Aircraft Network Deployment Optimization with k-Survivability

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***Abstract*—The network deployment required for an aircraft amounts to a considerable portion of the overall weight, due to the survivability demands for such critical applications. With complications in regulating and standardizing wireless communication technologies in aircraft environments, a completely wireless network is yet impractical. However, the architecture design of the network requires immediate improvement to facilitate more efficient means of transport for the future. In this work, we propose a mathematical approach, which aims to reduce the overall network weight, comprised of gateways and cables, whilst satisfying the survivability, maximum length, capacity and port constraints of the system. This is implemented as an ILP optimization problem with the objective of minimizing the overall network deployment weight by finding the gateway to device connections as well as the gateway deployment position. The performance of the proposed scheme is evaluated with varying values of constraints and compared to common network deployment techniques in use. The results demonstrate that significant gains obtained by using the proposed model, which outperforms conventional schemes consistently. It is also worth mentioning that the same method can be extended to wireless network scenarios with restrictions on the deployment area of nodes as well as survivability requirements.**

I. Introduction

Aircraft networks are filled with user nodes for functionalities such as access points, smoke detector, panels for passenger or in-flight entertainment. These nodes are often placed throughout the aircraft according to the row of passenger seats and sides of the aircraft. Meanwhile, the servers situated at the front of the aircraft usually require communications with servers situated at the back. In centralized architectures the gateways act as an intermediary, connecting the nodes to the servers, while providing a degree of redundancy in case of node or link failure. The optimization of harness used for digital communications is thus an important problem to study, since it currently represents around 25% of the total empty aircraft weight.

While present-day communication networks used in aircraft are mostly centralized, next-generation networks are headed toward decentralized architectures based around partially meshed topologies with strict survivability requirements. In those architectures, a backbone network made of gateways and servers are distributed across the aircraft. Although the gateways have an intermediary role, connecting the end devices to the server, they may as well have server functionalities embedded, thus eliminating the need for centrally located servers in the aircraft network. End devices such as sensors, passenger service units and lights are connected to multiple gateways in order to ensure survivability. While the physical position of those end-devices is usually fixed by external requirements such as seat placements, the position of the gateways can be viewed as a design parameter which can heavily influence the harness on board. In order to reduce the overall weight it is necessary to not only find the best associations between gateways and users, but also the location of the gateways, while also taking into account the survivability and other constraints. Joint optimization of gateway positions and connections, is a complex problem that requires a brute force search on all possible combinations, which is computationally expensive and impractical for large data sets.

The existing literature on this problem ranges from graph theory to fuzzy clustering [1]–[6], where the main aim is to reduce the overall cabling length of the network. The main focus in [1] is to use shortest path algorithms and optimization problems within a known network architecture to identify the cheapest path from a source to destination. Notably, in a previous work by the authors [2], the problem was approached via a graph theory heuristic algorithm, the connecting links between nodes were selected with the aim of reducing the total cabling length and ensuring a certain degree of survivability, however no differentiation was made between a gateway node and a user node. Furthermore, as the solution requires a search algorithm it is not deemed suitable for large problem sizes. In [3], a similar problem is studied in a vehicular network which aims to find the best position for base stations via a k-means clustering algorithm. However, this method does not offer any survivability measures. Authors in [4] propose heuristic solutions to find the position of a single gateway with the

§This work was performed while the author was with Airbus Group Innovations in Munich, Germany.

aim of improving the network throughput. In [5] the deployment of multiple gateways is studied and a version of the well known k-means algorithm is proposed to minimize the distance of the links. Since such algorithms do not take into consideration any physical restrictions on the position of gateways or survivability and other system constraints, they perform poorly for aircraft applications (as will be demonstrated later). Lastly, the work in [6] provides an approach for integrated network design, although it does not consider the issue of survivability, it aims to find suitable positions for both gateways and users, which is unsuitable for the system model and application here. In general, existing techniques often assume a known deployment of the network or otherwise fall short in the key aspect of survivability. In this paper, we propose an ILP optimization model for minimizing the overall weight by selecting the optimal association links and gateway positions within the permitted deployment region. The optimization problem takes into account important design parameters, such as survivability, maximum number of end-devices connected to a given gateway (number of ports) and maximum length of a link, as well as capacity limitation of gateways. To the best of our knowledge, the work here is the first to address network planning within a restricted environment with survivability and other system constraints. While the main motivation for this paper is the optimization of aircraft networks, the developed method can be applied to critical applications where survivability is of interest. Furthermore, it could also be extended to base station deployment in wireless networks supporting cooperative multipoint-transmission schemes such as joint transmission which requires more than one active transmission link.

Contribution: In this work we mathematically model the network as an ILP optimization problem under survivability, maximum length, capacity and port constraints. The problem determines the optimal gateway positions and associations with the aim of minimizing the overall weight; comprised of gateways and cabling. The performance gains of our proposed solution is then studied with various values for survivability, length and port constraint which indicate that the ILP model outperforms conventional schemes.

Paper Organization: The remainder of this paper is structured as follows. In Section II we define the system model. The optimization problem and its constraints, as well as the proposed reformulation into a solvable ILP model are provided in III. Section IV describes our version of the restricted fuzzy k-means algorithm developed for comparison to the proposed ILP model. In Section V we describe the simulation setup, while also discussing the performance gains via simulation results. Finally, in Section VI the conclusion is drawn from our results.

II. System Model

We consider a typical aircraft environment where the position of the user end devices is known and there exists physical restrictions on the possible positions for the gateways. Figure 1 illustrates the architecture of a typical aircraft network and the user layout. The network under study is comprised of G (potential) gateways and N end user devices, where the index of gateways is given by $i \in \{1, \cdots, G\}$ and similarly, $j \in \{1, \cdots, N\}$ represents the index of user end devices. With the gateways assumed to have server functionalities embedded, there is no need for a centralized server in the design, this may also be realized in a more advanced aircraft by having each gateway connect to a satellite server. A switch indicator $\alpha_i \in \{0, 1\}$ is used to describe if the i-th gateway should be activated, while an association indicator is used to define the connections between gateway i and user j, indicated by $\beta_{ij} \in \{0, 1\}$. The geographical position of the i-th gateway and the j-th user are represented by $\mathbf{x}_i \in \mathbb{R}^2$ and $\mathbf{y}_j \in \mathbb{R}^2$, respectively. Note that although in here we assume two dimensions, it can easily be extended to three dimensions to suit more realistic implementations. The gateways and cables have their corresponding weights defined by w_i (kg per unit) and p_{ij} (kg per meter). Similar to [2], the k-survivability of the network, implies that the network remains connected if fewer than k links or gateways fail. As a system constraint we require the maximum length of any link to be below l_{max}. Furthermore, the limitation on the maximum number of active ports of the i-th gateway is indicated by θ_i. Lastly, the service data rate requirement of each end device is denoted by γ_j, while the capacity constraint of each gateway is described by C_i. From here on, the entire set of gateways and user end devices will be represented by $\mathbb{K}_G$ and $\mathbb{K}_{UE}$, respectively.

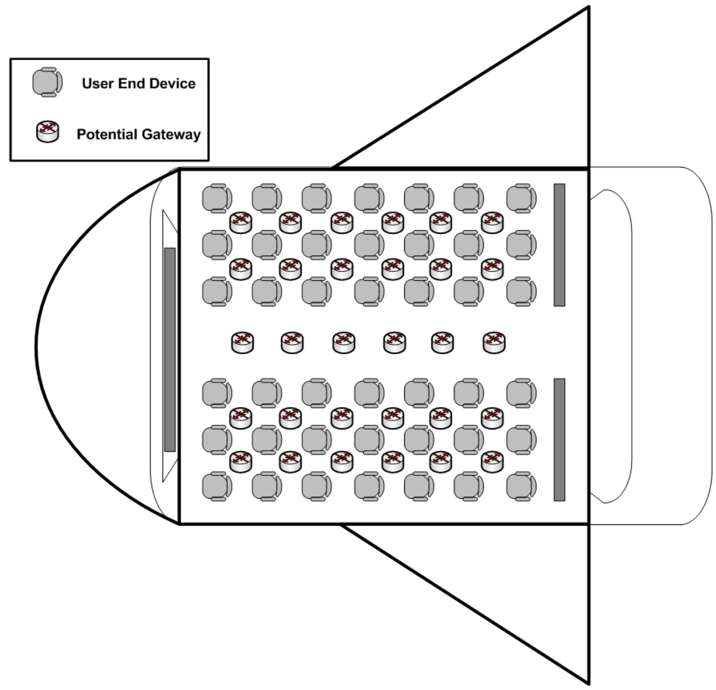

Fig. 1: Overview of a typical aircraft network architecture and user layout.

III. ILP Optimization Problem

In order to make an ILP formulation of the system model possible, potential gateway positions need to be defined inside the permitted regions. The optimization will jointly determine which of the potential positions and gateway to user connections are most suitable. The ILP optimization problem is described as follows

$$\min_{\alpha_i,\beta_{ij}} \quad \sum_{j=1}^{N}\sum_{i=1}^{G}\alpha_i\beta_{ij}p_{ij}\|\mathbf{x}_i-\mathbf{y}_j\|+\sum_{i=1}^{G}\alpha_i w_i \tag{1a}$$

$$\text{s.t.} \quad \alpha_i\beta_{ij}\|\mathbf{x}_j-\mathbf{y}_i\|\le l_{max}, \quad i\in\mathbb{K}_G, j\in\mathbb{K}_{UE}, \tag{1b}$$

$$\sum_{i=1}^{G}\alpha_i\beta_{ij}\ge k, \quad j\in\mathbb{K}_{UE}, \tag{1c}$$

$$\sum_{j=1}^{N}\alpha_i\beta_{ij}\le\theta, \quad i\in\mathbb{K}_G, \tag{1d}$$

$$\sum_{j=1}^{N}\alpha_i\beta_{ij}\gamma_j\le C_i, \quad i\in\mathbb{K}_G, \tag{1e}$$

$$\alpha_i,\beta_{ij}\in\{0,1\} \quad i\in\mathbb{K}_G, j\in\mathbb{K}_{UE} \tag{1f}$$

where (1a) represents the sum weight of all the deployed cabling and the gateways using the Euclidean norm. While (1b) describes the maximum length constraint on the links. The survivability constraint is defined in (1c) by allowing each user device to connect to at least k gateways, while constraint (1d) limits the number of users connected to a single gateway. Constraint (1e) ensures that the sum of the rates of the connected users does not exceed the capacity of the gateway. Due to the optimization problem above being jointly over both α_i and β_{ij}, it does not hold a suitable structure for solvers such as [7]. Using the fact that there can be no association to a gateway if it is turned off, the original problem is reformulated using an auxiliary variable, denoted by Π_{ij}, in the following form

$$\min_{\alpha_i,\Pi_{ij}} \quad \sum_{j=1}^{N}\sum_{i=1}^{G}\Pi_{ij}p_{ij}\|\mathbf{x}_i-\mathbf{y}_j\|+\sum_{i=1}^{G}\alpha_i w_i \tag{2a}$$

$$\text{s.t.} \quad \Pi_{ij}\le\alpha_i, \quad i\in\mathbb{K}_G, j\in\mathbb{K}_{UE}, \tag{2b}$$

$$\Pi_{ij}\|\mathbf{x}_j-\mathbf{y}_i\|\le l_{max}, \quad i\in\mathbb{K}_G, j\in\mathbb{K}_{UE}, \tag{2c}$$

$$\sum_{i=1}^{G}\Pi_{ij}\ge k, \quad j\in\mathbb{K}_{UE}, \tag{2d}$$

$$\sum_{j=1}^{N}\Pi_{ij}\le\theta, \quad i\in\mathbb{K}_G, \tag{2e}$$

$$\sum_{j=1}^{N}\Pi_{ij}\gamma_j\le C_i, \quad i\in\mathbb{K}_G, \tag{2f}$$

$$\alpha_i,\Pi_{ij}\in\{0,1\} \quad i\in\mathbb{K}_G, j\in\mathbb{K}_{UE}, \tag{2g}$$

note that while constraint (2b) ensures that there are no associations to a switched off gateway, constraint (2d) guarantees that the all users are connected to at least k gateways and hence, avoids the trivial case of having $\Pi_{ij}=0$ for all users. It is worth mentioning that as the overall network weight is minimized, constraint (2d) becomes tight at the point of optimality.

IV. Restricted Fuzzy k-means

Considering the popular use of k-means algorithms for network deployment, as demonstrated in [5], an adaptation of k-means is used for the purpose of comparison to the ILP model proposed in our work. Noting that the performance of such algorithms has not been studied in scenarios with a restriction on the location of the gateway as well as survivability and other network constraints, we define a version of the k-means suited to the aircraft network architecture and application. During the initialization step, the algorithm generates the initial positions of the gateways within the physically permitted areas. This is in contrast to regular k-means which allows initial positions to be anywhere. The users will then associate to the k closest gateways to ensure their survivability, as oppose to only the single nearest in the case of k-means. The distance between the connected gateways and users is minimized by finding the best gateway locations, subject to constraints on the permitted areas for gateway deployment. If any of the system constraints, Eqs. (1b) to (1e) are violated, the number of required gateways is incremented and the algorithm restarts. A general implementation of the aforementioned algorithm is provided in Algorithm 1. Note that from here on we will refer to the adapted version as k-means*, due to its differences with the original algorithm. It is worth mentioning that although this is inspired by the k-means algorithm [8], however, the survivability constraint means the adapted k-means* is also similar to fuzzy clustering algorithms, [9], in which objects are simultaneously associated to more than one cluster head.

Algorithm 1 k-means* algorithm

repeat
  while $\mathbf{y}_j^{iteration-1}\neq\mathbf{y}_j^{iteration}$ for any j **do**
    Associate users to k closest gateways
    Minimize $\sum_{i=1}^{G}\sum_{j=1}^{N}\beta_{ij}\|\mathbf{x}_i-\mathbf{y}_j\|$ subject to physical area restrictions
  end while
  if Any constraint violated **then**
    Increment number of gateways
  end if
until All constraints satisfied

V. Simulation Results & Discussion

In this section we describe the simulation scenario and illustrate the performance of our proposed solution. The proposed method is compared against methods such as k-means* algorithm and random deployment, which are commonly used for gateway and network planning [3], [5]. In order to assess the gains of the proposed solution in aircraft networks, a similar environment is setup. Without loss of generality, we assume that the distribution of user end devices in an aircraft is symmetrical, thus, it is sufficient to analyze only a section of the layout. Figure 2 shows the implementation of 60 user end devices in parallel rows and the potential gateway positions, as well as the selected ones obtained by the ILP solution, in an area of $30m\times 50m$. The physical restriction on gateway deployment is shown by the surrounding rectangle. Note that an overestimate of the number of gateways is recommended for the ILP. This can be approximated by first

TABLE I: Simulation Parameters

Parameter	**Settings**
Number of User End Devices	60
Number of Gateways (only for ILP)	45
Maximum Number of Ports, θ	$[8, 12, 16, 20]$
Maximum Length, l_{max}	$[11, 13, 15, 17, 19]$m
Survivability Factor, k	$[2, 3, 4, 5, 6, 7]$
Weight of Gateway, w_i	1.4kg/unit
Weight of Cable, p_{ij}	0.03kg/m
Gateway Capacity, C_i	100Mbps
User End Device Service Requirement, γ_j	$[1, 2, 4, 5, 10, 15]$Mbps

finding the absolute minimum number of gateways that will merely satisfy the port constraints, which is calculated in the following way

$$m = N \times k$$
$$Q = \max\left(\frac{m}{\theta}, k\right)$$

where m is the number of ports required to meet the survivability demands of the network and Q is the absolute minimum number of gateways. The number of ports of gateways, θ, is set to 16 similar to the work in [2]. For the case of 60 devices and the strictest survivability that we will study, $k = 7$, a minimum of 27 gateways are required, thus in the setup 45 potential gateway positions are used as an overestimate. Note that the resolution on the optimal position of gateways can be simply improved by increasing the set of possible gateway locations. The complete set of the simulation parameters, provided by Airbus Group Innovations, are included in Table I, unless a parameter is under simulation in which case the range will be specified. It is worth mentioning that the service rate requirements are spread uniformly across users and simulations were performed for a 500 system realizations.

Figures 2 and 3 demonstrate the final network architectures (for case $k = 2$) obtained from using the ILP and k-means methods correspondingly. One of the main drawbacks of the k-means which is the initialization step is shown in Fig. 3; with the sporadic gateway deployment and uneven clusters as well as the overlay of two gateways in the bottom left corner. Although there exists literature on improving the initialization, such as [10], distance minimizing algorithms do not directly take the system constraints into consideration. This is even more apparent when the user end devices are spread uniformly in less identifiable clusters. Furthermore, as the physical region for gateway deployment becomes more restricted, k-means* will converge to random deployment. Note that the architecture from the proposed ILP model achieves a combination of a ring and star topology, which as suggested in [2] offers low cabling whilst providing sufficient survivability. In order to evaluate the performance of the different deployments techniques, simulations were carried out with different survivability factors, length and port constraints.

In order to evaluate the achieved performance in terms of the overall weight, experiments were made with varying values of survivability, ranging from 2 to 7. Considering that random deployment method results in the worst performance, the overall weight of k-means* and ILP, are given as percentage of the random deployment weight for a more concise representation, as shown in Table II. It is clear that the ILP deployment is able to consistently offer a lower overall network weight with increasing values of survivability, while the performance of the k-means* is not significantly affected by the survivability requirements.

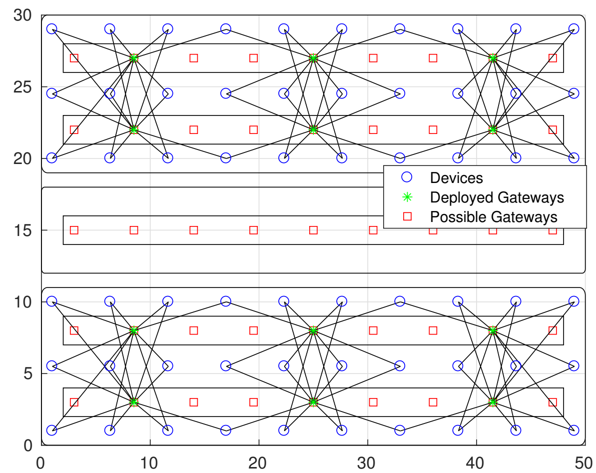

Fig. 2: ILP network architecture with $k = 2$, in an area of $30m \times 50m$. Use of the ILP model deems deployment in certain areas, such as the middle row, to be unfavorable to the overall objective.

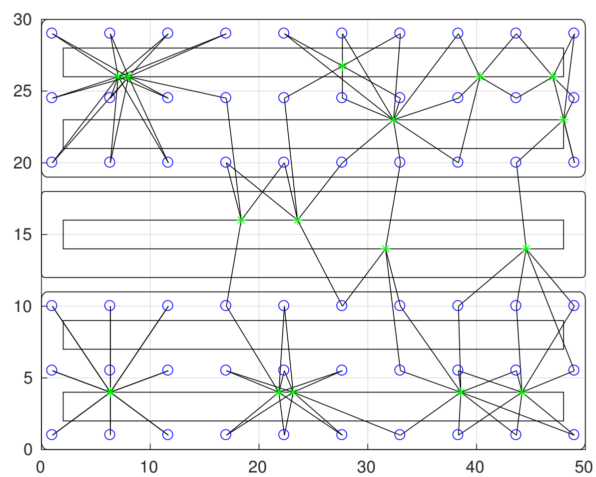

Fig. 3: k-means* network architecture with $k = 2$, in an area of $30m \times 50m$. K-means* results in higher gateway deployment, due to its initialization and indirect consideration of constraints. k-means* could also lead to overlay of gateways, as shown in the bottom left corner.

For better insight into the network deployment, we provide breakdown of the overall weight into gateway and cable weight as shown in Fig. 4. It can be observed that the proposed ILP is able to outperform k-means* by significant margins in achieving a lower gateway weight which is due to direct consideration of

TABLE II: Relative Network Weight vs. Survivability

	Overall Network Weight Ratio	
Survivability Factor, k	**K-means***	**ILP**
2	94.27%	71.52%
3	94.76%	79.82%
4	94.49%	85.34%
5	95.03%	85.68%
6	95.94%	87.34%
7	95.91%	88.82%

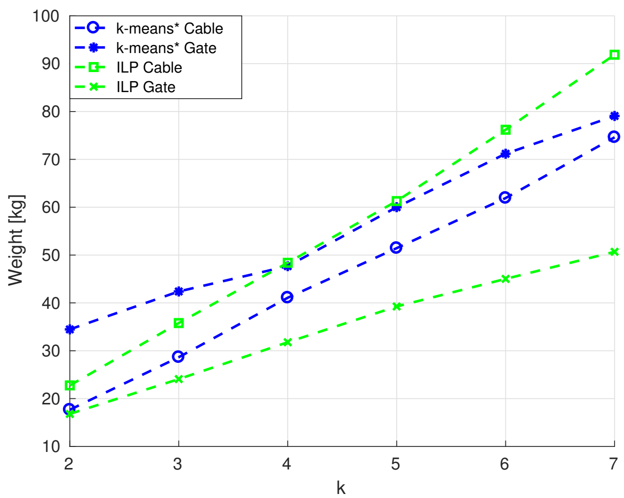

Fig. 4: Breakdown of cable and gateway weights vs. survivability factor. The proposed ILP is able to offer significantly less gateway weight, while only resulting a slightly higher cable weight (which can be overturned by increasing number of gateway in the set).

the constraints. However, as the gateway positions are not fixed using the k-means* algorithm, it is possible to achieve a slightly lower cabling weight. Note that this can be simply overturned by increasing the set of possible gateway positions.

A study on the run time of the deployment methods is made with increasing values of survivability. As demonstrated by Table III, the simulation run time required for obtaining the final deployment architecture using the k-means* increases greatly with higher survivability. This is due to the high number of iterations required for reaching the number of gateways that will satisfy the high survivability constraints. In contrast, increasing values of k results in a slight decrease in the run time of the ILP method, which is justified by the solver being able to find the optimal solution faster

when the solution subspace is reduced.

Another important design parameter is the maximum length constraint in the system as it has a direct affect on both the cabling weight and the number of gateways required. Figure 5 shows the result of this investigation with lengths ranging from 11 to 19 meters. The k-means* gateway deployment weight reduces significantly, since a more relaxed constraint is satisfied with less gateways. In contrast, in the proposed ILP method both the cable and gateway deployment weight remain constant, due the fact that the ILP realizes the deployment shown in Fig. 2 as optimal, even

TABLE III: Run Time Comparison vs. Survivability

	Run Time (s)	
Survivability Factor, k	**K-means***	**ILP**
2	621.69	23.20
3	1393.36	23.06
4	1353.60	22.57
5	1664.49	22.56
6	2527.15	22.56
7	4093.82	22.41

TABLE IV: Relative Network Weight vs. Length Constraint (k=2)

	Overall Network Weight Ratio	
Length Constaint, l_{max}	**K-means***	**ILP**
11	96.51%	53.03%
13	95.24%	60.01%
15	93.71%	74.15%
17	92.33%	78.24%
19	92.29%	78.55%

when the length constraint allows deployment in the middle row. A comparison of the overall network weight reduction relative to random deployment is provided in Table IV. It is evident that the ILP deployment method is able to offer a much better performance in comparison to k-means* and random deployment, especially when the maximum length constraint is short.

Lastly, the performances are investigated with gateway port numbers ranging from 8 to 20, for $k = 4$ (for better demonstration of the impact of ports). Table V shows that the overall network weight does not experience major changes with the port numbers, the cause of this can be observed in Fig. 6 where it can be observed that the weight required for more gateways, at low port values, is compensated by the cabling weight. This holds true for both the ILP and k-means* as increasing number of ports leads to a higher cable weight. However, once again it must be noted that the ILP solution still outperforms k-means* and random deployment.

VI. Conclusion

In this work, we investigated the network planning of aircrafts by finding the optimal gateway positions and user associations, while imposing a restriction on the deployment areas of gateways. An ILP optimization problem was developed, with the aim of minimizing the overall network weight subject to survivability, length, capacity and port constraints. To the best of our knowledge, this is the first work to develop a network deployment optimization problem for aircraft applications. Simulations were carried out for different values of the aforementioned constraints, demonstrating the significant weight reductions made possible by our proposed ILP solution in comparison to conventional schemes. Reducing the overall cabling and gateway weight does not only result in a more efficient means of transport, but also reduces the deployment and maintenance costs of the vehicle. Although the ILP model here was developed for aircraft applications, it may be adapted for use in other network planning scenarios, with survivability requirements and restrictions on the areas of gateway deployment. As future work, routing protocols and solutions may also be built upon our proposed model.

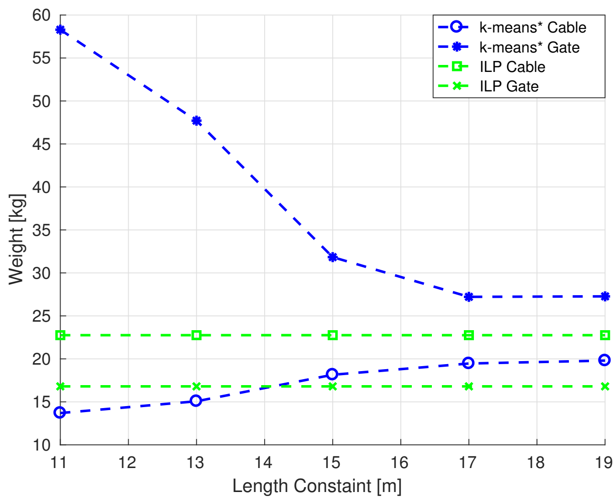

Fig. 5: Breakdown of cable and gateway weights vs. length constraint. With a more relaxed length constraint, k-means* deploys fewer gateways.

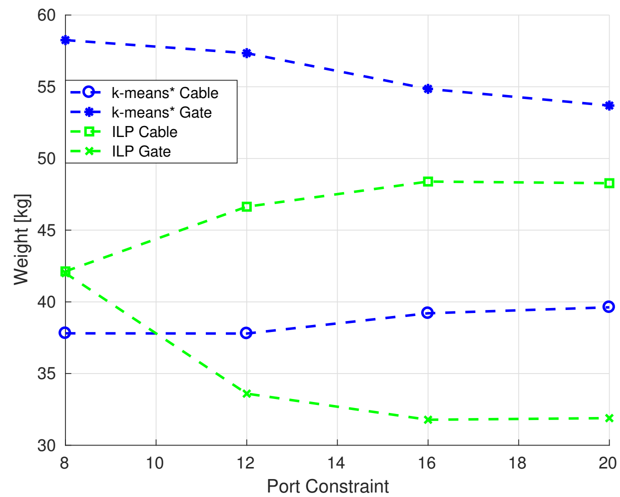

Fig. 6: Breakdown of cable and gateway weights vs. port constraint. Less ports requires more gateways to be deployed, while increasing the ports leads to higher cable weights.

TABLE V: Relative Network Weight vs. Port Constraint (k=4)

	Overall Network Weight Ratio	
Port Constraint, θ	**K-means***	**ILP**
8	95.54%	83.67%
12	95.33%	81.40%
16	95.26%	81.28%
20	95.23%	81.22%

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