Determination of Transmission Latency for Two Internet of Things Architectures in Digitalization of Distribution Networks

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***Abstract*—Traditional electrical grids have been transformed into the new smart grids to solve existing problems, such as the unidirectional flow of information, energy loss, increasing power demand, safety and reliability. Smart grids for a bidirectional flow of energy between consumers and service providers through generation, transmission, and distribution systems. They use several monitoring devices to analyze and control the power grid, set up in different power plants, distribution centers, and on a large number of consumption unit installations. Therefore, a smart grid requires high connectivity, automation, and tracking of such important devices. This is obtained with the support of the internet of things (IoT) platform over multiple networks automating functions and upgrading technological devices such as sensors and smart measures. In this work, we have the IoT platform as the main enabling environment in the digitalization of power grids. Due to the high number of automated locations relatively far from the distribution control centers, the communication channel latency of the IoT platform represents a very important measure of operational performance. The transmission latency of two IoT architectures, conventional and multi-tier, are formulated and obtained to compare and determine the best architecture. The gain in latency with the multi-tier architecture reaches 80%.**

***Index Terms*—Smart Grids, Internet of Things, multi-tier architecture, Transmission latency.**

I. Introduction

The traditional power system worked well from its inception in 1870 [1], during which time energy demand was fairly predictable. However, since 1970, there has been a change in the nature of electricity consumption, as the charging of electronic devices has become the fastest growing element of total demand, and new sources of high-power consumption have been developed, such as electric vehicles (EVs). Furthermore, today's power grids face increasing demands for reliability and security, from renewable energy sources and infrastructure transition issues.

To address these challenges, the smart grid (SG) paradigm has emerged as a promising solution with a variety of information and communication technologies. Such technologies can improve the effectiveness, efficiency, reliability, security, sustainability, stability, and scalability of traditional power grid. For example, SG provides a two-way communication flow between electricity suppliers and consumer units. SG features include advanced metering infrastructure (AMI), smart meters, fault tolerance and load balancing, as well as self-healing, i.e., automatic fault detection and restoration [2].

The Internet of Things (IoT) uses a variety of devices to monitor, analyze, and control the network. These monitoring devices are installed in power plants, transmission lines and towers, distribution centers, and consumer units, totaling hundreds of millions or even billions of units. In the SG, the connectivity, automation, and tracking of such a large number of devices require distributed monitoring, analysis, and control through high-speed, ubiquitous, and bidirectional digital communication. This is being realized in other applications through IoT technology, which is defined as a network that can connect any object to the Internet based on a protocol for information exchange and communication between multiple smart devices [3].

Initially, the Internet served as a means of connecting people with people and people with things [1]. However, by 2008, the number of things connected to the Internet exceeded the number of people in the world. The IoT is a network of physical objects connected to the Internet, equipped with embedded technology to interact with their internal and external environments. These objects sense, analyze, control, and decide individually or in collaboration with other objects through high-speed, two-way digital communications in a distributed manner. This behavior is necessary for SGs [4].

SG is considered one of the largest applications of the IoT. Today, although many household devices are connected to the Internet, there are still a large number that are not. For example, the number of microwave ovens and washing machines connected to the Internet is much smaller than the number that are not. Connecting devices that use electricity to the Internet would allow them to be operated remotely and during off-peak hours, saving costs and providing comfort through

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automation. Standardizing IoT technology for communication and as a basis for SG creates new opportunities for future innovations [5].

Digitalization modernizes, automates, and innovates power grid management systems, allowing greater control of real-time data for both distributors and traders, as well as consumers [6] and [7]. There are still major challenges in the development of smart devices, communication systems, cybersecurity, data management, and software that deserve attention and study [8].

The main objective of this work is to perform a comparative analysis of conventional and multi-tier IoT architectures to enable the monitoring of critical information in distribution systems. Assuming the operations center as the location where the main MQTT broker resides and the load buses along the distribution network topology as the location of the IoT clients, it is possible to calculate the transmission latency as a performance parameter. Remote brokers can be optimally allocated below the cloud, forming the multi-tier IoT architecture, in order to minimize transmission latency. The implementation of the K-means clustering algorithm, together with the bisection method, determines the ideal number of clusters to minimize transmission latency in the multi-tier IoT architecture.

II. Digitalization of the Electrical Power System

The implementation of SGs is based on the interconnection of the system, and for this, IoT devices, are characterized as the most suitable for the tasks. IoT devices are devices capable of connecting to the Internet, and also exchanging information with other digital devices, be they sensors, chips, trackers, or any other devices, making them suitable for the exchange of information in a smart network, thus enabling an increase in productivity, reduction of operational costs and greater speed in the verification and correction of faults.

IoT technology provides real-time interaction through network connection for users and devices through different communication technologies. It supplies power to the equipment and operates bidirectionally and at high speed, sharing multiple applications, increasing the overall efficiency of the SG [9]. Due to the long-range requirements and connectivity provided by IoT devices, the solution becomes valid and improved with the help of remote data monitoring. This allows management without the need for local infrastructure, wide area coverage, and low energy consumption, resulting in long-lasting meters. This communication is made possible by the Message Queuing Telemetry Transport (MQTT) protocol for machine-to-machine communication (M2M).

MQTT is recognized as the protocol most suitable for IoT platforms with high reliability, secure simultaneous communications for multiple recipients, and persistent messages [10]. The MQTT broker usually resides in the cloud. Although cloud computing meets the main needs of IoT systems, such as location awareness, mobility, and geographic distribution, it fails in the timely decision-making process, as required by SGs. Cloud computing alone is not enough to support ubiquitous systems due to the constraints of time delay, intermittent network connectivity, and restricted communication bandwidth [11].

The multi-tier architecture helps in solving the time constraint problems by introducing an intermediate layer between the cloud computing infrastructure and the IoT node devices that connect the application in the cloud and at the edge. The multi-tier computing model in [12] deploys the MQTT protocol in three layers, as detailed in Fig. 1.

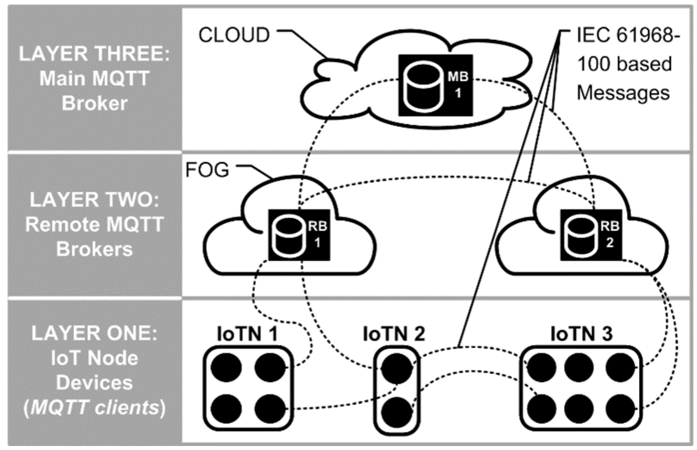

Fig. 1. Connection of IoT node devices into multi-tier computational model with IEC 61968-100 based messages [13].

Layer one hosts the IoT node devices close to the power grid, or power process. They allow running instances of the MQTT client. In the second layer, there are remote brokers that help the main broker in cloud computing. Layer three therefore has the main MQTT broker [13] and [5].

III. Formation of Multi-Tier Architecture

In this section, we present the proposed methods to determine the latency in the conventional IoT platform and to determine the minimum latency in a multi-layer IoT platform. First, we present the K-means algorithm used for network clustering using the geographic positioning data of the buses. Then, the bisection method is specified and applied in the optimization process to determine the appropriate number of clusters capable of minimizing the transmission latency in the multi-layer IoT platform.

A. K-means Algorithm

A distribution network contains a large number of buses and branches, considering that each bus has its own defined distance to the reference, which is usually the root bus. The greater the number of buses, the greater the distance from the reference point. Similarly, it can be defined that for the path taken by the data, the longer the path, the greater the data transmission latency, so it is necessary to reduce the distances.

The idea used to reduce these distances is the clustering of buses, which means grouping them according to these distances. To perform this clustering, it is possible to use the K-means algorithm, which allows greater control and management of georeferenced data, thus improving the monitoring, analysis, and visualization of the distribution system itself [15]. Clustering of K-means is based on the distribution of loading buses according to the concept of centroid, which is a center of each cluster, so that the centroid exists for each cluster such that it has the smallest distance in relation to the other members of the cluster, in this case the buses, and this centroid is the center of mass of the cluster [14].

The K-means clustering algorithm searches for an optimal configuration $\mathbf{C}$ defined in (1), dividing a data set into k non-overlapping groups. Let $\mathbf{X} = \{x_i | i = 1, 2, ..., n\}$ be an n-dimensional data set and the unique parameter k. Each group $\mathbf{C}_j$ encompasses a set of samples such that the sum of the Euclidean distances is minimized.

$$\mathbf{C} = \bigcup_{j=1}^{k} \mathbf{C}_j \tag{1}$$

The algorithm follows an iterative process that starts by randomly locating the nucleus of each group m_j. And assigns each of the samples x_i to the closest nucleus by calculating the sum of the Euclidean distances $d_2(x_i, m_j)^2$, according to (2).

$$\mathbf{C}^0 = \arg\min_{C} \sum_{j=1}^{k} \sum_{x_i \in \mathbf{C}_j} d_2(x_i, m_j)^2 \tag{2}$$

In each iteration t, the reassignment of samples to the kernel is carried out according to (3) and an update of the kernel location is done through (4) until convergence is reached. In each iteration, we seek to improve the clustering.

$$C_j^t = \{x_i | d_2(x_i, m_j^t) \leq d_2(x_i, m_{j^*}^t), \forall j^* = 1, 2, ..., k\} \tag{3}$$

$$m_j^t = \frac{1}{|C_j^t|} \sum_{x_i \in \mathbf{C}_j} x_i \tag{4}$$

Each centroid is built within each cluster on the basis of the smallest Euclidean distance between the samples and the centroid. When using the K-means algorithm, it is necessary to find the minimum and maximum values of the X and Y axes, X_{max}, X_{min}, Y_{max} and Y_{min}, to determine the initial positions of the k centroids according to (5) and (6).

$$m_{X,j}^0 = X_{min} + \frac{X_{max} - X_{min}}{k+1} j, \forall j = 1, 2, ..., k \tag{5}$$

$$m_{Y,j}^0 = Y_{min} + \frac{Y_{max} - Y_{min}}{k+1} j, \forall j = 1, 2, ..., k \tag{6}$$

With the K-means algorithm defined and the clusters created in the network, each with its respective centroid, the distances traveled by the data to the centroids are determined. Since the data come from the publishing client, for the multi-tier architecture, it is necessary that the path traveled is from the bus (sensor or client) to the centroid of the cluster (remote broker) and from there to the centroid at the root bus (representing the cloud that stores and manages the information - main broker), and the return path is repeated so that the data information returns to the publisher. For the conventional architecture, due to the lack of clustering, it is assumed that the value of the path traveled by the transmission data is the distance between the bus (sensor/client) and the root bus (main broker), without the use of remote brokers.

B. Transmission Latency

Transmission latency is critical to obtaining the fastest response. In general, transmission latency is the time it takes to travel the distance between the source and destination and back. This is indicatd by λ_t. In multi-tier architecture, multiple transmissions occur at different end points of a system. For every event that occurs at the IoT node δ, due to the sensor and/or actuator, it must be notified by δ. After notification, δ must be triggered to send a request to the remote broker φ. In the middle layer, φ must process it and, if necessary, it must be forwarded to the main broker Φ in the cloud. The same information/data must travel in the reverse direction to reach δ to give the answer to the particular request. The distances between two devices are represented by the symbol l.

The equation to calculate the transmission latency of the proposed multi-tier computational IoT model is given by (7) [12].

$$\overline{\lambda_{t_f}} = \sum (l_\delta^\varphi + l_\varphi^\Phi + l_\Phi^\varphi + l_\varphi^\delta) \tag{7}$$

For the conventional architecture, since there is no clustering of components, there is no route between remote brokers, so the latency equation is given by (8) [12].

$$\overline{\lambda_{t_C}} = \sum (l_\delta^\Phi + l_\Phi^\delta) \tag{8}$$

Considering possible delays due to the large transmission distances, and possible losses to the environment, it is possible that some packets will be retransmitted, a variable denoted by τ, assuming that τ is 1.5% of the total transmission time, an average of Transmission latency can be calculated by equation (8), with n being the total number of buses.

$$\lambda_t = \frac{\overline{\lambda_{t_t}} + \tau}{n} \tag{9}$$

C. Bisection Method

Using the K-means algorithm capable of returning the clustering for the buses, it is necessary to define the number k of clusters, so that the clustering returns only the ideal configuration for which the number of clusters is such that the transmission of data throughout the network becomes optimized with the shortest possible time (latency).

However, to calculate the minimum value of distances for an ideal clustering of the distribution network, it is necessary that the number of clusters is such that the sums of distances are minimized, and for this, it is possible to implement a non-linear programming elimination method , particularly the bisection method.

The bisection method is entirely based on the Intermediate Value Theorem, the idea is to guaranty a solution for a function within an interval $[a, b]$, such that from a sequence of divisions of the interval subintervals $[a, c]$ are obtained and $[c, b]$, and so on sequentially until the stopping condition is reached [16].

In the case under study, the bisection method is added to verify values in the range of number of centroids. The smallest possible split of the distribution network is for the integer two, i.e. $a = 2$, and the maximum possible split is considered to be one where each bus is a centroid of its own cluster, $b = n$. The stopping criterion analyzed is the smallest value for the total distance, $D_t(\cdot)$, this value being the sum of the distances between the bus and the centroid of its respective cluster, with the sum of the distances between the centroid and the root bus, thus returning the ideal number of clusters and the number of buses in each cluster for the ideal system configuration, minimizing the distances traveled by data during packet transmission.

With the K-means algorithm and the bisection method to determine the best configuration, it is possible to obtain the ideal number of clusters and the distance values between buses, centroids and the root bus, according to the pseudocode in Algorithm 1. Thus, the conventional and multi-tier latencies are calculated through (7) and (8), respectively. With the latency values for both architectures, the average latencies are calculated, as in (9).

Algorithm 1 Number of clusters in multi-tier architecture

Require: $a = 2$ and $b = n$
Ensure: k
Run: $k - means(a)$ and $k - means(b)$
Calculate: $D_t(a)$, $D_t(b)$ and $\Delta D = D_t(a) - D_t(b)$
while $\Delta D > 0$ **do**
    $c \leftarrow (a + b)/2$
    Run: $k - means(c)$
    if $D_t(a) < D_t(b)$ **then**
        Calculate: $D_t(c)$ and $\Delta D = D_t(a) - D_t(c)$
        $k \leftarrow a$
        $b \leftarrow c$
    else
        Calculate: $D_t(c)$ and $= D_t(b) - D_t(c)$
        $k \leftarrow b$
        $a \leftarrow c$
    end if
end while

IV. Results and Discussions

When comparing latencies in the conventional and multi-tier architecture of the IoT platform, an unbalanced three-phase distribution network of 13.8 kV with 136 buses is used [17]. The topology of the distribution network is presented in Fig. 2, which follows the addition of the bus positioning coordinates. Clustering and optimization algorithms were implemented in the C language and were executed on an Intel® Pentium® CPU N3540 @ 2.16GHz computing system.

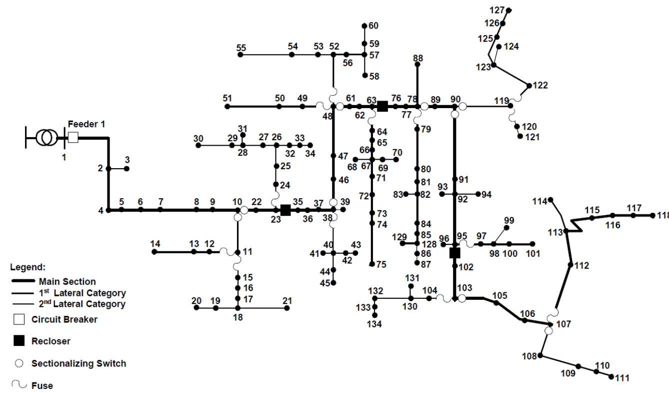

Fig. 2. Topology of the 136 radial bus test system.

For the calculations of each IoT architecture, the system must be geographically referenced in order to determine the distances between the main points, remote brokers, main broker, and sensors/clients. Initially, with the help of the coordinates (x_i, y_i) of each bus in the network, the minimum and maximum limits of the coordinates on the X and Y axes were determined, as well as the coordinate of the root bus, where the main broker of the system is located. The values obtained are shown in Table I.

TABLE I
MINIMUM AND MAXIMUM POSITIONS ON THE X AND Y AXES, AND POSITION OF THE MAIN BROKER

Axis	Minimum Position	Maximum Position	Main Broker
X (m)	31.00	958.00	31.00
Y (m)	11.00	557.00	202.00

A. Conventional Architecture

With the position of the root bus, Table I, and the buses, latency calculations were carried out in the conventional architecture, as defined by (8). The data transmission path is the round trip path. Data for the sum of distances between the buses (sensors/clients) and the root bus (main broker) can be found in Table II.

TABLE II
SUM OF DISTANCES AND LATENCIES IN CONVENTIONAL ARCHITECTURE

Sum of routes (km)	71.21
Sum of Latencies (ms)	0.57
Average latency (μs)	4.25

When calculating latencies, a propagation delay equal to 4μs/km is assumed for terrestrial radio communication systems [18]. From the value of the sum of the latencies and using (9), the conventional average latency is calculated for each bus.

B. Multi-tier Architecture

With Algorithm 1, an ideal number of clusters is obtained, in this case $k = 12$. For better visualization, the graph in Fig.

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3 was created with the positions of the buses and centroids of each cluster.

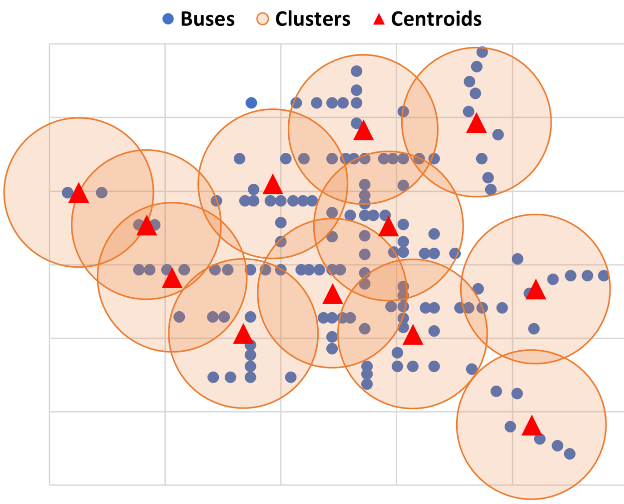

Fig. 3. Clustering of the 136 radial bus test system.

To calculate latency in the multi-tier architecture, remote brokers are allocated at the cluster centroids. In this way, the distances were calculated and, using the centroid coordinates, the distances between the buses and the centroid of each of the twelve clusters and the distances from each centroid to the root bus (main broker) were obtained. Using the sum of the distances calculated, the total distance of the data path for multi-tier latency was obtained. To calculate multi-tier latency, the round trip of the data plus the propagation delay must be considered. From the multi-tier latency value, using (9), the average multi-tier latency was calculated for each bus, as shown in Table III.

TABLE III
SUM OF DISTANCES AND LATENCIES IN MULTI-TIER ARCHITECTURE.

Sum of routes (km)	13.56
Sum of Latencies (ms)	0.11
Average latency (μs)	0.81

Comparing the latency values in Tables II and III, the gain with the multi-tier architecture is 80% compared to the conventional architecture. Therefore, the use of multi-tier architecture for clustering the distribution network system using IoT devices is valid and extremely efficient compared to the conventional method, since the allocation of IoT devices is fixed, regardless of the SG topology.

V. FINAL REMARKS

The IoT environment defined as enabling the digitalization of electrical energy distribution networks assists in the automation and tracking of network monitoring and analysis devices. Such devices capable of performing measurements are essential to maintain and improve the network. With the help of implementing a multi-tier architecture of the IoT platform for these devices on the network, it was possible to measure an 80% improvement in total and average latency performance for each bus compared to a conventional architecture.

The use of the optimization algorithm based on the K-means clustering method proved to be valid and accurate in obtaining an ideal number of clusters in such a way that the distances between brokers were minimal, consequently reducing latencies, bringing greater reliability and speed to the two-way information flow of the smart grid. Finally, this work concludes that the use of a multi-tier IoT architecture is the best compared to the conventional architecture, from the perspective of speed.

In the future, additional hardware technologies in multi-layered architectures should be studied using the latency model, as well as the cost of deploying this hardware.

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