Machine to Machine (M2M) Communications for Dynamic Pricing in Smart Grid Networks

Kenneth Kimani[1*], Kibet Langat[2] and Vitalice Oduol[3]

Abstract—Smart grid (SG) networks are characterized by a tight integration of a flexible and secure communications network supporting a very large number of sensor and actuator nodes. This communication network is vital in learning about the power consumption patterns of consumers and finding out the statistical characteristics of power sources. With the accurate information, the smart grid can plan, support and interact with consumers in a more efficient and economical way. In order to realize the intelligent electricity network, machine-to-machine (M2M) communication is considered as a core building block for the SG enabling the deployment of a wide-scale monitoring and control infrastructure. The integration of machine to machine communications in the grid network eliminates human related errors by automating the processes of reading and reloading of utility meters, collecting information on customer usage patterns and instantaneously informing the utility companies in case of any faults and/or outages in the network.

M2M communications enables new applications in the smart grid including smart metering and dynamic pricing of power in the grid. Smart metering in M2M facilitates flexible demand management where a smart meter measures consumption and communicates that information back to the local utility. Dynamic pricing is used to control power demand in response to fluctuation in power supply. When the power demand from customers is higher than the power production output, the utility provider needs to source for additional power supply from other sources such as diesel operated power plants which are more expensive and harmful to the environment, whereas, when the power demand is too low, the operator may suffer from an under-utilized infrastructure leading to wasted capacity.

M2M communications enables the effecting of dynamic pricing structures whereby customers are charged higher rates during peak hours to discourage much consumption and charged lower rates during off-peak hours to encourage consumption. The different levels of tariffs allow the consumer to make a smarter and more responsible choice and can be used as one of the mechanisms of effecting load balancing which is a very big hurdle in existing grid networks. In this paper, we discuss the application of M2M communications to the SG to achieve dynamic pricing structures. We also explore the challenges and opportunities achieved from the dynamic pricing in the smart grid.

Keywords— Advanced Metering Infrastructure, Dynamic Pricing Structures, Machine-to-Machine (M2M) Communications, Smart Grid, Smart Meters.

I. Introduction

Current smart grids are majorly composed of machine-to-human or human-to-human information production, exchange, and processing. However, due to the large geographical spread of grid networks coupled with the large numbers of devices and the resulting large amounts of data, this has proved to be unsustainable resulting in inefficiencies such as in meter transactions (meter reading in analog postpaid meters). Also, in most places especially in the rural areas, there still exist analog utility meters where the utility companies have to send manpower to go and physically collect the meters' readings. Even in places where the digital prepaid meters are said to exist, they still require human input to manually key in the prepaid tokens into the meter.

Recent years have seen an upsurge in the number of new electricity connections and as more and more energy consumers are connected to the power grid, energy demand is expected to be more volatile due to fluctuation of the demand at the power network, combined with potential variations in generation and the unpredictability of the availability of distributed renewable sources [1]. This necessitates a paradigm shift on how we collect, process and control data in the smart grid considering the large number of resources in a smart grid environment and the size of the data to be moved.

A significant amount of intelligence needs to be injected in the current grid networks through the incorporation of information and communication technologies to dramatically improve (or even change) the management and operation of every aspect of the power system. In order to realize the intelligent power network, machine-to-machine (M2M) communication is the most ideal to deploy a wide-scale monitoring and control infrastructure in order to enable real-time interaction with the power grid network [2].

The integration of machine to machine communications in the grid network is envisioned to eliminate human related problems by automating the various processes in the grid network [3]. The implementation of the M2M communication system in the smart grid network also paves the way for effecting of dynamic pricing structures whereby customers are charged higher rates during peak hours to discourage much consumption (consumption by critical uses) and charge lower rates during off-peak hours to encourage consumption which can then be deployed as a load balancing mechanism.

Machine to Machine (M2M) communication allows communication to take place amongst machines such as sensors, smart meters, and other equipments in the smart grid [4] enabling them to maintain a near real-time awareness of

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each other's operating requirements and capabilities without requiring human intervention. It is estimated that the amount of generated energy-related data will be up to tens of thousands of terabytes in the near future [5]. This poses a significant challenge for any existing communication network as well as future smart grid networks [6]. M2M communication supports large scale data transmissions and is envisaged as a solution where the power consumption of different domestic devices can be monitored and various grid services such as real time power pricing, power consumption scheduling and generation can be managed and controlled in real time by using the data collected from the smart meters [7]. The presence of the machine to machine communications network provides energy efficiency in the smart grid by enabling the balancing of the generation and consumption levels, thereby streamlining the production and consumption of power in the grid [8] .

The rest of the paper is organized as follows. In Section II, Machine to Machine Communications is introduced. The effect of load imbalance on the grid network is discussed in section III. Section IV discusses various methods of performing dynamic pricing in the smart grid. Section V explores the network architecture of the smart grid. The requirements for M2M communication in the smart grid are explored in section VI. In Section VII, the challenges of the smart grid that are solved with the adoption of M2M communications in the smart grid are summarized. Finally, the concluding remarks are presented in Section VIII.

II. MACHINE-TO-MACHINE (M2M) COMMUNICATIONS

Machine-to-machine (M2M) communications is an emerging communication paradigm that provides ubiquitous connectivity between devices along with an ability to communicate autonomously while requiring no human intervention [9]. M2M communications are characterized by fully automatic data generation, exchange, processing and actuation among intelligent machines, without or with low intervention of humans [4] [10]. The objective of M2M communications is to increase the level of system automation in which the devices and systems can be interconnected, networked, and controlled remotely, with low-cost, scalable, and reliable technologies in order to exchange and share data [11].

The European Telecommunications Standards Institute (ETSI) has proposed an end-to-end architecture for M2M communications [12] comprised of five key elements:

- **i)** The M2M component, which is usually embedded in a smart electrical device, replies to requests or transmits data.
- **ii)** The M2M gateway enables connectivity between the M2M components and the communication network.
- **iii)** The M2M server works as a middleware layer to pass data through various application services.
- **iv)** The M2M area network provides connectivity between M2M components and M2M gateways.
- **v)** The M2M communication network provides connection between M2M gateways and is M2M servers.

These five elements constitute the M2M system as specified by ETSI: the M2M component working in the device domain, the M2M area network and gateway in the network domain, and the M2M server and communication network in the application domain as shown in figure1 below. From the data management perspective, M2M communications consists of three phases: data collection, data transmission, and data processing. The data collection phase refers to the procedure used to obtain the physical data. The data transmission phase includes the mechanisms to deliver the collected data from the communications area to an external server. The data processing phase is the process of dealing with and analyzing the data, and also provides feedback on how to control the application.

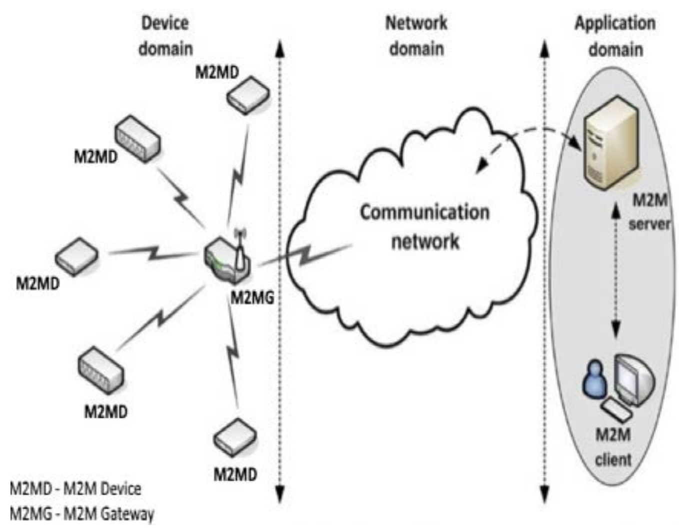

Figure 1: Architecture of M2M Networks [9]

In the context of M2M communications, the M2M server is located at the control center. The smart meters form the bulk of the M2M devices in a SG network. A smart metering service is considered to be one of the most prominent M2M applications, and is an advanced way to measure the consumption of electricity [4] [9]. A large number of metering machines monitor and record the energy consumption and automatically report to the smart metering server through M2M communications [13] [14].

The semiconductor industry's shrinking lithography and improving yield have led to reduced chipset cost and low power consumption leading to a rise in the number of connected devices that are not mobile phones and do not require human control and consequently leading to an increase in number of

M2M devices. Some of the most prominent M2M application areas include smart grids (grid control, industrial metering, demand response), vehicular telematics (fleet management, enhanced navigation, etc.), healthcare (telemedicine, remote diagnosis, etc.), manufacturing (production chain monitoring), and remote maintenance (industrial automation, vending machine control, etc.) [9].

III. Load Balancing

Load balancing is a process which involves resource management and an effective load distribution among the resources to ensure maximum utilization of resources is achieved. Kenya Power (Kenya's main power distribution utility company) has an estimated five million customers as of December 2016. Based on statistics from KPLC, the peak electrical load was 1228 MW and the total yearly electrical demand was 7.53 TWh, corresponding to an average demand of 860 MW. This shows that load balancing is a big issue for the utility provider. Figures 2 and 3 below show the average daily load profile and the average weekly load profile respectively.

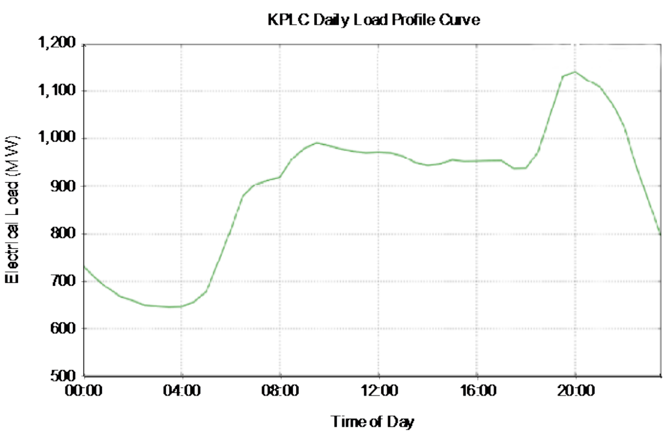

Figure 2: Average daily load profile curve

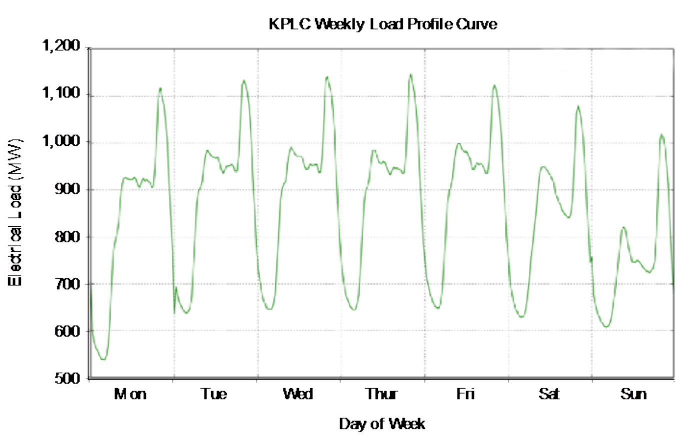

Figure 3: Average weekly load profile curve

The load profile curves show the peak time to be from 6 pm to 10 pm with the highest peak at 1140 MW at 8 pm compared to the off-peak period of between 12 am to 6 am with the lowest at 650 MW at 3am. If approximated demand is higher than actual demand, the supplied power is wasted (i.e., over-supply). On the other hand, if actual demand is higher than the approximated demand, additional power supply is required (i.e., under- supply).

Due to intermittent power supply from some renewable electricity sources such as wind power, tidal power, solar power and in absence of large scale, grid wide energy storage technology, there are periods in the load profile when there is excess demand beyond the supplied production levels resulting in load imbalance. Most of the current load balancing mechanisms concentrate on the use of peaking power plants to fill in demand gaps [15]. Theses peaking plants mostly run on diesel and are run only when there is a high demand for electricity. These diesel power plants are known to give out emissions that cause environmental pollution. They also generate power at a much higher price per kilowatt hour than base load power resulting in higher price of electricity. Load Factor is a measure of the efficiency of electrical energy usage; a low load factor is an indication that load is not putting a strain on the electric system, whereas a high load factor is an indication that the load is putting a strain on the electric system.

The Load Factor f_{LOAD} is given by

$$f_{LOAD} = \frac{Total\ Load}{Maximum\ Load\ in\ a\ given\ Time\ Period} \qquad (1)$$

Calculating the load factor for Kenya power, we find that

Peak Demand = 1228 MW

Total Yearly Electrical Load = 7.53 TWh

Number of days in billing cycle = 365

Load Factor (%) = {7530000 MWh / (365 days × 24 hours per day × 1228 MW)} × 100% = 69.99%

The process of load balancing in grids can be generalized into the following four basic steps as shown in figure 4 below.

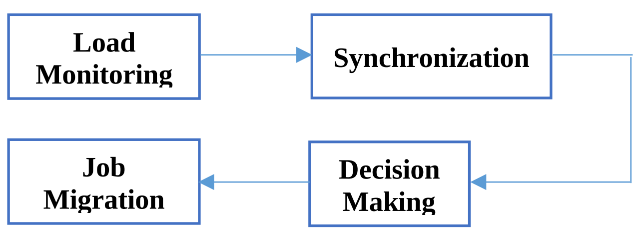

Figure 4: load balancing steps.

(i) Load Monitoring: Monitoring the resource load and state.
(ii) Synchronization: Exchanging load and state information between resources.
(iii) Decision Making: Calculating the new work distribution and making the work moment decision.
(iv) Job Migration: Actual data movement.

These four steps can easily be automated and synchronized by applying an M2M communication network.

IV. Dynamic Pricing in the Smart Grid

Energy pricing is based on tariffs. In the Kenyan context these tariffs are set by the Energy Regulatory Commission (ERC). In this case, energy tariffs are set based on the Fuel Cost Charge(FCC), the Foreign Exchange Rate Fluctuation Adjustment (FERFA), the Inflation Adjustment (IA), the Water And Resources Management Authority (WARMA) levy, the Energy Regulatory Commission levy (ERC) and the REP levy. This approach is largely a static pricing structure where the prices are adjusted once a month. However, this approach fails to take into account the instability on the grid network brought about due to load shifting during peak hours and off-peak hours [16].

Electricity pricing policies can be either static or dynamic. Static prices do not vary with a variation in demand, whereas dynamic prices change with changing demand levels. The main pricing policies are identified as:

a. **Flat tariffs**: In flat-tariff power pricing structures, all the consumers are charged the same price per unit of power throughout the day. The price therefore remains static even though power demand varies over the period of consideration. Consumers under this pricing scheme do not suffer from changing costs of power supply with a change in aggregate demand levels. The consumers do not face any risk of high electricity bills for any unavoidable or unplanned electricity consumption [16]. Therefore, they have no financial motivation to change their energy usage. Due to its static nature, this scheme is often viewed as a welfare pricing scheme.

b. **Block Rate tariffs**: This pricing scheme differentiates between customers based on the different blocks of quantified electricity consumption. In this scheme, the electricity consumption is grouped into multiple tiers based on the amount of consumption. With each increasing block of consumption the per-unit rate increases correspondingly.

c. **Seasonal tariffs**: This pricing scheme is based on charging different rates in different seasons to match the varying demand levels between different seasons. Electricity is charged at a higher rate during high-demand seasons and a lower rate during low-demand seasons.

d. **Time-of-use (TOU) tariff**: This is a tariff based on pre-declared tariffs that vary during different times of the day. This tariff is also known as time-of-day (TOD) tariff. The TOD tariffs are usually high during peak hours and low during off-peak hours and can be effected for either short or long terms [16].

e. **Superpeak TOU**: This tariff is similar to TOU, but the peak window is shorter in duration (about four hours) so as to give a stronger price signal.

f. **Critical peak pricing (CPP)**: This is a dynamic pricing scheme in which prices are high during a few peak hours of the day and discounted during the off-peak hours of the day. This scheme helps in reduction of excessive peak load and its peak price remains relatively uniform for all days.

g. **Variable peak pricing (VPP)**: This tariff is similar to CPP but the only difference is that the day to day peak prices vary per day. However, the consumers have to be informed about the peak prices beforehand [16].

h. **Real-time pricing (RTP)**: This tariff is the purest form of dynamic pricing. In this tariff, prices change at very small intervals in time thereby posing the greatest uncertainty to the consumers. It increases the efficiency of dynamic pricing by reflecting the actual supply cost and actual level of demand at any particular instance. However, in order to manage these frequent changes, it requires an advanced communication technology due to the high rate of data collection and transfer.

i. **Peak time rebates (PTR)**: In this tariff rebates or discounts are provided to consumers for consuming electricity below a certain predetermined level during peak hours. These rebates can then be redeemed at a later time.

Figure 5 below shows a sample of a bill from Kenya Power showing the pricing structure employed in calculating the energy bill.

BILLING DETAILS

umption	BILLING CONCEPT	AMOUNT IN SHILLINGS	
	BALANCE BROUGHT FORWARD	12,851.80	1
	FIXED CHARGE	240.00	2
689	CONSUMPTION	7,550.18	3
	FUEL COST CHARGE 519.0 cents/kwh	3,575.91	4
	FOREX ADJ.	0.00	5
	INFLATION ADJ. 9.0	62.01	6
	WARMA LEVY 5.0	34.45	7
	ERC Levy 3.0 cents/kwh	20.67	8
	REP Levy 5.00 %	377.50	9
	VAT 16.00 %	1,828.49	10
	20140403-CHEQUE PAYMENT	-12,851.80	11
	20140403-CHEQUE PAYMENT	-3.20	
	Round Adjustment	-0.01	
	Total Amount:	13,686.00	12

Figure 5: Current Billing structure from Kenya Power

Dynamic pricing is where consumers are charged varying prices depending upon the demand response curve. Dynamic pricing induces consumers to adjust their demand in response to the time-varying prices by switching off some of the non-urgent, non-critical loads. For example, dish washers in some households have a delayed start option. And yet, only a small fraction of consumers utilizes this feature and use the appliance later at night at off-peak times. This is bound to become more attractive with the rapid adoption of electric cars as more people are bound to be more interested in charging their cars during cheaper times of the night.

Demand response in a smart grid is expected to offer economic benefits to consumers while improving overall operation efficiency and reliability. A properly designed demand response program can reduce the peak load, compensate for uncertainties associated intermittent renewables, and reduce the cost of system operation. Demand response can easily be effected through through dynamic pricing mechanisms. Figure 6 below shows how the market forces of demand and supply are left to determine the equilibrium price at any particular point in time in case of RTP.

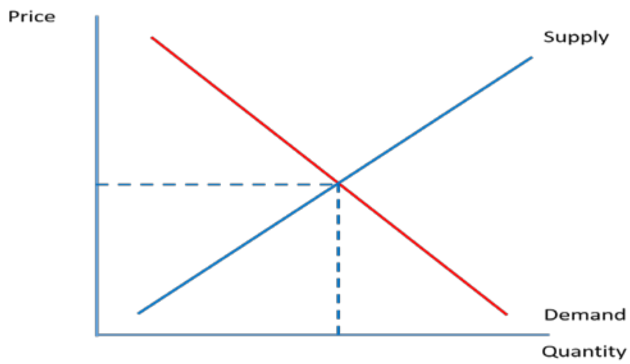

Figure 6: Demand - Supply price equilibrium curves

However, in order to implement this kind of time-sensitive pricing, utilities have to deploy more advanced smart meters to track how much energy people are using during certain times. This is a major reason why dynamic pricing is not more common. The availability of real-time pricing gives both consumers and suppliers' valuable indications to help manage their energy demands and supplies, respectively. Pricing applications broadcast pricing information to smart meters and smart appliances.

Other than demand-supply curve, a crucial factor that is considered in effecting dynamic pricing is market segmentation. Segmentation of the electricity market helps in differentiating customers based on various attributes. Attributes of market segments are helpful in setting the range of prices or the time span for maintaining a certain price in a dynamic pricing environment. Segmentation can be based on various demographic, behavioral and geographic factors. Current Segments are based on consumption data - high level and low level. There is also segmentation according to the market utilization – industrial and residential segments.

Important considerations that warrant for segmentation of electricity markets include welfare of vulnerable groups in society as these groups would be worst affected in case of improper dynamic pricing implementation. The effect of dynamic pricing schemes on low-income consumers show that low-income consumers are more sensitive to price signals than high-income ones. However, they are noted to have the lowest price responsiveness. This is because they have fewer opportunities to reduce consumption due to unavailability of specific home appliances in which the energy consumption can be controlled.

V. COMMUNICATION NETWORK ARCHITECTURE FOR THE SMART GRID

The SG has 4 main functional domains including power generation, transmission, distribution and power consumption [17]. However, in terms of the communication architecture, the SG is organized into three three-layered hierarchical domains consisting of Smart Grid Home Area Networks (SG-HANs), Smart Grid Neighborhood Area Networks (SG-NANs) and Smart Grid Wide Area Networks (SG-WANs) [9] as shown in figure 7 below.

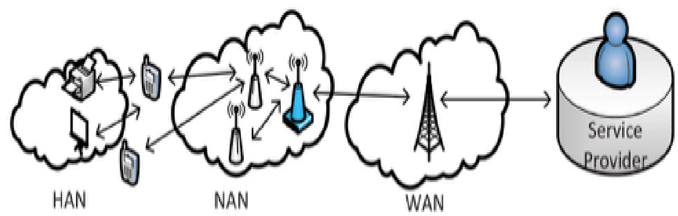

Figure 7: Hierarchical structure of SG communications [18]

a) *Smart Grid Wide Area Networks (SG-WANs)*

This is the upper layer of the SG communication architecture and serves as the backbone for communication between network gateways or aggregation points, NANs, SG substations, distributed grid devices, and the and the core utility systems. Both wireless and wired communication technologies can be used for communication requirements of the grid elements in SG-WAN [9].

b) *Smart Grid Home Area Networks (SG-HANs)*

This is the bottom layer of the hierarchical architecture within the SG dedicated to effectively managing the on-demand power requirements and consumption levels of the end-users. It is located in the customer domain and enables home automation networks for monitoring and control applications for efficient home energy management and user comfort. It consists of smart meters, sensors, actuators, and other intelligent devices around the home environment [5].

c) *Smart Grid Neighborhood Area Networks (SG-NANs)*

This is the intermediate layer of the SG communications architecture that connects multiple SG-HANs to the SG-WAN of the utility company [5]. A smart grid neighborhood area network communicates and manages several SG-HANs within its coverage area. NANs gather the energy consumption information from multiple HANs and transmits the information to utility center through the upper layer of the communication architecture, i.e. the SG-WAN [9].

These smart grid communication network domains can be implemented using a variety of communication technologies with M2M communication providing the base of any network layout implemented in the smart grid.

VI. Requirements of the M2M communication in SG.

M2M communications plays an important role in data exchange and can be adopted in many applications with the sole objectives of improving efficiency and reducing cost. The smart grid is one of the strongest driving forces for the advance of M2M communications [19]. The M2M communication architecture for the smart grid must therefore meet the needs of current and future applications in a cost-effective, scalable, reliable, and secure way. Several key features make M2M communications to be ideal for deployment in smart grid networks and are needed to efficiently support M2M traffic characteristics [20].

1. Support for mass device transmissions

This feature allows for the handling of simultaneous transmission attempts from an extremely large number of M2M devices so that the network is not overwhelmed by the large amount of devices attempting to communicate. The support for multiple device transmissions as offered by M2M communications is very attractive for smart grids.

2. Extremely low power consumption

Some devices on the smart grid are located in locations with limited supply of power while others are battery operated. Some devices especially in power generation are located in remote areas that experience infrequent human interaction. Due to the large number of devices in the smart grid it would be very uneconomical to have to replace the battery every so often considering that the grid covers large geographical regions. Most M2M devices are low power devices hence increasing the life span of these devices on the grid.

3. Small bursts data transmissions

Support for transmission of small bursts of information by M2M communications resonates with the type of traffic found in smart grids. Smart grid traffic consists of small bursts transmissions of mostly control and monitoring data.

4. Group control

Group control implies that the system supports group addressing and handling of M2M devices. Enabling group control of mass devices in smart grids is very important as it allows the easy broadcast of changes in dynamics in the grid network. Such changes include changes in pricing information due to uneven supply and demand which might lead to load imbalance in the grid network. Group control allows for easy addressing of extremely large number of devices**.**

5. Interoperability

A key feature of smart grids is the interconnection of a potentially large number of disparate energy distribution networks, power generating sources and energy consumers. The components of each of these entities will need a way of communicating that will be independent of the physical medium used and also independent of manufacturers and type of devices. As a result, multiple communication technologies and standards could coexist in different parts of the system. Interoperability will help to cater for the highly heterogeneous traffic patterns of most smart grid systems.

6. Scalability

With billions of embedded devices expected to be integrated in the smart grid in the next couple of years, it is important for the network to have capacity and spectrum efficiency to support a large increase in number of connected devices while still maintaining acceptable Quality of Service (QoS) standards. Such a steep expansion in the M2M connected devices presents a great challenge for the network infrastructure that must now be able to cope with an abundance of devices [21].

7. Delay-tolerant traffic

Time-tolerant traffic can support significant delays in data transmission and reception. This implies that the system can give lower access priority to or defer data transmission of time-tolerant traffic. This feature enables simplifications to the bandwidth request.

8. Extremely low latency

Extremely low latency requires that both network access latency and data transmission latency be reduced. This feature is required in many emergency situations. Changes to the bandwidth request and network entry/re-entry protocols may be required to support extremely low latency.

9. High reliability

High reliability implies that connectivity and reliable transmission should be guaranteed regardless of operating environment (e.g., mobility, channel quality). This is vital in supporting instant billing mechanisms where payments made should should be able to reflect automatically. Improved reliability may require changes to the link adaptation protocol or modulation/coding schemes. Other solutions may involve improved interference mitigation, device collaboration, or redundant path establishment [22]. M2M devices are also expected to be low cost, so that they can easily be embedded in real fields and extensively deployed in a large scale.

10. Priority access mechanism

Priority access is necessary in order define a scheme of prioritizing access to resources in the smart grid communication network. This is vital in communicating monitoring information that might pose a danger to the power consumers. It also avoids losses especially in an era of limited resources such as bandwidth [23].

VII. Mapping of M2M domains onto the Smart Grid

M2M communication allows data transfer for direct machine-to-machine communication with little or no human interaction [24]. Whereas current grid systems are optimized more for human-to-human (H2H) communications, M2M communications is designed for low power consumption, large number of devices, long-range and short-burst data transmissions. This informs the need to switch from current analog networks to M2M communications [13] [14], in which devices build a virtual mesh that is connected to a central aggregator. M2M communication for smart grid applications provides a communication architecture that is much better than current smart metering technologies as shown in figure 8 below.

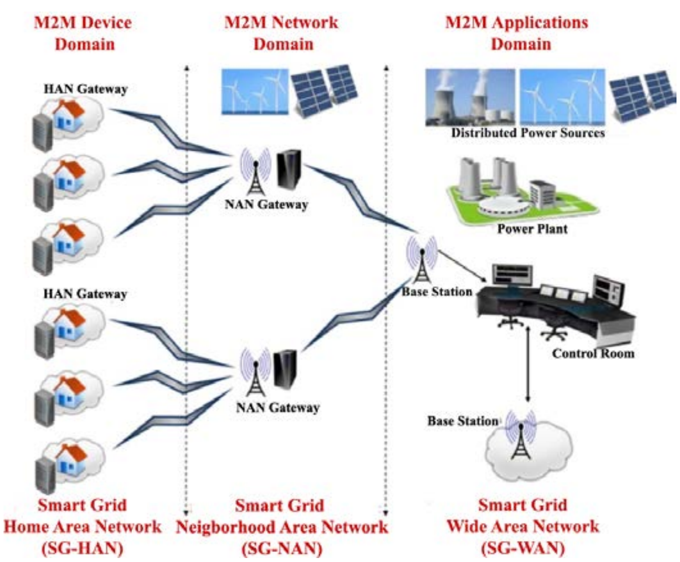

Figure 8: Mapping of the smart grid network onto the M2M architecture [25].

M2M communications architecture is hierarchical in that it comprises specific network segments for households, buildings or group of households, and neighborhoods, aiming at being flexible, adaptive, and scalable [11]. This hierarchical heterogeneous communications architectures comprising several network segments and combining different communications technologies present higher flexibility, so they fit a wider range of Smart Grid applications with their specific requirements and constraints [19]. This is the approach followed to design the M2M communications architecture and which is also aligned with the solution proposed as shown in figure 8 above.

The M2M communication network for the smart grid must be designed considering the scalability and energy efficiency requirements, periodic traffic patterns, and large-scale deployments. Optimal network design while minimizing the cost of M2M communications and data processing due to large amount of information collected is one of the main challenges hindering the full integration of M2M devices in the smart grid [26].

VIII. Conclusion

As the smart power grids continue to evolve, it is necessary to consider the most robust and reliable technology to facilitate communication in the grid networks. M2M communications play an important role in data exchange in the smart grid thereby enabling new services and applications. One of these applications is the effecting of dynamic pricing in the smart grid. This article presents an investigation into the application of M2M communications in effecting dynamic pricing in the smart grid.

Dynamic pricing of electricity is a demand-side management technique that is capable of stimulating demand response resulting in flatter load curves. Dynamic pricing policies are preferred over static pricing as these are reflective of the supply and demand imbalance which is a major problem for current power providers. The current load balancing schemes are noted not to involve the end users. However, use of pricing as a load balancing mechanism makes consumers to be more conscious of their power utilization at different times of the day and gives them a much bigger say and control in determining their own power prices. There are several dynamic pricing schemes each of which can be a suitable policy depending on the market.

M2M communications enables M2M components to be interconnected, networked, and controllable remotely, with low-cost, scalable, and reliable technologies. Because of the M2M features, a large number of metering devices can monitor and record their energy consumption and automatically report back to the utility control room through M2M communications. Automation brought about by the M2M communications helps customers to respond quickly to changes in prices while also reducing the human inefficiencies due to manual scheduling of tasks. M2M communications also enable the transmissions of usage patterns that are very vital in planning the network and also in carrying out maintenance of the grid. This contributes to achieving a balance between power generation and usage to significantly improve the power quality and efficiency of the electrical grid.

The real-time price-based coupling between supply and demand, helps in peak load reduction. However, it is noted that further research on electricity market segmentation is required to enable better implementation of dynamic prices. The benefits of M2M communications in the smart grid far outweigh the risks and this calls for wider adoption of M2M communications in the smart grid.

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