

I Choose You! But why?: Proposal and evaluation of policies to promote service nodes to switches in PRIME networks

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Abstract—PowerLine Intelligent Metering Evolution (PRIME) is a Narrowband – PowerLine Communication (NB-PLC) technology widely used in Advanced Metering Infrastructure (AMI) in Spain and overseas. PRIME networks are formed by one base node (which is part of the AMI data concentrator) and many service nodes (smart meters). The technology allows some smart meters to work as relays (switches), to extend coverage and improve communications performance, and is defined to be plug&play. Thus, whenever a new node joins the network, it listens to the channel waiting for beacons from the concentrator or the switches. If it does not hear anything, it sends kind of SOS message, which makes whatever service node that hear it to send a message to the concentrator requesting being promoted to switch. PRIME specification says nothing, however, on how the concentrator chooses the switch from the possible candidates, this belonging to the know-how of the meter manufacturers. In this paper, we propose several policies to do so and evaluate their impact on the network performance by using the PRIME network simulator SimPRIME. Although there are already publications on optimal positioning of switches in PRIME networks, typically it will not be possible to choose their positioning, so from the best of the authors’ knowledge this is the first research work that tackle the issue as it happens in practice, what makes the obtained insights more useful.

Keywords— *Advanced Metering Infrastructure, Narrowband-Power Line Communications, PowerLine Intelligent Metering Evolution, SimPRIME, Simulation, Smart Grid*

I. INTRODUCTION

PowerLine Intelligent Metering Evolution (PRIME)/ITU-T G.9904 [1] is a Narrowband–PowerLine Communication (NB-PLC) technology widely used in Advanced Metering Infrastructures (AMI) in Spain and overseas, being 20 M PRIME-compliant smart meters deployed worldwide by January 2019 [2]. Although the idea of defining an open technical specification that allows interoperability, and so high-quality meters at reasonable costs, was at the heart of the PRIME Alliance, the reality is that a few manufacturers have deployed most of the smart meters so far. Thus, the experience and knowledge that these few manufacturers are gaining from actual large-scale deployments put them in a position of competitive advantage that may put at risk the initial idea of the standard.

The PRIME network simulator SimPRIME [3], which has been extensively used for research studies during the last years [4]–[12], takes special importance in this context, since it represents a flexible and cost-effective solution for players with low market share to perform experiments and gain knowledge, thus helping them to be more competitive.

This paper focuses on the mechanism defined in the PRIME specification that allows promoting smart meters to switches with relay capabilities. This mechanism aims to extend the coverage and improve the quality of the communications, and also allows PRIME-compliant smart meters to be plug&play. However, the specification says nothing about possible criteria to choose the node to be promoted to switch from a group of candidates, so this belongs to the know-how of the manufacturers.

Thus, in this paper we propose several criteria that can be applied in the concentrator to do so and evaluate their impact on the network performance by using SimPRIME, as a token of how it can be used for the aforementioned purposes. Although there are already publications on optimal switch positioning in PRIME networks [5], typically it will not be possible to choose their positioning, so from the best of the authors’ knowledge this is the first research work that tackle the issue as it happens in practice, what makes the obtained insights more useful.

The remainder of the paper is structured as follows. Section II briefly summarizes PRIME standard, paying special attention to the mechanism under study, and SimPRIME. Section III presents the proposed promotion policies and explain how they are implemented in SimPRIME. Section IV analyzes the preliminary results obtained from the simulation of an actual scenario. Finally, section V draws conclusions and outlines future research work.

II. BACKGROUND

A. Overview of PRIME

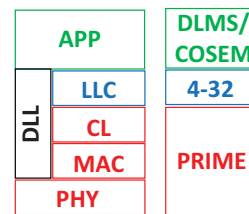


Fig. 1. Protocol stack

Fig. 1 shows the protocol stack in the “last-mile” of an AMI which takes advantage of the low voltage cables to transmit data using NB-PLC PRIME technology. It can be seen that it is composed of PRIME, which specifies the Physical (PHY), Medium Access Control (MAC), and Convergence (CL) layers, and Device Language Message Specification/Companion Specification for Energy Metering (DLMS/COSEM), at the application layer. In many already

deployed PRIME networks, at least in Spain, the metering legacy protocol IEC 61334-4-32 is used at the Logical Link Control (LLC) layer, which is an optional component of the Data Link Layer (DLL).

The “last-mile” of an AMI comprises the communication of a data concentrator (typically placed at the secondary substation, at least, in Europe [13]) and the smart meters (placed at the customer premises), which can be seen as a Local Area Network (LAN) which is part of the so-called Neighborhood Area Network (NAN). Thus, if the communications are bounded to these devices, the use of a network protocol (i.e., IP) is not mandatory.

At the PHY layer, PRIME uses Orthogonal Frequency-Division Multiplexing (OFDM) modulation, where carriers may use different constellations allowing raw data rates up to 130 Kbps. However, in practice, manufacturers are currently implementing the most robust option, namely Differential Phase Shift Keying (DBPSK) with Forwarded Error Correction (FEC) ON, which allows a raw data rate of 21.4 Kbps.

At the MAC sublayer, two types of nodes are defined, namely: the Base Node (BN) and the Service Node (SN). The BN (which is part of the AMI data concentrator) coordinates the PRIME network, being only one per network. The SNs are the smart meters in AMI terminology and they may play just the role of Terminal (i.e., receiving commands and sending data from/to the concentrator) or they may be promoted to Switches, which are communications repeaters whose main goal is to increase coverage (i.e., they not only receive commands or send their data from/to the concentrator, but also forward the commands or data related to other SN that “hang” from them). Thus, the physical topology of PRIME networks is a bus, but the logical topology is a tree, since different levels of switches may exist, as Fig. 2 shows.

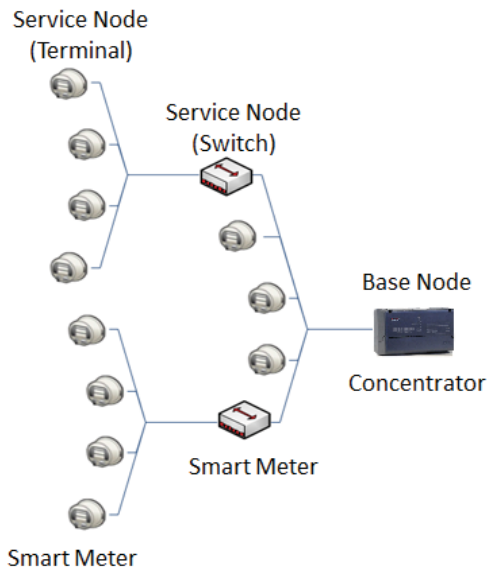


Fig. 2. Logical topology of a PRIME network. In the upper branch, PRIME terminology is used. It can be seen that a Service Node can act either as Terminal or as Switch.

As it has already been mentioned, PRIME networks are defined to be plug&play, which requires several specific mechanisms at the MAC sublayer. First, the concentrator and the switches announce themselves by means of Beacon

Protocol Data Units (BPDU) at the very beginning of a super-frame which repeats periodically every 276 OFDM symbols. If a SN that is plugged into the network hears either the beacons from the concentrator or from a switch, it just registers directly to the concentrator or through the switch. Otherwise, it sends a kind of SOS message known as Promotion Needed Protocol Data Unit (PNPDU). Whenever any SN hear such a PNPDU, they send a Promotion Request message (PRO_REQ_S) to the concentrator. Once the concentrator has received all the promotion requests, it decides to promote one of the SN that has requested so. The criteria that follows the concentrator to make such a decision are unknown and this paper focuses precisely on them.

Once the concentrator has made such a decision, it sends a notification message (PRO_REQ_B) to the selected SN. The promotion procedure does not end here, but the SN has to acknowledge the reception of the PRO_REQ_B by means of a PRO_ACK, so that the concentrator is sure that this SN will work as switch from this moment on. Then, the SN that was just plugged into the network will start receiving BPDU through the new switch and will register to the PRIME network through it. The registration procedure is also a 3-way handshake, i.e., the SN requests to register by sending a REG_REQ, if the BN accepts the registration request, it sends a confirmation to the SN along with its network parameters (e.g., ID) by means of a REG_REP, and the SN has to acknowledge the reception of such a REG_REP by means of a REG_ACK. Fig. 3 illustrates the promotion and registration procedures defined in PRIME.

In order to facilitate understanding the rest of the paper, it is worthwhile to mention that the protocol also include keep-alive messages, which work as a kind of network management mechanism.

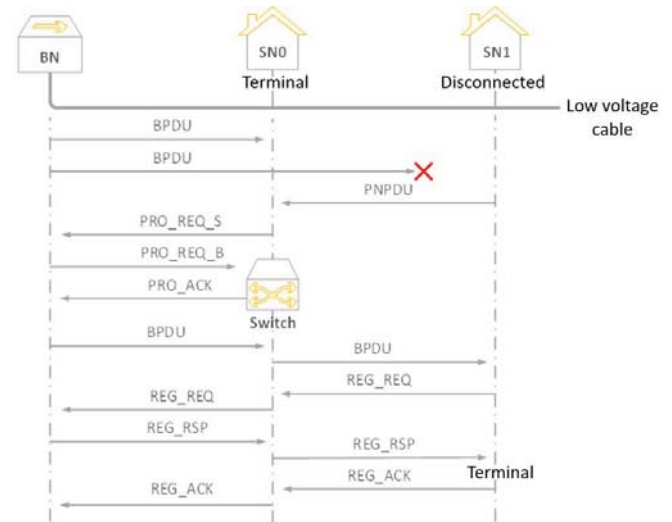


Fig. 3. Promotion and registration procedures defined in PRIME

B. Overview of SimPRIME

SimPRIME is a well-known PRIME network simulator whose operation and implementation is covered in the existing literature. Nevertheless, in this section it is briefly reviewed to try to make the paper self-contained, thus facilitating understanding the rest of the paper.

SimPRIME combines MATLAB and OMNeT++, which is a widely used event-driven open-source network simulator

[14]. Fig. 4 shows the overall functional architecture of SimPRIME.

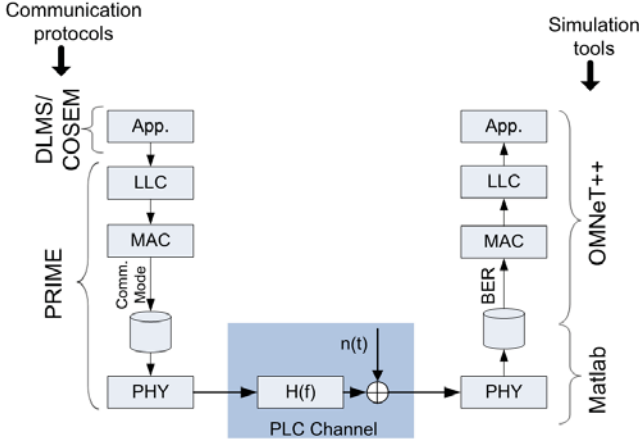


Fig. 4. Functional architecture of SimPRIME

Current version of SimPRIME allows performing two types of simulations: (1) simulations where the logical topology of the PRIME network dynamically evolves (i.e., terminals may be promoted/demoted to/from switches or they may register/deregister) based on the regular mechanisms that have just been explained in the previous section; or (2) simulations where the logical topology of the PRIME network is fixed, typically based on a standard topology file which is stored and updated by the concentrator (the so-called “S11 report”). In this paper we will be focused on (1).

In both cases, an attenuation matrix which specifies the attenuation between any pair of nodes is obtained. Fig. 5 helps better understanding such an attenuation matrix. The first row of such a matrix refers to the attenuation of the downlink communications (i.e., from the BN to the SN). In the example of Fig. 5, a message from the BN cannot reach SN[1]. It should be noted that -1000 dB is not a real value, but a fictitious value which is used to indicate that communication is not possible. The first column refers to the attenuation of the uplink communications (i.e., from the SNs to the BN). In the example of Fig. 5, any of the SN can reach the BN. The rest of the entries of the matrix refers to the attenuation between any pair of nodes. Namely, the entries above the main diagonal of the matrix refer to the attenuation for the downlink communications and the entries below the main diagonal refer to the attenuation for the uplink communications, since the SN are indexed by SimPRIME just like they appear in the low voltage cable. It should be noted that the matrix is not symmetric because the attenuation depends on the impedance [15] and the impedance a given node “sees” upwards in general is not be the same as the impedance it “sees” downwards.

Once the attenuation matrix is obtained, assuming a transmission power of -3 dBW, the Signal-to-Noise Ratio (SNR) at any other node of the network can be computed based on eq. (1), where P_N represents the baseline noise, which is assumed to be the same at every node of the network:

$$\text{SNR}(N \rightarrow M) [\text{dB}] = P_{tx}(@ \text{ node } N) - \text{Att}_{NM} - P_N \quad (1)$$

	BN	SN [0]	SN [1]
BN	-	0	-1000
SN [0]	0	-	0
SN [1]	0	0	-

Fig. 5. Example of attenuation matrix. The entries of the matrix are in dB. -1000 dB is not a real value, but a fictitious value which is used to indicate that communication is not possible.

Once the SNR is known, the Bit Error Rate (BER), associated to such a SNR and the constellation in use, can be obtained from the BER vs SNR curves which are pre-computed for each constellation using MATLAB. Once the BER is known, the Frame Error Rate (FER) is computed based on eq. (2), which assumes independency between the probability of error of each bit:

$$\text{FER} = 1 - (1 - \text{BER})^{\text{packet_length}} \quad (2)$$

It should be noted that this is indeed a simplification, since in practice the relationship of the BER with the FER depends on the modulation and is not the same in the header as in the payload (typically more robust modulation schemes that allow lower data rates are used in the header).

The FER is the input to the upper layers, which are modelled in OMNeT++. Regarding OMNeT++, it is worthwhile to mention that there are three types of files:

- .ini: to configure the simulations
- .ned: to define modules and their relationships
- .cpp: to define the functionality of the modules

III. PROPOSED POLICIES AND IMPLEMENTATION

A. Proposed policies

In order to figure out the policies that can be applied in the concentrator to decide the SN that promotes to switch, first we have to figure out which are the parameters that may influence such a decision. For our proposal, we have considered:

- The latency in the communications.
- The jitter, which is the standard deviation of the latency and represents a key figure of merit for real time communications.
- The SNR.
- The communication mode, which depends on the coding scheme and the FEC mode used and is indeed related with the SNR, since, for a given SNR, PRIME looks for the combination between coding scheme and FEC mode that yields the lowest BER.
- The logical topology of the network, which influences the number of hops (and so retransmissions) for the communication between the BN and a given SN.

The proposed promotion policies are as follows:

- First Come First Serve (FCFS) / Last Come First Serve (LCFS): The BN grants the promotion to the first or last PRO_REQ_S that receives respectively.
- Round Robin: The BN selects the SN that promotes to switch randomly. This policy may be used as reference to check whether making the decision based on a given criterion makes a difference or not.
- Round robin with memory: This policy is related with the idea that a SN that requests promotions many times and is not promoted may be a good candidate since it is well-connected. Thus, in this case the BN will make the decision randomly, but the probability distribution will not be uniform, but the more time a SN has requested to be promoted, the higher its probability to be chosen at a given moment in time.
- SNR: The metric used by the BN to grant the promotion in this case is the SNR. Hence, there are two possibilities: promoting either the SN that has the highest SNR with the BN or the SN that has the highest SNR with the unconnected SN which has sent the PNPDU.
- COST: The BN will promote the SN based either on the cost of the uplink (UPCOST), or on the cost of the downlink (DOWNCOST) or on the mean cost of both ways (MEANCOST). Table I shows the COST as defined in the PRIME standard, which depends on the coding scheme and FEC mode, as has already been said. The lowest cost will determine the selection of the SN, since it means the fastest transmission. It should be noted that in PRIME the total cost of the communication between a SN and the BN is the sum of the cost of each of the logical hops involved.

TABLE I. COST DEFINED IN THE PRIME STANDARD [1]

CS/FEC mode	COST
8PSK/FEC OFF	0
QPSK/FEC OFF	1
BPSK/FEC OFF	2
8PSK/FEC ON	1
QPSK/FEC ON	2
BPSK/FECON	4

- Latency: The BN stores the latency with each SN each time they exchange keep alive messages. In this policy, the BN will select the SN with the lowest latency in average from the list of SN that have requested promotion.
- Jitter: In this policy, the BN select, from the list of SN that have requested promotion, the SN with the lowest standard deviation of the latency.

B. Implementation in SimPRIME

In order to implement the proposed policies in SimPRIME, the associated functionality needs to be included in the .cpp file of the BN (e.g., by using a switch statement) and a parameter needs to be defined in the .ini so that we can choose the policy to be applied in each set of simulations from the configuration file.

All the proposed policies have been implemented in SimPRIME, except from the Round Robin with memory policy, which has been left as future work.

In order to implement the functionality in the BN, first it should be noted that a listening window is defined in the BN. Such a listening window represents the time that the BN is listening to PRO_REQ_S. Thus, for a given promotion procedure, the listening window starts when the first PRO_REQ_S from a given disconnected SN is received and ends after a configurable period of time. Once the listening windows ends, the BN executes the promotion policy selected in the configuration file (.ini).

In the case of FCFS/LCFS policies, the promotion depends on the order of the received PRO_REQ_S. In the case of the Round Robin policy, a SN is selected randomly from all the SNs that have requested promotion in this listening window. In the case of SNR and COST policies, the decision is based on information which is contained in the received PRO_REQ_S, so such messages are processed upon reception to obtain the metric that will be used in each case. Finally, for the Latency and Jitter policies, the BN has to process the information that gathers by means of the keep alive mechanism. So, based on this management mechanism, it records a vector associated with the communications with each SN that stores end-to-end latency or Round Trip Time (RTT). If the policy is Latency, the BN computes the mean latency of all the candidates based on its own records and promotes the SN with the lowest latency. If the policy is Jitter, the BN computes the standard deviation of the latency of all the candidates based on its own records and promotes the SN with presents the lowest value.

IV. PRELIMINARY EVALUATION AND RESULTS

A. Evaluation setup

In order to perform a first evaluation of the proposed policies, an actual PRIME scenario has been selected from the literature [16]. The selected scenario is an actual PRIME network deployed in Barranquilla (Colombia), which is composed by a BN and 7 SN. It is a small PRIME network, which has pros and cons. On the one side, it facilitates the configuration of the simulation, the debugging of possible problems, and the interpretation of the results. On the other side, it is not such a representative scenario, so more simulations considering different scenarios may be needed to draw significant conclusions.

Fig. 6 shows the attenuation matrix for this scenario. The size of the scenario allows identifying clearly that the BN will not be able to directly communicate with the SN[2] in the downlink and that the SN[5] will not be able to communicate with the BN in the uplink. Therefore, switches will be needed, and so promotion procedures are guaranteed.

	BN	SN [0]	SN [1]	SN [2]	SN [3]	SN [4]	SN [5]	SN [6]
BN	-	- 8	- 48	- 1000	- 58	- 72	- 77	- 75
SN [0]	- 20	-	- 39	- 1000	- 69	- 69	- 70	- 67
SN [1]	- 60	- 39	-	- 1000	- 1000	- 50	- 65	- 78
SN [2]	- 78	- 63	- 69	-	- 72	- 1000	- 36	- 52
SN [3]	- 60	- 59	- 69	- 77	-	- 1000	- 77	- 69
SN [4]	- 76	- 60	- 38	- 1000	- 1000	-	- 1000	- 1000
SN [5]	- 1000	- 55	- 54	- 43	- 1000	- 1000	-	- 63
SN [6]	- 76	- 62	- 71	- 59	- 69	- 1000	- 70	-

Fig. 6. Attenuation matrix for the actual scenario considered for the evaluation of the proposed policies. The entries of the matrix are in dB.

B. Analysis of results

Table II shows the IDs that are assigned to the implemented policies for the simulations.

TABLE II. IMPLEMENTED POLICIES AND IDs USED IN THE SIMULATIONS

Policy	ID
FCFS	1
LCFS	2
RR	3
UPCOST	4
DNCOST	5
MEANCOST	6
JITTER	7
LATENCY	8

The first experiment that has been simulated represents the regular operational procedure where the concentrator polls each of the smart meters of the PRIME network to obtain their hourly consumption report (the so-called “S02 Report”). The metric used to evaluate the impact of the promotion policy in place is the time that the concentrator needs to retrieve such a hourly consumption report from all the smart meters of the network (so-called TTRall).

Fig. 7 shows the obtained results, the vertical axis representing a box and whisker plot of the TTRall (in seconds) and the horizontal axis representing the promotion policy. As it can be seen, there are no significant differences in the obtained results, which may be due to the reduced size of the considered PRIME network.

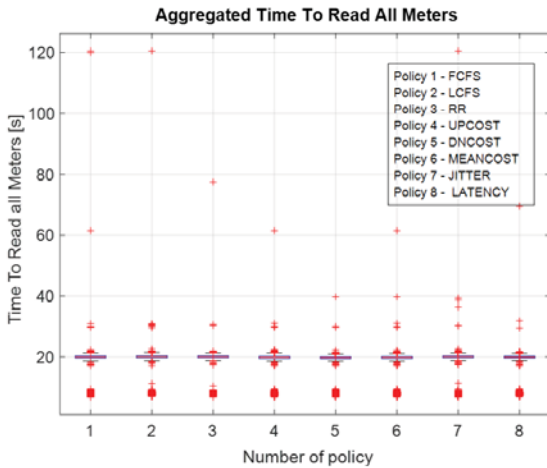
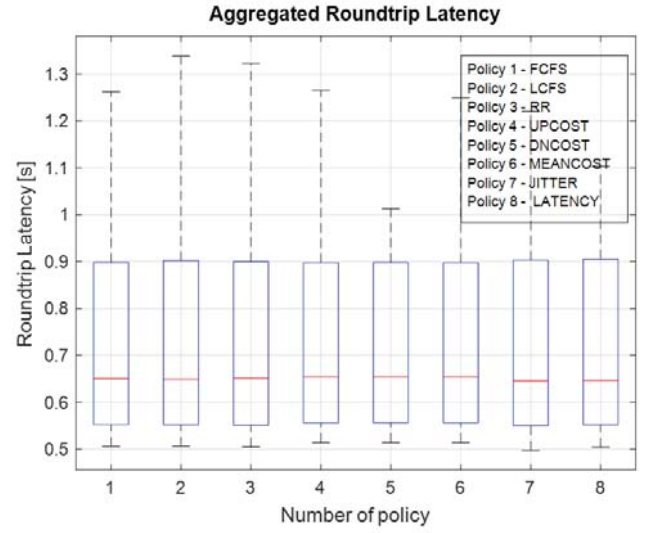
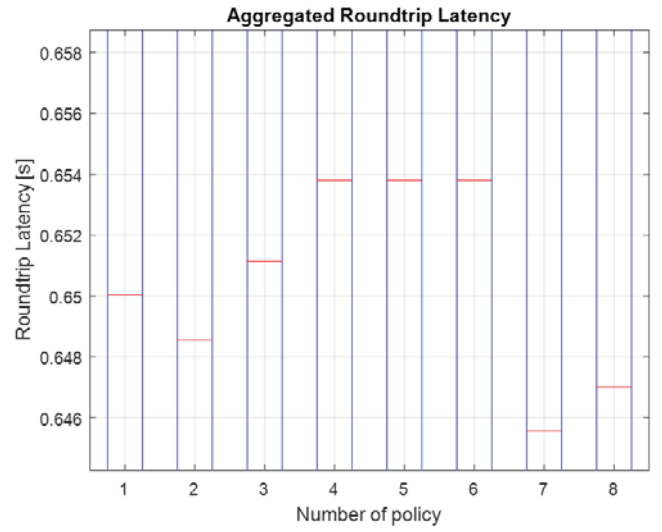


Fig. 7. TTRall vs promotion policy



(a)



(b)

Fig. 8. (a) RTT vs promotion policy; (b) Zoom in to the vertical axis (RTT)

The second experiment simulates the same situation, but paying attention to the RTT, which is the difference in time from the request sent by the concentrator to each smart meter to the response of such a smart meter that contains the hourly consumption data. Fig. 8(a) shows the obtained results, the vertical axis representing a box and whisker plot of the RTT (in seconds) and the horizontal axis representing the promotion policy. Again, there are no significant differences in the obtained results, although, if we zoom in the figure (Fig. 8(b)), we can see that the policies that yield the best results (in the order of ms) are the ones that consider latency and jitter. Nevertheless, since the differences are small, it would be reasonable selecting the policy that requires less computational complexity, which is the FCFS policy.

V. CONCLUSIONS AND FUTURE WORK

PRIME technology is widely used in the last mile of AMI. The specification leaves some procedures open in order to promote competency and innovation. This paper focuses on the promotion procedure, which allows increasing the coverage and improving the quality of the

communications, as well as that the PRIME-compliant smart meters are plug&play, thus representing a key procedure in PRIME networks.

However, neither the specification says nothing about which criteria can be applied at the concentrator to choose the most appropriate SN to become a switch from the list of candidates nor this issue has been addressed from this perspective in the literature yet.

Thus, as one of the main contributions of the paper, we propose a set of promotion policies that may influence the overall performance of the PRIME network. In addition, we also carried out a preliminary evaluation of the proposed policies based on an actual scenario from the literature in order to illustrate the potential of the PRIME network simulator SimPRIME to gain knowledge of this kind of procedures in a cost-effective way.

As future work, we plan to simulate other representative scenarios (e.g., high density residential areas and low density residential areas [17]) under different conditions (e.g., with or without impulsive noise or with the presence of other well-known sources of noise [18], [19]) in order to go deep on the influence of the promotion policy on the overall performance of the PRIME network. In addition, we also plan to implement the Round Robin with memory policy for future simulations.

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