Low-Cost Sensor Enabled Explosive Detection to Protect High Density Environments

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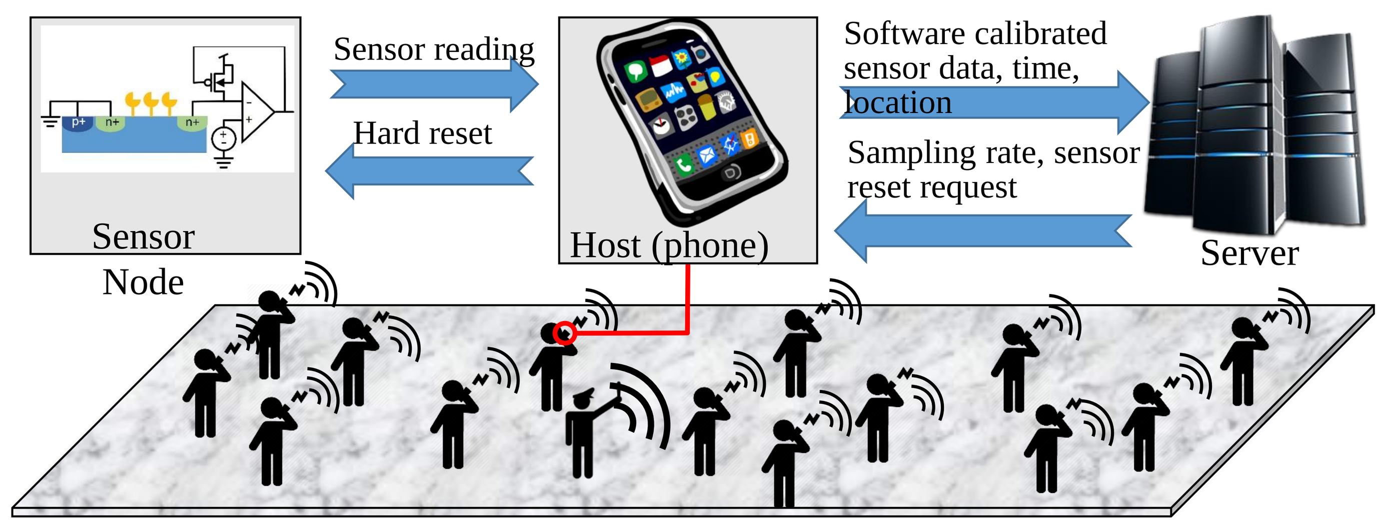
Introduction

- Protecting large area gatherings from acts of terrorism is challenging due to lack of well controlled access points
- Replaceable sensors that move with the crowd is proposed
- Simple node: sensors paired with cell phones of willing users
- Supernode: officers equipped with higher sensitivity, more reliable devices
- Server: data collection, processing, direction of supernodes, calibration prompt of sensors



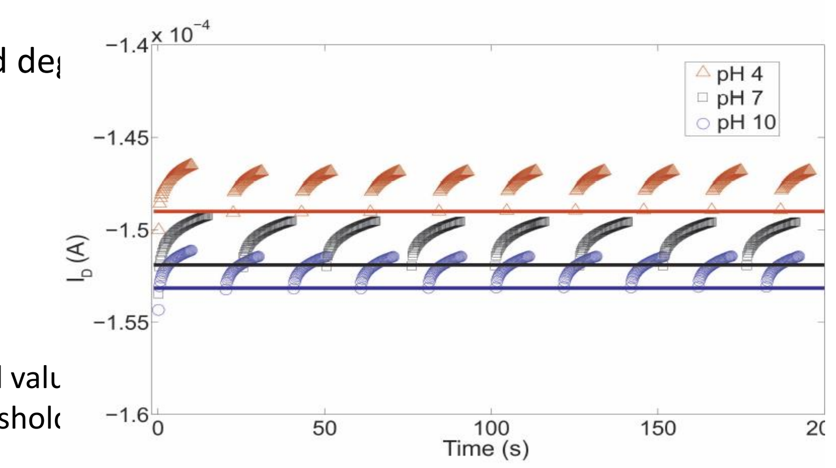
- Challenges
  - Low-cost sensors (ChemFETs) drift and degrade soon after deployment
  - Low accuracy prevents from making decisions based on a single sensor
  - Sensors can be calibrated in the field autonomously, but need to know when
  - Energy consumption should be kept to a minimum
  - User experience should not be negatively affected
  - No control over movement of nodes
  - Limited number of supernodes

Detection Algorithm

- Use spatial and temporal locality (data time and location stamped)
- Use multitude of sensors to check one another and lower detection distances
- Validator Based Detection
  - Once positive result is observed, it is corroborated with other sensors in the vicinity (spatially and temporally)
  - The number of required validators adjusted wrt density
  - Validation only by unique nodes
- Grid Average Based Detection
  - Use maximum detection distance to divide coverage area into grids
  - Moving average reading compared to threshold
  - Time duration of moving average adjusted wrt density

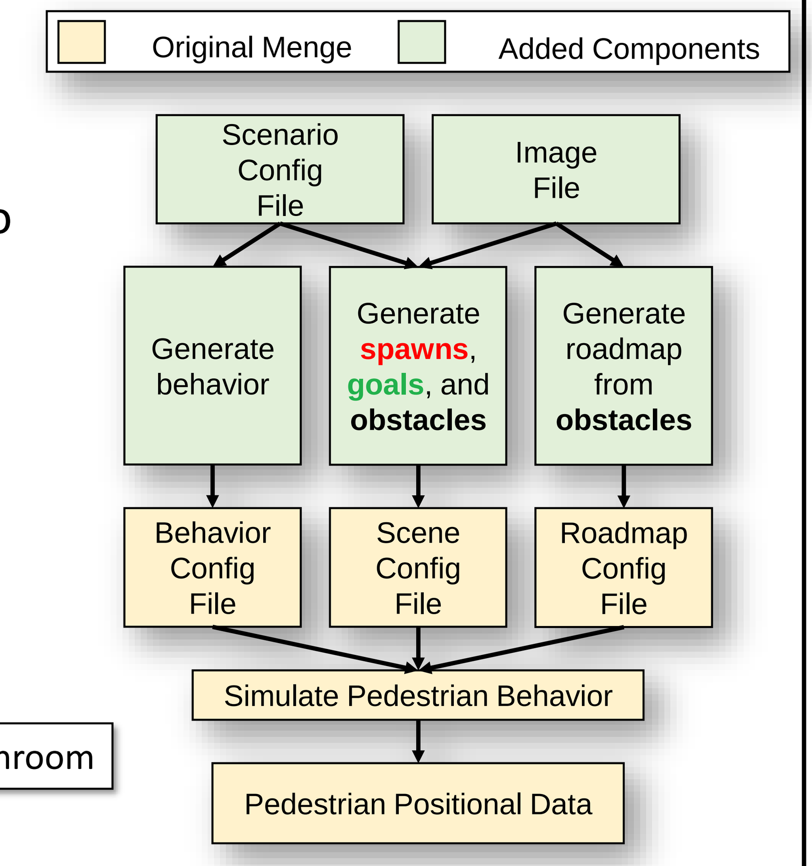
Sensor Hard Reset

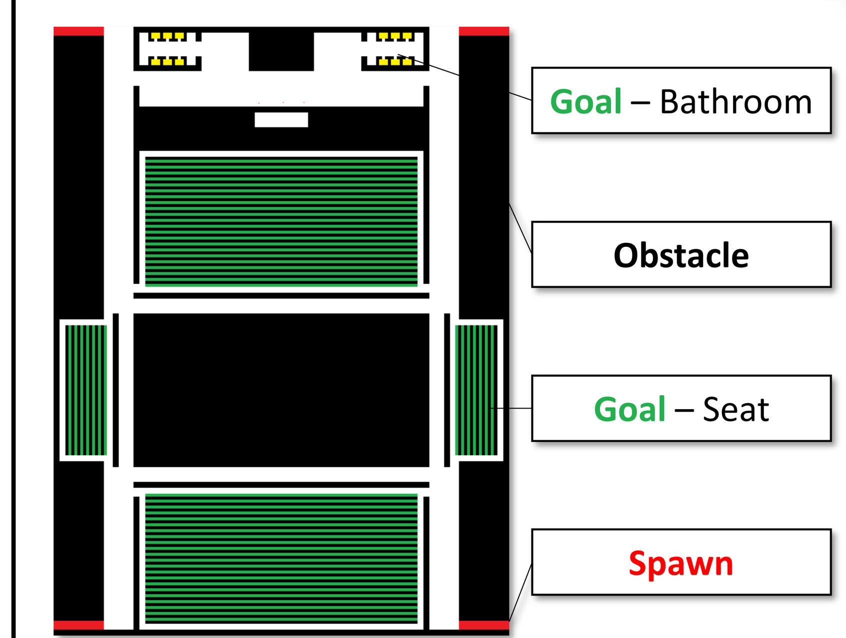
- Sensor hard reset
  - Due to accumulation mechanisms, sensor sensitivity continuously drifts and de
  - Hard reset reverses accumulation, brings the sensor back to fresh status
  - Hard reset takes sensor off-line for several seconds
  - Hard reset has an energy cost that is roughly equal to 2x conversion energy
- Two mechanisms to initiate sensor hard reset
  - Host initiated reset
    - Host maintains internal parameters
    - Host initiates sensor hard reset if the sensitivity degrades below 50% of its original valu
    - Host initiates sensor hard reset if the maximum error term exceeds detection threshol
  - Server initiated reset
    - Server maintains moving grid averages of coverage area
    - If a node deviates more than 6σ of the grid readings, the node is deemed to be an outlier
    - Server sends a request to the host to initiate hard reset



Crowd Movement Simulator

- Create scenario generator for MENGE Crowd Simulator to automate the generation of complex crowd movements to enable realistic simulation of large populations.
- Moving pedestrians follow probabilistically defined state machine and automatically route to destinations.

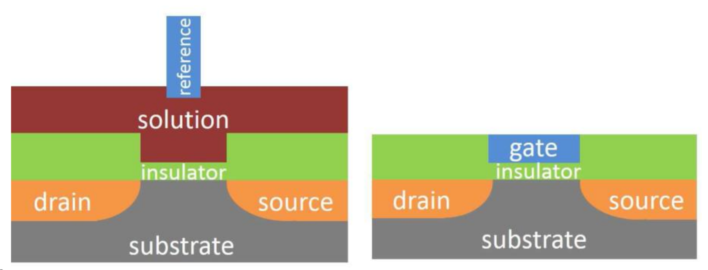




- Complex areas defined with a black and white image, using colors to denote different locations for users to travel to.

Sensor Design and Host Calibration

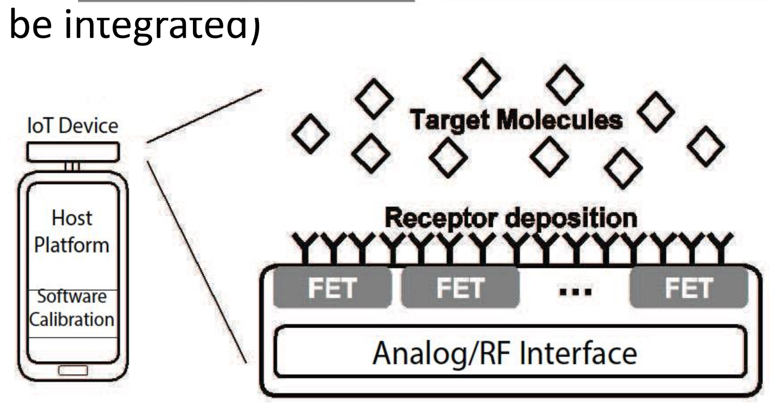
- ChemFETs are chosen due to
  - Very low cost manufacturing (<10c per sensor)
  - Reasonable sensitivity (10ppb range)
  - CMOS compatible (sensor and basic AFE can be integrated)



- Threshold voltage changes via fast, slow, and long-term response drift

$$\Delta V_{TH}(t) = \Delta V_{TH_{(F,S)}}(t) + \Delta V_{TH_{(D)}}(t)$$

$\Delta V_{TH_{(F,S)}} \rightarrow fast, slow\ response\ drift$
$\Delta V_{TH_{(D)}} \rightarrow long-term\ response\ drift$



- I_{DS} is related to shift in V_{TH} under constant V_{GS}

$$\Delta I_{DS}(t) = \underbrace{\mu \frac{\epsilon_{SL}}{x_{SL}} V_{DS}}_{gm} \underbrace{\left[V_{TH}(t) - V_{TH}(0)\right]}_{\Delta V_{TH}}$$

$\mu \rightarrow mobility$
$\epsilon_{SL} \rightarrow dielectric\ constant$
$x_{SL} \rightarrow thickness\ of\ surface\ insulator$
$V_{DS} \rightarrow drain-source\ voltage$
$V_{TH} \rightarrow threshold\ voltage$

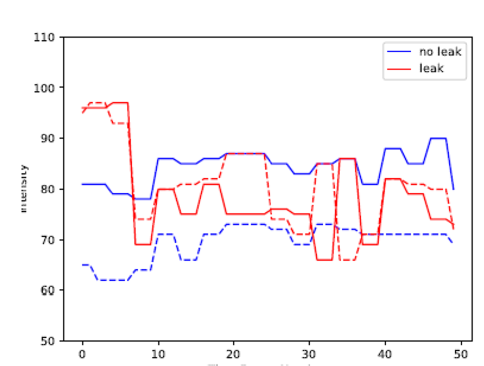
- Deviation in drain current (ΔI_{DS}) as a function of
  - Concentration of the target molecule
  - Temperature
  - Time

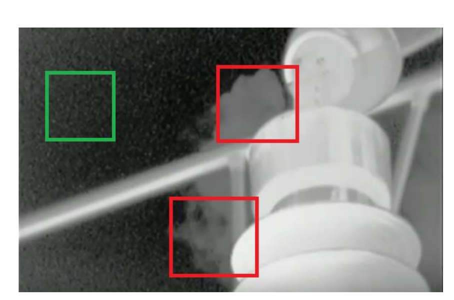
$$R_T = c_1 \cdot e^{-\frac{c_2}{T}} \quad \text{and} \quad R_{pH} = c_3 \cdot pH$$

R_T and R_{pH} are the drift rates
c_1, c_2, and c_3 are drift rate coefficients
f_r, s_r, and d_r are the drift coefficients
τ_f , τ_s, and τ_d are the time constants

Gas Leak Detection Using Uncalibrated Sensors

- Both chemical and infra-red (IR) sensors generate distinct responses under similar conditions because of sensor drift and/or noise.
- We process ***time-series*** sensor signals using deep neural networks (DNN).
- Two ***novel*** neural networks (NN) are developed.
- We consider the task of Gas leak detection using infrared-VOC data.





Recognition Results for Gas Leak Detection

Model	No-Gas Accuracy	Gas-Leak Accuracy	Total Accuracy
Ordinary CNN	98.0%	94.2%	96.1%
AddNet	99.1%	97.3%	97.1%
DiscGAN	99.0%	97.1%	98.1%

Robust DiscGan NN

Advantageous in the case of unbalanced dataset

Training
Phase 1: Unsupervised adversarial training as in generative adversarial NNs (GANs)
- only uses the underbalanced class data as real data
- Generator tries to fool the discriminator by creating synthetic data resembling the real data

Phase 2: Supervised training of the discriminator as a classifier
- Uses data from both classes.

Energy-Efficient Additive NN

Replace dot-product with vector addition with sign compensation

$$w \oplus x = \sum \text{sgn}(w_i\, x_i)(|x_i| + |w_i|)$$

Event Based Detection Scenarios

- Design and implement event-based CPS simulator to accurately and efficiently simulate new detection algorithms, communication requirements, and sensor drift models.
- Utilize movement and chemical concentration simulations as inputs to improve real world correlations. Statistics processing allows for design space exploration and validation.