GRID-CITY: A Framework to Share Smart Grids Communication with Smart City Applications

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Abstract—Smart grids (SG) have been successfully deployed in several countries. In Brazil, the main agency for the wide(r) SG deployment are the electricity companies that operate under federal or state government concession. This paper presents a framework for sharing the SG communication infrastructure with smart city applications. This sharing would accelerate the development and implementation of new applications, especially in less developed countries or in regions with scarce communication resources. We present preliminary performance results for an existing SG. Our results indicate that, with only the energy metering application, the network operates with a duty cycle of less than 2%. Our work will assess the impact on overall performance of smart city applications sharing the SG.

Index Terms—Smart Grid, Smart City, Integration, Wi-SUN

I. INTRODUCTION

The electricity companies face ever more stringent quality of service demands, and are responding to that pressure by employing automation at the transmission and distribution networks. This in turn implies the need for superimposing data communication networks over the existing electricity networks so the operators may monitor state at various points, and perform actions to quickly recover the service in case of failures. The smart grids (SG) were developed to provide the capabilities for continuous monitoring and reaction at all points of interest in an electricity production and distribution network.

The Companhia Paranaense de Energia (COPEL) installed an SG in the city of Ipiranga, Paraná, Brazil, between 2017-2019 as part of its investment plan. Fig. 1 shows Ipiranga's location. The city was chosen because its 5250 consumers are spread over 927 square kilometers, a density of 5.66 consumers per km², and approximately 60% of the consumers are located in rural areas. The mobile telephone network covers only the small urban area of the municipality [1].

Fig. 1: Ipiranga City Location.

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The smart grids encompass a power layer and a communication layer, as shown in Fig. 2. Shown at the top, the power layer traditionally comprises large scale power stations (hydroelectric, thermoelectric, nuclear, wind turbine farms, photo-voltaic panel farms, biodigestors), transmission and distribution networks and assorted circuitry (high and low voltage power lines, substations, transformers, voltage regulators, capacitor banks, protection and measurement units), and the final consumer power intake, usually connected to the distribution network through and energy meter. Currently, smaller power sources are also attached to the distribution networks, or within the consumer premises, as indicated by the solar panels and wind turbines on the right of the diagram.

The communication layer, shown at the bottom of Fig. 2 stretches from the operation and control centers that manage the transmission and distribution circuits through the Intelligent Electronic Devices (IEDs) installed along the power lines and substations, all the way to the energy meters and Advanced Metering Infrastructure (AMI) devices at the customers. The AMI and metering devices support the additional services provided by the energy/utility companies. Because of its wide reach, both in terms of functionality and geography, a wide variety of technologies are needed.

Towards the endpoints of the communication layer, at “the last mile” managed by the energy companies, are the
Neighborhood Area Networks (NANs). The NANs connect the metering and control devices to the Home and/or Personal Area Networks (HAN or PAN) at the client’s premises.

The SG at Ipiranga is implemented with two communication layers, a backhaul wireless network and an AMI that implements the Wireless Smart Ubiquitous Networks (Wi-SUN) specification. The backhaul, shown in Fig. 3(a), connects 21 automation devices (reclosers and voltage regulators displayed as yellow pins and red balloons) and supports the AMI (data collectors as green stars). The AMI layer is shown in Fig. 3(b) and (c) and comprises 18 data collectors (green stars), 154 routers (blue flags) and 5250 smart meters (those in rural areas as green paddles, those in urban areas as yellow paddles).

The Wi-SUN specification is gaining acceptance as a communication layer for NANs, not only for SGs or utilities networks, but also for smart cities and IoT applications. The specification is based on IEEE 802.15.4g, and is promoted by the Wi-SUN Alliance [3]. The alliance published a standardized blueprint for a Field Area Network (FAN) to allow for the interconnection of devices from different manufacturers.

In spite of its non-trivial cost, Ipiranga’s SG has shown to be economically viable because of the reduction in operational costs it brought. A large proportion of field operations can now be performed remotely, yielding a monthly average reduction of a staggering 3750 Km in service team vehicular displacements, and a 41% decrease in equivalent service interruption time per unit consumer. Furthermore, the overall quality of energy provision improved as the protection devices and reclosers, being operated remotely, allow for the self-healing of the electricity network.

With the Ipiranga’s SG economical viability proven, there is some spare (data) network capacity that might be used to support other classes of application, in particular those related to smart cities and IoT.

This paper introduces a framework for the integration of applications unrelated to metering and electrical network control into an existing SG. We present preliminary data on the current network utilization and assess the demands that would be imposed by three candidate applications. The text is organized as follows. Section II presents the integrated framework; section III presents the measured data of the performance of the SG’s current state; section IV gives an overview of the demands imposed by the smart city applications under consideration. Section V discusses related work, and in section VI we indicate our future work directions.

II. System Overview

The architecture that integrates the SG with Smart City applications is shown in Fig. 4. The endpoint devices are embedded systems that link into the existing Wi-SUN metering infrastructure via radio. In our prototype the smart city application servers and related databases are connected to the SG through the MQTT Broker.

The SG’s transport protocol is UDP and thus the application protocols are restricted to those which operate with best effort message delivery. The application protocol chosen is MQTT-SN, a draft specification by OASIS that adapts MQTT to sensor networks [4].

A. MQTT

Message Queuing Telemetry Transport (MQTT) is an application level protocol for message exchange between devices, that is based on a publish-subscribe model. MQTT is a simple
protocol both in terms of implementation and (low) bandwidth, making it suitable for IoT embedded applications.

There is a central entity, called message broker, that mediates all communication. Client devices announce their interest in messages of a certain topic (encoded as an UTF-8 string) by sending a SUBSCRIBE message to the broker. Clients may publish data on a given topic by sending PUBLISH messages to the broker. The broker replicates the message to all clients who are subscribed to that topic. Thus, publishers and subscribers are disjoint sets, and one client has no knowledge of the others.

MQTT requires a transport protocol that guarantees ordered and lossless transmission such as TCP. However desirable, unfortunately this protocol is not compatible with the SG deployed at Ipiranga.

B. MQTT-SN

The MQTT for Sensor Networks (MQTT-SN) protocol was designed to overcome the limitations imposed by the scarcity of resources in sensor networks. The main MQTT-SN features when compared to “pure” MQTT are:

- does not need a reliable transport layer;
- reliable delivery is handled at the application layer;
- shorter messages, allowing for a smaller MTU and lower speed;
- uses a Topic ID (just 2 bytes) rather than Topic Name (UTF-8 string);
- supports connection-less publications (QoS -1); and
- better support for sleepy devices and energy savings.

MQTT-SN networks are integrated to an MQTT broker through a gateway which adapts the two protocols. Applications based on “pure” MQTT need not be modified if deployed on MQTT-SN networks. The gateway may or may not be on the same network as the other devices; clients send their messages through a forwarding node that encapsulates the messages as needed.

The MQTT-SN protocol is compatible with Ipiranga’s SG and was thus chosen. It also supports MQTT applications, which is a bonus as this protocol is widely used.

C. Application – SG integration

The Meter Data Collection (MDC) is a data collection management system that provides functions for integrating SG devices with application servers, through an HTTP based collection of web services and a bidirectional interface. The messages are encoded in Base64 and encapsulated into an XML structure, which is then transported as HTTP requests/responses. These HTTP messages are only exchanged between the MDC and application servers, and do not cross the SG as radio messages.

The Eclipse Paho [5] open-source gateway was chosen as the MQTT-SN implementation. As the gateway is not directly connected to the SG, an MQTT-SN forwarder was employed to allow proper addressing of data packets between the gateway and the IoT devices.

III. Preliminary Evaluation

The backhaul layer comprises a set of radios that operate at the 915 MHz range, with data rates from 125 kbps to 1.25 Mbps, using point-to-point and multi-point links. The Wi-SUN layer also operates at the 915 MHz range, with data rates from 50 to 200 kbps. The collector modules make the interface adaptation between the two layers, transferring data packets to/from the endpoints (smart meters and other IoT devices) and the MDC subsystem. Each data collector can handle up to 2000 endpoints and form a PAN with a channel hopping pattern distinct from that of its neighbors, since the collector radios employ the IEEE 802.15.4e Time Slotted Channel Hopping (TSCH). The router modules can handle up to 1500 endpoints, and their function is to decrease the number of hops in a (physical) radio link. The endpoints are the smart meters, AMI devices, and prototype RF modules. These modules are customized to support the new applications. For improved security, the modules must be explicitly registered and configured in order to operate within the company’s network.

In an assessment of the SG’s actual performance, it was found that each of the 18 collectors handles from 200 to 700 smart meters. To estimate the collector’s duty cycle, the daily average of input (IN) and output (OUT) packets were collected with a 200 kbps transmission rate and 512 byte packets. The average latency of packets (ping messages) was also measured. Table I shows the data for 6 of the 18 collectors. Collectors 1 and 2 are in town and the others in rural areas. The data were gathered in January, 2021.

<table>
<thead>
<tr>
<th>collector ID</th>
<th># smart meters</th>
<th>average latency (ms)</th>
<th># pkts IN</th>
<th># pkts OUT</th>
<th>duty cycle 200 kbps (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>677</td>
<td>1184</td>
<td>21454</td>
<td>47233</td>
<td>1.59</td>
</tr>
<tr>
<td>2</td>
<td>705</td>
<td>961</td>
<td>18484</td>
<td>33798</td>
<td>1.21</td>
</tr>
<tr>
<td>3</td>
<td>324</td>
<td>1105</td>
<td>25029</td>
<td>22703</td>
<td>1.10</td>
</tr>
<tr>
<td>4</td>
<td>207</td>
<td>730</td>
<td>18065</td>
<td>21363</td>
<td>0.91</td>
</tr>
<tr>
<td>5</td>
<td>250</td>
<td>591</td>
<td>16364</td>
<td>25671</td>
<td>0.97</td>
</tr>
<tr>
<td>6</td>
<td>359</td>
<td>651</td>
<td>12357</td>
<td>21968</td>
<td>0.79</td>
</tr>
</tbody>
</table>

In its current configuration, with only AMI devices, Ipiranga’s SG displays duty cycles well within the suggested range [6]. With duty cycles below 2%, it is tempting to consider smart city applications to increase utilization. However, one must take into account that the low utilization is necessary
to conserve the device’s energy stores. We are investigating smart city applications for experimental deployment and by performance and functionality evaluation.

IV. PROSPECTIVE APPLICATIONS

The applications under consideration are shown in Table II. The first application under evaluation is a weather station that sends data to a server at 15 minute intervals. The second is water metering, which has communication demands that are a small fraction of electrical metering. The third application is the control of street lighting to save energy by adjusting the luminosity according to the environmental conditions. The AMI application, presented in Sec. III, is shown for reference. The table shows the size of each information quantum (payload), the interval between two quanta (in minutes), the total bytes transferred per day, and the daily packet number, considering that an upstream packet carries up to 439 bytes.

<table>
<thead>
<tr>
<th>Application</th>
<th>Payload (bytes)</th>
<th>min. interval (minutes)</th>
<th>total bytes (per day)</th>
<th># packets (per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather station</td>
<td>80</td>
<td>15</td>
<td>7680</td>
<td>18</td>
</tr>
<tr>
<td>Water metering</td>
<td>20</td>
<td>60</td>
<td>480</td>
<td>2</td>
</tr>
<tr>
<td>Street lighting</td>
<td>16</td>
<td>60</td>
<td>384</td>
<td>2</td>
</tr>
<tr>
<td>AMI</td>
<td>286</td>
<td>15</td>
<td>27456</td>
<td>64</td>
</tr>
</tbody>
</table>

V. RELATED WORK

The number of publications related to the Wi-SUN specification has been growing steadily because of the increase in usage and its constant evolution. The fourth revision of the IEEE 802.15.4-2020 [7] standard incorporated enhancements to the Smart Utility Network (SUN) physical layers (PHYs) supporting up to 2.4 Mbps data rates and ultra-low-power operations.

In [8], the authors study Wi-SUN networks with linear topologies. In [9], the authors survey the application of IoT concepts to the deployment of SGs. In [10], the authors suggest that SG infrastructure be used for the deployment of IoT devices, on top of WiFi (IEEE 802.11) and Ethernet (IEEE 802.3) networks. In [11], the authors present a Wi-SUN performance evaluation for out of doors applications. In [12], the authors survey the communication layers in SGs, the several standards available, and the requirements imposed by the main applications. In [13], the authors present simulation results for QoS in NAN for SGs, comparing the RPL routing protocol variants. In the experiments, the simulated PHY and MAC layers were those for WiFi (IEEE 802.11b). In [14], the authors describe the development and assessment of devices that support the IEEE 802.15.4 and Zigbee PRO protocols as a viable alternative for implementing SGs. In [2], the authors survey some of the technologies available for implementing SGs and discuss the latency and bandwidth requirements of typical applications. Their survey does not include the Wi-SUN specification.

VI. CONCLUSIONS AND FUTURE WORK

We present a framework for the integration of smart city and IoT applications into the smart grid communication network. This framework was developed and will be tested on the smart grid of Ipiranga, Paraná state, Brazil.

Our preliminary performance data indicates that the data collectors in the wireless, Wi-SUN adherent, network operate with a duty cycle under 2%. This is a good indication that the smart grid can support new applications, besides electricity metering. We present the performance demands of the three applications currently under investigation.

We will assess the duty cycle and scalability of the Wi-SUN network with the new applications. We will also address some of the known issues, such as the long (data) network restart period following an energy blackout, and look for ways to minimize the energy dissipation by applications which require frequent communication exchanges.

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