Efficient Gateways Placement for Internet of Things with QoS Constraints

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Abstract—**In the Internet of Things (IoT) era, a large number of data packets are exchanged among devices over the Internet. IoT (smart) end devices forward their traffic to the Internet, either by direct communication to LTE networks, or by multi-hop transmissions to a specific gateway. Acquiring both types of communication capabilities would be unnecessarily costly for IoT end devices. Instead, to lower the overall cost, only devices performing as gateways could be fully equipped with such capabilities, while the rest of the devices could have simple low cost wireless transmitters for forwarding the traffic towards a gateway. Towards this end, the decision on gateway placement is critical to provide low cost and Quality of Service (QoS). To address this design problem, we present an Integer Linear Programming (ILP) that minimizes the total cost of the network with respect to the deployed devices, while achieving mandatory QoS requirements. Using this formulation we obtain solutions for random topologies that exhibit the effectiveness of our approach in terms of network cost and efficiency.**

Keywords—cost optimization, gateway placement, Internet of Things (IoT), sensor network, smart city

I. INTRODUCTION

The evolution of wireless (either local or wide area) communications and technologies, along with the processing capabilities of mobile devices, has given a significant boost to the Internet of Things (IoT) concept. The main idea of the IoT is that usual electronic devices (sensors, smart home appliances, surveillance cameras, traffic monitoring, actuators, etc.) equipped with necessary transmission hardware, are able to exchange data, directly or through the Internet, in order to provide respective information about events or act in advance to prevent undesired incidents from happening. The deployment of the IoT will allow easy access to specific device information from users. As a result, the IoT can enable a diversity of applications, such as smart grid, smart cities, home or industrial surveillance, home or industrial automation, e-learning, or upgrade a multitude of public services, such as traffic monitoring, healthcare, public lightning, parking and many others that would improve the quality of residents' life and moreover save world's resources.

The variety of the types of devices and applications that must be accommodated by the IoT concept bring forward the need for new architectures, communication protocols, models and services to bridge the current implemented technologies. In particular, the IoT infrastructure conveys a multitude of data types that correspond to different applications, each with specific QoS requirements, which must be processed at different units. Within this context many IoT standards have been proposed from major groups such as the *World Wide Web Consortium* (W3C), *Internet Engineering Task Force* (IETF), EPCglobal, *Institute of Electrical and Electronics Engineers* (IEEE) and the *European Telecommunications Standards Institute* (ETSI). Regarding these standards, significant attention has been paid on the architecture specification, communication and application protocols as well as service discovery protocols [1] [2].

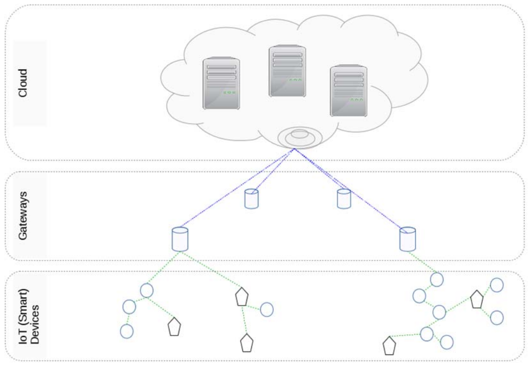


Figure 1: Fog Network Architecture

A benefit of IoT deployment is that the generated data from embedded devices (like smart meters and sensors) can be processed to extract significant analytics, by which individual citizens or business administrators could profit. However, there is a vast amount of data that requires significant network, storage and computing resources for this to be achieved. Hence, there is a need for methods and respective resources to efficiently transmit and process the data at low cost. To this end, "fog computing" could be an efficient IoT design [1] since it can operate as a bridge between the IoT end devices and cloud services that provide sufficient computing resources for data analytics. Furthermore, in the fog computing paradigm, the intermediate gateway devices can perform some data aggregation and minor processing (taking decisions distributedly) and thus depleting the processing load on clouds.

A typical fog computing architecture is illustrated in Fig. 1. It comprises of: (a) numerous IoT end devices that generate the data, (b) gateways that can serve as bridge interfaces to extend the connection to other networks, and (c) cloud servers connected on a hierarchical network forming a tree infrastructure. Regarding data exchange, the IoT end devices transmit the data to the gateways, either directly or by multi-hop transmissions through adjacent IoT end devices that act as relays (existing communication protocols for MANET and WSN [3] or IEEE 802.15.4 and 802.11ah for WMN can be applied for such communication). Then, the gateways perform some processing and forward the data to the cloud servers directly through WAN (e.g. LTE-A).

To be more specific, the IoT (smart) end devices can be integrated in Single Board Computers with onboard sensors, or provide fundamental interfaces for short range communication [like Radio Frequency Identifiers (RFID), Ultra-Wide Bandwidth (UWB) or Near Field Communication (NFC)] to receive data from nearby sensors/smart meter devices and forward it to upper layer devices or adjacent IoT end devices. Thus, IoT end devices are low cost conventional devices that operate with minimal hardware for wireless transmission and lightweight communication protocols. On the other hand, gateway devices, in addition to data exchange from/to sensor/meter devices, must also provide internet communication. In order to support both functionalities and improve mesh networking flexibility, a gateway must be equipped with multiple interfaces for wireless transmission among different access technologies. Moreover, the core hardware of a gateway must have adequate resources to support minor data processing functionalities.

A fog network infrastructure deployment for the IoT must be both bandwidth and cost efficient. Hence, reducing the installation cost of the network would make IoT attractive for respective vendors and service providers. Since gateway devices are much more expensive than simpler IoT smart devices, a cost effective IoT network can be achieved by efficiently selecting gateways and IoT end devices necessary for the network to be established. To this end, we consider in this study the problem of planning a correspondingly appropriate and efficient IoT network. We assume a given topology of metering/sensor facilities, whose transmission of monitoring values is connected to specific QoS requirements, and a set of potential IoT end devices, to be deployed at these facilities, with different specifications (such as data rate, transmission range, cost). The problem is formulated as an Integer Linear Program (ILP) that aims to obtain the minimum number of gateways along with suitable IoT end devices to optimize the overall installation cost without compromising the related QoS requirements. Following this approach, our experimental results exhibit significant cost savings along with a trade-off between cost effectiveness and QoS provisioning.

The remainder of this paper is organized as follows: In Section II we refer to previous studies and comment on related work with respect to our work's novelty points. In Section III, we provide a detailed description of the assumed network model and formulate the ILP problem. Obtained solutions of the ILP over random topologies are presented in Section IV. Finally, section V concludes this paper.

II. Related Work

Irrespectively of the underlying topology and protocols (WSN, WMN, M2M or IoT), gateways placement in wireless networks as well as clustering and coverage problems in wireless ad-hoc networks, have long been under consideration [4] [5] [6]. In the simpler approach, the clustering problem refers to finding the minimum number of cluster head nodes that collect and aggregate the data of the nodes in the cluster. This approach is applied in base station scenarios where only one hop communications is involved. When multi-hop paths can be applied, the establishment of hierarchical networks with data aggregators is preferred for efficiency purposes.

In [7], the authors explore the placement of gateways, which they call Internet Transit Access Points (ITAPs), in wireless neighborhood networks and sensor networks by accounting for link capacity, wireless interference and variable traffic constraints. They study multi-hop networks, in which houses or sensor nodes occupy devices that send or forward data to servers on the internet via ITAPs. Hence they propose ILP formulations and placement algorithms to obtain the minimum number of ITAPs for a given topology under three different wireless link models (ideal link and two variants of a general link model). The link model is associated with the throughput on links, which bounds the path length. However, they assume that every node is equipped with identical transmission devices and thus all wireless links on the network are the same. Furthermore, the set of potential ITAP locations are points in the plane that can be reached by a set of nodes via a wireless link, but not including nodes' locations as candidate ITAP locations, which does not always provide the minimum network installation cost.

Authors in [8], also, study the optimal placement of a given number of gateways on a wireless mesh backbone network in order to achieve maximum throughput. They formulate the related problem as an ILP and provide a greedy algorithm that defines the gateways' locations in order to optimize the cross-layer throughput. They take into account the capacity reduction on wireless links due to interference in case of simultaneous transmissions. The aim of the algorithm is to provide interference free link scheduling. Again, there is no distinction between gateway and client devices and the installation cost is predefined since the number of gateways is given a priori.

Another gateway placement algorithm is proposed in [9], where the authors consider the capacity of every link as a QoS constraint. Given the link capacities and an inequality that correlates the total one-hop capacity of the network with the expected path length, authors bound the maximum number of hops from a node to the gateway in order to achieve QoS. In several other studies [10] [11] [12], optimization methods such as genetic algorithm, simulation annealing and tabu search meta-heuristics have been applied to minimize the number of gateways in wireless networks without, however, considering the connection polymorphism of real wireless networks due to transmitters with different characteristics and the overall installation cost of the network. In recent studies [13], the mobility of wireless mesh network client devices is also considered, regarding placement of gateways in dynamic WMNs. They propose a social-based swarm optimization method that exploits the social relationship notion of users, in which groups with similar interests move with high probability to the same direction.

In this study, our aim is to minimize the number of gateways of the IoT network infrastructure in order to lower the installation cost. Furthermore, as opposed to previous works, we consider different non-gateway communication devices to be deployed at the facilities' locations. These devices vary on the transmission capabilities and consequently on the cost. Each device is selected with respect to its transmission specifications in order to ensure sufficient capacity for the flow demands that need to be satisfied.

III. Gateway Placement Formulation

In our problem setting, we consider a set of stationary nodes (representing facilies) placed at specific locations. Each node represents a point that generates corresponding metering data and utilizes a respective IoT end device. The IoT end device is capable of transmitting/receiving data to/from the internet through gateways. This communication can be achieved either directly or through multi-hop transmissions. In the first case, the IoT end device must be equipped with suitable hardware and software to function as a gateway. In the latter case, it is preferred for the IoT end device to utilize simpler and lower cost transmission equipment, which transmit their data to nearby devices until a gateway is reached. The simple transmission devices can be selected from a set of devices with different transmission specifications and cost. The candidate locations of a gateway include the positions of the IoT end devices and some intermediate points that are discovered through Voronoi diagrams (the discovery phase is explained in Section III.B). In summary, we assume two classes of IoT devices: gateways and a set of lower-end transmission devices with different capabilities. Transmission devices are placed at the given locations, while gateways can be placed at these locations (replacing the low-end related device there) or at the Voronoi points. Within this context, we pursue to optimize the placement of gateways and the selection of suitable transmission devices in order to minimize the installation cost of the network, while respecting predefined QoS requirements. Let us note that we consider nodes with no mobility (referring to the smart city case). According to these assumptions, it is evident that an offline algorithm is sufficient since changes on the topology are minor and infrequent. Furthermore, we do not consider any security aspects.

A. *Low-End Transmission Device Specifications*

To optimize an IoT network, we assume a set D of different transmission devices that can be placed in specific locations to forward the data to some gateway points. Each device $d \in D$:

- operates at a specific data rate r_d that is irrespective of the implemented MAC protocol
- reaches a fixed transmission range β_d based on the device technology
- is assigned a specific price p_d by the vendor

B. *Gateway Candidate Location Points Discovery*

A gateway could be located at any place of the IoT area from where all or a portion of the IoT end devices could reach it either directly or over a multi-hop path. To narrow the options, we consider as an initial set of candidate positions for the gateways, the positions of the facilities. Assuming that every end device on a facility may have at least one neighbor it can directly communicate with, and moreover that the short transmission range (which is considered the one with the least cost) devices may be close enough to communicate, the initial set could be sufficient. However, there may be cases where a gateway placed at the centroid of a specific subarea would be more efficient for data aggregation. To also cover these cases, we extend the aforementioned set by the Voronoi vertices (intersection of Voronoi edges) of the Voronoi diagram [14] that is generated by the given facility locations. In particular, we construct a Voronoi diagram with the facilities being the site points and find all the Voronoi vertices. The Voronoi vertices are the intersection points of three or more Voronoi edges thus making them equidistant points of corresponding three or more site points. The final set V_G is derived by excluding any Voronoi vertices whose distance from the neighboring site points is larger than the largest T_i, meaning that a physical connection from any facility is infeasible.

C. *Optimal Gateway and Transmission Device Placement Formulation*

Given the complete set of feasible gateway positions V_G, the set E of links between devices can be obtained based on the transmission range of the IoT devices. Hence the network can be represented as a graph $G(V_G, E)$ and the problem can be obtained as a single source uncapacitated facility location problem (SSUFLP) [15]. Towards to problem formulation we define the following parameters:

CONSTANTS

- $V_L \subseteq V_G$, is the set of facility locations
- f_i, is the traffic generated at facility i. This is the aggregate traffic generated from the set of metering/sensor at that location
- p_V, is the price of a gateway and p_d of a device
- s_{ij}, is the distance between nodes i, j

VARIABLES

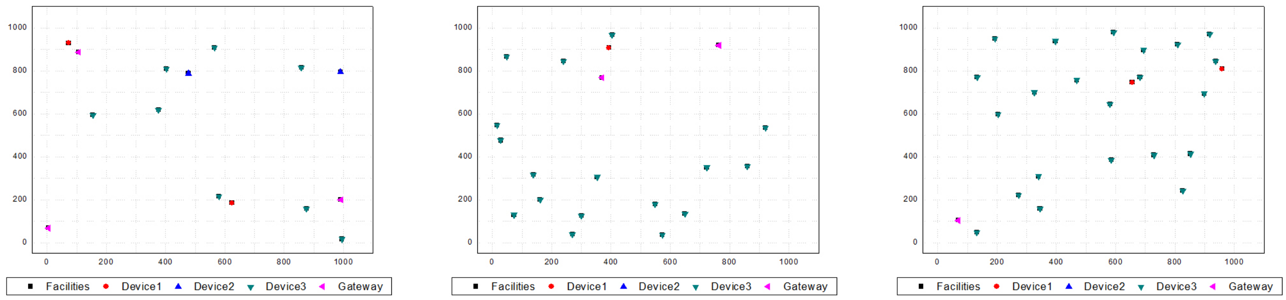
- $Y_i^d \in \{0, 1\}$, indicates whether node i deploys device d or not
- $Z_v \in \{0, 1\}$, indicates whether a gateway is deployed at position $v \in V_G$ or not
- $L_{nm}^{iv} \in \{0, 1\}$, indicates whether link (n, m) belongs to the path from lamppost i to gateway v

Our objective is formulated as follows:

$$\text{minimize } \sum_{i \in V_L} \sum_{d \in D} p_d Y_i^d + \sum_{v \in V_G} p_V Z_v \tag{1}$$

subject to

$$\sum_{v \in V_G} \sum_{\substack{m \neq i \in V_L \\ m \neq v}} L_{im}^{iv} + \sum_{v \in V_G} L_{iv}^{iv} = 1, \quad i \in V_L \tag{2}$$



a) b) c)

Figure 2: Network planning for a) 15 nodes, b) 20 nodes and c) 25 nodes topology

$$\sum_{v\in V}\sum_{n\in V_L} L_{nv}^{iv} = 1, \qquad i\in V_L \qquad (3)$$

$$\sum_{n\in V_L} L_{nm}^{iv} = \sum_{\substack{k\in V_L\\ k\neq v}} L_{mk}^{iv} + L_{mv}^{iv}, \qquad i,m\neq i\in V_L,\ m\neq v\in V_G \qquad (4)$$

$$\sum_{d\in D} Y_i^d \le 1, \qquad i\in V_L \qquad (5)$$

$$s_{nm}\cdot L_{nm}^{iv} \le \sum_{d\in D}\beta_d\cdot Y_n^d, \qquad i,n,m\neq v\in V_L, v\in V_G \qquad (6)$$

$$s_{nv}\cdot L_{nv}^{iv} \le \sum_{d\in D}\beta_d\cdot Y_n^d, \qquad i,n\in V_L, v\in V_G \qquad (7)$$

$$L_{nv}^{iv} \le Z_v, \qquad v\in V_G, i,n\in V_L \qquad (8)$$

$$L_{nm}^{iv} \le Z_v, \qquad v\in V_G, i,n,m\neq v\in V_L \qquad (9)$$

As Eq. (1) implies, we aim to minimize the total cost of the IoT network infrastructure deployment. In order to assure that we obtain a feasible network, we apply suitable constraints. Condition (2) ensures that the corresponding traffic, originating from facility i, will be transmitted through a single outgoing link, and as condition (3) imposes, and Eqs (8), (9) ensure, will be destined to a single gateway. Moreover, Eq. (4) ensures that no traffic will be lost from intermediate nodes. Each facility is constrained to deploy a communication device as Eq. (5) imposes, which combined with Eqs (6), (7), implies that the device can be either a gateway or one from the set D. Furthermore, the latter conditions ensure that the communication between two facilities can be achieved if the receiver is inside the range of the transmitter in means of Euclidian distance.

In order to provide QoS, the capacity of the links must be enough to serve several simultaneous transmissions. Thus, the following constraint must be included, which ensures that the aggregate flows that traverse a link do not exceed the data rate of the link. In case the transmitter is a gateway, then a big number $\mu >> 1$ is used to always satisfy the condition.

$$\sum_{i\in V_L}\sum_{v\in V}\sum_{m\in V_G} f_i L_{nm}^{iv} \le \sum_{d\in D} r_d Y_n^d + \mu Z_n, n\in V_L \qquad (10)$$

Moreover, to accommodate specific packet delay QoS constraints, the following constraint, combined with Eq. (10) that ensures the required flow for each transmission, should be taken into account. Assuming that a packet of length X for a given flow f_i has delay constraint K, condition (11) can further limit the path length from facility i to the corresponding gateway v.

$$\sum_{n\in V_L}\sum_{m\in V_L}\left(\frac{X}{f_i}+\frac{s_{nm}}{c}\right)L_{nm}^{iv} \le K, \quad i\in V_L, v\in V_G \qquad (11)$$

where c is the signal propagation velocity (speed of light). Currently, we do not consider any load balancing on the network since we opt for the optimal installation cost. However, a load distribution operation is implicitly applied from Eq. (10). In particular, in cases where the smart devices with larger data rates are more expensive, the ILP aims to keep the load in reasonable values to avoid respective increases of the total cost.

IV. Experimental Results

In order to evaluate the effectiveness of the proposed formulation, we conducted a number of simulation experiments under different network planning scenarios. We consider two kinds of topologies: (a) a random topology, with different numbers of facilities randomly placed in a 1000x1000 meters plane according to a 2-dimensional uniform distribution, and (b) a mesh-like topology (such a structured topology can represent a smart city or highway scenario with lampposts as facilities equipped with sensors, traffic cameras, etc). The candidate communication devices to be utilized for the fog network correspond to custom devices assembled with commercial hardware and software. A gateway utilizes a Raspberry Pi 2 chip (RPi 2) and multiple antennas, while end transmission devices rely on Arduino Uno R3 board with single transceiver. Hence, the cost of each device is the sum of the respective vendors' cost for each component. The data rate and transmission range values were obtained from real field measurements and correspond to the furthest point at which a device can transmit with zero packet loss [16]. Table I summarizes the specifications of the devices under consideration.

Table I Device Specifications

Communication Device	**Data Rate**	**Transmission Range**	**Cost (Euros)**
Device1	2 Mb/s	70 m (no antenna)	14
Device2	1 Mb/s	200 m (with antenna)	21
Device3	250 Kb/s	330 m (with antenna)	21
Gateway	LTE-A		55

Regarding topology (a), Fig. 2 depicts the obtained network for 15, 20, 25 facilities randomly placed at the field. The solutions obtained using CPLEX [17] to solve the formed ILP problems for the case where no flow constraints applied (only the constraints (2) – (9) where applied). The results exhibit that the proposed formulation can optimally provide the desired

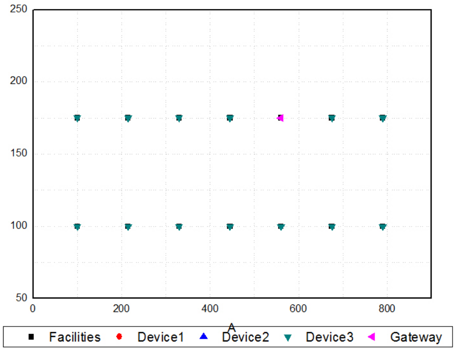
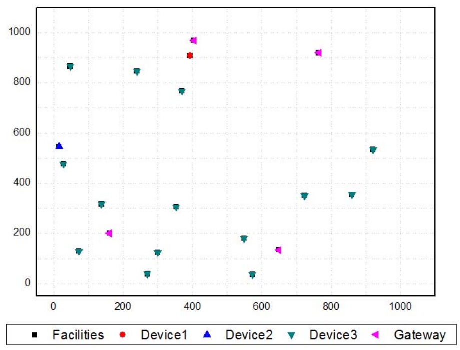


Figure 3: Network planning for mesh-like 2x7 topology

network assigning every facility to a gateway either by single or multi-hop transmission. Furthermore, they show that as the topology becomes denser the network becomes more efficient. Utilization of transmission devices instead of gateways results into savings of up to 60%, compared with the case where a gateway is deployed at each facility. Fig. 3 validates the aforementioned behavior on a mesh 2x7 topology where facilities are placed close enough to ensure connectivity between adjacent nodes.

For the above scenarios, the only significant characteristic for the configuration of the network is the transmission range. We also consider the performance obtained through our formulation when QoS constraints are applied. In that case, each facility is assigned a predefined flow randomly selected between 100 and 500 Kb/s following a uniform distribution. Suitable average delay value selected in order to limit the number of hops, within a path, to at most four The range of the load is selected regarding the data rates of the devices in order not to exclude any of them but also to limit the number of hops within a path. Fig. 4 shows that our approach can capture such QoS restrictions and the network configuration adapts to the given flows. Here, the difference of Device class 2 and class 3 becomes obvious since the respective data rate is taken into account. Moreover, since the data rate of each device is limited, the links that are close to the gateway in Figs 2b and 3 become congested and thus more gateways must be utilized as Fig. 4 depicts. It becomes evident that QoS constraint bounds the length of the paths towards the gateway, thus limiting the number of simultaneous transmissions from links adjacent to a gateway.

In cases where intermediate points can be utilized for gateways placement, Fig. 5 shows that the use of Voronoi points as candidate positions can be more efficient and further decrease the overall installation cost. As can be seen, the cost savings are more significant when QoS constraints are applied, where more gateways must be utilized to satisfy the network requirements. In this case, the configuration of the network provides more alternatives that make additional gateways unnecessary or balance the extra cost from additional gateways by utilizing more low cost devices. In general, regarding only the installation cost (meaning that the deployment of a Voronoi point is not necessary to satisfy flow requirements on the network), placing a gateway at a Voronoi point will add extra cost since there would be no device in that point. In particular,



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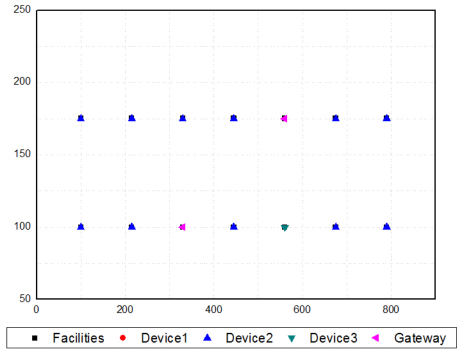


b)

Figure 4: Network planning for a) 20 nodes and b) 2x7 mesh-like topology considering QoS constraints

lets assume a group Δ of nearby facilities, from which one deploys a gateway and serves the others. Transpose the gateway at a Voronoi point for this group requires the addition of an extra IoT device to the previously gateway facility. To benefit the installation cost from this alteration, the additional cost shall be counterbalanced by the replacement of nearby IoT end devices with others lower cost devices. Thus, in order such a utilization to be cost effective, the following criterion should be satisfied:

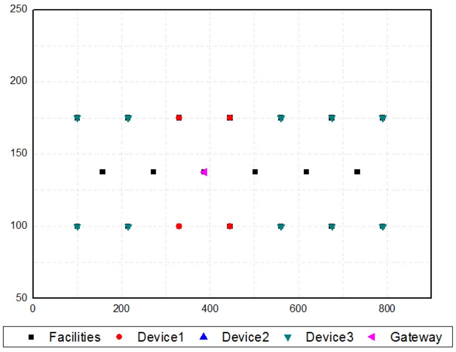
$$\sum_{h \in \Delta'} p_h^{'} < \sum_{h \in} p_h$$

where p_h is the cost of the device deployed in facility h. Δ' is the group as formed after the gateway alternation and $p_h^{'}$ is the cost of the new IoT device in facility h.

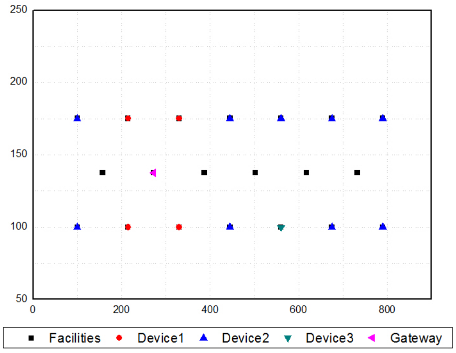
As an example we present the special case where all Δ-1 facilities (except the one that deploys a gateway) utilize the same device with cost p on the initial configuration. Transposing the gateway at the respective Voronoi point and replacing the IoT devices with others that cost p', a reduction of the installation cost could be obtained when the difference in the costs satisfies:

$$p' < \frac{\Delta - 1}{\Delta} p$$

This implies that, in such cases, significant savings can be achieved either due to the difference in cost or in the number of the facilities that would replace the transmission devices.



a)



b)

Figure 5: Network planning for 2x7 mesh-like topology considering with Voronoi points a) without and b) with QoS constraints

V. CONCLUSION

Towards the utilization of fog computing for Internet of Things (IoT), we proposed an ILP formulation of the gateway placement and low-end transmission device allocation problem that minimizes the overall installation cost of the network, while satisfying specific QoS requirements. The communication devices differ in their transmission capabilities, which also relate to their cost. The effectiveness of the proposed ILP formulation is evaluated by simulation results on several topologies and traffic flow scenarios. The results exhibit savings, up to 52%, on the overall installation cost, which may increase to 60% when centroid points are considered as gateway candidate positions in case of QoS restrictions.

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