

NB PLC and Software Defined Networking for Smart Grid Applications

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Abstract — During the last years, the installation of Distributed Energy Resources (DERs) and the expected diffusion of Electrical Vehicles (EVs), is increasing the complexity of the distribution grid, making the management of the grid operated by Distribution System Operators (DSOs) more difficult. The Smart Grid approach tries to provide a response to these troubles, by means of a strong interaction between the power grid and Information and Communication Technology (ICT) infrastructures. The drawback of this approach is an increase in the management effort of the ICT infrastructures, for which the DSO are not prepared. Software Defined Networking (SDN) is an approach developed to manage complex ICT infrastructures of datacenters, and its main target is to simplify the network configuration and management. The Smart Grid could benefit from the use of an SDN approach for the management of the communication infrastructure, as highlighted from previous research works. The target of this paper is to present a real case application of the SDN technology for the management of DERs over the distribution grid. The communication between electrical devices placed along the power grid and the secondary substations is provided by using Modbus RTU protocol over narrowband power line communication (NB-PLC). The preliminary characterization highlights that the Round Trip Time (RTT) on NB-PLC segment is affected by the used frequency band and by the modulation scheme. In the worst case (i.e., transmission at 72 kHz and a BPSK coded modulation, for a total data rate of 4.9 kb/s), the RTT is in the order of 140 ms, compatible with the requirements of the application.

Keywords—*Software Defined Networking; Narrow-Band Power Line Communication; Smart Grid; Performance Characterization; Distribution Grid Automation*

I. INTRODUCTION

Today, the Distributed Energy Resources (DERs) are widely diffused. They are installed in every modern grid and many of them unpredictably inject power in the grid, making the control of the distribution grid very difficult for local

Distribution System Operators (DSOs). Fortunately, giant steps have been done in the deployment of the so called Smart Grids (SGs) that add a communication infrastructure to the traditional grid design. Using the Information and Communication Technology (ICT) infrastructure, the real time exchange of measurement and control data is made possible, simplifying the job of the DSOs [1]. As a matter of fact, the energy efficiency described in the EU Framework Programme Horizon 2020 will be possible only if the adoption of Smart Grids is completed. The importance of the SG approach is so high that the extension to distribution systems other than electricity (e.g. water, natural gas, heating) is also investigated by the scientific community [2].

It is important to say that the communication system, which is the backbone of the SG, is also the most (cost) critical to be deployed, especially where the grid was installed several years ago. Where installation of a new network infrastructure is unfeasible, the use of heterogeneous/hybrid networks [3] is one of the most promising choices. In these cases, the substation, the meters, and the protections can be connected by using technology with limited installation costs (e.g., Narrow Band Power Line Communication (NB-PLC), Broadband Power Line (BPL), Wi-Fi). However, the heterogeneity of the network infrastructure leads to a complexity of configuration and maintenance that may impair the DSOs. In such a context, the use of Software Defined Networking (SDN) [4] may be interesting. The SDN can reduce configuration times since there is a central SDN controller that manages the entire network. Nevertheless, mapping the SDN, which is a recent technology with its issues [5][6], to the SG applications [7] means to consider new aspects, beside the classical security, availability and scalability. In particular, the Quality of Service (QoS) required by SGs is the main challenge for SDN architectures, that require extra effort in the designing and customization phases.

The main goal of this paper is to present a real application

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of SDN technology in SG: the use of SDN reconfigurable communication for the management of DERs in a distribution grid. The considered system shows a heterogeneous network over a national wide area. In particular, the attention will be paid to the characterization of the SDN communication infrastructure, based on NB-PLC, by means of the evaluation of key performance indicators, such as: Round Trip Time (RTT), time synchronization, availability, packet delay.

The paper has been structured as follows. After a brief introduction of the technologies involved in the research, the proposed approach is described in Section III. The approach has been first validated and characterized in the laboratory of University of Palermo. Finally, some conclusions are summarized in the final section.

II. TECHNOLOGY OVERVIEW

A. Automation of Smart Grid and NB-PLC

The deployment of automation systems in distribution networks is an essential step for the development of SGs. Automation in the distribution network involves the automatic control of Medium Voltage (MV) switches, the remote control of distributed generator power production, the voltage and frequency regulation both at MV and at Low Voltage (LV) levels. The authors have also investigated this topic, developing new proposals for SG automation. As an example, in [9] a new monitoring system was developed which considers the power measured in each secondary substation and it evaluates the power flows in the whole MV network. Based on the power flow monitoring, the DSO can take the proper decisions for the network management, sending control commands to the Distributed Generation (DG) connected to the MV and LV network. To this aim, a new Interface Protection System (IPS) was developed in [10]. It allows the DSO to control the DG inverter remotely, by shuttering the power production or varying the power factor, for frequency and voltage regulation purposes. Moreover, a command can be also used to remotely disconnect the DG from the grid for anti-islanding purposes. Besides these innovative features, the developed IPS also implements the standard requirements of [13], measuring voltage and frequency and comparing them to the respective anti-islanding thresholds.

To accomplish all these tasks, a capillary communication network is essential. Besides faster communication networks, such as fiber optic and wireless systems, mainly used to connect the secondary substations to the control center, NB-PLC can play an important role to reach LV users and prosumers. NB-PLC, in fact, has the main advantages of very low cost because of its ease of installation, since the network already exists (i.e., the power line), and the absence of a service provider cost, since the utilities are usually owners of the network. Moreover, the use of the power line guarantees the required capillarity of the communication system, too.

Different frequency bands are made available from the regulations of different countries, such as the European CENELEC bands (3–148.5 kHz), the US FCC (Federal Communications Commission) band (10–490 kHz), the Japanese ARIB (Association of Radio Industries and

Businesses) band (10–450 kHz), and the Chinese band (3–500 kHz). Different modulation techniques and communication protocols were developed in recent years. A comprehensive analysis of those already deployed or still in experimentation is reported in [14]. One of the main SG applications based on NB-PLC that is already widely diffused in many countries is the Automatic Meter Reading (AMR). In some countries, such as Italy, this technology is considered so reliable that it will be employed also in the second generation of energy meters, which are going to be installed in the next years. The AMR infrastructure is characterized by data concentrators installed in the secondary substations, which periodically collect the LV smart meter data via NB-PLC. The data concentrators are usually connected to the control center by means of wireless infrastructures, such as General Packet Radio Service (GPRS), HiperLAN or Long Term Evolution (LTE). A similar communication architecture can be used also to connect other field devices, such as the DG IPSs, to the control center, thus performing further SG applications. The developed solution for LV DG remote control was used as a case study to verify the benefits of the SDN approach.

B. Software Defined Networking

The network infrastructure includes several network devices, like switches, routers, and gateways, that are used to transfer data packets from source to destination. The forwarding of messages follows a defined set of rules; such rules must be provided in first place during installation, and then updated every time the network interconnection is changed. The separation between the control plane (the layer that decides how to forward messages over the infrastructure) and the data plane (the layer that applies the rules defined by the control plane) is the core of the SDN approach. The rules are managed by a centralized SDN controller, and the key point is that these rules can be easily adjusted to the required QoS because the SDN has a view of all the network requirements. There is no limit to the flexibility of a SDN since rules can be built over any message property starting from traditional ones (MAC address, IP address, TCP port, VLAN) and including also more specific application properties (e.g. SG latency, SG business model, protection trip). Once the rules are ready in the SDN Controller, they are included (downloaded) in the SDN devices of the data plane. On the top of the control plane, an application plane is also possible for dealing with other network related services (Performance and Security Monitoring, Business Logic). To sum up, the SDN system can self-configure the network without requiring manual management, speeding up reaction time and increasing flexibility.

It is clear that the benefits of a centralized SDN approach applied to the SG apply mainly to the management point of view. In detail, two aspects of management are relevant for SG that uses heterogeneous networks:

- handling of the configuration phase, since every sub-network or protocol may have its own set of limitations to be managed concurrently;
- faulty situations, where the management of the communication infrastructure is oriented to the recover of

a stable situation where (at least) critical data can flow without extra delay.

III. THE PROPOSED APPROACH

A. The reference architecture

The integration of protections, measurement and control devices on the distribution grid is going to create a demanding request for the communication infrastructures. As already mentioned, the management of the communication infrastructure requires wide skills in network engineering, which are not typically available among DSO staff. The SDN approach is able to simplify and automate the network configuration and maintenance. In the proposed architecture, the SDN approach is applied to manage the communication infrastructure connecting the DSO intranet with the secondary substations (see Fig. 1). In the rest of the paper, this communication layer is called supervisory layer. The network devices installed in the secondary substations and able to exchange information with the SDN controller are called SDN bridges. SDN bridges exchange configuration and forwarding rules with the SDN controller by means of a dedicated configuration protocol. Several configuration protocols are available, but the most common and supported by network devices is OpenFlow. The geographical extension of the distribution grid requires the installation of a great number of SDN bridges. In order to limit the installation costs, low-cost and high-performance SDN bridges are required, such as the device characterized in [8]. Such a network device is able to support multiple connections toward the DSO control center, including (but not limited to) Gigabit Ethernet and LTE. At field level, the SDN bridge forwards the commands, from the DSO main control center to the devices on the field, like DG IPS. Several communication media are used to allow the interconnection with devices in the field. The connections typically adopted are IEEE 802.15.4, Wi-Fi, BPL, and NB-PLC. Among those, in this paper the attention was focused on NB-PLC for the mentioned advantages of capillarity and reduced costs of installation and service.

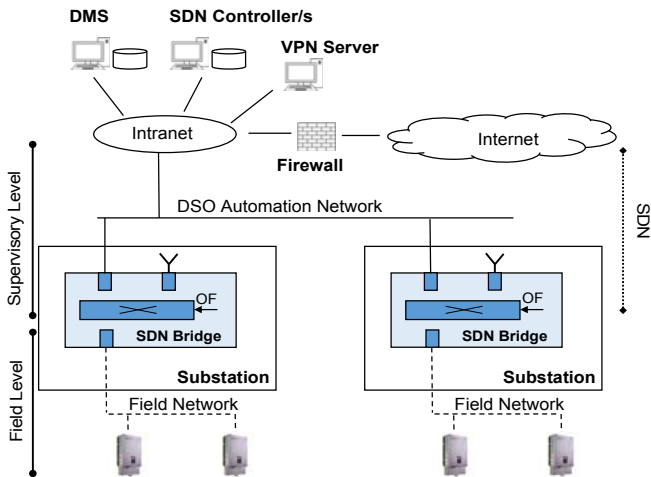


Fig. 1. The reference architecture about the adoption of SDN for the automation of Smart Grid.

B. Power Line Communication

In the case study of DG remote control, the IPS are the field devices to be connected to the DSO SDN architecture. Thus NB-PLC modems have to be included both in the IPS and in the SDN bridges. This solution is compliant with the modern standard on DG connection to LV networks [11][12], such as Italian CEI 0-21 standard [13], which suggests the use of PLC to carry DSO messages.

In more detail, thanks to the SDN bridges, the DSO messages are forwarded to all the IPSs connected to the portion of LV network powered by the relative secondary substation. Then, the addressed IPS sends the control message to the connected inverter, to change its operation mode in terms of active and reactive power generated according to predefined standard curves [13]-[12].

The communication time requirements for this application can be satisfied with relatively low bit rate. Thus, the attention was focused on the single carrier modulation techniques operating in the frequency range of CENELEC bands (3-148.5 kHz).

To implement the proposed solution two ST7580 PLC modems were used. They can implement the following modulation techniques: Frequency Shift Keying (FSK) or Phase Shift Keying (nPSK) with a maximum baud rate of 9600 baud/s. A bit rate up to 28.8 kbit/s can be achieved by using the 8PSK modulation. An error correction mode can be also activated. In this case, two coded bits are transmitted for each information bit (code rate $\frac{1}{2}$), halving the communication bit rate but increasing the communication robustness through error correction [15]. The available modulation techniques and relative bit rates are reported in Table I.

TABLE I.
ST7580 AVAILABLE MODULATION TECHNIQUES

Modulation	Symbol rate [baud/s]	Information bits per symbol	Bit rate [kbit/s]
BPSK coded	9600	0.5	4.8
QPSK coded	9600	1	9.6
BPSK	9600	1	9.6
QPSK	9600	2	19.2
8PSK	9600	3	28.8
BFSK	1200	1	1.2
BFSK	2400	1	2.4
BFSK	4800	1	4.8
BFSK	9600	1	9.6

To implement the aforementioned field network, two devices were developed both based on a STEVAL-IPP001V2 board, which embeds the ST7580 PLC modem. The first device is used as IPS concentrator to forward the SDN bridge messages to all the IPSs connected to the secondary substation LV lines. The second is the IPS itself, whose firmware handles both the communication task, forwarding the received PLC messages to the DG inverter, and adjunctive measurement and protection tasks, according to the rules for DG connection to LV networks [13]. The IPS, in fact, embeds also a meter board, with voltage and current transducers, which is used to measure the network parameters and verify the anti-islanding

thresholds. Finally, a IPS digital output can switch a contactor to disconnects the DG from the network, for example in the case of islanding detection.

IV. EXPERIMENTAL CHARACTERIZATION

A. Characterization protocol

1) Characterization of field level communication

As mentioned in the previous section, the proposed approach is based on a strict integration of communication technologies, whose connection point is represented by the SDN bridge. Given the different characteristics of the communication media, the performance characterization has been divided in two parts: one for the field level communication and one for the supervisory level. The field level characterization has been performed by estimating the RTT. The RTT is defined as the time needed by packet to reach its destination and the relative response to be received at the transmitter. The RTT is a performance index of responsiveness and real time capability of the network under analysis. Typically, the devices on the power line are connected each other using a fieldbus, such as Modbus RTU. In particular, in our scenario we consider a DG inverter interconnected to the SDN bridge, by means of a Modbus RTU link carried over NB-PLC. The IPS device is responsible for the transmission of RTU packets over the power grid. The protocol used to estimate the RTT over the Modbus link is shown in Fig. 2.a. The SDN bridge sends periodic Modbus RTU requests to the DG inverter, and waits for its answers. In this case, the RTT is defined as the time interval between the Modbus RTU request and response.

2) Characterization of the supervisory level communication

In this case, the performance indices considered are slightly different with respect to the previous case. At the supervisory level, the SDN controller and SDN bridges are exchanging information about the configuration and forwarding rules. Typically, the network configuration is downloaded by the SDN controller into the SDN bridges at the start-up of the network. Subsequently, when a new device is connected to the network or the topology is modified, the SDN bridge forwards to the SDN controller the packets it is not able to handle, by default. The responsiveness of the SDN network has been evaluated by estimating the RTT over the connection between the SDN controller and SDN bridges. Typically, bridges and controller are connected through a Virtual Private Network (VPN) to guarantee a secure data exchange (see Fig. 2.b). In addition, the throughput of the VPN connection has been also evaluated to estimate the throughput supported between SDN bridges and SDN controller.

B. Experimental set-up

Fig. 3 shows the experimental test set-up. A SDN bridge is installed in a secondary substation, placed in the laboratory of the University of Palermo. The SDN bridge forwards the network messages to the IPS concentrator through the RS-232 link. The PLC signal is then sent to all the IPSs connected to the secondary substation LV lines. The IPS communicates with the DG inverter via Modbus RTU/RS-232, sending the control commands and receiving the inverter operation mode and status. To characterize the proposed architecture, laboratory tests were firstly performed. A SDN bridge was installed in the laboratory of the University of Palermo, Italy.

The SDN bridge has been implemented using a PC Engines GmbH APU2C4 board, equipped with an AMD Embedded G-series GX-412TC CPU, 1 GHz quad core, 64 bit, 4 GB DDR3-1333 RAM, 3 NIC Intel i210AT, one LTE miniPCIe Sierra Wireless AirPrime MC7455 card. The board is equipped with Arch Linux x86-64 distro, kernel version 4.7.2. Open vSwitch 2.5.0 [16] has been installed on the board. Open vSwitch is a multilayer virtual switch licensed under the open source license. It is designed to enable network automation supporting standard management interfaces and protocols, like OpenFlow 1.5 [17]. In our system, Open vSwitch is used to handle the connection of the SDN bridge with the supervisory level. For a more detailed description of the platform and a full characterization, see [8].

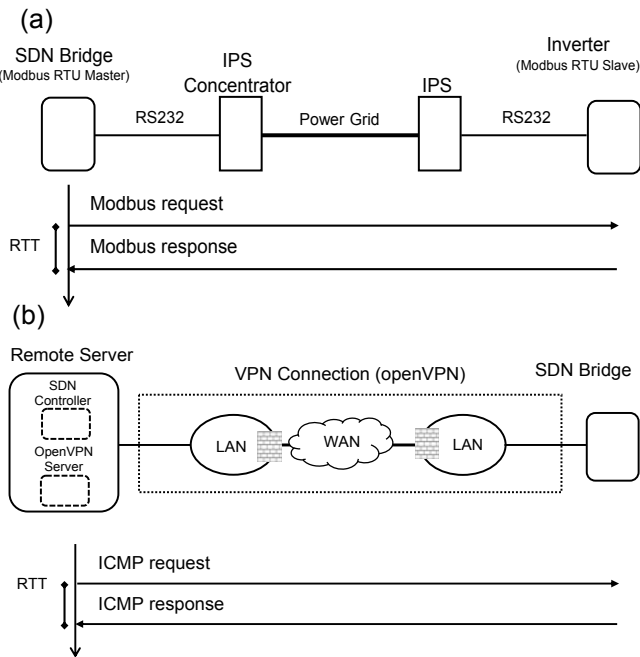


Fig. 2. The validation protocol used to estimate the performance of the communication over the field level connection (a) and over the supervisory level communication (b).

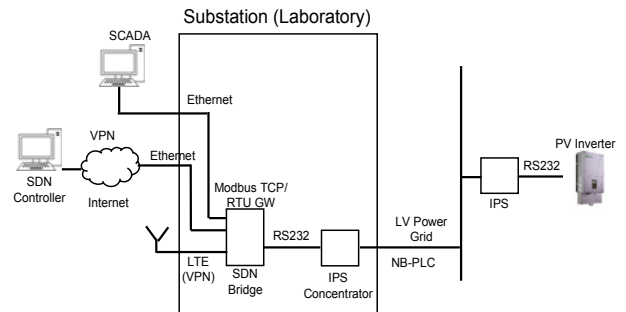


Fig. 3. The experimental test set-up.

The SDN controller is hosted on a remote server of the University of Brescia, Italy. The SDN Controller is based on Ryu, version 4.8, a Python-based SDN framework. Ryu provides software components with an API that makes the design of new network management and control applications fast and relatively simple.

The SDN bridge is connected to the SDN controller through a VPN connection. The VPN connection is established using OpenVPN. The OpenVPN server is hosted on the same server hosting the SDN controller. OpenVPN has been configured to transfer the data using UDP and the data channel is coded using AES-256-GCM. The SDN bridge is physically connected to the supervisory network by means of the cabled network of the University of Palermo (and then to the public network) and, additionally, through the LTE public network. The LTE connection is a backup connection to be used when the cabled network is not available.

To test the PLC communication from the SDN bridge to IPS, a short LV line of a few meters was used. In this way, the influence of the line length could be ignored and the transfer time dependency from PLC transmission parameters could be investigated. Performing the RTT test from the SDN bridge, the PLC round trip time was measured for different center frequencies and modulation techniques.

C. Results

1) Validation of field level communication

As mentioned in Section IV.a, the performance of the field level communication has been characterized by estimating the RTT on the NB-PLC communication link. The RTT has been estimated by measuring the time the IPS device takes to answer with a Modbus RTU response (6 bytes) to a Modbus RTU request (5 bytes) sent by the SDN bridge. In the considered scenario, the Modbus RTU messages are transmitted over the NB-PLC link, therefore the RTT is affected by the modulation and the central frequency adopted by the power line. Several tests have been performed, by changing the transmission band (72 kHz and 90 kHz) and the modulation scheme (BPSK coded, BPSK, QPSK, QPSK coded and 8PSK). The frequency distribution of the RTT measured when data are transmitted in the frequency band at 72 kHz and with BPSK coded modulation, is shown in Fig. 4.

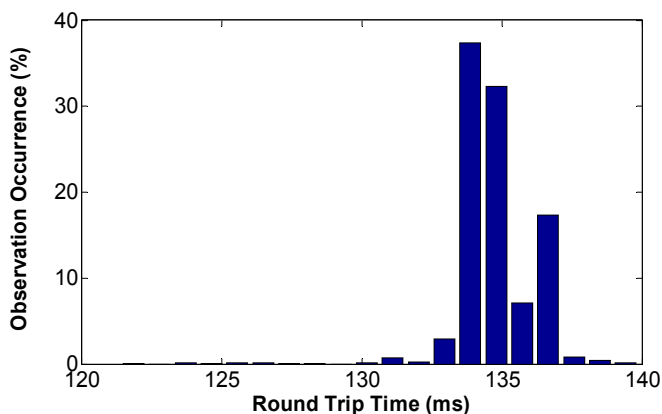


Fig. 4. The frequency distribution of the RTT on the NB-PLC link (72 kHz, BPSK coded, 4.8 kb/s).

The mean value is 135 ms and the jitter, defined as the maximum variation of the RTT during the observation interval, is 15 ms. The statistics of the tests performed by changing frequency band and modulation scheme are summarized in Table II. It should be highlighted that the datarate of the NB-PLC could affect the overall the RTT.

TABLE II. PERFORMANCE OF THE FIELD LEVEL COMMUNICATION UNDER DIFFERENT OPERATIONAL CONDITIONS.

Band (kHz)	Mod.	Datarate (kb/s)	Mean (ms)	Std. Dev. (ms)	Jitter (ms)	95-per. (ms)
72	BPSK coded	4.8	135	2	15	138
72	BPSK	9.6	90	2	16	92
72	QPSK	19.2	90	2	15	94
90	BPSK coded	4.8	135	1.5	14	137
90	BPSK	9.6	90	1.6	14	92
90	QPSK	19.2	90	2	16	94
90	QPSK coded	9.6	90	1.5	13	92
90	8PSK	28.8	90	2	15	93

2) Validation of supervisory level communication

The supervisory level communication is used for the exchange of data between the DSO control center and the secondary substations. In addition, it is used to exchange the network configuration between the SDN controller and SDN bridges. Typically, the supervisory level exploits the public network infrastructure for the data exchange. In order to avoid any malicious access to the data, the devices are interconnected each other using a VPN network. In the following, the performance of the VPN has been characterized. The RTT has been evaluated using Internet Control Message Protocol (ICMP) services. The ICMP protocol is used to estimate the RTT over the VPN connection between the SDN controller (installed at the University of Brescia) and the SDN bridge installed in the laboratory of the University of Palermo. The two places involved in the experiment are about 900 km far away. The SDN bridge is connected to the Ethernet network of the laboratory. The frequency distribution of the VPN connection RTT, obtained considering 3000 samples, is shown in Fig. 5. The mean of the RTT is 27 ms, while the standard deviation is 0.6 ms. The jitter is in the order of 18 ms. This means that, in the case of a network topology change, the reconfiguration of the SDN network requires at least 27 ms. The trend of the RTT during the experiment is shown in Fig. 6.

The throughput of the VPN connection has been estimated, to have an idea of the maximum amount of data that can be exchanged across the VPN in a given time interval. The throughput measurement has been made using the software iperf3. The iperf3 tcp server runs on the remote server at the University of Brescia, while the iperf3 client runs on the SDN bridge. The throughput has been measured for 300 s. The results are shown in Fig. 7. The mean throughput is in the order of 65.9 Mb/s.

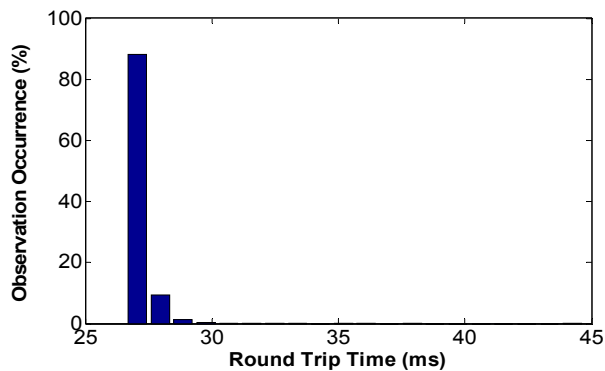


Fig. 5. The frequency distribution of the RTT estimated over the VPN, forming the supervisory level.

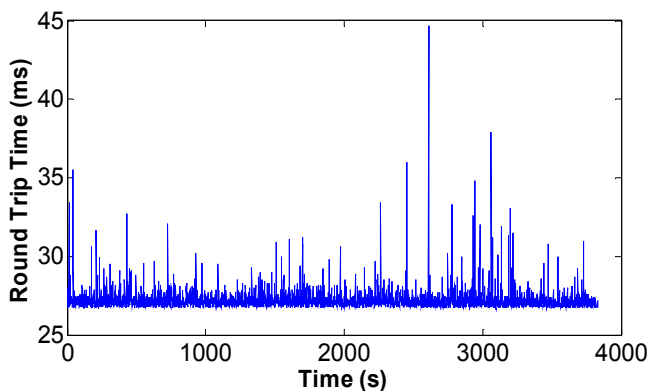


Fig. 6. The RTT over the VPN, forming the supervisory level.

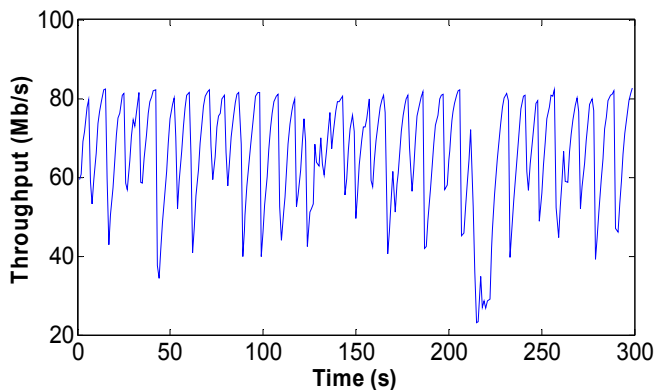


Fig. 7. The throughput over the VPN, forming the supervisory level.

V. CONCLUSIONS

The management of the communication infrastructure of SGs can benefit from the SDN technology. The goal of the paper was to show a real application concerning the management of DERs connected to the distribution grid. The considered scenario includes heterogeneous networks (with

NB-PLC) that must be managed by a SDN controller on a national wide network. The laboratory results show that the RTT on the NB-PLC segment is affected by the modulation scheme. In the worst case, the RTT is in the order of 140 ms, compatible with the requirements of the application.

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