1} \end{pmatrix} + P_{k+1} G_{k+1}^T R^{-1} (Y_{k+1} - G_{k+1} \hat{X}_{k+1}).
\]

Select next sample point to minimize covariance
Measured Field is a color map. Mobile robots have color sensors.

Raster Scan

Adaptive Sampling

Mobile sensors
Built at DIAL Lab
By Dan Popa

Implementation at ARRI’s Distributed Intelligence & Autonomy Lab (DIAL)

\[
R = r_0 + r_1x + r_2y, \quad G = g_0 + g_1x + g_2y, \quad B = b_0 + b_1x + b_2y
\]

\[
r_0 = 0.2307, r_1 = 0.0012, r_2 = -0.00048, g_0 = 0, g_1 = 0.0002,
\]

\[
g_2 = 0.0018, b_0 = 1.0, b_1 = -0.00078, b_2 = -0.001\]
Greedy Adaptive Sampling Algorithm

Select next sample point to minimize covariance only among neighboring cells
Cross-Layer Navigation Using Potential Fields

\[ m_i \ddot{r}_i + v_i \dot{r}_i = \mathbf{F}_i \]  

Mobile node eqs. of motion

\[ \mathbf{F} = -\nabla U(\mathbf{r}) \]  

attractive forces to the goals, repulsive forces among the robots and obstacles

\[ \mathbf{F}_{restore}(i, j) = u_{ij} (\mathbf{r}_j - \mathbf{r}_i) \]  

Restoring force to avoid getting out of communication range

\[ F_c = -\nabla C \quad C = W \log_2 \left( 1 + \frac{K}{WN_o} \frac{P_i}{d^a} \right) \]  

Link communication capacity with internode distance \( d \)

Information potential

\[ \mathbf{F}_{inf} = -\frac{\partial (||P_k(r)||)}{\partial r} \]  

\( P_k(r) \) is the adaptive sampling error covariance calculated via the EKF

Energy cons.

\[ v_i(t) = v_o (1 + k_{vi} E_i(t)), \quad E_i(t) = \int_0^t \mathbf{F}_i(\tau) \dot{r}_i(\tau) d\tau \]  

Conserve energy by making damping increase with motion energy expended

\[ \hat{M}_{k+1} = (\hat{X}_{k+1}^\perp - X_k^\perp)^T W (\hat{X}_{k+1}^\perp - X_k^\perp) \]  

Work to go to next predicted state for adaptive sampling
Initial configuration
Node 20 at (0,0) is a sink

Final configuration after
(7,8) is selected as a target point

Nodes 3, 12, 14 go to (7,8) to sense information
Other nodes move to maintain comm. links
Dynamic Localization of Mobile WSN

Dang, F. Lewis, D. Popa

Node position

\[ X_i = [x_i, y_i]^T \]

Estimator for position

\[ \begin{bmatrix} \dot{X}_i \\ \ddot{X}_i \end{bmatrix} = \begin{bmatrix} O_2 & I_2 \\ O_2 & O_2 \end{bmatrix} \begin{bmatrix} X_i \\ \dot{X}_i \end{bmatrix} + \begin{bmatrix} O_2 \\ I_2 \end{bmatrix} f_i^{x,y} \]

1. Relative Localization

Potential fn.

\[ V_{ugs} = \sum_{i=1}^{N} \sum_{j=1 \atop i \neq j}^{N} \frac{1}{2} K_{ij} (r_{ij} - \bar{r}_{ij})^2 \]

Theorem. Let virtual force be given by

\[ \ddot{f}_i = -\sum_{j=1}^{N} \frac{N}{K_{ij}} (r_{ij} - \bar{r}_{ij}) \frac{(X_i - X_j)}{\|X_i - X_j\|} - K_v \dot{X}_i \]

Then the position estimates reach steady-state values that provide optimal estimates of the actual relative localization of the nodes in the sense that \( e \) is minimized.

Proof:

\[ L = V_{ugs} + \sum_{i=1}^{N} \frac{1}{2} \dot{X}_i^T \dot{X}_i \]

2. Absolute Localization

\( m \) nodes with GPS

\[ X_{ip}^a; p = 1, 2, ..., m \]

abs. loc. pot. fn.

\[ V_{abs} = \frac{1}{2} \sum_{p=1}^{m} \sum_{j=1}^{N} K_{ip}^a (r_{ip}^a - \bar{r}_{ip}^a)^2 + \frac{1}{2} \sum_{p=1}^{m} K_{ip}^a \| e_{ip}^a \|^2 \]

with

\[ e_{ip}^a = [(x_{ip}^a - \bar{x}_{ip}^a)^2 + (y_{ip}^a - \bar{y}_{ip}^a)^2]^{1/2} \]

Theorem. Let virtual force be given by

\[ f_{ip} = \sum_{j=1}^{N} K_{ip,j} (r_{ip,j} - \bar{r}_{ip,j}) \frac{(X_{ip} - X_j)}{\|X_{ip} - X_j\|} - K_v \dot{X}_{ip} \]

nodes with no GPS

\[ \begin{align*}
  f_{ip}^a &= -K_v^a (X_{ip}^a - \bar{X}_{ip}^a) - \sum_{j=1}^{N} K_{ip,j}^a (r_{ip,j} - \bar{r}_{ip,j}) \frac{(X_{ip}^a - X_j)}{\|X_{ip}^a - X_j\|} - K_v^a \dot{X}_{ip}^a \\
  \end{align*} \]

nodes with GPS

Proof:

\[ V_p = \frac{1}{2} \sum_{p=1}^{m} K_{ip}^a \| e_{ip}^a \|^2 + \frac{1}{2} \sum_{p=1}^{m} \sum_{j=1}^{N} K_{ip,j}^a (r_{ip}^a - \bar{r}_{ip,j}^a)^2 + \frac{1}{2} \sum_{p=m+1}^{N} \sum_{j=1}^{N} K_{ip,j} (r_{ip,j} - \bar{r}_{ip,j})^2 \]
Range-Free Localization of Mobile WSN

1. Localization of Stationary Nodes

\[
x_{k+1}^i = A_k^i x_k^i + B_k^i u_k^i + G_k^i w_k^i
\]

\[
z_k^i = H_k^i x_k^i + v_k^i
\]

\[
A_k^i = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, B_k^i = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, G_k^i = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, H_k^i = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
\]

uncertainty in comm. range

\[
R_k = \sigma_{Bot}^x \sigma_{Bot}^y = \begin{bmatrix} \sigma_{Bot}^x & 0 \\ 0 & \sigma_{Bot}^y \end{bmatrix}, \quad \sigma_{Bot}^x = \frac{Range_{x}}{\sigma_{const}}, \sigma_{Bot}^y = \frac{Range_{y}}{\sigma_{const}}
\]

Algorithm 1: Static sensor node localization algorithm

1. At each discrete time instant,
2. if robot broadcast received by sensor
3. then
4. Update sensor state and uncertainty estimates using KF
5. else
6. Propagate estimates using time updates
7. end if

The first reading localizes the node to a projection on the robot’s path
2. Simultaneous Localization of Mobile Robot & Stationary Nodes

\[ \dot{X} = a(X, u, t) + G(t)w \]

GPS update when available

\[ Z_{k}^{\text{gps}} = h^{\text{gps}}[X(t_k), k] + v_{k}^{\text{gps}} \]

Update from UGS position when available

\[ Z_{k}^{\text{ugs}} = h^{\text{ugs}}[X(t_k), k] + v_{k}^{\text{ugs}} \]

Algorithm 2: Mobile robot localization algorithm.
1. Navigate robot along desired path.
2. Broadcast location information at discrete intervals.
3. if broadcast from GPS received
4. Update robot state and uncertainty estimates using measurement Eq. (20).
5. end if
6. if broadcast from sensor received
7. Update robot state and uncertainty estimates using measurement Eq. (21).
8. end if

Includes uncertainty in position and in comm. range

Includes uncertainty in position and in comm. range

Mobile robot localization turned off

With Mobile robot localization
3. Adaptive Localization

Mobile robot moves to localize the un-localized sensors

**Problem**: how does it know where to go to localize nodes with unknown positions?

Network communication connectivity is exploited

Initiation of the navigation request "NAV-REQ" packet from the robot

Badly localized sensors reply back with a localization request "LOC-REQ" packet. Already localized adjacent receiving nodes add their location and forward the request.

---

**Algorithm 3**: Adaptive localization algorithm.

2. Wait to receive Localization request, LOC-REQ, packets.
3. For all LOC-REQ with the same friendly neighbor
4. Combine uncertainty scalars of the requesting sensors.
5. End for
6. Pick friendly neighbor with maximum combined uncertainty scalar of the requesting sensors.
7. If multiple maxima arise
8. Among the maxima, pick the most localized friendly neighbor.
9. End if
10. Navigate around the picked friendly neighbor executing the simultaneous localization algorithm, on the sensors and on the mobile robot.
11. Repeat Steps 1-10 as required.
Failure of two nodes causes loss of sensor coverage

**Reliability Theory**

Survivor Function = prob. that a unit is still functioning at time \( t \)

\[
s(t) = 1 - \text{cdf}
\]

Reliability block diagram of square grid

\[
s_{\text{block}} = 1 - (1 - s_a)(1 - s_b s_c) \]
\[
= s + s^2 - s^3
\]
\[
s_{\text{net}} = (s_{\text{block}})^N
\]

Reliability block diagram of hex grid

\[
s_{\text{block}} = 1 - (1 - s)(1 - s^3)
\]
\[
s_{\text{net}} = (s_{\text{block}})^{N/2}
\]
Finding node lifetime pdf

Node lifetime

\[ T_{\text{node}} = \frac{E_{\text{init}} - E_{\text{threshold}}}{\sum w_i P_i} \]

- power consumed in mode i
- fraction of time spent in mode i

Assume only 2 modes, then binomial pdf

\[ P\{w_1 = x\} = c^x p^x (1 - p)^{T-x} \]

\[ \text{Pr node is idle} \]
\[ \text{Pr node is active (defined by net protocol)} \]
\[ T = \text{nr. of time units} \]

Results

Fig. 4. Probability Density Function of the lifetime of a node. (a) Theoretical pdf, (b) Actual pdf.

Fig. 5. Probability Density Function of the network lifetime employing the square-grid placement scheme. (a) Theoretical pdf, (b) Actual pdf.
Energy Conserving Sensor Coverage

Sample time #1

Grey = area not covered

Selected Sensors

Extra nodes selected for connectivity

Entire area covered in 2 sample times
latency (delay) = 2

Formal algorithms for specifying QoS
% coverage of sensors
max latency
Math Basis

Circular sensing region $SR_i$ of radius $r$

Select min. nr. $K$ of sensors s.t.

$$DSC \subset Q \cap \bigcup_{i=1}^{k} SR_i$$

and entire region is covered within desired latency $T$

$$\sum_{i=1}^{N} t_i \leq T$$

Assume:

- sensors are uniformly distributed
- location info not available

1. Find Required Number of Sensors for DSC

DSC= probability of coverage of point $(x,y)$

Find probability that a point $(x,y)$ is not covered by randomly selected sensor $P_q q(x,y)$

Then, min. number of sensors needed to cover DSC is

$$k = \frac{\log(1 - DSC)}{\log \left( \frac{a^2 + 4ar}{a^2 + 4ar + m^2} \right)}$$

| Algorithm | Construct_RS$(k, |V|)$ Begin |
|-----------|-------------------------------|
| 1. | $\delta \leftarrow \left\lceil \frac{|V|-1}{h} \right\rceil$; /* the number of reporting rounds in $C$ */ |
| 2. | Allocate a bit array $A[\delta]$ and initialize all the entries with zero; |
| 3. | $i \leftarrow RAND[1, \delta]$; |
| 4. | $A[i] \leftarrow 1$; |
| 5. | return $A[\delta]$; /* reporting sequence $RS_{s_i}$ */ |
| End-Algorithm | |

Fig. 5. Algorithm for Constructing Reporting Sequence ($RS_{s_i}$)
2. Add Extra Routing Nodes for Comm. Connectivity

Test probable connectivity of $k$ sensors in $k-1$ steps, adding nodes when needed

![Diagram](image)

$$P_{S_i} = \text{radio range of node } i / \Lambda$$

$$P_{r_0} = \sum_{j=1}^{k-1} \binom{k-1}{j}(P_{s_i})^j(1-P_{s_i})^{k-1-j}$$

$$P_{r_1} = P_{r_0} \times \left(1 - \left(1 - \sum_{j=1}^{k-2} \binom{k-2}{j}(P_{s_i})^j(1-P_{s_i})^{k-2-j}\right)^2\right)$$

$$P_{r_2} = P_{r_1} \times \left(1 - \left(1 - \sum_{j=1}^{k-3} \binom{k-3}{j}(P_{s_i})^j(1-P_{s_i})^{k-3-j}\right)^2\right)$$

$$P_{r_{k-2}} = P_{r_{k-3}} \times \left(1 - \left(1 - \sum_{j=1}^{k-2} \binom{k-2}{j}(P_{s_i})^j(1-P_{s_i})^{k-2-j}\right)^2\right)$$

$$P_{r_{k-1}} = P_{r_{k-2}} \times (1 - P_{s_i})^{k-1}$$

Fig. 7. Probabilistic Model for Estimating The Connectivity of Selected $k$ Sensors

Algorithm Find $\hat{k}$ Begin
1: procedure FK ($P_r$, $\hat{k}$, $\omega$, $\gamma$) begin
2: if $((1 - P_r) \times \hat{k} \leq 1)$
3: then $\hat{k} \leftarrow \hat{k} + 1$;
4: else $\gamma \leftarrow \gamma + \lfloor P_r \times \hat{k} \rfloor$;
5: $P_r' \leftarrow P_r(E[\omega + d]^2, \gamma)$;
6: $\hat{k} \leftarrow \hat{k} + FK(P_r, \hat{k} - \lfloor P_r \times \hat{k} \rfloor, \omega + d, \gamma)$;
7: end-if
8: return $\hat{k}$;
9: end-procedure
10: FK($P_{r_{\text{conn}}}$, $k$, radio range ($r$), step ($l$) = 1); /* Main Algorithm */
End-Algorithm

Fig. 8. Recursive Algorithm for Computing $\hat{k}$

3. Construct Data Gathering Tree (DGT)

For routing and sensor scheduling

Data sink sends flood message
Each sensor keeps a forwarding record with best upstream candidate
Sensors broadcast join request setup msgs.

Localized sensor scheduling algorithm
Distributed Greedy Algorithm for Connected Sensor Cover

Energy conserving sensor coverage
Find minimum connected sensor cover (MCSC)  

Def. MCSC
1. Monitored area contained in Union of node sensor regions
2. Induced communication graph is connected via multihop

Problem of finding MCSC is NP-hard [Garey and Johnson 1991]

Graph = (nodes, edges)
Communication radius $R_c$
Sensing radius $R_s$

Assume $R_c \geq 2R_s$

Induced comm. graph $G_c = (V, E_{R_c})$
edge $i,j$ exists if $d(s_i, s_j) < R_c$

Induced sensing graph $G_s = (V, E_{R_s})$
edge $i,j$ exists if $d(s_i, s_j) < 2R_s$

Def. Independent Set
A subset of vertices such that no two vertices has an edge in G.

Def. MIS
An IS that is not contained in any other IS

Finding MIS for a general graph is NP-hard

Ghosh and S. Das, June 2005
Suboptimal MCSC using greedy approach

Phase 1 – Find Maximal Independent Set (MIS)

Use greedy approach looking only at 1-hop nearest neighbors

Def. Eligible next node given node $s_i$
1. $s_j$ not yet included in the connected MIS
2. $s_j$ a one-hop neighbor of $s_i$
3. sensing circle of $s_j$ does not overlap any selected sensing circles

Algorithm 1 Phase 1: Distributed greedy algorithm to find a connected MIS.

1: Initialization:
2: $\Gamma \leftarrow \phi$;
3: Choose the first node $s_0$ and include it in $\Gamma$; $s_b \leftarrow s_0$;
4: Steps at each $s_b$:
5: $N_{sb}(R_c - 2R_s) \leftarrow \phi$;
6: for all $s_b \in N_{sb}(R_c)$ do
7: if $2R_s \leq d(s_b, s_0) \leq R_c$ then
8: $N_{sb}(R_c - 2R_s) \leftarrow N_{sb}(R_c - 2R_s) \cup s_b$;
9: end if
10: end for
11: if $N_{sb}(R_c - 2R_s) \neq \phi$ then
12: Find that $s_k \in N_{sb}(R_c - 2R_s) \setminus N_{sb}(R_c - 2R_s) \cap \cup_{s_j \in \Gamma, s_j \neq s_b} N_{s_j}(2R_s)$, such that $d(s_b, s_k)$ is minimum;
13: $\Gamma \leftarrow \Gamma \cup s_k$;
14: else if $N_{sb}(R_c - 2R_s) == \phi$ then
15: $s_k \leftarrow s_q$, such that $d(s_b, s_q) = \max \{d(s_b, s_i), \forall s_i \in N_{sb}(R_c)\}$;
16: end if
17: $s_k$ becomes the next $s_b$ to execute the same steps 5 – 16.
Phase 2- Select extra nodes to get full sensor coverage

Result of Phase I MIS

has holes

Construct Voronoi Diagram for nodes selected in Phase 1

Voronoi Diagram divides the plane into convex polygons whose edges are equidistant from two nodes

Algorithm 2- Choose best 1-hop neighbor that maximally covers holes in its polygon

Voronoi structure allows efficient formal algorithm for doing this
Math Analysis

Let N nodes be uniformly randomly distributed over area A. Density is \[ \rho = \frac{N}{A} \]

Then number of nodes in Phase I MIS is bounded by

\[ \frac{N}{5 \rho \pi R_s^2} \leq \zeta \leq \frac{N}{\rho \pi R_s^2} \]

Time complexity of first algorithm is \( O(\zeta N) \)

Time complexity of second algorithm is \( O(\zeta \log \zeta) \)

---

Fig. 5. Simulation: Dark circles represent sensing ranges of nodes belonging to connected MIS: (a) \( N = 150, R = 15m, A_Q = 10,000m^2 \). (b) Variation of connected MIS cardinality with sensing radius \( R_s \).
(n,t) Threshold cryptography via polynomials

Random secret polynomial: \( f(x) = a_0 + a_1 x + a_{t-1} x^{t-1} \)

where secret key is \( D = f(0) \)

\( f(x) \) Can be reconstructed from \( t \) points from the set \{f(1), f(2), \ldots, f(n)\}, with \( n \) = number of nodes

Select masking polynomial \( h(x) \) and securely predeploy personal secrets \( h(i) \) on each node \( i \).

The Sink broadcasts \( w(x) = f(x)g(x) + h(x) \)

Where revocation polynomial is \( g(x) = (x-r_1)(x-r_2)\ldots(x-r_w) \)

with the set of compromised nodes \( \{r_1,\ldots,r_w\} \)

Then each node \( i \) can evaluate its personal key \( f(i) = \frac{w(i) - h(i)}{g(i)} \)

Compromised nodes have \( g(i) = 0 \) and cannot find personal key

Now, \( t \) nodes can collaborate to exchange personal keys \( f(i) \) and so compute \( f(x) \), and hence find the secret group key \( D = f(0) \)

Since \( h(i) \) is securely predeployed and \( f(x) \) is random, the scheme can be shown to be unconditionally secure
2. Enhancement to avoid disclosing personal key \( f(i) \)

Select a random concealing polynomial \( L(x) \) of degree \( t-1 \) and securely predeploy concealing secret \( L(i) \) on each node \( i \).

The sink selects a random \( t-1 \) degree polynomial \( f(x) \) such that the secret is \( D = f(0) + L(0) \).

Instead of exchanging personal keys \( f(i) \), the \( t \) collaborating nodes exchange the concealed personal key \( s(i) = f(i) + L(i) \).

Since \( s(x) \) has degree \( t-1 \), it can be reconstructed using \( t \) concealed personal keys from \( t \) nodes.

Then, the group secret is \( D = s(0) \).

Theorem 1. Assume that the local exchange of concealed secrets is secure. Then the scheme is unconditionally secure, and has \( t \)-revocation capability.

The concealing key allows improved defense against compromised nodes, who now do not know the personal keys \( f(i) \).

This also allows self-healing strategies, i.e. in the presence of lost broadcast messages from the Sink.
Multi-Layer Approach to Defense Against Compromised Nodes

Cross-Layer Design

Figure 1: Multiple Layer Defense against Compromised Nodes
Distributed Energy-Efficient Self-Organization

LEACH selects cluster heads based on energy available
Selects randomly and does not give evenly spaced heads
Requires global info – total number of nodes, and total energy available in all nodes

Expellant Self-Organization (ESO)

Based on cluster radius $R_c$, energy available, and number of neighbors

Energy threshold

$$E_{th} = \gamma_1 \max_{i \in N} E(i) + (1 - \gamma_1) \frac{\text{mean } E(i)}{n(i)}$$

$E(i)$ = energy of node $i$
$N$ = set of neighbors

Number of neighbors threshold

$$n_{th} = \gamma_1 \max_{i \in N} n(i) + (1 - \gamma_1) \frac{\text{mean } n(i)}{n(i)}$$

$n(i)$ = number of neighbors of node $i$

Fig. 3. Flow chart of a node in ESO.
Fault-Tolerant & Energy Efficient Cross-Layer Routing

Qilian Liang, Oct. 2005

Use fuzzy logic to select node for next hop transmission using:
1. Distance of next node (NN) to destination- should be small
2. Remaining battery capacity of next node- should be large
3. Mobility of next node- should be small

**Rules:**  If (NN is near dest.) and (NN has large remaining energy) and (NN is stationary)
THEN (NN is a strong candidate)

The required information is periodically locally broadcast via beacons

When a node wishes to transmit, it sends a ROUTE NOTIFICATION,
and the receiving nodes send a REPLY packet

If a node fails, the previous node broadcasts a ROUTE DELETION packet
Cross-Layer Routing in Sensor Networks

Luo, Yonghe Liu, Sajal Das, 2006

Graph (nodes, edges) \( G = (V,E) \)

Find Data Gathering Tree

Transmission cost \( t(e) = w(e) c(e), \ e = \text{an edge} \)

\( w(e) = \text{amount of data} \)
\( c(e) = \text{transmission cost – congestion, distance, latency, energy used} \)

Fusion cost \( f(e) \)

Minimize the total cost \( \sum_{e \in \text{route}} [f(e) + t(e)] \)

Fusion Cost for \( L \) bits = \( 2L \times 5 \) nano Joules

the resulting data has \( L(1+\eta) \) bits

Data correlation model \( \eta = 1 - e^{-\alpha r} \)

\( r = \text{node separation, good for field measurements} \)

Fonda, Zawodniok, S. Jagannathan, ISIC Munich 06

Maximize the cost with link cost factors given as

\[
\frac{\text{remaining energy at next node}}{(\text{delay to reach next node}) \times (\text{dist. from next node to destination})}
\]

Dijkstra’s Algorithm can be used
Transmission Costs

Transmission cost per hop \( \propto d^\gamma, \quad 2 \leq \gamma \leq 4 \)

Total energy per packet using N hops

\[
E = \alpha N + \beta \sum_{\text{hops}} d_i^\gamma
\]

- Setup cost
- Trans. cost
For data representing the same property:

**General distance measure**

\[ d(P_1, P_2) = f \{ E_1 \{ C(L) \} \} \]

\( f(.) \) an increasing fn.
\( C(.) \) a convex fn.

**J-divergence**

\[ J(P_1, P_2) = E_1 \{ (L - 1) \log L \} \]

**Matsusita distance**

\[ d(P_1, P_2) = \{ E_1 \{ (\sqrt{L} - 1)^2 \} \}^{1/2} \]

**Bhattacharyya’s distance**

\[ B(P_1, P_2) = -\log(1 - d^2) \]
Distance is not symmetric

**Fig. 3.** Two probability distributions $P_i(x)$ and $P_j(x)$ with different variance measures.

**Fig. 4.** (a), (b) Definition of "confidence distance measure" $d_{ij}$ or $d_{ji}$.

Confidence distance measures

\[
\begin{align*}
\bar{d}_{ij} &= 2 \int_{x_j}^{x_i} P_i(x/x_i) P_j(x_j) \, dx = 2A \\
\bar{d}_{ji} &= 2 \int_{x_j}^{x_i} P_j(x/x_j) P_i(x_j) \, dx = 2B
\end{align*}
\]

For multiple sensors, use matrix

\[
D = \begin{bmatrix}
    d_{11} & d_{12} & \cdots & d_{1m} \\
    d_{21} & d_{22} & \cdots & \vdots \\
    \vdots & \vdots & \ddots & \vdots \\
    d_{m1} & d_{m2} & \cdots & d_{mm}
\end{bmatrix}
\]

Draw a digraph having edge $(i,j)$ if

\[
d_{ij} \leq \text{threshold}
\]

Luo, Lin, Scherp 1988

Sensor 2 supports Sensor 3

Outlier-
Correct or discard
Information Fusion & Sensor Selection in WSN

Select the best set of sensors that meet the goals of the applications with guaranteed QoS

Middleware for customized services and resource assignment

Use Bayesian Networks

Expected utility given evidence

\[ E(U(\{S_n\}) = \sum_i P(G_i(\{S_n\})/\{S_n\}) U(G_i(\{S_n\})) \]

\( G_i(\{S_n\}) \) is the goal state reached as a result of the selected sensor set \( \{S_n\} \)

Utility of sensors can be written \( U(G_i(\{S_n\}) = \{u_n\} \)

Where utility factor for sensor \( s_n \) is

\[ u_n = \alpha D_n + (1 - \alpha) \frac{1}{\text{cost}(s_n)} \]

and \( D_n \) is a measure of the definitiveness or accuracy of sensor \( s_n \)
Security Threat Example

Utility is maximized by using sensor set \{RFID2, Video3\}
This gives 70% threshold

Table 1: Utility numbers for sensors in the example scenario

<table>
<thead>
<tr>
<th>Sensor</th>
<th>{D_i}</th>
<th>{Cost_i}</th>
<th>{u_i}</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFID1</td>
<td>4</td>
<td>1</td>
<td>3.4</td>
</tr>
<tr>
<td>RFID2</td>
<td>19.85</td>
<td>2</td>
<td>15.98</td>
</tr>
<tr>
<td>Video1</td>
<td>2.5</td>
<td>3</td>
<td>2.066667</td>
</tr>
<tr>
<td>Video2</td>
<td>1.45</td>
<td>4</td>
<td>1.21</td>
</tr>
<tr>
<td>Video3</td>
<td>9.3</td>
<td>5</td>
<td>7.48</td>
</tr>
<tr>
<td>Biometric</td>
<td>3.95</td>
<td>6</td>
<td>3.193333</td>
</tr>
</tbody>
</table>
UWB

Ultra Wideband Sensor Web

\[ s(t) = \sum_{j} w(t - jT_f - c_j T_c - \delta d_{\lfloor j/N_s \rfloor}) \]

where \( w(t) \) is the basic pulse of duration approx. 1 ns, often a wavelet or a Gaussian monocycle, and \( T_f \) is the frame or pulse repetition time. In a multi-node environment, catastrophic collisions are avoided by using a pseudorandom sequence \( c_j \) to shift pulses within the frame to different compartments, and the compartment size is \( T_c \) sec. Data is transmitted using digital pulse position modulation (PPM), where if the data bit is 0 the pulse is not shifted, and if the data bit is 1 the pulse is shifted by \( d \). The same data bit is transmitted \( N_s \) times, allowing for very reliable communications with low probability of error.

**Precise time of flight measurement is possible.**

Use UWB for all three:
- Communications
- Node Relative positioning
- Target localization
Multi-Static Radar Target Localization

Uses time of flight

Intersection of two ellipses with semimajor and semiminor axes

\[ a = \frac{(d + d_2)}{2}, \quad s = \frac{d_{12}}{2}, \quad b = \sqrt{a^2 - s^2} \]

Simultaneous solution of two quadratic equations, one for each ellipse

\[ X^T A X = 1 \]
\[ X^T B X = 1 \]

gives position of target.
References


