On-Demand Unmanned Aerial Vehicle Deployment and Profit Maximization for Internet of Maritime Things Networks

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Abstract

Smart gadgets are increasing with the development of sixth-generation (6G) mobile communication systems. Similarly, the number of internet of maritime things (IoMT) devices are also increasing due to the rapid development in maritime activities for trade, research, defense, and recreation. To fulfill the demand for IoMT devices at the beach and seaside during occasional events, we consider the deployment of unmanned aerial vehicles (UAVs). The UAVs are efficient for on-demand deployment and service provision for IoMT devices. In this work, we consider network profit maximization on UAVs deployment and their efficient service allocation to the IoMT devices. A combinatorial optimization problem (integer linear programming) is formulated, which is NP-hard. To deal with a complex problem, we provide Bender Decomposition (BD) based algorithm. The simulation results provide the effectiveness of our proposed algorithm.

I. INTRODUCTION

The connected world is the objective of sixth-generation (6G) mobile networks [1], which need to ensure worldwide connectivity of each device [2], [3]. At the same time, human activities at sea are increasing due to a tremendous amount of trade, defense, tourism, and research [4], [5]. Therefore, to ensure the worldwide wireless coverage of each device in the 6G networks, it is necessary to integrate the internet of maritime things (IoMT) devices [6]. The key contribution of our proposed works is as follows:

- We propose the on-demand IoMT network architecture for service provision from the network operator.
- We formulate a joint IoMT association and UAV deployment integer linear programming (ILP) problem to maximize the network operator profit while ensuring IoMT quality-of-services (QoS).
- We proposed an iterative algorithm based on Bender decomposition (BD) to solve this ILP.
- We provide numerical simulation results, which ensure the efficient convergence of the proposed algorithm.

II. SYSTEM MODEL

In this paper, we consider the service provided by the network operator to the beach and seaside IoMT devices. These devices are low power and less antenna gain, making it difficult for these devices to get connectivity from far base stations (BS). Additionally, when coverage demand increases in remote seaside events, network operators need to fulfill the demand from these users, which is difficult to manage with existing terrestrial-based network architecture [7]. Therefore, to provide on-demand services, network operators deploy UAVs, which are reliable and efficient in deployment. Hence, we introduce the UAV deployment and their services allocation to each IoMT device. We consider the set of IoMT devices $\mathcal{M} = \{1, 2, 3, .., M\}$ and a set of UAVs $\mathcal{U} = \{1, 2, 3, .., U\}$.

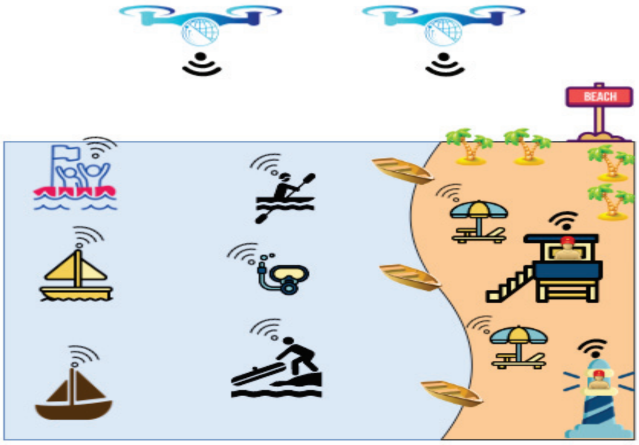

Fig. 1: Illustration of IoMT On-Demand Network

III. PROBLEM FORMULATION

In this section, we formulate the on-demand UAV deployment and profit maximization problem. The profit P_{ij} is

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This work was partially supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2020R1A4A1018607), and by Institute of Information communications Technology Planning Evaluation (IITP) grant funded by the Korea government(MSIT) (No.2019-0-01287, Evolvable Deep Learning Model Generation Platform for Edge Computing) *Dr. CS Hong is the corresponding author.

incurred if the IoMT device $j \in \mathcal{M}$ is associate with the already deployed UAV $i \in \mathcal{U}$. Additionally, the jth IoMT device can only associate to the respective ith UAV if and only if the ith UAV is deployed by the network operator. Our target is to deploy the subset of UAVs $S_i \subset U_i = 1, 2, ..., U$, such that the total network profit is maximized. Therefore, the optimization problem can be formulated as follows:

$$\max_{\boldsymbol{a},\boldsymbol{b}} \quad \sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{M}} P_{ij}a_{ij} - \sum_{i\in\mathcal{U}} C_i b_i, \tag{1a}$$

$$\text{s.t.} \quad \sum_{i\in\mathcal{U}} a_{ij} = 1, \quad \forall j \in \mathcal{M}, \tag{1b}$$

$$0 \le a_{ij} \le b_i, \quad \forall i \in \mathcal{U}, \forall j \in \mathcal{M}, \tag{1c}$$

$$a_{ij}, b_i \in \{0, 1\}, \quad \forall i \in \mathcal{U}, \forall j \in \mathcal{M}, \tag{1d}$$

where C_i is the cost associated with each UAV deployment. In case of P_{ij}, this value is dependent upon various parameters i.e., each IoMT device j service demand, the throughput each device experience by the UAV i and overall quality of service (QoS). The optimization problem obtained in (1) is a ILP, which is NP-hard in nature. To tackle with this ILP , we propose the BD decomposition based algorithm in section IV.

IV. PROPOSED ALGORITHM

In this section, we introduce our proposed algorithm based on BD. Before applying BD on the main problem, we relax the IoMT device's association variable a_{ij} to continuous form. After relaxation, we decompose the main problem into two problems i.e., master problem (MP) and subproblem (SP) on the basis of decision variables [8]. The MP deals with complicating UAV deployment decision variables and SP deals with IoMT device association relax variables. The upper and lower bounds of the original problem are then developed using the previously stored values. Bender cuts are used in the MP to split the solution area and have the optimum point of integer variables. When the upper bound matches the lower bound, the iteration procedure ends, indicating that the algorithm has converged. The entire BD method for solving the approximate solution of the problem in (1) is described below.

Initialization: Initially, the loop counter for BD is initializes, i.e., $k = 1$. Afterward, we randomly initialize the value of complicating variable for the UAV deployment. Moreover, we introduce an auxiliary variable ζ to represents the optimal value of SP in MP. The value of ζ can be initialized as ζ^{down} to avoid the infeasible solution.

SP: To obtain a solution of continuous IoMT association variables, the SP is formulated by fixing the complicating UAVs deployment variables. As a result, the SP is given as follows:

$$\max_{\boldsymbol{a}} \quad \sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{M}} P_{ij}a_{ij} - \sum_{i\in\mathcal{U}} C_i \tilde{b}_i, \tag{2a}$$

$$\text{s.t.} \quad \sum_{i\in\mathcal{U}} a_{ij} = 1, \quad \forall j \in \mathcal{M}, \tag{2b}$$

$$0 \le a_{ij} \le \tilde{b}_i, \quad \forall i \in \mathcal{U}, \forall j \in \mathcal{M}, \tag{2c}$$

$$a_{ij} \ge 0, \quad \forall i \in \mathcal{U}, \forall j \in \mathcal{M}, \tag{2d}$$

$$b_i = b_i^k : \theta_i^k, \quad \forall i \in \mathcal{U}, \tag{2e}$$

where $\tilde{b}_i$ indicate the fixed value of complicating UAV deployment variables and θ_i indicate the dual variable of constraint (2e) to capture the sensitivity linked with UAVs association. The relax optimal solution in SP can be converted into discrete by using following ranges:

$$a_i = \begin{cases} 0, & 0 \le a_i \le 0.5, \quad \forall i \in \mathcal{U} \\ 1, & 0.5 < a_i \le 1, \quad \forall i \in \mathcal{U}. \end{cases} \tag{3}$$

Bounds Calculation: The stopping criterion is determined by generating the upper and lower limit differences. The upper limit of objective function (1) can be calculated as after the subproblem has been solved, which can be given as:

$$U^k = \sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{M}} P_{ij}a_{ij}^{*k} - \sum_{i\in\mathcal{U}} C_i \tilde{b}_i, \tag{4}$$

where the a_{ij}^{*k} indicate SP optimal solution in iteration k. The lower limit can be found as:

$$L^k = \alpha^k - \sum_{i\in\mathcal{U}} C_i b_i^{*k}, \tag{5}$$

where b_i^{*k} indicate MP optimal solution in iteration k. If the difference between U^k and L^k is less than a certain value, then BD iterations are terminated, and the optimal solution is given as $\{\boldsymbol{a}^*, \boldsymbol{b}^*\}$. Otherwise, the iteration is repeated and continue towards the MP.

MP: The continuous relaxation variable is fixed in the MP. The MP is formulated as a small ILP problem after modifying the loop counter $k = k + 1$, which is given as follows:

$$\max_{\boldsymbol{b},\zeta} \quad \zeta - \sum_{i\in\mathcal{U}} C_i b_i, \tag{6a}$$

$$\text{s.t.} \quad \zeta \le \sum_{i=1}^{U} \theta_i^t(\boldsymbol{b}_i - \boldsymbol{b}_i^t) + \sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{M}} P_{ij}a_{ij} - \sum_{i\in\mathcal{U}} C_i \tilde{b}_i^t, \quad t = 1, ..., k-1, \tag{6b}$$

$$\zeta \ge \zeta^{\text{down}}, \tag{6c}$$

$$\sum_{i\in\mathcal{U}} a_i \le 1, \tag{6d}$$

$$b_i \in \{0, 1\}, \quad \forall i \in \mathcal{U}, \tag{6e}$$

where the constraint (6b) indicate the bender optimality cut, which is generated by former iteration values. After solving this MP, we can find the optimal solution of ζ and $\boldsymbol{b}$.

V. SIMULATION RESULTS AND DISCUSSION

In this section, we discuss the numerical results to demonstrate the effectiveness of our proposed algorithm. We consider 50 IoMT devices are randomly distributed in 200 nautical mile square (NM^2) area. The IoMT devices are considered static in position in the studied period. Therefore, we consider distance based free-space pathloss model to calculate the throughput of each IoMT device. We utilize the optimization solver i.e., Gurobi for both problems i.e., SP and MP.

Convergence Performance: In Fig. 2, we present the outer loop of BD versus the upper and lower bound of the algorithm. We can observe from the figure that in 3 UAVs deployment, the algorithm converges very fast, just within three iterations. Similarly, in Fig. 3, we consider 6 UAVs deployment; the BD algorithm took 20 iterations to converge. In both configurations, the number of IoMT devices are M=50.

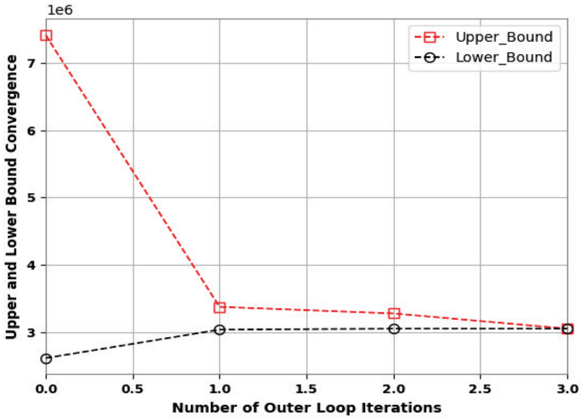

Fig. 2: Algorithm convergence when UAVs=3

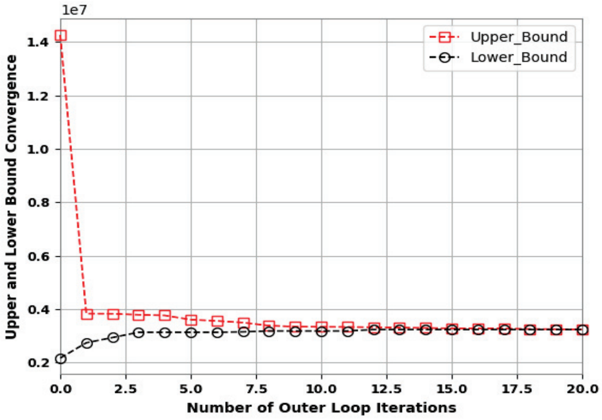

Fig. 3: Algorithm convergence when UAVs=6

Impact of IoMT devices on Network Profit: In Fig. 4, we present the number of IoMT devices versus the network profit. We can analyze that the network profit increases with the increment in IoMT devices because more IoMT devices will require connectivity to generate profit, which is quite simple. We compare the profit with two network configurations in the figure, i.e., UAVs=3 and UAVs=6. We can observe from the figure that when 6 UAVs are deployed network performed better than 3 UAVs.

VI. CONCLUSION

This paper studied the fundamental analysis of on-demand UAVs deployment for the network of the IoMT devices. We formulate an ILP problem for joint UAV deployment and the IoMT association. To solve this ILP, we proposed a BD algorithm. The results of simulations have proven the effectiveness of our proposed algorithm for UAV deployment in the IoMT network.

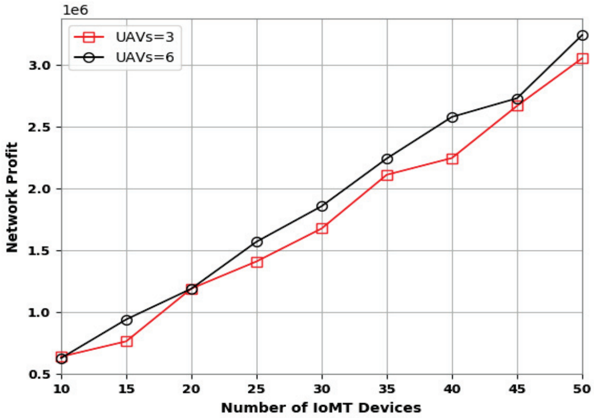

Fig. 4: Network Profit relation with the number of IoMT devices

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