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Resource placement strategy optimization for smart grid application using 5G wireless networks

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ABSTRACT

With the evolution of 5G-network, wireless mobile networks are growing to take a strong stand in attempts to achieve ubiquitous large-scale acquisition, connectivity and processing. Smart-grids are among the critical areas that can benefit from the capabilities of the 5G-network, especially internet of things (IoT) applications such as massive machine-type-communications or ultra-reliable low-latency communications. A distributed cloud-services use the cloud, fog and edge computing infrastructures and applications to take advantage of every available resource including network equipment and connected objects to optimize cost, energy, and latency depending on the planned optimization criteria. In this article, we present smart-grid solution based on cloud-services and 5G-network, then we study the integration of smart-grid services in the cloud based on: placement in the cloud and in the end-device, and finally we introduce our proposed solution based on Intelligent placement strategy. The scenarios are evaluated by the iFogSim simulator, and the analyzed results compare the standard cloud placement, edge placement and our intelligent placement with regard to the optimization of the energy consumption, latency, and network usage. The findings show that cloud energy consumption can be substantially reduced using Intelligent Placement while respecting the potential central processing unit (CPU) processing power-limit for each IoT-device used and network constraints in smart-grid.

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1. INTRODUCTION

Smart grid technology offers a solution for improved power generation and more reliable transmission and distribution. Compared to conventional grids, it is easier to install and to take up less space due to its simplicity. The smart grid concept aims to improve the observability of the grid, the controllability of assets, and the efficiency and protection of the power system, including the economics of operation, maintenance, and planning. Therefore, smart grid technology is envisioned to be used at the micro-grid stage, which will eventually be connected to all other micro-grids to form a large smart grid network. The fundamental concepts implemented in 5G networks, on the other hand, perfectly meet the connectivity requirements of smart grid services. Two of the three service scenarios identified in 5G networks are extremely well suited to the requirements of smart grid services. In particular, the massive machine type communication (mMTC) and ultra-reliable low latency communication (URLLC) scenarios are ideal for the communication needs of smart grid data collection and monitoring services. The mMTC service enables massive machine connectivity of up to 10 million connections per square meter, according to [1]. In addition, the URLLC service, with exceptionally high reliability, supports applications with strict latency specifications of no more than 1 millisecond. Specifically, the network slicing principle implemented in 5G networks allows for logically independent (virtual) network entities that can serve multiple applications on the same network without interacting with each other. Therefore, two network slices for mMTC [2] and URLLC can be dedicated to supporting smart grid data collection and control systems, while the same physical network can also serve other applications and industries. In addition, the 5G fundamentals of network function virtualization (NFV), software-defined networking (SDN), and cloud computing [3] facilitate the processing of smart grid big data and timely operational decisions. The aim of this article is to shed light on the new architectures of smart grids and how they can be improved and optimized by using placement strategies in a distributed cloud infrastructure connected with the 5G network. The rest of this paper is organized as follows. Section 2 presents an overview of related works of the smart grid applications. Section 3 summarizes the smart grid general model and its network requirements. Section 4 discusses the implementation of smart grid solution based on 5G technology using our application and presents the model and the studied simulation scenarios. In section 5, we will introduce in more detail our application placement strategy named “smart placement” for cost and energy optimization of smart grid solutions in the cloud infrastructure. Finally, section 6 presents result and analysis for all performed simulations.

2. RELATED WORKS FOR SMART GRID APPLICATIONS

Constant demand for electricity is a fundamental problem that must be closely examined in the age of the smart grid. The main objective of the traditional electricity grid is to adjust electricity generation to coordinate the demand for critical electricity. Smart grid must therefore continue to adjust demand in line with available production [4]–[7]. Therefore, all connection methods in the transmission [8] and distribution sides must provide extremely secure communications for detection and control. Smart meters, sensors, precise control systems and data processing are a smart grid. It is important to implement smart grid and meter technologies to make electrical systems more sustainable. One of the most complex aspects is the management of remote contacts between the different head-of-network systems with which smart meters are associated. It is necessary to have an information system including all client stations and the public service. This requires reliable communication systems, which is an essential element of the visibility of the smart grid [9]–[14]. According to a study by Chang *et al.* [15], 5G communication networks are more multi-purpose and adaptable than previous generations [16]. As a result, they should expand on a larger scale, enabling the fourth industrial revolution to begin. It enables the integration of broadband, ubiquitous detection, and knowledge, leading to greater changes in public and industrial markets. Historically, 5G has pursued a tendency to build need through the paradigm of energy [17] among public networks in wireless modes. With fog and edge computing, as well as automation and intelligent control, integrating 5G networks into smart grid will help utilities to create new business models [18]–[21]. New applications and market vendors using wireless technologies are also growing faster now. Internet of things (IoT) [22], health systems, force sectors, financial technology and a variety of other applications benefit greatly from 5G networks. Due to its ability to connect multiple devices at anytime and anywhere, the IoT [23]–[28] is currently attracting a lot of interest in various areas. It is about connecting billions of different devices with different functions and allowing them to communicate with each other.

3. SMART GRID GENERAL MODEL AND NETWORK REQUIREMENTS

3.1. Smart grid general model

The smart grid is an intelligent and multi-infrastructure system for the management of energy resources, it is composed of sensors and distributed management equipment to interact with the various entities of the energy network and thus allow the protection and optimization of energy resources [29]. The ability to further integrate renewable energy sources into the system and to oversee the use and production of energy is the main advantage of smart grids, as shown in Figure 1, through a two-way flow of energy and data between energy production, distribution, and consumption. Power generation is the first step in smart grid value chain, which includes nuclear, hydro, and renewable energy sources, and relies on large-scale monitoring and management technologies to interact with the next step. Power consumption is the last step on smart grid value chain, and it affects residential and industrial energy users. Consumers are increasingly using alternative energy production methods to produce electricity (solar energy). It is therefore important to monitor their use and their production in order to improve the service.

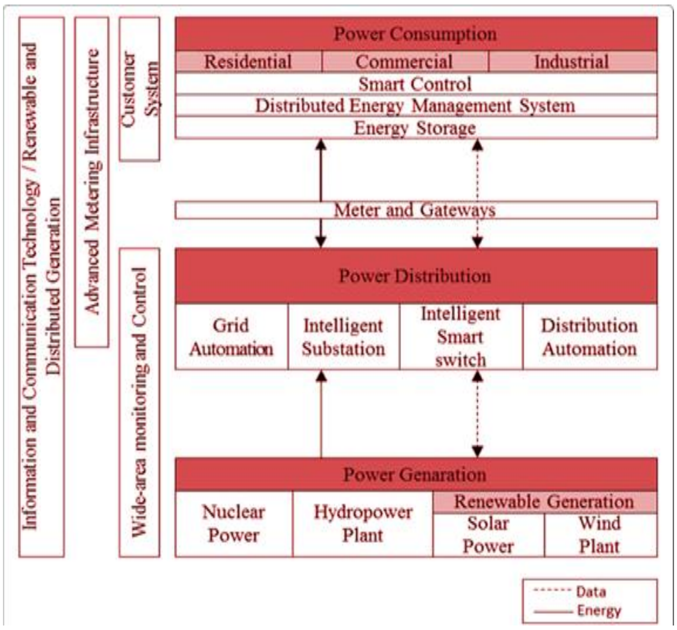

Figure 1. Energy and data flow in both directions between power generation, distribution, and consumption

Smart grid technologies have attracted a lot of attention in recent years because, in addition to providing reliable, safe, and effective energy management, they also improve power quality, which is the most important factor in electrical grids. Centered on intelligent transmission and distribution, regulations, and pricing processes for real-time power markets, the smart grid model ensures effective power quality control [30], [31]. Smart meters and intelligent energy delivery, which provide information about the power supplied to utilities and customers, are important for power quality control. Unfavorable effects are caused by high or low voltage. It renders electronic equipment which is useless and even dangerous to use. The advantage of smart grid is that it improves the power system's performance and reliability by maximizing voltage, allowing for the most efficient use of electronic equipment, and allowing for fault tolerance in the electrical grid. In addition, smart grids integrate information, connectivity, and networking, as well as automation, into traditional power systems, transforming the way energy is saved and distributed between utilities and consumers. Smart grids are now widely regarded as the most important component of many foreign energy policies in a variety of fast-growing countries. These smart grids work on the basis of all grid-connected components being well-monitored and regulated in every function.

3.2. Smart grid network requirements

5G and the smart grid architecture [32], [33] pave the way to a variety of assets on both the transmission and distribution sides. Slicing services provided by 5G technology will allow end-to-end flow and quality of service isolation according to the requirements of each application [34]–[39] and provides a set of fundamental elements, including the management of communication services and the management of network segments. Modern smart grid systems require low bandwidth and medium end-to-end latency for automated power distribution architectures [40]–[43] and low end-to-end latency with medium bandwidth for low power distributed architectures [44].

The intelligent network concept requires the assistance of different applications, each with its own set of requirements for communication links and network topologies. Applications like advanced counting, real-time payments, distributed automation, fault prevention, load management and the distributed energy resource management system (DERMS) have specific requirements for throughput, latency, and communications flow. OpenSG [45] and the US Department of Energy [46] have analyzed more than 1,300 different data streams with specific requirements, including payload size and type, data transmission frequency, required reliability, protection, latency, and importance.

The advanced metering infrastructure (AMI) is installed between a distribution network and a customer's home. As a result, the majority of the data which passes through this body are related to counting and measurement, payment details and fault reporting. Examples of typical onsite communication include the automation of smart devices that track energy consumption, the historical study of energy consumption, communication with EVs micro-generators, and onsite solar systems. The data throughput per system should be approximately 10 to 100 kbps [45], which will not exert significant pressure on the bandwidth of the links. However, larger structures, such as office buildings and industrial parks, need to be scaled appropriately as the number of communication devices can be very high. Counting does not require a high level of contact efficiency. On the other hand, on-site micro-generation and the prevention of distribution network overload require extremely secure connections. In addition, meter latency standards are not strict and are usually in the order of a few seconds. Although the demand response system (DR) requires similar latency and bandwidth, it is not a "critical" application. Due to the failure prevention mechanisms, the distributed energy resources (DER) may require relatively low latencies less than 20 ms, but for non-emergency operations, a 300 ms delay should be sufficient. The DER is a "critical" program that requires a high level of reliability. The bandwidth specifications for the DER are the same as the AMI or DR. Wide area situational awareness (WASA) is a technique for tracking the electrical network across large geographical areas to improve the overall network efficiency and to prevent power outages. Therefore, WASA is a "critical" application which requires low communication latency and high reliability of communication technologies. Due to the vital conditions associated with high voltage lines and the isolation of potential defects, substation and automation distribution must have latencies less than 100 milliseconds.

4. SMART GRID SOLUTION BASED ON DISTRIBUTED CLOUD AND 5G TECHNOLOGY

4.1. System concept and architecture in 5G network

The smart grid is based on digital technology and uses two-way digital communication to provide power to customers. The flow of electricity from the distribution company to the customer becomes a two-way conversation, which saves customers' money and resources while providing greater transparency in terms of end-user usage and carbon emission reductions. As a result, we build the architecture shown in Figure 2. This architecture consists of several layers that interact with each other to connect the physical world of objects to the virtual world of networks and the cloud. The smart grid system layered model consists of four basic layers, each dependent on the services offered by the other layers. Table 1 summarizes the smart grid layered model used for new generations of electricity distribution systems [47].

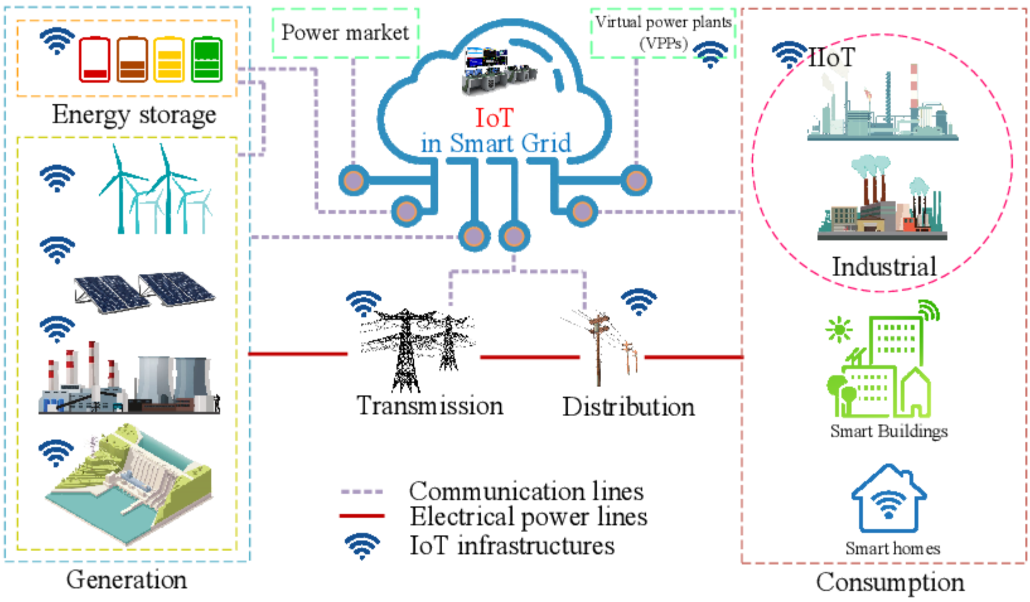

Figure 2. Proposed smart grid architecture with cloud infrastructure and 5G network

Table 1. Smart grid layered model

Layer	Name	The main role
4	Data analysis layer	Data visualization and analysis, energy resources and equipment's analysis for large-scale and small-scale distributed energy.
3	Application layer	Data acquisition and resource management and DERMS.
2	Communication and control layer	Network connection, wireless communication protocols, power line carrier (PLC), Lease Line, and 5G wireless communication which features high bandwidth accessibility
1	Physical equipment	Smart AMIs, Storage, voltage control and protection equipment, modern sensors, and power grid switches.

4.2. Smart grid application used for our simulation scenarios

This form of application illustrates how smart grid systems track, analyze, regulate, and share data across the supply chain to improve performance, reduce energy consumption and costs, and increase the transparency and reliability of the energy supply chain [48]. A communication infrastructure is required to transport the detected data/control signal to/from the sensor and actuator. To ensure continuous and stable operation of the intelligent network, the communication network will provide a two-way flow of detected data (e.g., energy consumption, voltage subsidence and current) from various devices (e.g., smart meters, voltage/current sensors, and transformers) to the respective monitoring and control systems. The required bandwidth for this application is extremely high, even for a moderate-sized power distribution system (about 100 Mbps). Figure 3 illustrates the application model user for our simulation scenarios.

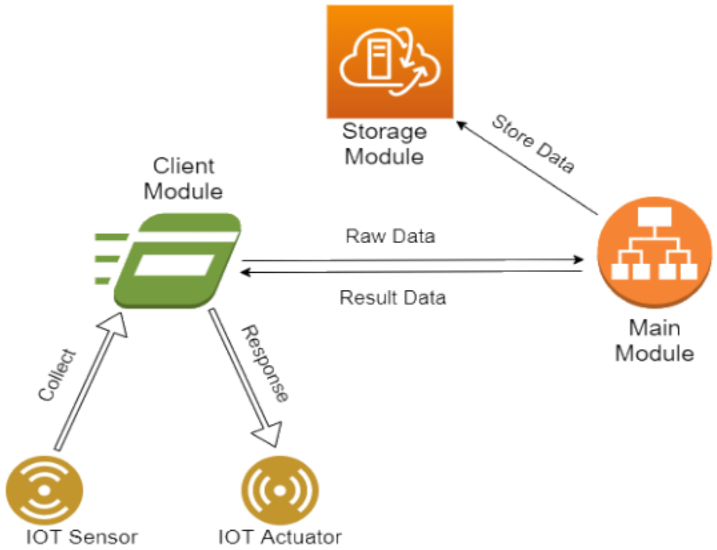

Figure 3. Application model for smart grid application

4.3. The architecture and parameters used in our scenarios with iFogSim simulator

To model and simulate the architecture and the application for smart grid in the iFogSim simulator [49], the following steps are used. First, the specific configuration for the physical elements of the network is created and given. Random access memory (RAM), processing capacity in millions of instructions per second (MI/S), cost per million instruction processing (MIPS), up and down bandwidth, power consumption and idle, and their hierarchical level are all part of the configuration parameters. It is necessary to build the associated IoT devices (sensors and actuators). The next step is to build the logical elements to model the monitoring application, such as AppModule, AppEdge and AppLoop. AppEdge objects contain information about the tuple type, direction, processor and network length, and source and destination module reference that are provided when building AppModules. Finally, management components (module mapping) are implemented to define various policies for scheduling and placing AppModules. When assigning AppModules to fog devices, users can consider total energy consumption, latency, network usage, operating cost, and system heterogeneity, and can extend the abstraction of the module mapping class accordingly. The specifications of an AppModule must be compatible with the specifications of the corresponding tuple type and met by the available fog resources, according to the information of the AppEdges. Knowledge of the physical and logical elements is passed to the controller object once the mapping of AppModules and fog devices are complete. The controller object then simulates the entire system using the CloudSim engine. Figure 4 shows the hierarchical topology which is used in the iFogSim simulator to model the smart grid infrastructure.

The devices in the fog environment are organized in a three-tier hierarchical order. The IoT sensors and actuators are attached to the lower-stage end units. The access point devices act as a link between the 5G new generation radio and the cloud, allowing commands to be sent and received via the application. Fog devices in the same hierarchical level are homogeneous for the sake of simplicity. Both sensors have the same sensing frequency. In addition, configuration of the links between each network on the application must be done (the parameters: uplink/downlink throughput, Latency and for equipment, it is computing power).

This configuration is based on the 5G network capabilities, and a standard sensor in the market with CPU of 1,200 MIPS is used. Moreover, more capacity of sensing can be applied. Concerning the cloud, the default parameters are followed. Table 2 gives the common parameters for the simulation scenarios.

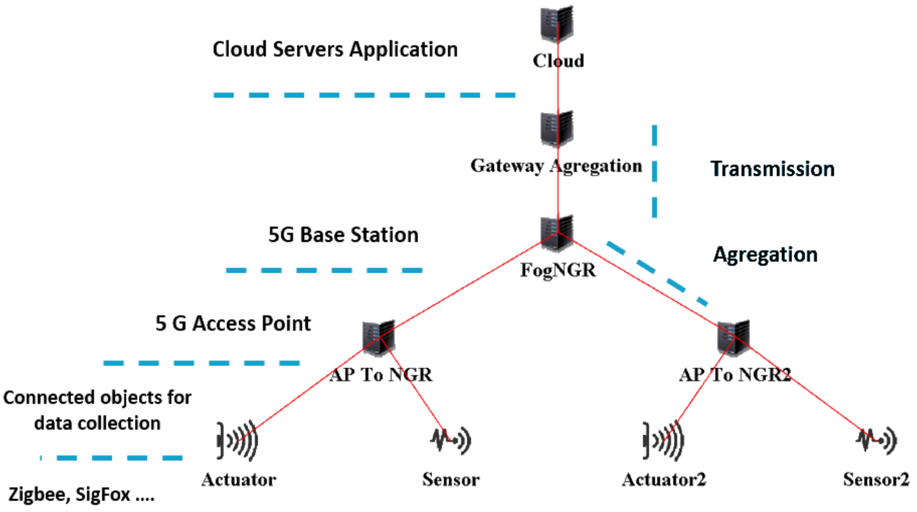

Figure 4. Simulated smart grid architecture on iFogSim

Table 2. IFogSim simulation parameters

Parameters	Cloud	Gateway Aggregation	FogNGR	AP To NGR
MIPS	44800	2800	8000	1200
RAM	40000	4000	4000	500
Uplink bandwidth (KB/s)	10000	10000	10000	10000
Downlink bandwidth KB/s	10000	10000	10000	270
Level hierarchy	0	1	2	3
Rate per MIPS	0.01	0.0	0,0	0.0
Uplink latency (ms)	None	6	5	1

4.4. Simulation scenarios

In this simulations, 3 scenarios will be carried out, using the architecture of Figure 4 which depends on the placement of the application modules presented in Figure 3. The first scenario called "placement on the cloud" places the modules (main module and the storage module) in the cloud. In the second scenario called "APP TO NGR placement," the modules of the application (client module and main module) are placed in the industrial objects (IIoT) which represent the data collection nodes (represented in Figure 4 by the name "APP TO NGR") and the storage module is placed in the cloud. Scenario 3, which is called "intelligent placement," presents the main contribution of the study, which allows us to distribute the client and main module according to the constraints of the infrastructure used. The three scenario is detailed in the next section.

5. PROPOSED INTELLIGENT PLACEMENT STRATEGY FOR SMART GRID SERVICES BASED ON 5G NETWORK

This section is to introduce the data placement methodology for IoT in fog infrastructure. It is called intelligent placement algorithm which can help us on the application to reduce energy consumption and operational cost taking into consideration the network bandwidth and latency constraints of the smart grid application. The objective is to see the impact of the proposed strategy according to the constraints of the operator's network. Before the strategy implemented is introduced, the strategy policy is to be identified; it defines how application modules are placed in fog devices during the strategy phase, which can be driven by goals like end-to-end latency reduction, network utilization reduction, operating cost reduction, or energy consumption reduction. The abstract strategy policy is the Module placement class, which must be expanded to include new policies. Using the placement policy, the aim is to execute the main module and the client module in the end devices or the fog system, depending on resource availability. On the architecture design, the storage module is implemented in the cloud. Figure 5 shows the flowchart of the application placement strategy for better comprehension.

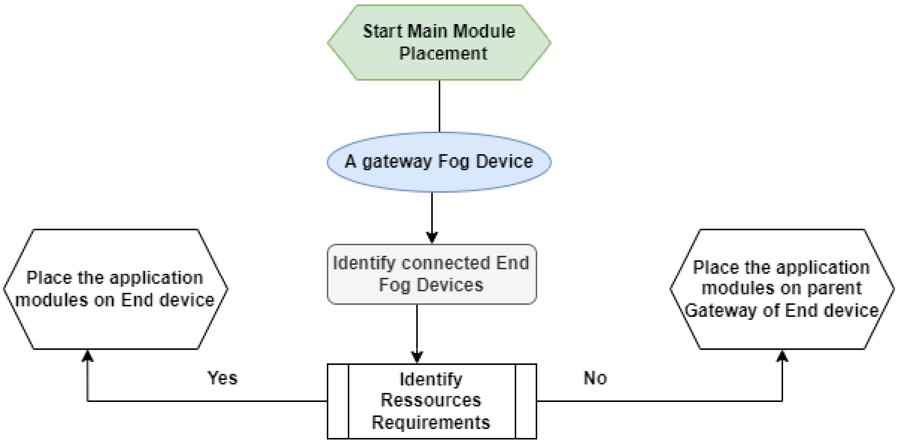

Figure 5. The flowchart for the intelligent placement algorithm

6. PERFORMANCE ANALYSIS

From Figure 6, it could be said that the energy consumption in the cloud can be considerably reduced by carrying out the application processing with the intelligent placement algorithm while keeping the low latency constraint. The intelligent algorithm will place the processing in the new generation radio in case the end device does not have the necessary CPU to perform the processing. Two important parameters are used in this algorithm: the first parameter is CPU limit of the end device, and the second is the number of fog objects in parallel processing to run the different application modules. In this simulation, for a CPU limit of 1,200 Mip at the end devices which is typical of smart grid applications and a limit of 6 end devices, running the application in parallel, our intelligent algorithm optimizes the energy consumption in the cloud by 39% for 6 end device in parallel compared to the energy consumption in the case of processing the application only in the cloud.

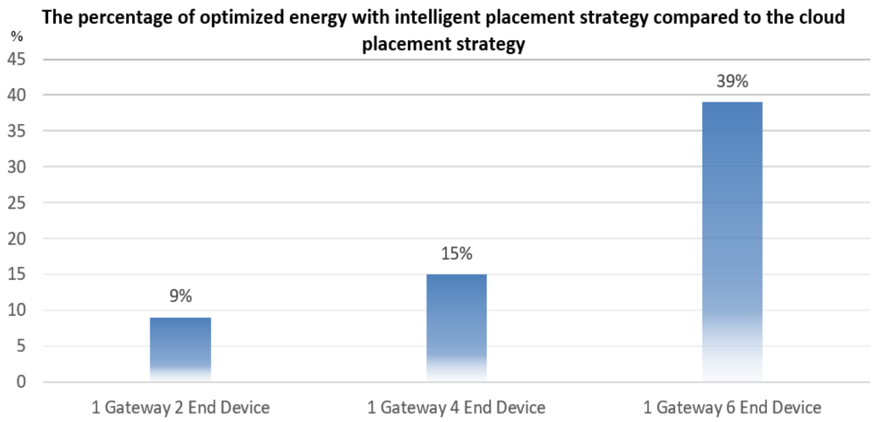

Figure 6. The percentage of optimized energy with intelligent placement strategy compared to the cloud placement strategy

For the latency, the algorithm gives a very good performance (lower than 6ms for 4 end device in parallel) but for 6 end device in parallel the latency increases to 100 ms this is justified by the reduced processing capacity of the new generation radio (CPU: 8000 MIPs). In these simulation scenarios which increase the latency of processing of application instructions. The increase of the CPU power of the new generation radio will allow reducing the latency to 6 ms. Figure 7 gives the results of the latency between the cloud and the end devices for the 3 simulation scenarios.

Figure 8 demonstrates that the intelligent placement algorithm presents the best results compared to the other two scenarios when the number of end devices exceeds 5 devices. This is justified by the exploitation of end devices resources which will optimize the cost at the cloud level. Concerning the network flow, the application processing with such intelligent algorithm keeps the best performance compared to the processing in the cloud and also the processing in the end device with a gain in network consumption that can go to 17% compared to the placement in the cloud and a gain of 61% compared to the placement in the end device as it can be seen in Figure 9.

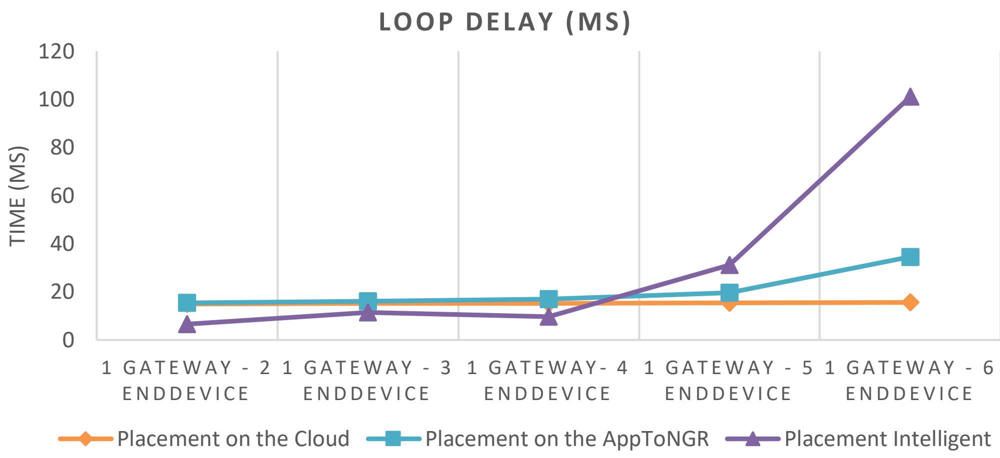

Figure 7. The loop delay for end devices for the three simulation scenarios

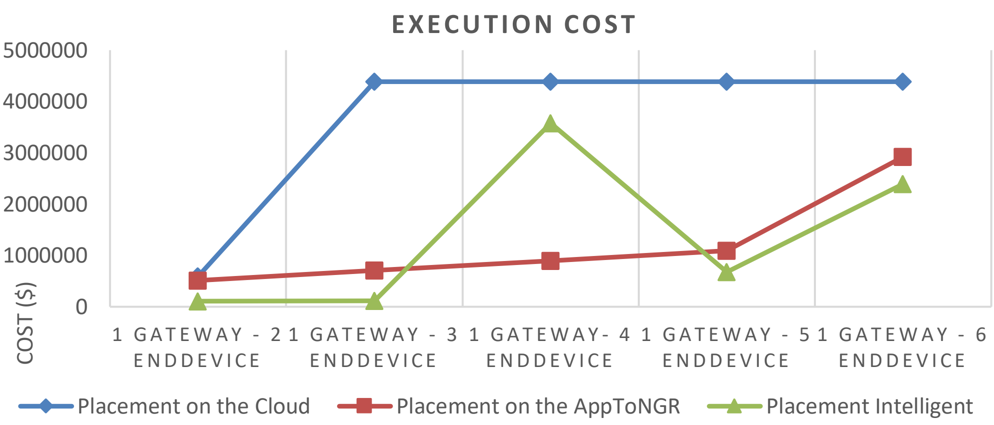

Figure 8. Execution cost in the cloud for the three simulation scenarios

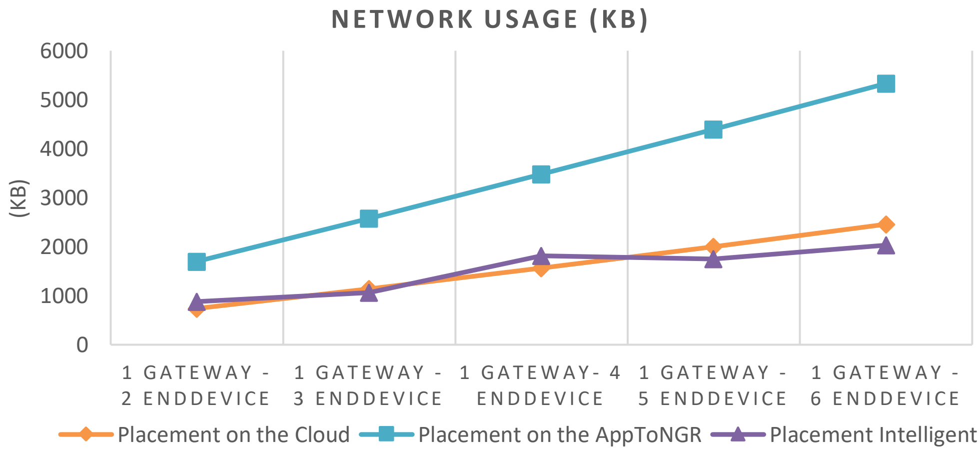

Figure 9. Network usage for end device for the three simulation scenarios

7. CONCLUSION

In this paper, the integration of smart grid services on the Fog cloud compared to the traditional cloud strategy is studied. An intelligent placement algorithm is proposed for smart grid to reduce energy consumption and the deployment cost in the cloud. Using the iFogSim simulator, the overall performance of the proposed algorithm is assessed and the results in terms of device cost and energy consumption in the cloud are evaluated. The results show that energy consumption in the cloud can be considerably decreased by processing the application at the end devices level with respect to the possible limit of CPU processing power for each IoT end device. Latency and network usage respect quality of service constraints in the case of intelligent placement for this type of smart grid application.

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