Multi-UAV Path Planning for Sweep Coverage

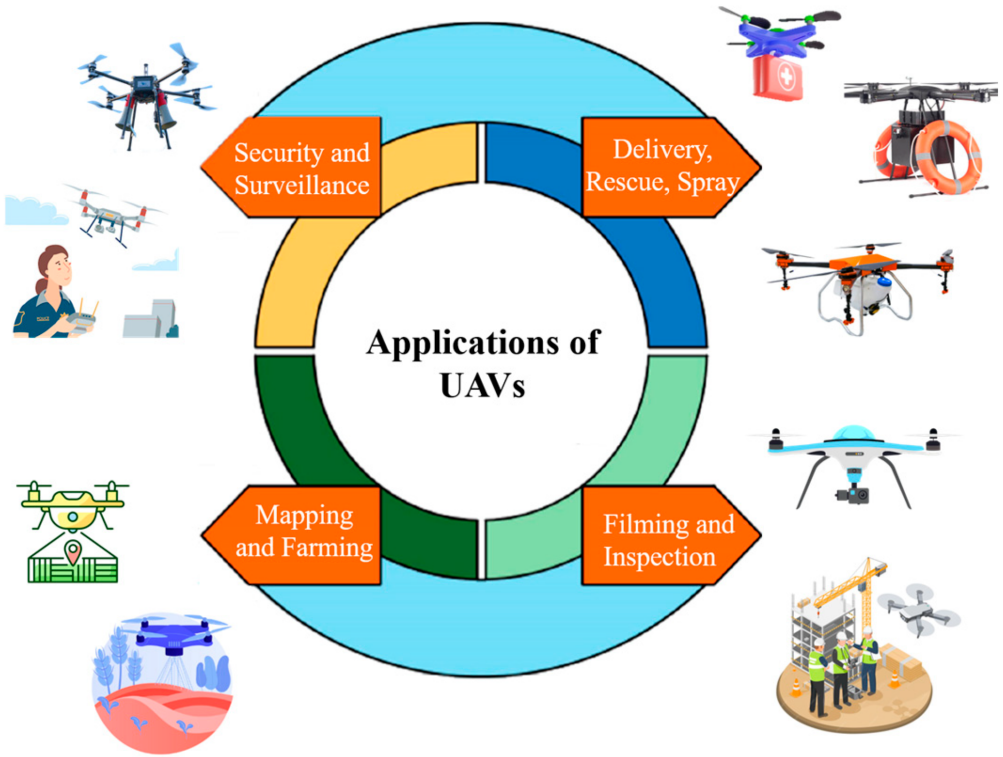
Seshan Srirangarajan

Associate Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi, New Delhi, India

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Introduction

Applications of Unmanned Aerial Vehicles (UAVs)

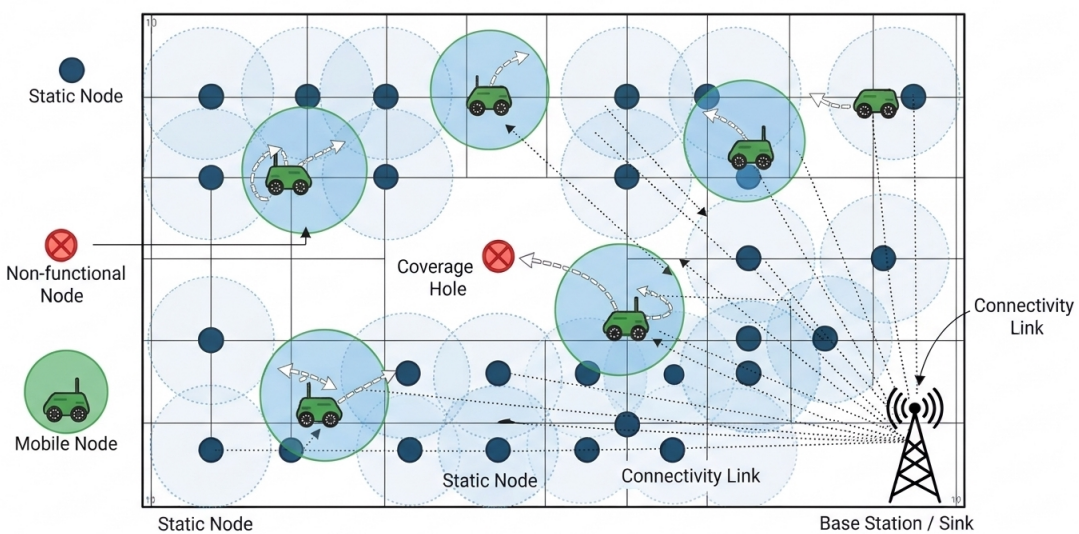


Source: Mohsan et al. (2023)

Planning the paths of a set of collaborative UAVs is key to many of these applications.

Introduction: System Model

- Objective: maximize area coverage
- Static deployment: leads to coverage holes and overlapping coverage due to non-functional nodes or sub-optimal node placement
- Mixed wireless network: combination of static and mobile nodes, can balance optimal coverage and cost effectiveness
- Mobile nodes: can move and change their locations post initial deployment, allowing robust network coverage



Introduction: System Model

In the context of wireless sensor networks (WSNs) and UAV networks

- Continuous coverage: monitor the complete area of interest at all time instances, uses static nodes.
- Sweep coverage: periodic monitoring where the area of interest is monitored periodically, uses mobile nodes that move through the area.
- In many applications, periodic or sweep coverage is sufficient, such as data gathering and message ferrying.

Outline

Our recent research on path planning for mixed WSNs and UAV networks

- Optimization-based framework for efficient node placement and path planning strategies for optimal coverage
- Path planning for connectivity-based sweep coverage
- Reinforcement learning-based strategies for sweep coverage

Network Model

Consider a rectangular network area

- $M \times N$ unit grid cells
- Each grid cell location (i,j) represents center of that grid cell
- Mixed WSN with a few static and mobile nodes, and a single data sink node

Objective

- Place the static nodes and plan the paths of mobile nodes such that all grid cells in the network area are covered at least once (1-coverage) by a node (static or mobile).

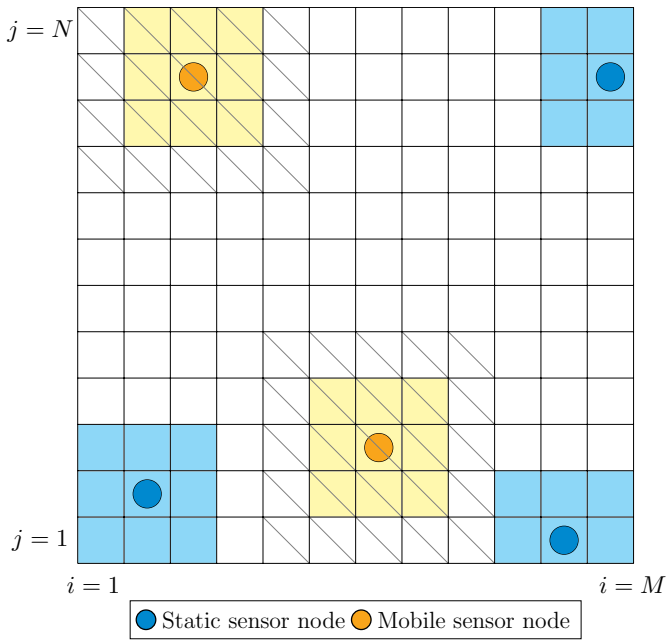


Figure. Typical network model.

Notations

Symbol	Definition
N_s	Number of static sensor nodes
N_m	Number of mobile sensor nodes
$\mathcal{C}$, $\lvert\mathcal{C}\rvert$	Set of all the cells in the network area and its cardinality
$\mathcal{B}$	Set of cells at the boundary of the network area
$\mathcal{A}$	Set of cells other than the boundary cells
$\mathcal{C}_s$	Set of cells covered by static nodes
$\overline{\mathcal{C}}_s$	Set of cells not covered by static nodes
cr	Area coverage ratio
r_s	Sensing radius of a sensor node
ρ_x, ρ_y	One-step traveling range of mobile node along x and y directions
$\hat{s}_o$, $\hat{m}_o$	Overlapping cell coverage factor for static and mobile sensor nodes' coverage
$K_{\max}$	Maximum number of time-steps
$x_{i,j}^s$	$x_{i,j}^s = 1$ if the s^{th} static sensor node is located at cell (i,j), otherwise $x_{i,j}^s = 0$.
$x_{i,j}^{l,k}$	$x_{i,j}^{l,k} = 1$ if the l^{th} mobile node is located at cell (i,j) in the k^{th} time-step.
$c_{i,j}^s$	$c_{i,j}^s = 1$ if the cell (i,j) is covered by the s^{th} static sensor node, otherwise $c_{i,j}^s = 0$.
$c_{i,j}^{l,k}$	$c_{i,j}^{l,k} = 1$ if the cell (i,j) is covered by the l^{th} mobile node in the k^{th} time-step, otherwise $c_{i,j}^{l,k} = 0$.
$c_{i,j}$	$c_{i,j} = 1$ if the cell (i,j) is covered by a sensor node during any time-step, otherwise $c_{i,j} = 0$.

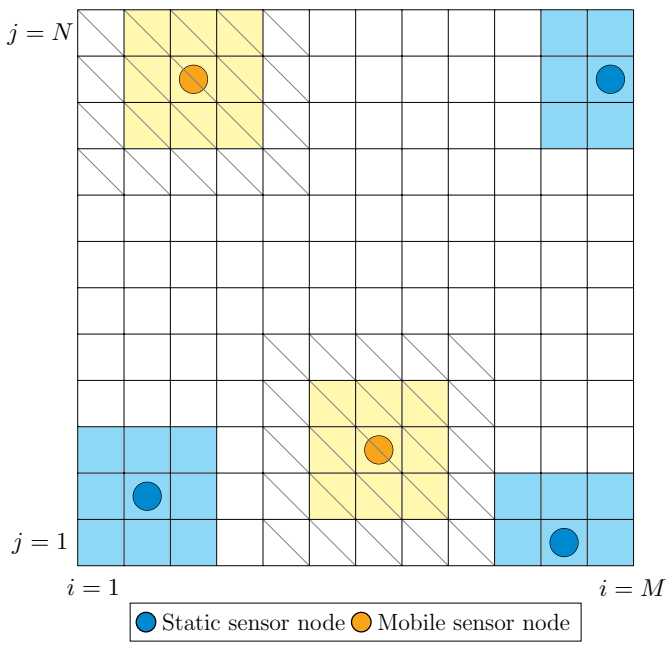


Figure. Typical network model.

Objectives and Assumptions

Objectives

- Static node deployment in the first phase, and followed by
- Path planning of mobile nodes to maximize area coverage or minimize sweep coverage period

Assumptions

- Network is connected: sensor nodes can communicate with the sink at all times (multi-hop connectivity is considered later)
- Static node placement and mobile nodes path planning is carried out centrally
- Distances are assumed to be hop distances (though can be easily modified to Euclidean distance)

Static Node Placement

Proposed strategies result in mixed integer linear programming (MILP) formulations

- Optimally place static nodes to maximize area coverage
- If boundary cells are not covered by static nodes, mobile nodes would have to cover these resulting in larger number of movements and redundant coverage
- Proposed static node placement strategy gives higher importance/weight to covering the boundary cells

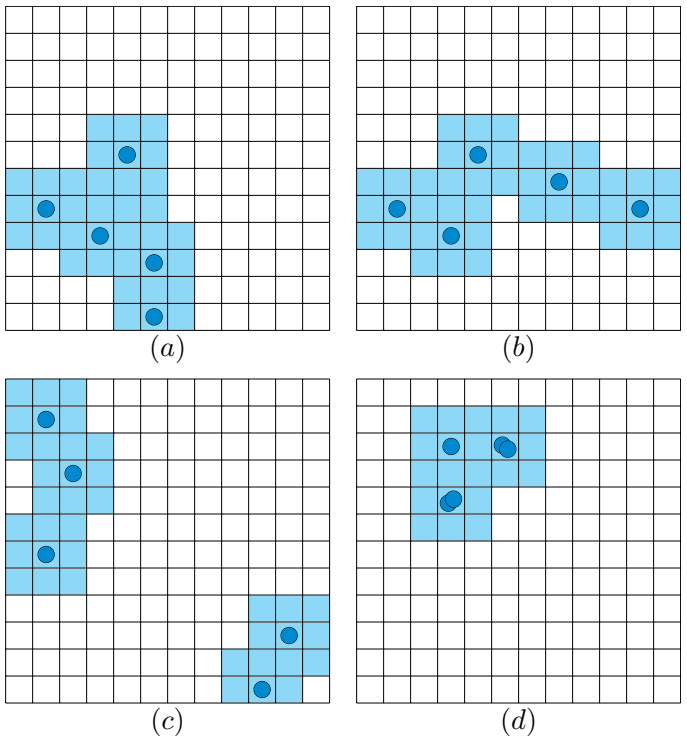


Figure. Random placement of static nodes

Static Node Placement Strategy

Optimal static node placement through coverage maximization (MILP-Static)

$$\text{(Objective function):}\ \max \left(\sum_{\substack{s=1 \\ (i,j)\in\mathscr{A}}}^{N_s} c_{i,j}^{s} + \alpha \sum_{\substack{s=1 \\ (i,j)\in\mathscr{B}}}^{N_s} c_{i,j}^{s} \right) \tag{1}$$

$$\text{(Position constraint) s.t.} \sum_{(i,j)\in\mathscr{C}} x_{i,j}^{s} = 1 \ ; \forall s = 1, \ldots, N_s \tag{2}$$

$$\text{(Coverage constraint)}\ c_{i,j}^{s} = \sum_{p=-r_s}^{r_s} \sum_{q=-r_s}^{r_s} x_{i+p,j+q}^{s} \ ; \forall (i,j) \in \mathscr{C}; s = 1, \ldots, N_s \tag{3}$$

$$\text{(Overlapping coverage constraint)} \sum_{s=1}^{N_s} c_{i,j}^{s} \leq \hat{s}_o \ ; \quad \forall (i,j) \in \mathscr{C} \tag{4}$$

Path Planning of Mobile Nodes: Coverage Maximization

After static node placement, mobile nodes' path planning for coverage maximization (MILP-Cov)

$$\text{(Objective function):}\ \max \sum_{(i,j)\in\overline{\mathscr{C}}_s} c_{i,j} \tag{5}$$

$$\text{(Position constraint)}\ \text{s.t.} \sum_{(i,j)\in\overline{\mathscr{C}}_s} x_{i,j}^{l,k} = 1\ ;\quad \forall l = 1,\ldots,N_m; k = 1,\ldots,K_{\mathbf{max}} \tag{6}$$

$$\text{(Mobility constraint)}\ x_{i,j}^{l,k+\mathbf{1}} = \sum_{p=-\rho_x}^{\rho_x}\sum_{q=-\rho_y}^{\rho_y} x_{i+p,j+q}^{l,k}\ ;\quad \forall (i,j)\in\overline{\mathscr{C}}_s; \tag{7}$$

$$l = 1,\ldots,N_m; k = 1,\ldots,(K_{\mathbf{max}}-1)$$

$$\text{(Coverage constraints)}\ c_{i,j}^{l,k} = \sum_{p=-r_s}^{r_s}\sum_{q=-r_s}^{r_s} x_{i+p,j+q}^{l,k}\ ;\quad \forall (i,j)\in\overline{\mathscr{C}}_s; \tag{8}$$

$$l = 1,\ldots,N_m; k = 1,\ldots,K_{\mathbf{max}}$$

$$c_{i,j} \geq c_{i,j}^{l,k}\ ;\forall (i,j)\in\overline{\mathscr{C}}_s; l = 1,\ldots,N_m; k = 1,\ldots,K_{\mathbf{max}} \tag{9}$$

$$c_{i,j} \leq \sum_{l=\mathbf{1}}^{N_m}\sum_{k=\mathbf{1}}^{K_{\mathbf{max}}} c_{i,j}^{l,k}\ ;\quad \forall (i,j)\in\overline{\mathscr{C}}_s \tag{10}$$

$$\text{(Overlapping coverage constraint)}\ \sum_{l=\mathbf{1}}^{N_m}\sum_{k=\mathbf{1}}^{K_{\mathbf{max}}} c_{i,j}^{l,k} \leq \hat{m}_o\ ;\quad \forall (i,j)\in\overline{\mathscr{C}}_s \tag{11}$$

$$0 \leq c_{i,j}, c_{i,j}^{l,k} \leq 1; \forall (i,j)\in\overline{\mathscr{C}}_s; l = 1,\ldots,N_m; k = 1,\ldots,K_{\mathbf{max}} \tag{12}$$

Path Planning of Mobile Nodes: Movement Minimization

Following static node placement, alternative strategy of mobile nodes' path planning for movement minimization (MILP-Mov) achieving desired coverage ratio (cr)

$$\text{(Objective function):}\ \min \sum_{k=1}^{K_{\max}} \sum_{l=1}^{N_m} \sum_{(i,j)\in\overline{\mathscr{C}}_s} x_{i,j}^{l,k} \tag{13}$$

$$\text{(Position constraint) s.t.} \sum_{(i,j)\in\overline{\mathscr{C}}_s} x_{i,j}^{l,k} \leq 1 \ ; l = 1,\ldots,N_m; k = 1,\ldots,K_{\max} \tag{14}$$

$$\text{(Coverage ratio constraint)} \sum_{(i,j)\in\mathscr{C}} c_{i,j} \geq cr \cdot |\mathscr{C}| \tag{15}$$

Constraints (21), (8), (9), (10), (11), (12)

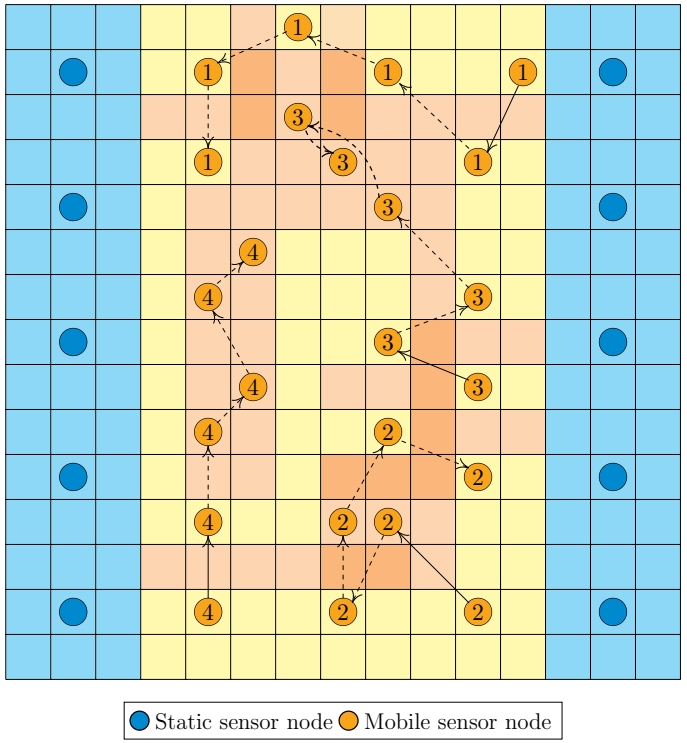
Simulation Setup

- Network area sizes range from 8×8 to 20×20
- Sensing range $r_s = 1$, movement range $\rho_x = \rho_y = 2$
- Overlapping coverage factors $\hat{m}_o = 3$ and $\hat{s}_o = 1$
- Algorithms were implemented in Matlab using IBM ILOG CPLEX optimization software
- Branch and cut method as MIP strategy search

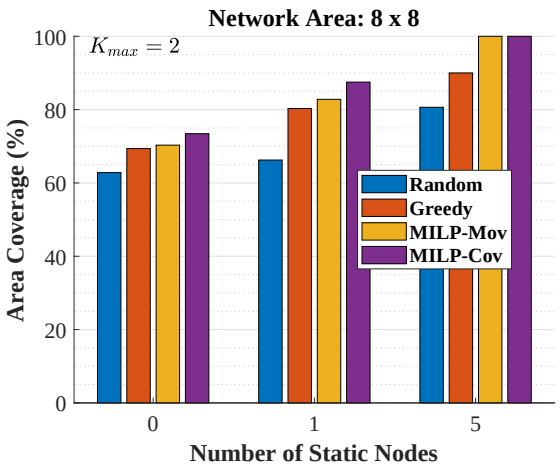
Simulation Results: Static Node Placement

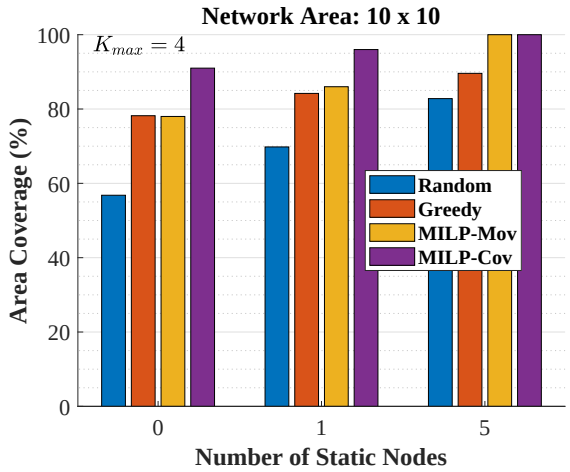
AREA COVERAGE (MILP-COV) USING TWO DIFFERENT STATIC NODE PLACEMENT STRATEGIES: RANDOM AND MILP-STATIC.

Network Area	N_m	N_s	Area Coverage (%)	
			Random	MILP-Static
8×8	1	3	63.18	85.93
	1	5	68.23	100
	2	3	95.93	100
	2	5	93.39	100
	3	3	100	100
	3	5	94.47	100
10×10	1	3	42.12	60
	1	5	44.91	77
	2	3	75.11	88
	2	5	78.14	96
	3	3	93.24	99
	3	5	94.88	100



Simulation Results: Path Planning Performance (MILP-Cov)

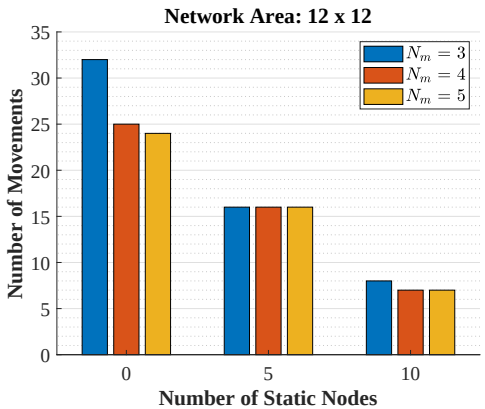


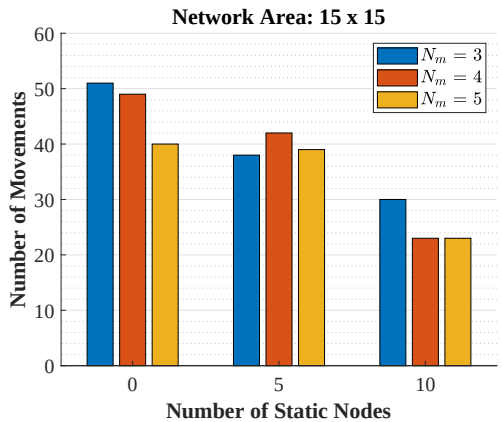


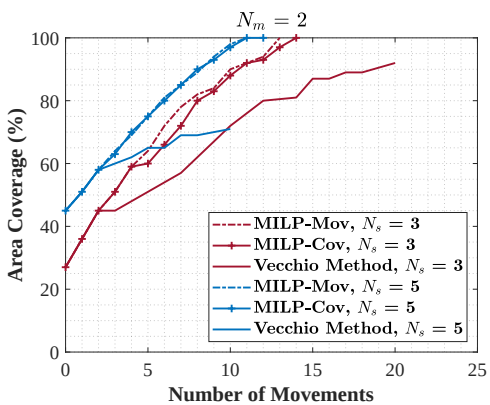
EFFECT OF SENSING AND TRAVELING RANGE ON AREA COVERAGE USING MILP-COV IN A 20×20 NETWORK AREA WITH $N_s = 5$, $N_m = 3$, AND $K_{\text{MAX}} = 5$.

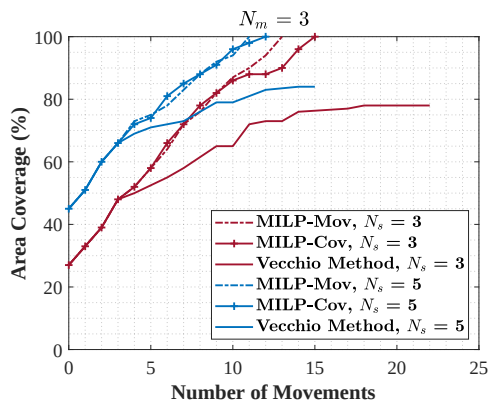
r_s	$\rho_x = \rho_y$	Area Coverage (%)
1	1	33.00
	2	42.00
	3	45.00
	4	45.00
	5	45.00
	5 ($K_{\max} = 10$)	78.50
2	1 ($K_{\max} = 3$)	63.50
	2	91.25
	3	99.50
	4	100.00
	5	100.00

Simulation Results: Path Planning Performance (MILP-Mov)









M. Vecchio and R. Lopez-Valcarce, "Improving area coverage of wireless sensor networks via controllable mobile nodes: A greedy approach," J. Netw. Comput. Appl., vol. 48, pp. 1–13, 2015.

Path Planning for Connectivity-based Sweep Coverage

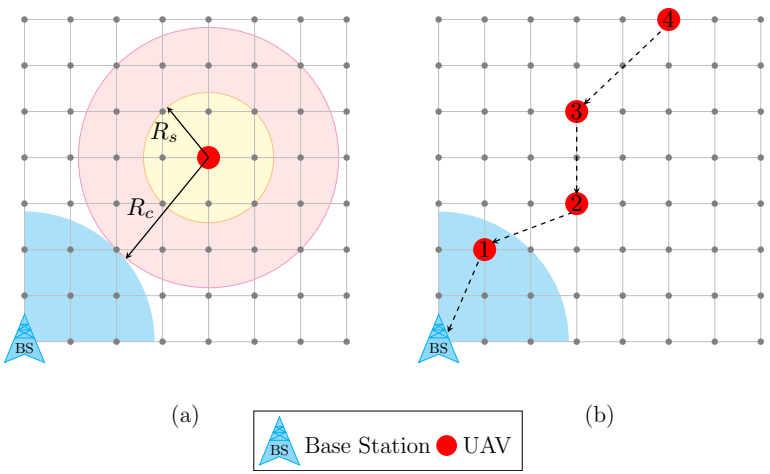
Quality of service in wireless surveillance networks relies on area coverage and connectivity

- Wireless surveillance networks comprising of UAVs
- Data collected by UAVs must be communicated to the data sink/base station in real-time
- Objective: improve area coverage while ensuring UAVs remain connected to the base station at all times

Connectivity is achieved through

- At least one UAV must always be connected to the base station
- UAVs that are not directly connected to the base station must maintain communication link(s) with UAVs that are connected to the base station

System Model and Notations



List of system parameters, decision variables, and their notations.

Symbol	Definition
s	Base station (or sink) location
$G_{\bar{s}}$	Set of all the grid points in the area of interest (Note: $\bar{s}$ indicates that the sink location is excluded from this set)
C_s	Set of grid points within the communication range of the sink location s
C_i	Set of grid points within the communication range of the grid point i
S_i	Set of grid points within the sensing range of the grid point i
N	Number of UAVs (or mobile nodes)
$K_{\max}$	Maximum number of time-steps
$C_{\max}$	Total number of grid points to be covered (Note that, $C_{\max} = \lvert G_{\bar{s}} \rvert$, the cardinality of $G_{\bar{s}}$)
cr	Area coverage ratio: ratio of the number of grid points covered at least once at any time-step and $C_{\max}$ $(0 \leq cr \leq 1)$
$z_{i,n}^k$	Binary variable; $z_{i,n}^k = 1$ if the nth UAV is located at grid point i at the kth time-step, otherwise $z_{i,n}^k = 0$.
$c_{i,n}^k$	Continuous variable; $c_{i,n}^k = 1$ if the grid point i is covered by the nth UAV at the kth time-step, otherwise $c_{i,n}^k = 0$.
c_i	Continuous variable; $c_i = 1$ if the grid point i is covered by any UAV at any time-step, otherwise $c_i = 0$.

Path Planning for Coverage Maximization (max-Cov)

$$\text{(Objective function):} \quad \max \sum_{i \in \mathscr{G}_{\bar{s}}} c_i \tag{16}$$

$$\text{(Position constraint)} \quad \text{s.t.} \sum_{i \in \mathscr{G}_{\bar{s}}} z_{i,n}^{k} = 1 \; ; \qquad n = 1, \ldots, N; k = 1, \ldots, K_{\mathbf{max}} \tag{17}$$

$$\text{(Collision avoidance constraint)} \quad \sum_{n=\mathbf{1}}^{N} z_{i,n}^{k} \leq 1 \; ; \qquad \forall i \in \mathscr{G}_{\bar{s}}; k = 1, \ldots, K_{\mathbf{max}} \tag{18}$$

$$\text{(Sink connectivity constraint)} \quad \sum_{n=\mathbf{1}}^{N} \sum_{p \in \mathscr{C}_s} z_{p,n}^{k} \geq 1 \; ; \qquad k = 1, \ldots, K_{\mathbf{max}} \tag{19}$$

$$\text{(Inter-UAV connectivity constraint)} \quad z_{i,n}^{k} \leq \sum_{p \in \mathscr{C}_i} z_{p,(n-\mathbf{1})}^{k} \; ; \; \forall i \in \mathscr{G}_{\bar{s}}; n = 2, \ldots, N; k = 1, \ldots, K_{\mathbf{max}} \tag{20}$$

$$\text{(Mobility constraint)} \quad z_{i,n}^{k+\mathbf{1}} \leq \sum_{p \in \mathscr{C}_i} z_{p,n}^{k} \; ; \; \forall i \in \mathscr{G}_{\bar{s}}; n = 1, \ldots, N; k = 1, \ldots, (K_{\mathbf{max}} - 1) \tag{21}$$

$$\text{(Coverage constraints)} \quad c_{i,n}^{k} = \sum_{p \in \mathscr{S}_i} z_{p,n}^{k} \; ; \; \forall i \in \mathscr{G}_{\bar{s}}; n = 1, \ldots, N; k = 1, \ldots, K_{\mathbf{max}} \tag{22}$$

$$c_i \geq c_{i,n}^{k} \; ; \qquad \forall i \in \mathscr{G}_{\bar{s}}; n = 1, \ldots, N; k = 1, \ldots, K_{\mathbf{max}} \tag{23}$$

$$c_i \leq \sum_{k=\mathbf{1}}^{K_{\mathbf{max}}} \sum_{n=\mathbf{1}}^{N} c_{i,n}^{k} \; ; \qquad \forall i \in \mathscr{G}_{\bar{s}} \tag{24}$$

$$0 \leq c_i, c_{i,n}^{k} \leq 1 \; ; \; \forall i \in \mathscr{G}_{\bar{s}}; n = 1, \ldots, N; k = 1, \ldots, K_{\mathbf{max}} \tag{25}$$

Path Planning for Movement Minimization (min-Mov)

Objective: Plan the path of a set of UAVs while minimizing the total number of movements required to achieve a desired coverage ratio while maintaining multi-hop connectivity to sink.

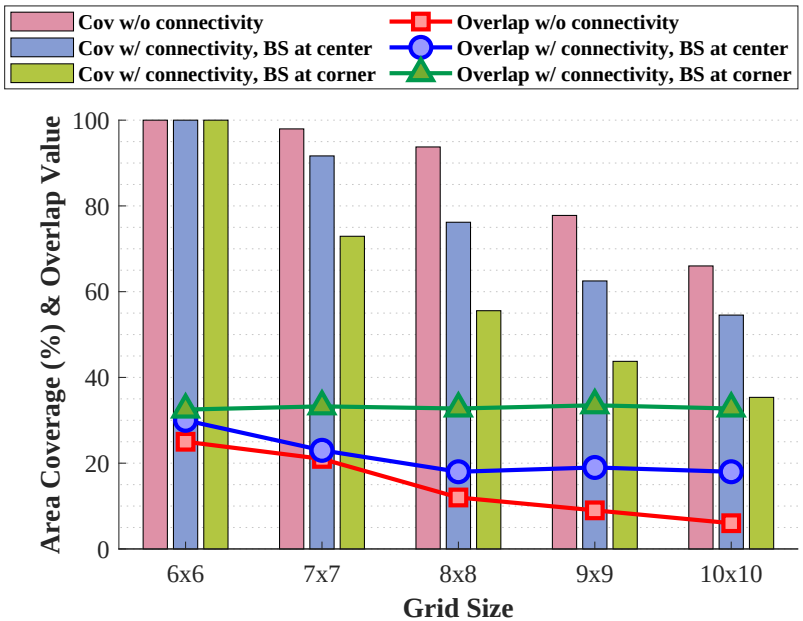
$$\text{(Objective function):}\quad \min \sum_{k=1}^{K_{\max}} \sum_{\substack{n=1 \\ i \in \mathcal{G}_{\bar{s}}}}^{N} z_{i,n}^{k} \tag{26}$$

$$\text{(Position constraint) s.t.}\quad \sum_{i \in \mathcal{G}_{\bar{s}}} z_{i,n}^{k} \leq 1 \;;\; n = 1, \ldots, N; k = 1, \ldots, K_{\max} \tag{27}$$

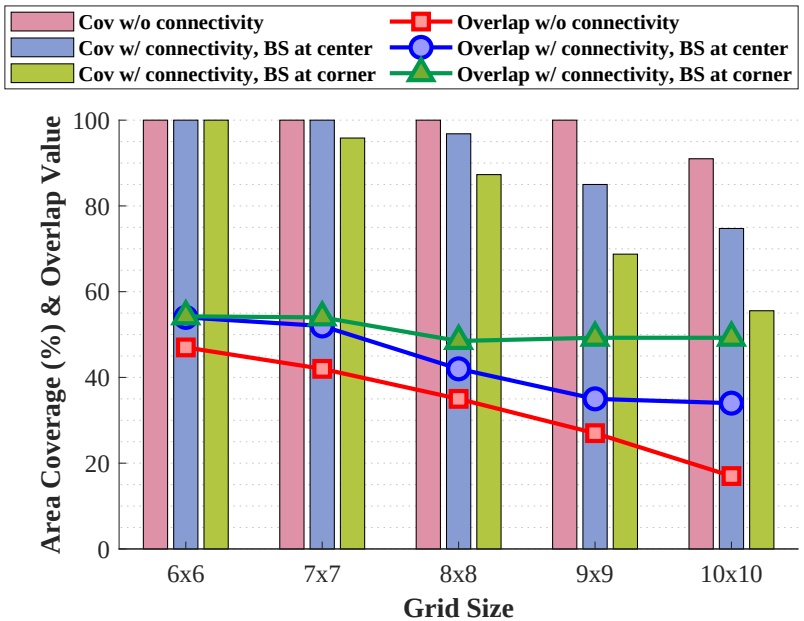
$$\text{(Coverage ratio constraint)}\quad \sum_{i \in \mathcal{G}_{\bar{s}}} c_i \geq cr \cdot C_{\max} \tag{28}$$

Constraints (18), (19), (20), (21), (22), (23), (24), (25)

Simulation Results: Coverage Maximization Performance

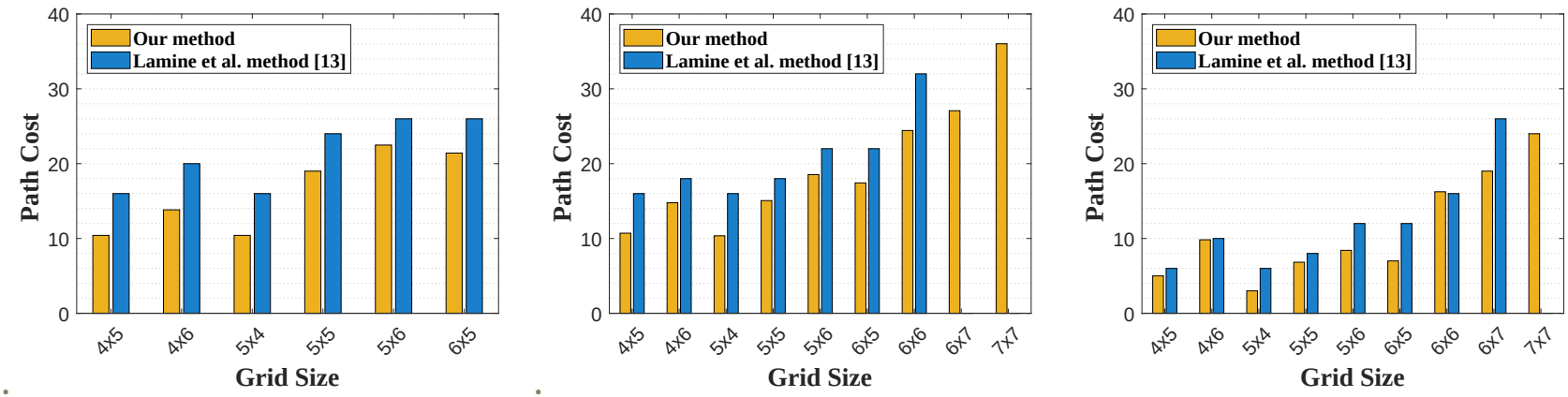


(a) $N = 2$



(b) $N = 3$

Simulation Results: Movement Minimization Performance



(c) $R_s = 1$ and $R_c = 2$ (d) $R_s = 1$ and $R_c = 3$ (e) $R_s = 2$ and $R_c = 2$

Figure. Comparison of path cost for full (100%) coverage for different grid sizes, and different R_c and R_s values with two UAVs.

A. Lamine, et al., "Linear models for total coverage problem with connectivity constraints using multiple unmanned aerial vehicles", Int. J. Sen. Netw., vol. 34, No. 1, pp. 15–25, 2020.

Reinforcement Learning-based Path Planning Strategy

- MILP-based methods yields optimal paths but requires solving an NP-hard problem.
- Consider a learned policy trained in three steps: expert data generation, behavioral cloning (BC), and proximal policy optimization (PPO).
- Observation space: UAV positions, coverage mask, obstacle mask, UAV connectivity flags.
- Action space defined based on obstacle mask and movement feasibility set.

(BC + PPO) Path Planning Policy

- Expert data generation: Global MILP solution generates diverse optimal trajectories which are replayed to produce expert state-action pairs.
- Behavioral cloning (BC): The policy is pre-trained over the expert data, encoding MILP-optimal coordination patterns into the network weights.
- Proximal policy optimization (PPO): The BC-initialized policy is fine-tuned with PPO.
- Obstacle layouts randomized over each episode to improve generalization and mitigate distribution shift inherent to BC.

Coverage Performance: MILP vs (BC+PPO)

Grid	N	Sink	MILP (%)	BC+PPO (%)	Gap (%)
8×8	2	center	85.7	79.4	6.3
8×8	2	corner	52.4	52.4	0.0
8×8	3	center	100.0	93.7	6.3
8×8	3	corner	71.4	69.8	1.6
9×9	2	center	68.8	66.2	2.6
9×9	2	corner	43.8	43.8	0.0
9×9	3	center	83.8	80.0	3.8
9×9	3	corner	60.0	52.5	7.5
10×10	2	center	59.6	51.5	8.1
10×10	2	corner	33.3	33.3	0.0
10×10	3	center	76.8	73.7	3.1
10×10	3	corner	48.5	42.4	6.1

- The BC+PPO policy achieves coverage within 10% of the optimal value for all configurations.
- On larger grids, MILP exploits global coordination that the learned policy is unable to fully replicate.

Summary and Future Research

- Developed path planning strategies for a set of collaborative UAVs while maximizing coverage or minimizing movements
- Ensure that connectivity of each UAV to the base station is always maintained
- Computational complexity of solving MILP increases exponentially with number of integer/binary variables
- Reinforcement learning (RL)-based path planning algorithms need to be explored further
- Obstacle avoidance is required in many applications

Publications based on this Work

- S. Kumari, and S. Srirangarajan, "Node Placement and Path Planning for Improved Area Coverage in Mixed Wireless Sensor Networks", IEEE Robotics and Automation Letters, Vol. 9, No. 8, pp. 6800-6807, Aug. 2024.
- S. Kumari, and S. Srirangarajan, "Multi-UAV Path Planning for Connectivity-based Sweep Coverage", Ad Hoc Networks, Vol. 178, pp. 103966, 2025.
- S. Khan, A. Prasad, and S. Srirangarajan, "Energy-Aware Coverage Path Planning for UAV Fleets on Surveillance Missions", under review.

Thank you, Questions?

Email: seshan@ee.iitd.ac.in