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A Mathematical Optimization Approach for Prioritized Services in IoT Networks for Energy-constrained Smart Cities

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Abstract

The development of smart cities has been positively impacted by advances in Internet of Things (IoT) technology. In addition, new levels of service have emerged due to the demands of new types of applications, whereby these new service levels must be managed by priorities depending on the technological requirements of each service in order to efficiently route information from an origin IoT device to a base station. However, the current global energy crisis demands more awareness from technology systems in terms of energy consumption efficiency, reduction of carbon footprint, and sustainability. In this sense, we propose a mathematical optimization model capable of routing different services in an IoT network, considering different levels of priority in the services offered, while simultaneously reducing energy consumption in the network for services with priority. In other words, the proposal aims to extend the lifetime of IoT networks in critical energy urban infrastructure, ensuring the highest possible quality in the services offered on the network. Finally, our proposal is evaluated in different IoT network scenarios, considering different types of services and network sizes.

Keywords: Mathematical Optimization Model, Critical Services, Energy Consumption, Smart Cities, IoT networks.

1 Introduction

The Internet of Things (IoT) has allowed the rapid development of smart cities due to their interconnected devices and systems are the basis of smart urban infrastructure, which has enabled a lot of applications such as telemedicine, vehicular traffic monitoring and public security [1].

In addition, in many cases handling critical services such as healthcare monitoring, emergency response and security systems, require real-time data processing and high reliability when it is necessary to send critical service information through the IoT network. For this reason, these critical services must be prioritized in order to assure that the service information reaches a base station as fast as possible with high reliability and to guaranteeing the operation and durability of these critical services on the network [1], [2].

Moreover, IoT services in smart cities have important energy consumption challenges because many IoT devices could demand a lot of energy consumption. Furthermore, the current global energy crisis puts pressure on energy consumption to become increasingly intelligent and adaptive in order to reduce carbon footprints and procuring energy efficiency and sustainability [3], [4].

In order to approach these challenges, it is required to propose innovative solutions for handling prioritized services using the best resources of the network in terms of available energy in the network. In this sense, we propose a deterministic solution in terms of a mathematical optimization model capable of prioritize services for building routing paths where the nodes used are those with the highest possible energy. In other words, packets belonging to prioritized services are routed to the base station using the best nodes in terms of energy consumption.

Given the previous context, the idea is to propose a mathematical optimization model for handling different types of services considering that network nodes have different energy levels. In this sense, the main goal of our proposal is finding routes with nodes of high energy level for services with priority in order to guarantee a high performance for this type of services. In order to understand in detail our problem, we are going to describe the IoT network shown in Figure 1.

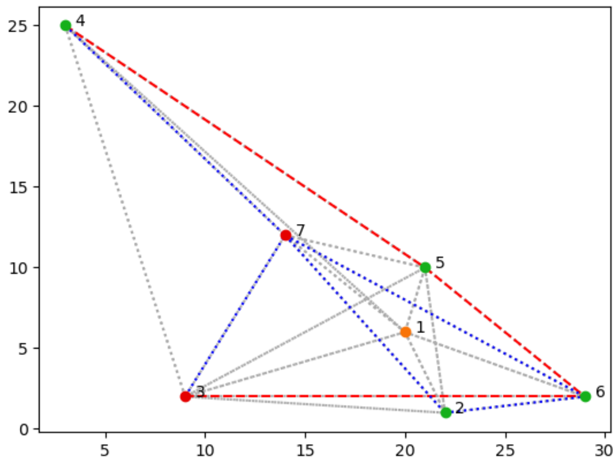


Figure 1: Result for scenario 1.

We assume that this IoT network has symmetrical links between the different nodes; therefore, we could model it as a non-directed graph. We represent the input graph as a set compound of a set of nodes and a set of links [10].

In this network, we could have several source nodes and some destinations nodes (base stations). In this particular case, the source nodes are the nodes 3 and 4, and we assume just one base station, the node 6. The source nodes have two types of services: service 1 (service with priority) and service 2 (a non-prioritized service). In real applications, a service is a specific type of information that must be transmitted from a source node to a base station such as the temperature, the humidity or pH level. Some services are more important than others, for example, heart rate is more important/critical than ambient temperature in a medical application, that is, some services require priority and others do not.

Then, from each source node and from each service is necessary to send certain amounts of packets through the network using the rest of network nodes to achieve the base station. However, services with priority should be transmitted over the nodes with high energy level (the green nodes) because this type of service has high performance requirements. In other words, we need that prioritized services use the nodes with the highest energy to guarantee the operation and durability of these critical services on the network. As we can see in Figure 1, prioritized services (the red links) from source nodes 3 and 4 are transmitted through the network using nodes with high energy level (the green nodes), while non-prioritized services (the blue ones) should be routed over the rest of the network nodes, possibly nodes with low energy level or maybe nodes with high energy level, in case of they are available (not occupied by prioritized services).

Current solutions are focused on either proposing mathematical optimization models that are not exactly adjusted to our problem or proposing routing heuristics/meta-heuristics that do not offer an optimal solution.

In [5], the authors proposed a Reinforcement Learning (RL) algorithm routing scheme to optimize energy consumption in IoT networks, but does not consider handling different types of services. In addition, due to this proposal is based on a probabilistic technique, it does not offer optimal solutions.

The authors, in [6], propose a routing scheme to compute optimal routing shortest paths using Dijkstra's algorithm by selecting the min-cost path based on the priorities of traffic flows. However, this approach does not manage the fact of handling multiple packets and sending them for multiple links until reaching the base station, which it is considered in our approach.

In [7], the authors propose an application-aware QoS routing algorithm for SDN-based IoT networking to guarantee multiple QoS requirements of high-priority IoT applications. However, they do not present a mathematical optimization formulation that could be very useful since it provides an optimal solution.

The authors, in [8], propose a energy-aware and Quality of Service (QoS) routing mechanism for mesh-connected visual sensor nodes in a hybrid Internet of Things (IoT) network. They propose a mathematical optimization model but this model does not have the capability of disseminate packets through the network. In other words, the packets from a service cannot be separated, they have to be transported all together for the discovered routes. This is due to their decision variable is a binary variable, while our decision variable is a real positive variable.

In [9], the authors propose to build a data path selection model to identify the most effective path through which to route the data packets in an effective manner. They proposed a routing algorithm but they do not present a mathematical optimization formulation that could be very useful since it provides an optimal solution.

In summary, we propose a mathematical optimization model to establish that services with priority will select routes using nodes with the highest energy level as much as possible, while non-prioritized services will be relegated to using low-power nodes in case there is no availability to use high-power nodes.

The main contributions of our mathematical optimization model are the following:

- It is a generic mathematical optimization model, whereby is can be used in scarce or large IoT networks.
- It can configured several source nodes and destination nodes (base stations).
- It can handle prioritized and non-prioritized services.
- The prioritized services are forced to be routed using nodes with the highest possible energy level in order to proportionate availability, reliability and durability of these services in the network.
- Packets from prioritized and non-prioritized services can be disseminated in separated links due to the nature of our decision variable, that is, a real positive variable.

The remainder of this paper is organized as follows. The mathematical optimization model for the problem is described in section 2, while in section 3, we presents the implementation of different testing scenarios and their results. Finally, section 4 shows the conclusions and future works.

2 Mathematical Optimization Model Proposed

In this section, we present a mathematical optimization model in order to achieve the purpose of this paper, that is, send priority services through the paths that have the best nodes in terms of energy level.

In this model is possible to send all services (with priority and non-prioritized) through the same link $i - j$, but the objective function is responsible for separating them. In other words, the objective function makes its best effort to separate the packets from one service from the other. This concept will be explained as follows.

2.1 Notation

The sets, parameters and variables required by our mathematical model are described in Table 1.

Table 1: Notations of the proposed model.

Sets	**Description**
N	Set of network nodes.
O	Set of source nodes. O is a subset of N.
D	Set of desination nodes (base stations). D is a subset of N.
S	Set of services.
Parameters	**Description**
u_{ij}	Amount of packets supported for each (i, j) link.
b_i^s	Amount of packets offered or required from an $i-$ node for a $s-$service.
Ec_i	Consumed energy at the $i-$node.
Decision Variables	**Description**
X_{ij}^s	Amount of packets from a $s-$service that are sent through the link (i, j) (Real positive domain).

According to Table 1, more details are described as follows:

- If a link exists between nodes $i - j$, u_{ij} must be greater than 0, otherwise, $u_{ij} = 0$.
- If a node is a source node, that is, a node that requires to send packets to the base station, then, b_i^s must be greater than 0. For example, if $b_4^1 = 5$, five packets must be carried to the base station from the node 4 at service 1.
- If a node is a destination node, that is, it is a base station that requires to receive packets from source nodes, then, b_i^s must be less than 0. For example, if $b_6^1 = -5$, five packets are required in the base station from service 1.
- If a node is not a source node neither a destination node, then, this node is a intermediate node (also know as relay node), that is, the packets received by this node must be transferred to another node. For example, if $b_2^1 = 0$, then, the node 2 at service 1 is an intermediate node. Notice that the fact of existing relay nodes, means that we are assuming multi-hop communications, that is, the packets from a source node could be transmitted to intermediate nodes in order to achieve the base station.
- We assume that the minimum value of Ec_i is 1, indicating that the i node is full of battery. On the contrary, we assume the maximum value of Ec_i is 99, the i node has consumed almost all of its battery.
- For the variable decision, for example, if $X_{45}^1 = 5$, it means that 5 packets were sent from node 4 to node 5 as a part of a route to achieve the base station (node 6).

2.2 Objective Function: Minimizing Energy Consumption

An IoT network could be composed of heterogeneous nodes, and each one of them could have different energy consumption in both transmission and reception. Given the nature of IoT networks, some nodes that belong to this network could be mobile phones, sensors, or laptops. Therefore, the proposed mathematical models, in order to reduce power consumption, should select the path with the lower overall energy consumption to increase the battery life of these kind o devices. The objective function 1 takes into account both the energy consumption used by the source node (i node) in the transmission process and the energy used by the destination node (j node) in the reception process, over the entire path.

$$min \sum_{i \in N} \sum_{j \in N} \sum_{s \in S} Ec_i * Ec_j * X_{ij}^s \tag{1}$$

According to 1, it is desirable that the packets transmitted over the network, use the $i - j$ links with less energy consumption. In this sense, Ec_i and Ec_j are multiplied to select the smallest possible values of Ec_i and Ec_j. With a sum of Ec_i and Ec_j, the same effect is achieved in the objective function but the distance between good and bad feasible solutions are not too high. In other words, by multiplying, we assure more distance between good and bad feasible solutions than by adding.

2.3 Model Constraints

According to the general problem statement, some services must be sent from origin nodes to any destination node (base station). This scenario is denoted in the following constraints:

Origin, Intermediate and Destination Nodes Constraints

Expression 2 allows us to summarize the behavior of source, intermediate and destination node, which are described as follows:

- If we are dealing with a source i node, then b_i^s is greater than 0, that is, an amount of b_i^s packets must be leave from the source node (i node) at the s service.
- If we are dealing with a destination i node (a base station), then b_i^s is less than 0, that is, an amount of b_i^s packets must be go in to the destination node (i node) at the s service.
- If we are dealing with a intermediate i node (a relay node), then $b_i^s = 0$, that is, the amount of packets going in to the i node are the same to the numer of packets leaving the i node.

$$\sum_{j \in N} X_{ij}^k - \sum_{j \in N} X_{ji}^k = b_i^k \quad \forall k \in S, \forall i \in N \tag{2}$$

In addition to constraint 2, it is necessary to assure that a source node does not receive packets from another node, that is, a source node cannot be an intermediate node (Expression 3).

$$\sum_{k \in S} \sum_{i \in N} X_{ij}^k = 0 \quad \forall j \in N \mid j \in O \tag{3}$$

In addition to constraint 3, it is necessary to assure that a destination node (a base station) does not send packets to another node (it only receives packets), that is, a destination node cannot be an intermediate node (Expression 4).

$$\sum_{k \in S} \sum_{j \in N} X_{ij}^k = 0 \quad \forall i \in N \mid i \in D \tag{4}$$

Capacity Constraint

Expression 5 assures that the amount of packets from different services could be transmitted in a specific link (i,j). Otherwise, some packets must be sent to another $i - j$ link.

$$\sum_{k \in S} X_{ij}^{k} \leq u_{ij} \quad \forall i \in N, \forall j \in N \tag{5}$$

In summary, we have mathematical optimization model formulation that represents an IoT network with several source nodes and destination nodes (base stations), at which is required to find optimal paths to transmit several services from source nodes to destination nodes (base stations) using the with highest possible energy.

3 Implementation and Results

Our mathematical optimization model was implemented in Python using the optimization library *Pyomo*. This model corresponds to a Linear Programming (LP) mathematical optimization model, which can be solved using linear solvers like the GLPK solver of Pyomo, which uses the Simplex Method to solve this model. For this reason, this model can be solved in a very reduced time, which is very useful for large networks. As follows, we present different illustrative scenarios for testing our mathematical optimization model.

Our mathematical model is compound of the objective function presented in expression 1 and the constraints 2, 3, 4 and 5 shown previously. In Figure 2, the basic network for testing is presented.

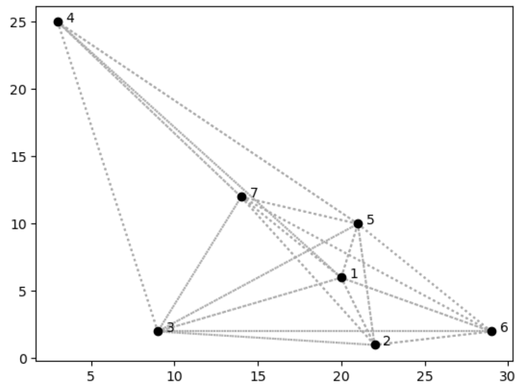


Figure 2: IoT basic network scenario.

3.1 Scenario 1

In Table 2, we show the main parameters that will be used in this scenario.

Once the mathematical model is performed, we obtained the following result (see Figure 3 and Table 3):

Table 2: Main parameters.

Parameters	Value
Number of IoT nodes	7
Sources nodes	3 and 4
Destination nodes (Base station)	6
Number of services	2
Services with priority	Service 1 (red links)
Services without priority	Service 2 (blue links)
Packets offered by source node 3 at service 1	5
Packets offered by source node 3 at service 2	5
Packets offered by source node 4 at service 1	5
Packets offered by source node 4 at service 2	5
Packets required by destination node 6	20
u_{ij}	20 packets in all existing $i-j$ links.
E_{c_i} $\forall i \in N \mid i \neq 6$	A random value between 1 and 99
E_{c_6}	Full of battery (a value of 1).

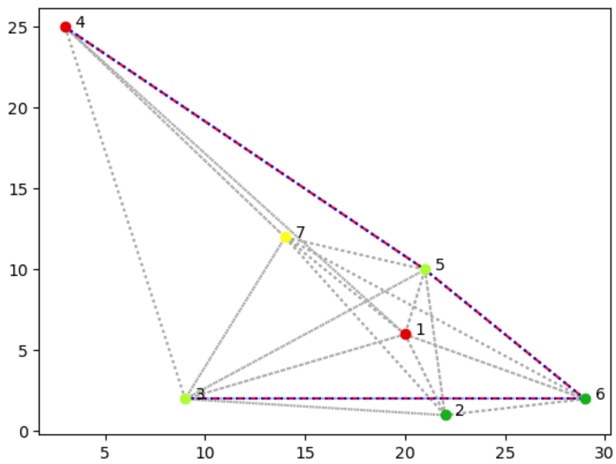


Figure 3: Result for scenario 1.

Table 3: Amount of packets per link for each service for scenario 1.

Service	Link	Amount of packets
1	3-6	5
1	4-5	5
1	5-6	5
2	3-6	5
2	4-5	5
2	5-6	5

For a better understanding of Figure 3, different colors are asigned to the network nodes as follows:

- **Dark green color:** it indicates that the node has an energy consumption (Ec_i) between 1 and 20, that is, it has a very high energy level.
- **Ligh green color:** it indicates that the node has an energy consumption (Ec_i) between 20 and 40, that is, it has a high energy level.
- **Yellow color:** it indicates that the node has an energy consumption (Ec_i) between 40 and 60, that is, it has a mid energy level.
- **Orange color:** it indicates that the node has an energy consumption (Ec_i) between 60 and 80, that is, it has a low energy level.

- **Red color:** it indicates that the node has an energy consumption (Ec_i) between 80 and 99, that is, it has a very low energy level.

According to the previous color notation, the idea is the packets from all services (services 1 and 2) are transmitted through the network by the nodes with as little energy consumed as possible (green color nodes), in other words, by the nodes with high energy level.

Considering the results in Figure 3, we can see that the packets from source node 3 at service 1 arrives directly to the base station (node 6) through the $3-6$ link. Notice that this service 1 is considered with priority and is denoted in red color for a better visualization and understanding. Similarly, the packets from source node 3 at service 2 arrives directly to the base station (node 6) through the same $3-6$ link, that is, services 1 and 2 share the same path to achieve the base station because the capacity of this link allows them this sharing. Moreover, in concordance with the objective function (Expression 1), services 1 and 2 avoid paths using nodes with low energy level, that is, the nodes 7 or 1 (the yellow one and red one correspondingly). The same situation occurs considering the packets from source node 4 at services 1 and 2. They share the same links ($4-5$ and $5-6$ links) to achieve the base station, avoiding nodes with low energy level like nodes 1 or 7.

According to Table 3, we can confirm that all packets are relayed at intermediate nodes as it was established in constraint 2. For example, the five packets from source node 4 at service 1 that entered to node 5, they leave from this node. The similar situation occurs with the 5 packets from the service 2. Finally, as we can see in Table 3, the 20 packets required at base station arrived successfully from source nodes (nodes 3 and 4) from services 1 and 2.

In summary, this mathematical model allows us to share links between different types of services using the intermediate nodes with high energy level in order to guarantee the services operation as much time as possible.

3.2 Scenario 2

In Table 4, we show the main parameters that will be used in this scenario. This scenario is almost the same as the previous scenario (2) but the capacity of all links is reduced to 5 packets. This modification is performed to analyze the mathematical model results when the capacity value is low in each link.

Table 4: Main parameters.

Parameters	Value
Number of IoT nodes	7
Sources nodes	3 and 4
Destination nodes (Base station)	6
Number of services	2
Services with priority	Service 1 (red links)
Services without priority	Service 2 (blue links)
Packets offered by source node 3 at service 1	5
Packets offered by source node 3 at service 2	5
Packets offered by source node 4 at service 1	5
Packets offered by source node 4 at service 2	5
Packets required by destination node 6	20
u_{ij}	**5 packets in all existing $i-j$ links.**
E_{c_i} $\forall i \in N \mid i \neq 6$	A random value between 1 and 99
E_{c6}	Full of battery (a value of 1).

Once the mathematical model is performed, we obtained the following result (see Figure 4 and Table 5):

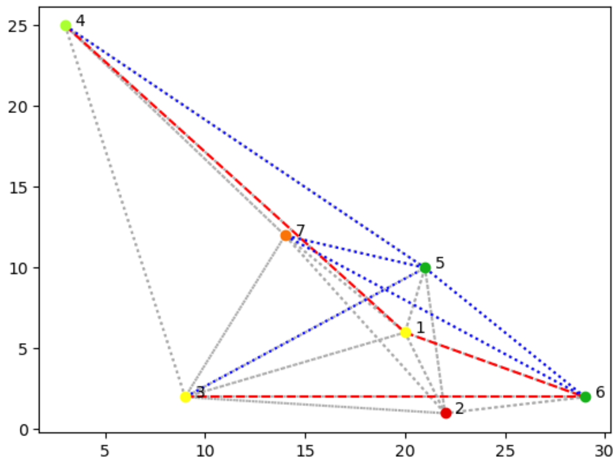


Figure 4: Result for scenario 1.

Table 5: Amount of packets per link for each service for scenario 2.

Service	Link	Amount of packets
1	4-1	5
1	1-6	5
1	3-6	5
2	3-5	5
2	5-7	5
2	7-6	5
2	4-5	5
2	5-6	5

According to Table 5 and similar to the scenario 1, we can confirm that all packets are relayed at intermediate nodes as it was established in constraint 2. Regarding Figure 4, we observe that priority services are separated in different links, but it is possible that a service with priority (service 1) selects a route using nodes with low energy level, which it is not desirable because it will cause that the operation of services with priority will stop in the future, which is not positive for the operation and performance of services with priority. In other words, it is preferable that services with priority select routes using nodes with high energy level and services without priority use routes with low energy level.

In summary and based on this second scenario, this mathematical model allows us to separate the different types of services but it is possible that services with priority select routes using nodes with low energy level, affecting the performance of services with priority. For this reason, it is necessary to modify the mathematical model in order to achieve this new capability, which is proposed in the next scenario 3.

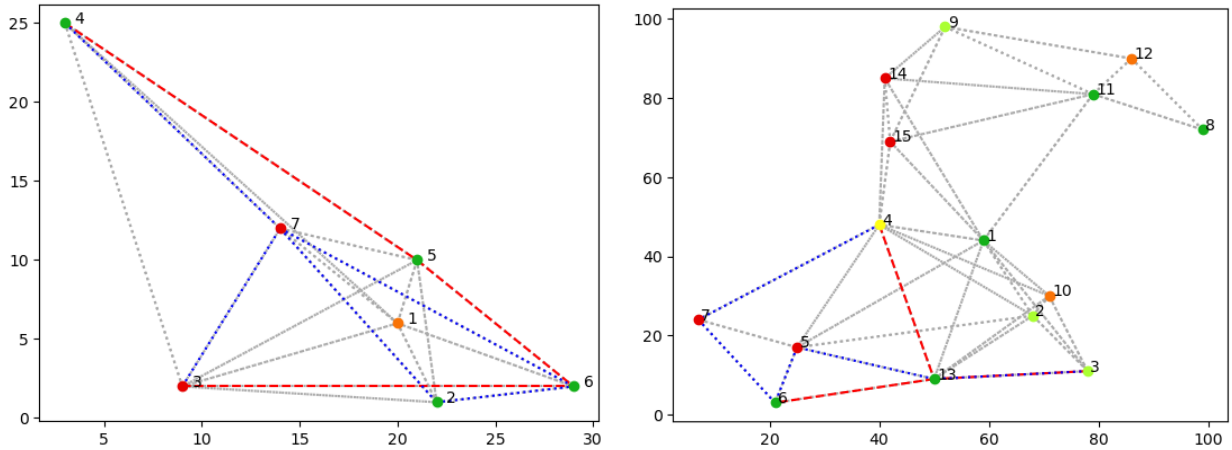
3.3 Scenario 3

According to the conclusion given at the end of the scenario 2, it is necessary to propose a modification in which services with priority use routes with nodes with high energy level. In this sense, we propose to change the objective function (Expression 1) by this one:

$$min \sum_{i \in N} \sum_{j \in N} \sum_{s \in S | s = s_1} Ec_i * Ec_j * X_{ij}^s \tag{6}$$

This new objective function (Expression 6) has a little difference regarding to the old objective function (Expression 1). The difference is that the new objective function only considers the packets of services with priority and does not take into account the packets of services with no priority. Therefore, services with priority will select routes using nodes with the highest energy level as much as possible. On the contrary, non-prioritized services will be relegated to using low-power nodes in case there is no availability to use high-power nodes.

Once the mathematical model is performed, we obtained the following result (see Figure 6):



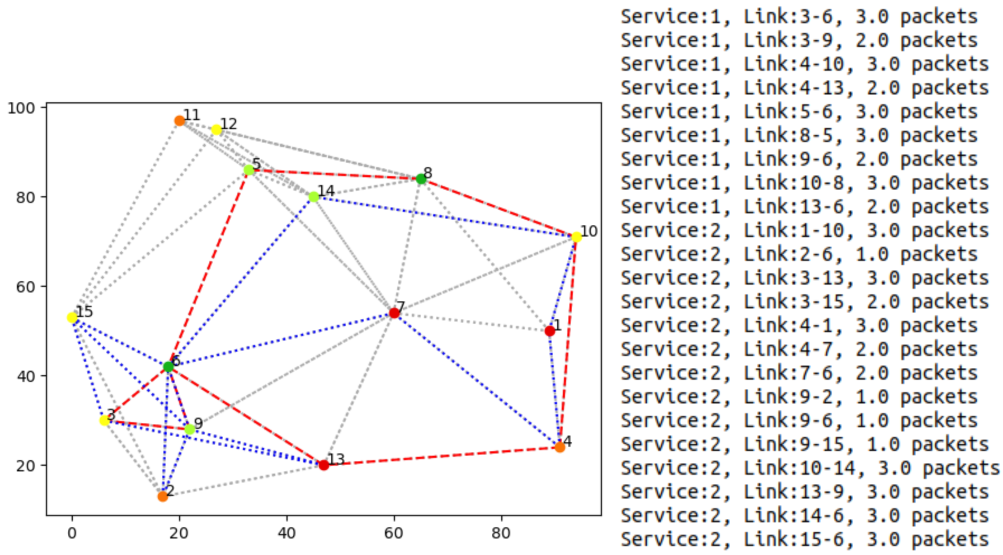
(a) Network of 7 nodes.

(b) Network of 15 nodes.

Figure 5: Scenario 3 results.

According to Figures 5a and 5b, services with priority (the red links) preferred nodes with high energy level (the green ones), while no-prioritized services (the blue links) used nodes with low energy level (the red and orange ones). In Figure 5a, from source nodes 3 and 4, services with priority (the red links) use nodes with high energy level (green nodes), that is, the paths $4-5-6$ and $3-6$, while no-prioritized services (the blue links) use nodes with low energy level (red nodes), that is, the paths $4-7-6$ and $3-7-2-6$. This situation also occurs in bigger scenarios (network of 15 nodes in Figure 5b), where from source nodes 3 and 4, services with priority (the red links) use nodes with high energy level (green nodes), that is, the paths $4-13-6$ and $3-13-6$, while no-prioritized services (the blue links) use nodes with low energy level (red nodes), that is, the paths $4-7-6$ and $3-13-5-6$.

Finally, it is important to mention that our mathematical model is capable of packets separation. For example, in Figure 6a, if the source node 3 needs to send 5 packets to a base station, 2 packets go for the $3-9$ link and 3 packets go for the $3-6$ link, and these packets continue to spread over the network, as can be seen in Figure 6b. The same situation occurs with the service 2 from source nodes 3 and 4, which can be confirmed through the packets dissemination shown in Figure 6b. Take into account that for this scenario we considered two source nodes: nodes 3 and 4 with two types of services, service 1 (the red links) and service 2 (the blue links). We considered one base station (node 6) and the packets offered by each service were 5 packets.



(a) Packets separation network. (b) Packets dissemination results.

Figure 6: Packets separation and large network results.

In addition, our mathematical model can be used for large network and for many source nodes, as can be seen in Figure 7. In this scenario, three source nodes were considered: nodes 2, 3 and 4; one base station: the node 6; and two types of services: service 1 (the red links) and service 2 (the blue links). As we observed in previous scenarios, prioritized services (the red links) from each source nodes tended to use nodes with high energy level (the green nodes), while non-prioritized services (the blue links) tended to use nodes with low energy level (the yellow, orange or red nodes), showing the well performance of our model, that is, procuring that the prioritized services use the nodes with the highest possible energy in order to proportionate availability, reliability and durability of these services in the network. Notice that in this scenario only appears the red and blue links for a better understanding, that is, the grey links are not shown for properly observe paths between source nodes and the base station for each service.

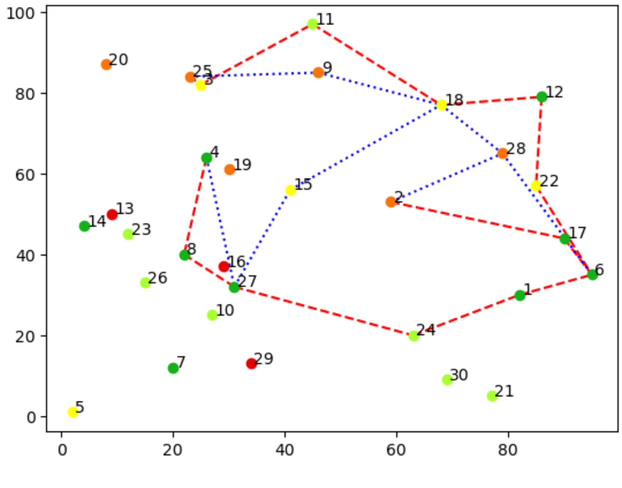


Figure 7: Large network with three source nodes and one base station.

In terms of the number of high energy nodes (green nodes) used respect to all nodes employed by each type of service, we obtained the results in Table 6.

This metric can be described as follows. For the scenario of Figure 5b, from the source node 4 to the base station (node 6) considering a priority service, the solution path is 4-13-6. In this sense, without considering the source node, the number of green nodes used were two nodes, 13 and 6 nodes, that is, 2/2. In addition, from the source node 3 to the base station (node 6) considering a priority

Table 6: Usage of high energy nodes (green nodes) for each type of service.

Scenario	Green nodes in priority services	Green nodes in no-priority services
Figure 5a	$3/3 = 100\%$	$2/3 = 66\%$
Figure 5b	$4/4 = 100\%$	$3/5 = 60\%$
Figure 6a	$4/5 = 80\%$	$4/10 = 40\%$
Figure 7	$11/13 = 84\%$	$7/14 = 50\%$

service, the solution path is 3-13-6. Without considering the source node, the number of green nodes used were two nodes, 13 and 6 nodes, that is, 2/2. In this sense, we have a total amount of 4/4 for priority services in this scenario, as we can see in Table 6. On the other hand, from the source node 4 to the base station (node 6) considering a non-prioritized service, the solution path is 4-7-6. In this sense, without considering the source node, the number of green nodes used was one node, the 6 node, that is, 1/2. In addition, from the source node 3 to the base station (node 6) considering a non-prioritized service, the solution path is 3-13-5-6. Without considering the source node, the number of green nodes used were two nodes, 13 and 6 nodes, that is, 2/3. In this sense, we have a total amount of 3/5 for non-priority services in this scenario, as we can see in Table 6. According to this example, the calculations of the rest of scenarios were performed in a similar way.

According to Table 6, we can see that the model tends to favor priority services respect to no-prioritized services, the number of high energy nodes (green nodes) are more used by priority services than no-prioritized services. In other words, from all nodes used by priority services for carrying packets from source nodes to the base station, 80% or more are high energy nodes, providing better energy resources to priority services, and then, extending the lifetime of priority services in the network. On the contrary, for non-prioritized services the number of high energy nodes is reduced to approximately 50%, allowing high energy nodes to be used by priority services.

In summary, our mathematical model with this new objective function (Expression 6) establishes that services with priority will select routes using nodes with the highest energy level as much as possible, while non-prioritized services will be relegated to using low-power nodes in case there is no availability to use high-power nodes.

4 Conclusions

In this work, we proposed a mathematical optimization model capable of routing different services in an IoT network, considering different levels of priority in the services offered, while simultaneously reducing energy consumption in the network for services with priority.

Based on the different testing scenarios, our mathematical model was possible to be used in in scarce or large IoT networks, where the prioritized and non-prioritized services were handled to be routed using nodes with the highest possible energy level in order to proportionate availability, reliability and durability of these services in the network. In addition, the mathematical model was designed so that packets from prioritized and non-prioritized services could be disseminated in separated network links.

Due to our mathematical model offers optimal results, they can be used as reference values for designing routing algorithms in order to determine how good they are respect to the mathematical model.

For future works, we are planning to enhance our mathematical model by adding more realistic parameters and by proposing routing algorithms to be compared against the mathematical model. More future works details include the following:

- Consider more parameters related with energy consumption, such as energy harvesting and detailed parameters for energy consumption for transmission and reception. Take into account that energy harvesting consists of having extra energy through nature energy sources such as Eolic or Solar energy to be employed by all or some IoT devices in order to extend the network lifetime.

- Propose heuristic or meta-heuristic algorithms and validate its performance through optimal values given by the mathematical optimization solution.
- Simulate more communication and network details by implementing testing scenarios using Discrete Event Simulation techniques or using network simulators such as NS-3, OMNeT++, IoT-NetSim and CupCarbon.

Author contributions

The authors contributed equally to this work.

Conflict of interest

The authors declare no conflict of interest.

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