# CPS: Medium: Reconfigurable Aerial Power-Efficient Interconnected Imaging and Detection (RAPID) Cyber-Physical System

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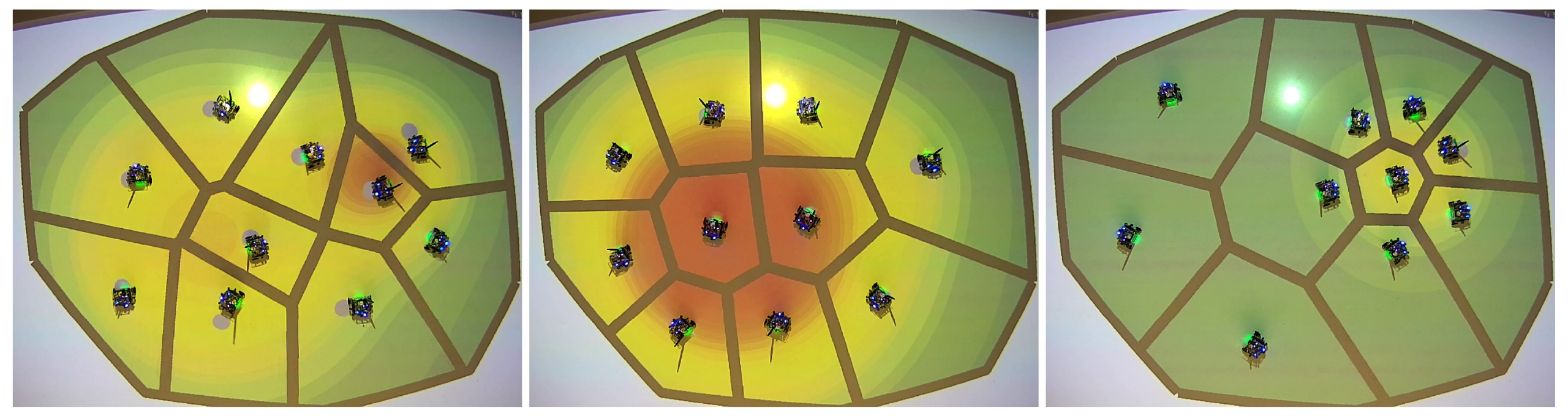
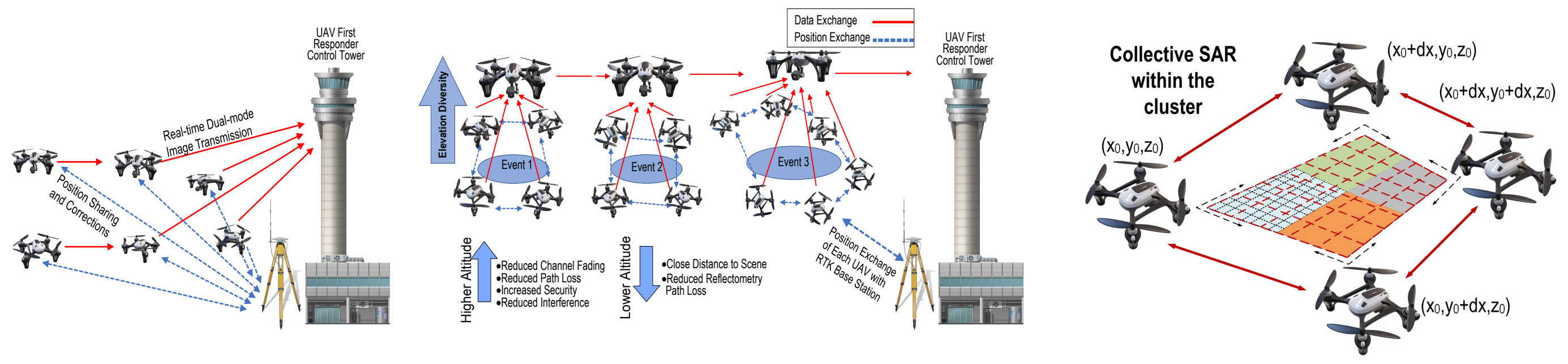
## Project Overview

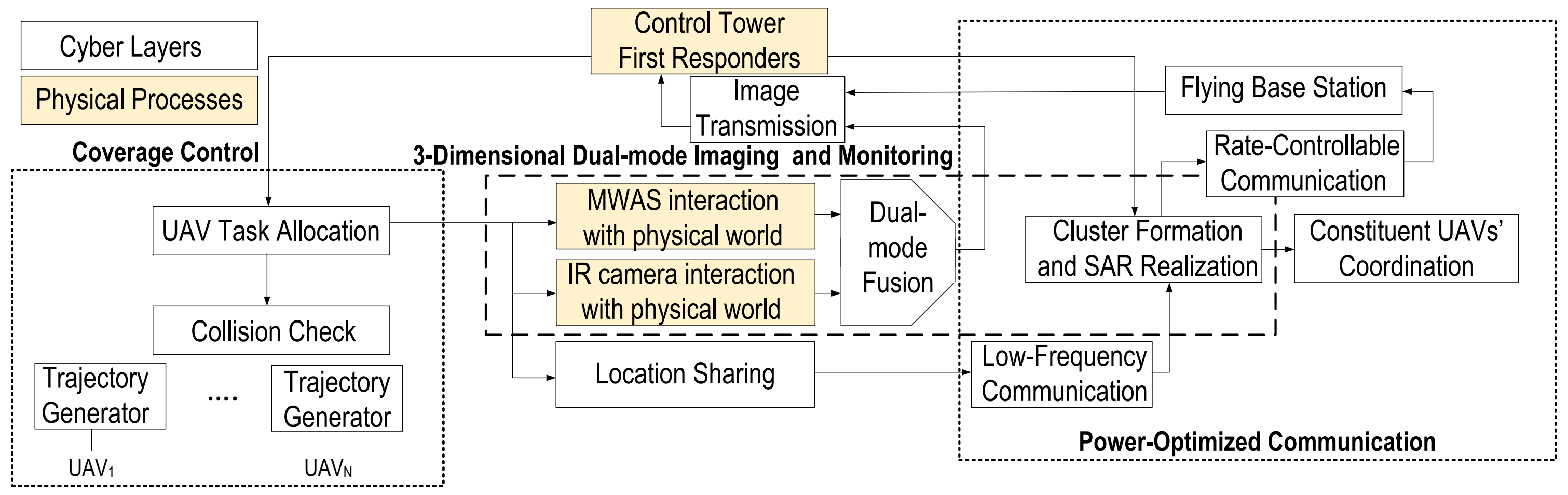
The grand vision of this project is to design a novel self-coordinating, reconfigurable, mobile surveillance CPS that can bring forth the the following goals to practice:

1- Disallowing or minimizing the damage due to an incident by detecting a series of superficial and in-depth compositions of the scene and immediately reporting the image information to first responders.
2- Saving lives of first responders by performing a wide range of identification, monitoring, and data collection tasks that cannot be conducted by humans in a short span of time.
3- Bringing beyond-optical perception to non-urban areas and environments with extreme conditions, e.g., high temperature/elevation.





## Hierarchical Structure of the proposed CPS



## Broader Impacts on the Society

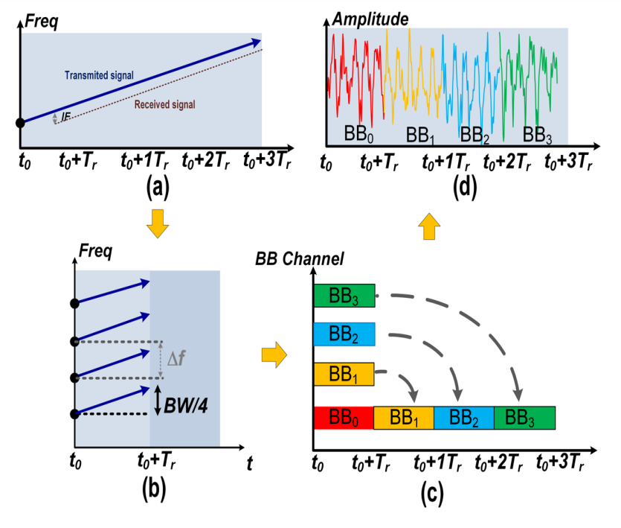
**We envision three major benefits of the proposed research to the society:**

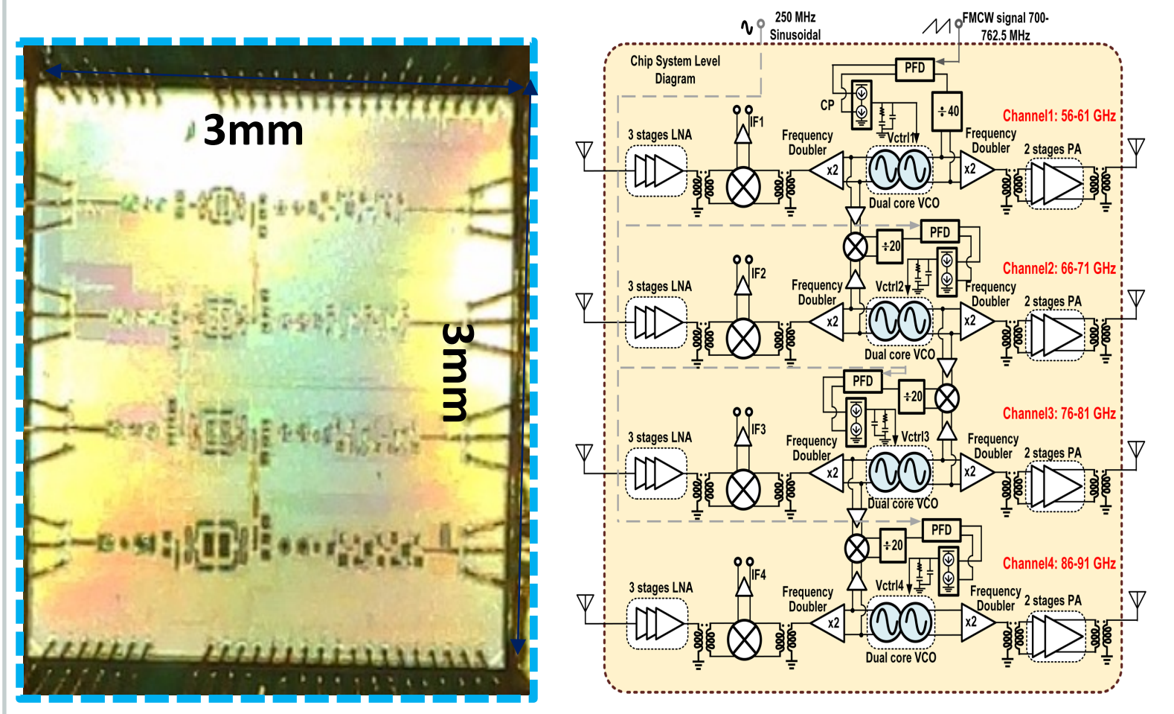
- The humanitarian and financial crisis due to COVID-19 outbreak illustrated that new measures of public safety for various occupations are necessary. According to US department of labor, first responders have one of the high-risk occupations in terms of exposure to COVID-19 virus [176]. The proposed research significantly lowers the burden on first responders, and subsequently, their exposure to hazardous circumstances.
- The rapid growth of Orange County, California as a high-tech powerhouse in the nation with many small and large companies unfolds seamless opportunities for the collaboration of PIs of this interdisciplinary project and local technology sectors in the emerging fields of 5G, UAV-based surveillance, and autonomous systems (among others).
- UAV-based networks are rapidly growing enabling applications such as shipping and delivery, weather forecast, geographic mapping, etc. The data of sensing/communication tasks performed by UAVs in this project can be disseminated with research scholars and companies that pursue other applications.

## Aim 1: Dual mode Long-Range and High-Resolution mm-Wave Radar and Infrared Camera

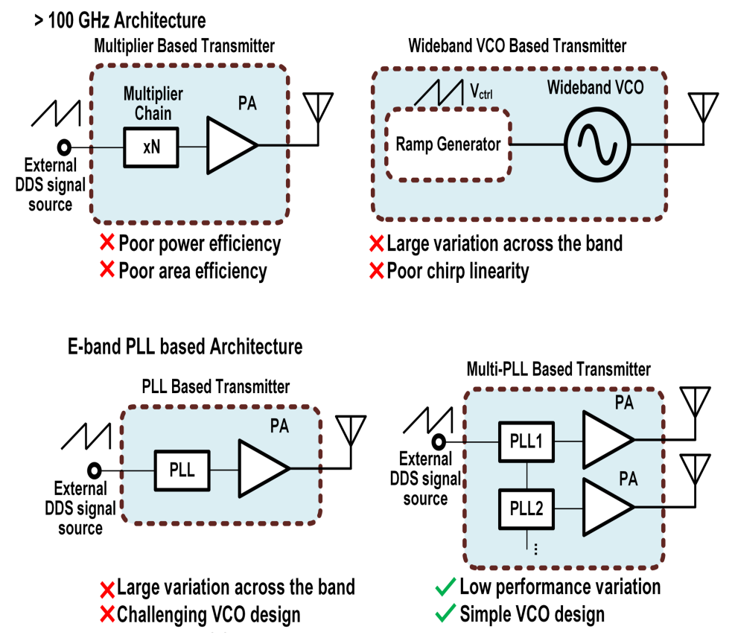
### Broadband Phase-locked Segmented FMCW Radar

- Removing the temporal limit of conventional radars by co-generation of synchronized chirps on a single die without necessarily increasing the frequency

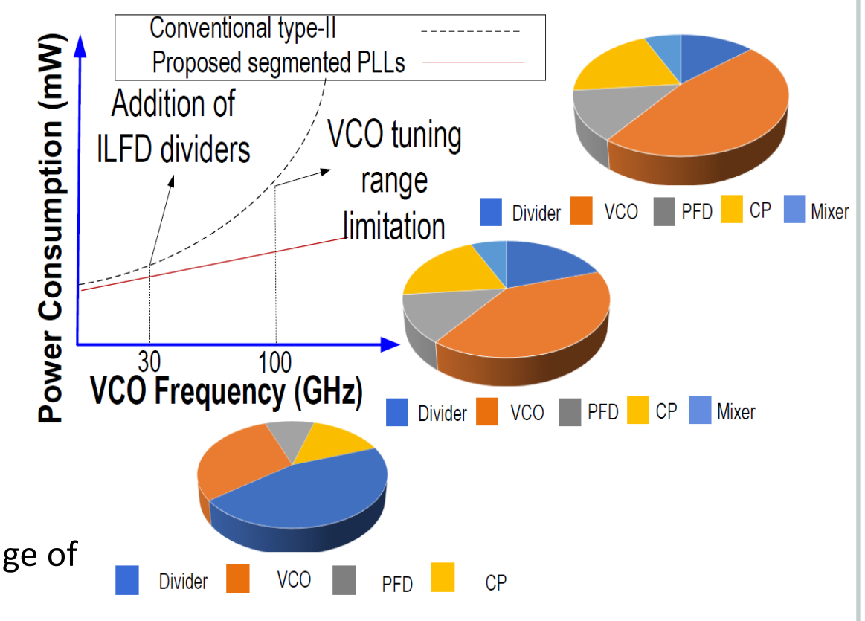




- Enhancing the signal generation efficiency by incorporating segmented phase-locked configuration

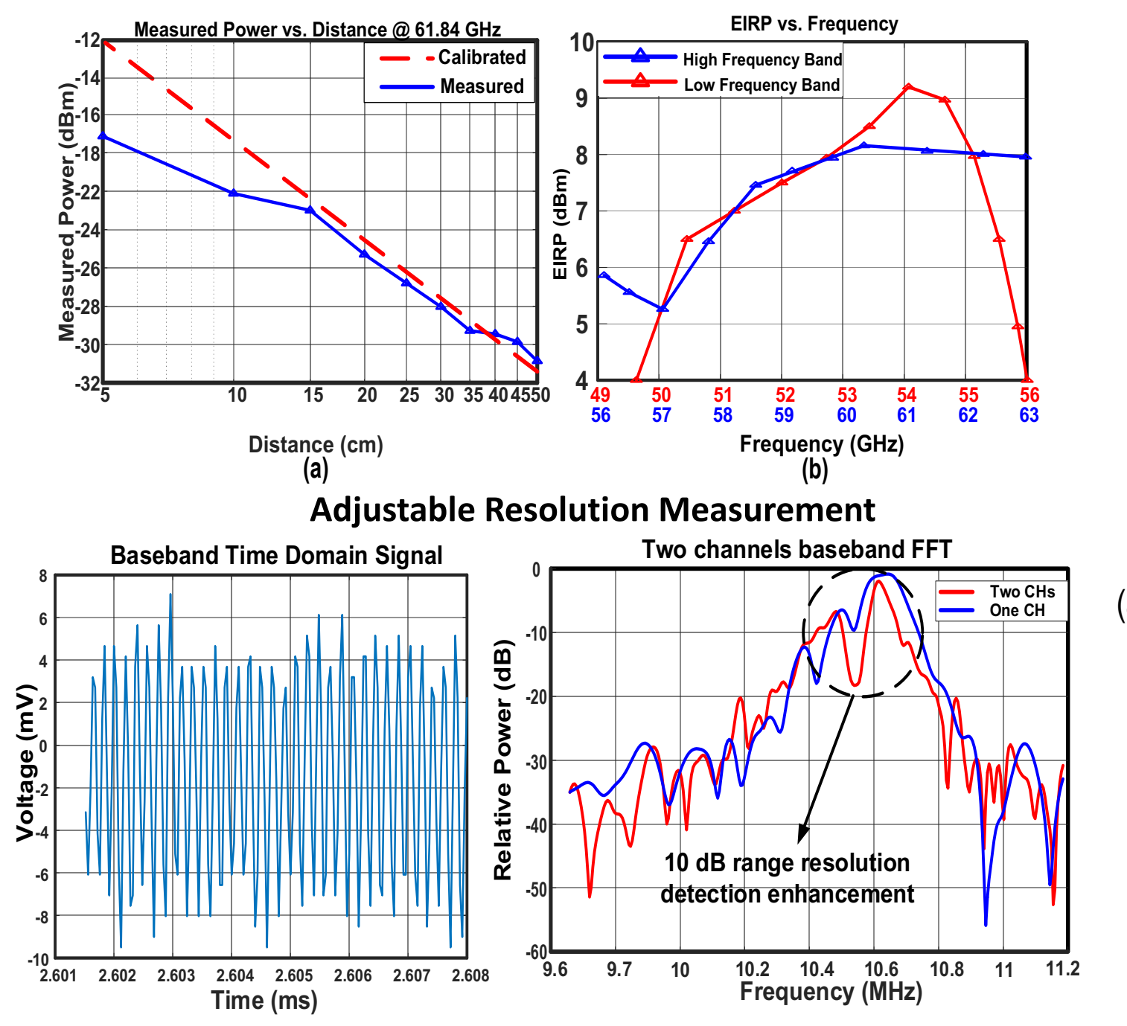


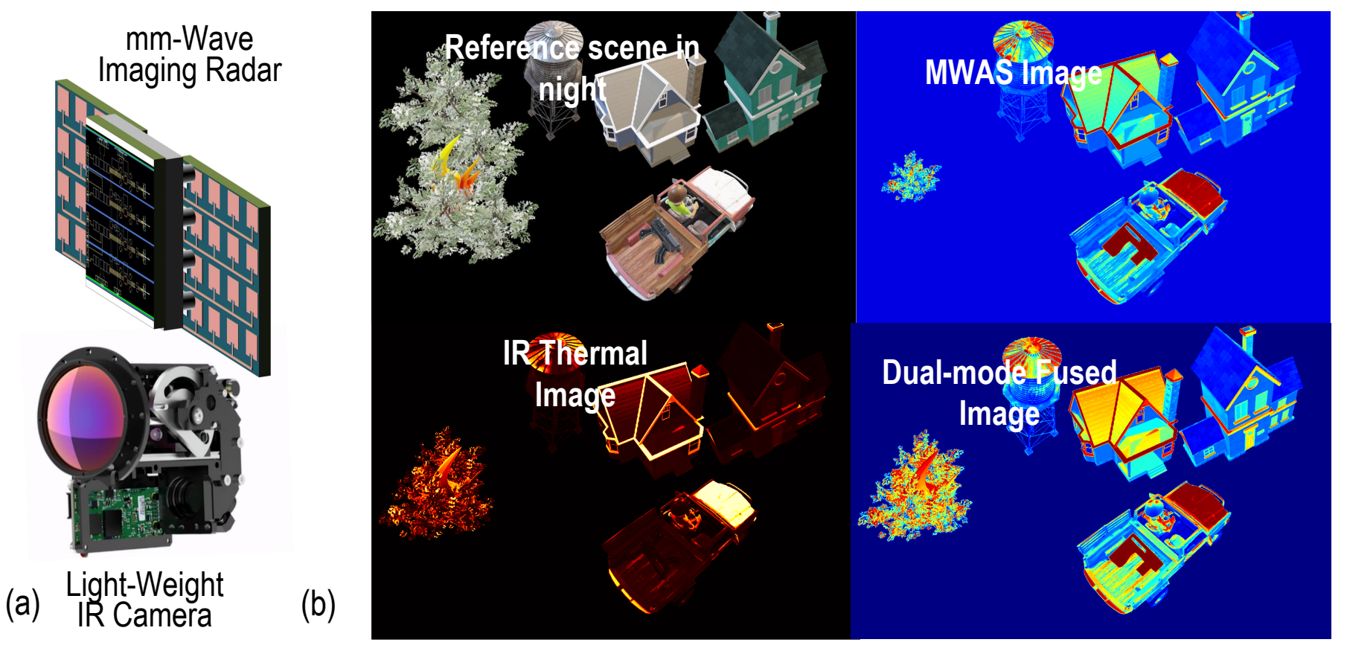
- DC power reduction by more than 90%
- 4-times enhanced resolution
- 10-times enhanced signal-to-noise ratio
- 100-times extended range of coverage



### Effective Isotropic Radiated Power Measurements

### Adjustable Resolution Measurement





**Data Fusion:** We adopt a data fusion approach for images with non-consistent spatial resolutions. One idea for the fusion of the two modalities is performing a multi-objective inversion in terms of the spatial image x, using infra-red and radar data vectors $\boldsymbol{d}_I$ and $\boldsymbol{d}_R$, as shown in the top figure.

## Broader Impact on Other Disciplines

The proposed research will transform our understanding of semi-autonomous CPS networks for first responder assistance. The technological innovations in this proposal for the design and implementation of mm-wave imaging and communication systems as well as the coverage control of drones using elevation diversity will be useful in other CPS networks. The interaction between mobile drones which also are equipped with these light-weight and low-power imaging technologies can be adopted in other dynamic sensor networks where the interaction of multiple vehicles is required.

The PIs of this project have already started to interact with a broad audience of people to disseminate the knowledge from this proposal and will continue to engage in these education and outreach activities in the following years.

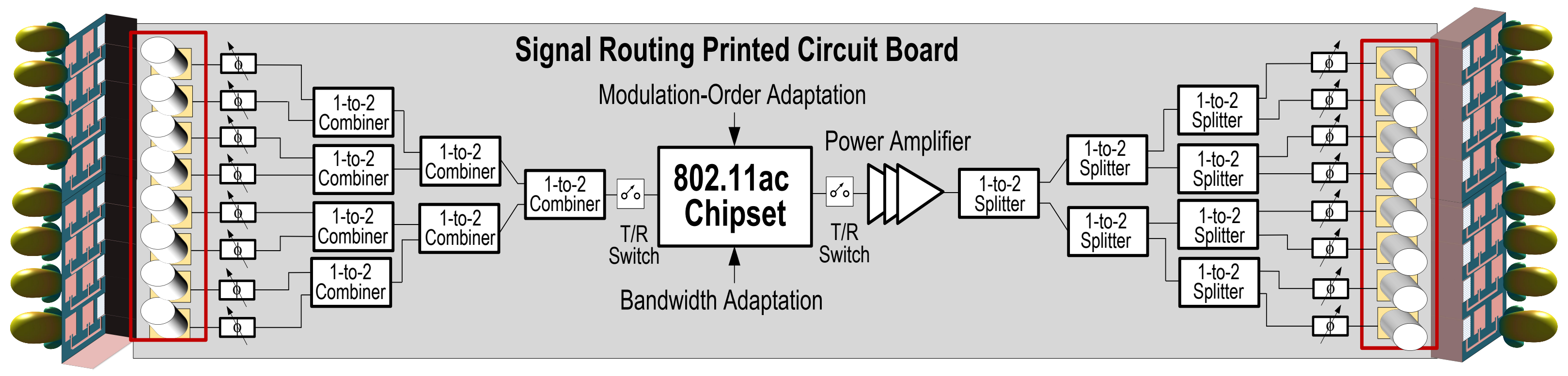
## Education and Outreach

UCI has been among the first institutions to offer a professional graduate program on embedded and cyberphysical systems (ECPS). The current focus of the course curricula in this program is primarily on behavioral/abstract models of ECPS and system software. The PIs intend to expand this program and add two graduate-level classes on (a) UAV-based sensing and communication circuits and (b) UAV-based CPS networks. At the undergraduate level, UCI EECS curricula cover various courses in analog/digital integrated circuits and control systems, while emerging topics such as integrated radars, mm-wave communications, and energy-aware dynamic control are not discussed in any (under)graduate classes.

PI visited Whitney high school in Los Angeles and presented a demo of mm-wave radars to the science Olympiad team members.

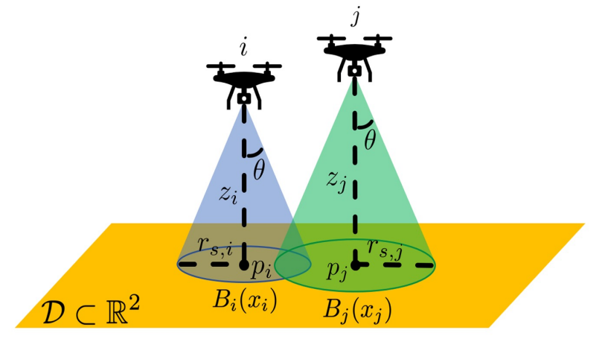
## Aim 2: Power Efficient Rate Controllable Communication System

- One requirement of the RAPID CPS: UAVs should instantly exchange image content or commands to central control stations or neighboring UAV's for high-resolution imaging and information relaying
- This wireless content exchange must be done at extremely high power efficiency
- Two modes of communication:
  1. Command communication and location exchange among the UAVs, handled by low-power UHF-VHF transceivers, and
  2. Image transmission, handled by rate-controllable transceiver arrays
- A single transceiver chip that adaptively supports the four required types of wireless communication scenarios



## Aim 3: Area Coverage Using Multiple Aerial Robots with Coverage Redundancy and Collision Avoidance

### Overview



**Motivation:** We want to deploy a team of UAVs equipped with downward facing cameras to efficiently cover a 2D domain. The sensing quality and the size of effective sensing region (field of view) of an UAV both depend on its altitude.

**Goals:** Several existing methods similarly discourage the overlapping of the fields of view of the UAVs, while we prefer to propose a method that benefits from the overlapping for robust coverage. In addition, the trade-off between the size of effectively sensed areas and the overall sensing quality should be automatically taken care of by the proposed coverage controller.

### Methodologies

**State of** **Planar Position** **Altitude**

$$x_i = [p_i^\top, z_i]^\top \quad p_i \in \mathbb{R}^2 \quad z_i \in \mathbb{R}_{\geq 0}$$

**Sensing Disk of a UAV**

$$B_i(x_i) = \{q \in \mathcal{D} \mid \|p_i - q\| \leq r_{s,i}(z_i)\}$$

**Sensing Quality Function**

$$f(x_i, q) = \begin{cases} g(z_i), & \text{for } q \in B_i(x_i) \\ 0, & \text{otherwise} \end{cases}$$

where $\dfrac{\partial g(z_i)}{\partial z_i} < 0, \ \forall z_i \geq 0$

**Joint Probability of Detection Function**

$$P(x, q) = 1 - \underbrace{\prod_{k=1}^{N} (1 - P_k(f(x_k, q)))}$$

The probability of an event at $q$ point not detected by any robots

$$P(x, q) = 0, \ \text{for } q \notin \bigcup_{i=1}^{N} B_i(x_i)$$

### Methodologies

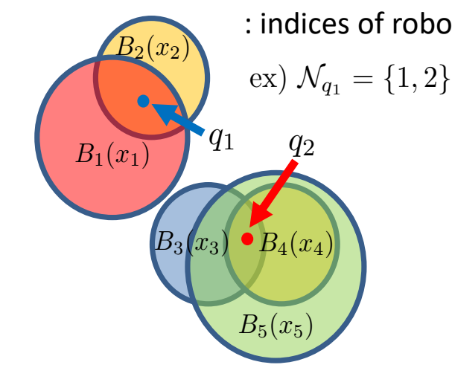
**Coverage Performance Function**

$$\mathcal{H}(x) = \int_{B(x)} \left(1 - \prod_{k \in \mathcal{N}_q} (1 - P_k(g(z_k)))\right) \phi(q) dq$$

where $B(x) = \bigcup_{i=1}^{N} B_i(x_i)$ : union of effective sensing disks

$\mathcal{N}_q = \{k \in \mathcal{N} \mid q \in B_k(x_k)\}$ : indices of robots covering point

ex) $\mathcal{N}_{q_1} = \{1, 2\}, \ \mathcal{N}_{q_2} = \{3, 4, 5\}$



$P_k$ : individual probability of detection with $\dfrac{\partial P_k(g(z_k))}{\partial z_k} < 0$

### Methodologies

**Gradient Ascent Controller**

$$\frac{\partial \mathcal{H}(x)}{\partial x_i} = \begin{bmatrix} \frac{1}{z_i \tan(\theta)} m_{b,i}^p(x) \left(c_{b,i}^p(x) - p_i\right) \\ \frac{\partial P_i(g(z_i))}{\partial z_i} m_i^p(x) + \tan(\theta) m_{b,i}^p(x) \end{bmatrix}^\top$$

where

$$m_i^p(x) = \int_{B_i(x_i)} (1 - P_{\mathcal{N}_q \setminus \{i\}}(x, q)) \, \phi(q) dq$$

denotes the probability-weighted mass of the sensing disk,

$$m_{b,i}^p(x) = \int_{\partial B_i(x_i)} (P_{\mathcal{N}_q}(x, q) - P_{\mathcal{N}_q \setminus \{i\}}(x, q)) \, \phi(q) dq$$

denotes the probability-weighted mass of the boundary of the sensing disk,

$$c_{b,i}^p(x) = \frac{\int_{\partial B_i(x_i)} q \, (P_{\mathcal{N}_q}(x, q) - P_{\mathcal{N}_q \setminus \{i\}}(x, q)) \, \phi(q) dq}{m_{b,i}^p(x)}$$

denotes the probability-weighted center of mass of the boundary of the sensing disk.

### Methodologies

**Control Barrier Function**

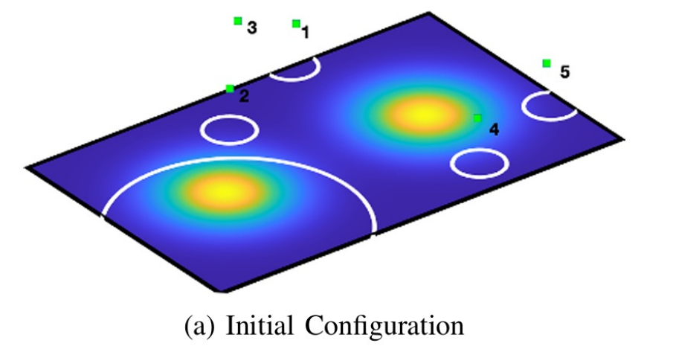
$$h_{ij}(x_i, x_j) = \|x_i - x_j\|^2 - d_{\text{safe}}^2 \geq 0$$

**Safe Decentralized Controller**

$$u_i^* = \underset{u_i}{\arg\min} \|u_i - \hat{u}_i\|^2$$

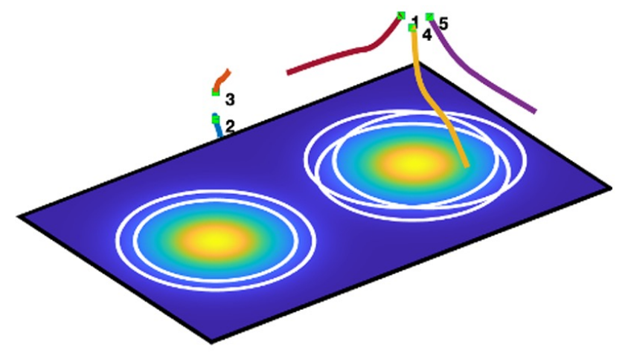
$$\text{s.t. } 2(x_i - x_j) u_i \geq -\frac{\alpha(h_{ij}(x_i, x_j))}{2}$$

### Results

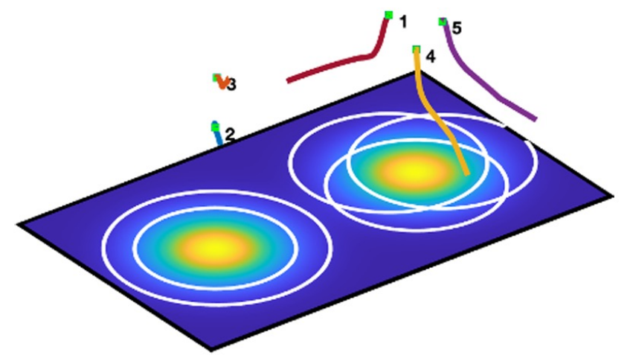


(a) Initial Configuration

### Results



(b) Final Configuration without CBFs



(c) Final Configuration with CBFs

with $P_i(g(z_i)) = g(z_i) = \dfrac{1}{z_i^2 + 1}$

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