Optimal Communication Topology Determination and Sensor Selection for Independent Airspace Surveillance

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The paper presents an approach to sensors selection and network topology determination for independent airspace surveillance with maximum outcome and minimum cost using ground based distributed sensing, computing and communication network infrastructure. The selection criteria includes minimum estimation error, maximum airspace coverage, minimum communication time and power consumption while guaranteeing the system observability and providing in-time quality information to a monitoring observer. The developed algorithm uses multi-objective optimization strategy taking into account trade-offs between conflicting objectives and relaxations for in time implementation. It is implemented utilizing graph theoretic tools. The approach is validated in a desktop simulation environment using synthetic sensors data generated for a simulated multi-vehicle flight scenario in the selected regional airspace.

I. Introduction

II. Problem Formulation

We consider a stationary infrastructure I of distributed across a region of interest ground based nodes N_i, $i = 1, \dots, k$, each of which is an integrated platform of a set S_i of heterogeneous sensors, a wireless communication modem M_i, a power unit P_i and a computing unit C_i. We assume that the sensors provide multi-modal multi-rate information about the associated airspace via established by modems wireless communication network to interested users, such as air vehicles, fleet operators, airspace controllers, or data storage facilities connected to information exchange platforms. Our objective is to develop an optimization algorithm for sensor selection and communication topology determination in order to provide in-time information to users at minimum cost, while achieving a maximum coverage of the selected region of airspace operations.

Let the nodes be located at $\boldsymbol{r}_i$ with respect to some inertial coordinate frame, have a power capacity of p_i and a maximum transmit power of w_i for all $i = 1, \dots, k$. Based on the maximum powers and the adopted communication model, a maximum transmit distance $\rho_i^{\max}$, $i = 1, \dots, k$ for each modem can be computed from the perspective of an acceptable signal to noise ratio. Additionally, we assume that the user receives data through the closest modem no matter it is stationary or mobile. This implies that the user communicates with only one modem at a time based on the separation distance from it and switches to the next one as it crosses the coverage area borderline. We will denote

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$U_i \in H(m_k)$ to indicate that the user U_i is in the coverage area $H(m_k)$ of modem m_k. As air traffic evolves in the region of interest, the data acquisition pattern changes. Therefore, the resulting optimal subset of data providing sensors and the communication network topology are time dependent, hence the optimization algorithm need to be implemented at each time instance the data acquisition changes have been detected.

We represent the distributed node infrastructure under the consideration as a connected undirected graph of k nodes, which is denoted as

$$\mathcal{G} = (\mathcal{N}, \mathcal{E}) \,, \tag{1}$$

where $\mathcal{V} = \{V_1, \ldots, V_k\}$ is the set of nodes, representing the nodes locations, $\mathcal{E}$ is the set of edges connecting the vertices, and $\mathcal{A} \in \mathbb{R} = \{a_{ij},\ a_{ij} = a_{ji}\}$ is the adjacency matrix of graph $\mathcal{G}$, that is

$$\mathcal{E} = \{(i,j) : a_{ij} > 0\} \,. \tag{2}$$

The graph $\mathcal{G}$ has no self-loops, so $(i,j) \in \mathcal{E}$ implies that $i \neq j$. We assume that initially $\mathcal{G}$ is connected meaning that for any pair of vertices (i,j), there is a path consisting of edges in $\mathcal{E}$ to reach from i to j, and is complete meaning that there are edges to reach from every i to every j. Neighborhood a vertex i is defined as follows:

$$\mathcal{N}_i = \{j : (i,j) \in \mathcal{E}\} \,, \tag{3}$$

and degree of a vertex i is denoted as δ_i and is defined as the cardinality of $\mathcal{N}_i$. The Laplacian matrix of $\mathcal{G}$ is defined as

$$\mathcal{L} = \mathcal{A} - \Delta \,, \tag{4}$$

where $\delta = diag(\delta_1, \ldots, \delta_k)$ is the degree matrix of the graph. For a connected graph, the Laplacian matrix is symmetric and non-negative definite. Minimum eigenvalue of a Laplacian matrix is $\lambda_1 = 0$ with corresponding eigenvector $\mathbf{1} = [1, 1, ..., 1]^\top$. For a connected graph, the null space the Laplacian matrix is $1 - D$ and is spanned by the vector $\mathbf{1}$ and the second smallest eigenvalue λ_2 is always positive.

To comply with maximum transmit distance $\rho_i^{\max}$, $i = 1, \ldots, k$ of modems, we modify the adjacency matrix $\mathcal{A}$ as follows

$$a_{ij} = \begin{cases} \rho_{ij}, & \rho_{ij} \leq \rho_0 \\ 0, & \rho_{ij} > \rho_0 \end{cases} \tag{5}$$

where $\rho_{ij} = \|\boldsymbol{r}_i - \boldsymbol{r}_j\|$ and $\rho_0 = \min(\rho_i^{\max},\ i = 1, \ldots, k)$, which effectively assigns distance as edges weights and removes edges with distances exceeding ρ_0. Therefore the modified graph $\mathcal{G}$ represents the communication topology satisfying the transmit range constraints.

Next we compute the data transmit rates from every vertex to its neighborhood based on the adopted communication model and the corresponding edges weights assigned on the previous step and update the adjacency matrix $\mathcal{A}$ with the corresponding rates.

The proposed algorithm at each time instance selects the sensors providing measurements data, computes the transmit time based on the data sizes and transmit rates, updates the edges weights one more time, and finds the shortest path from selected sensors corresponding vertices to the closest to the user vertex using the last updated graph.

III. Simulation example

As a simulation example scenario we consider San Francisco Bay area air traffic monitoring over a specified region presented in Figure 1, where magenta eye icons display the nodes locations on the Google Earth map, green polygon is the area of interest for air traffic surveillance and the red landmarks are the users location. Figure 2 displays the simulation environment in $2-D$ in a ENU Cartesian frame, where blue circles indicate nodes locations and red stars indicate users locations.

The complete connected graph representation of the communication network with unlimited range is depicted in Figure 3, Figure 4 displays the graph of limited to 3000 m range communication network.

An example of optimal sensors and communication topology selection presented in Figure 5, where only sensors covering the yellow polygon have been selected and the communication network is a directed graph displaying the information flow from the senors (blue circles) to the user (red square).

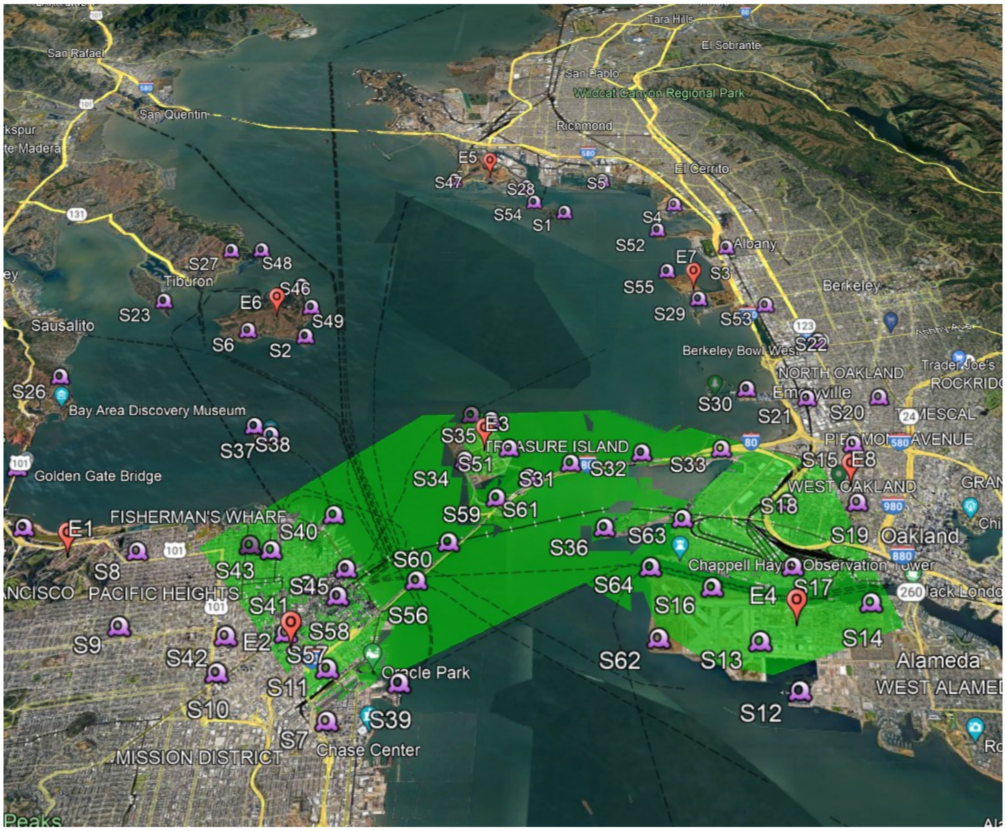

Fig. 1 Simulation Scenario.

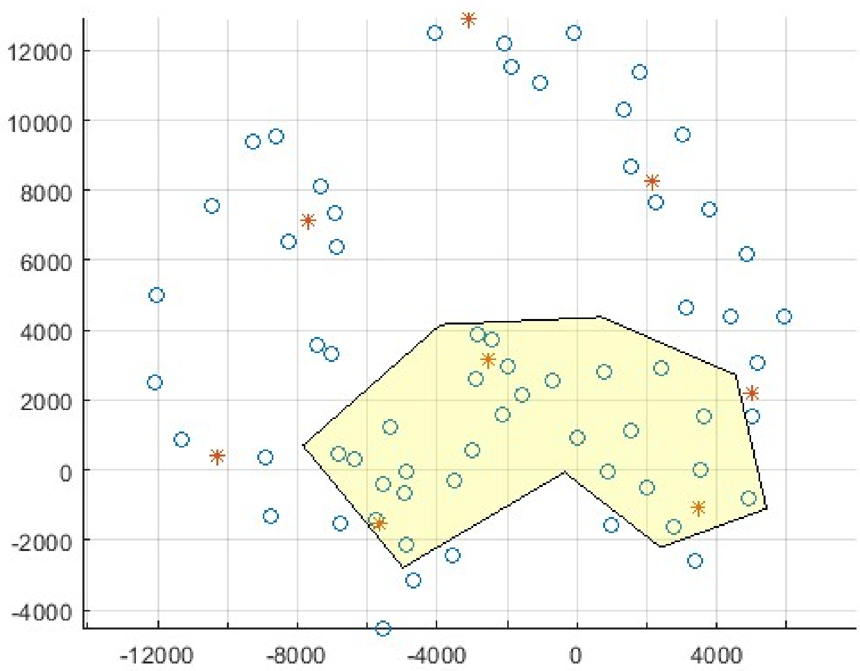

Fig. 2 ENU coordinate representation of simulation scenario

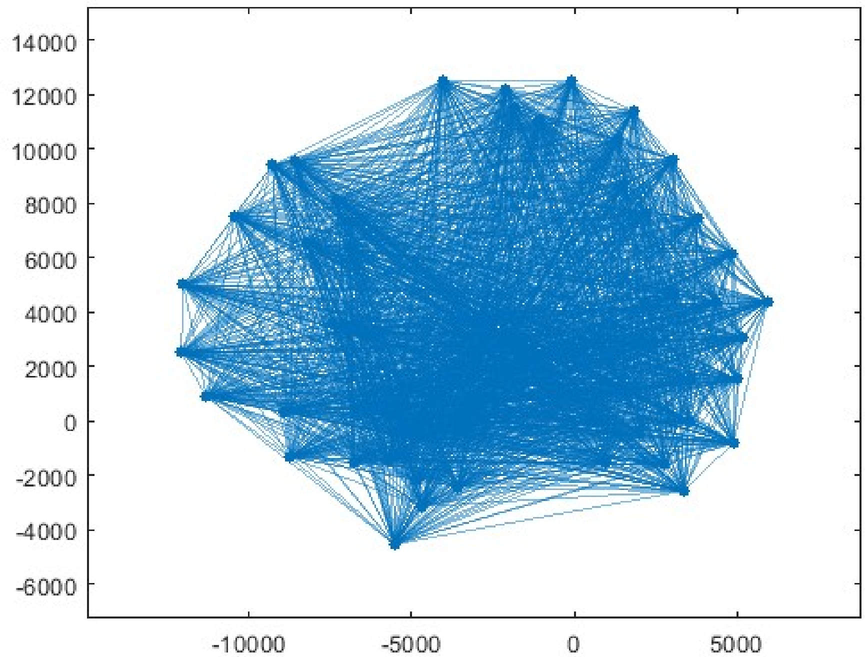

Fig. 3 Complete connected graph of unlimited communication network.

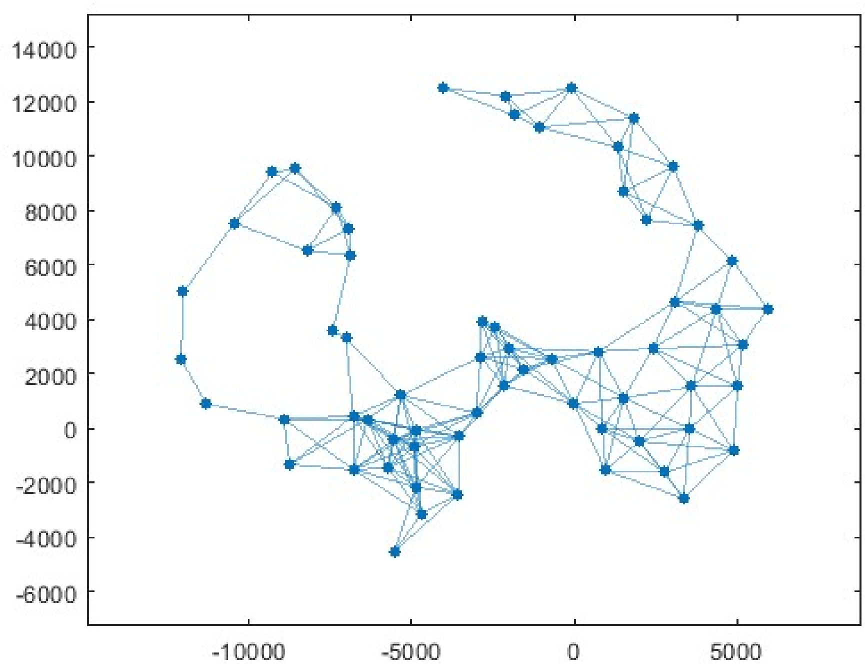

Fig. 4 Limited to $3000\ m$ **range communication network.**

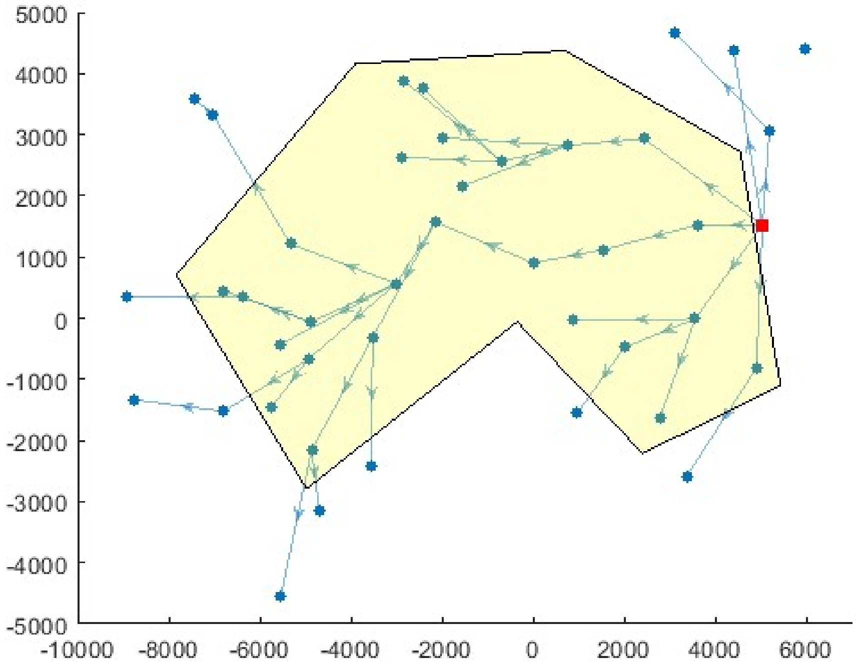

Fig. 5   Optimal sensors and communication topology example.

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