Performance assessment of the PRIME MAC layer protocol

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Abstract—The PRIME (PoweRline Intelligent Metering Evolution) protocol is a very popular multicarrier narrowband PLC protocol that fits the needs of advanced metering infrastructure applications. This paper proposes a performance assessment of the PRIME MAC layer protocol obtained through OMNeT simulations in different scenarios. The contribution of the paper is twofold. The first contribution is an approach to overcome a well-known problem of discrete-event simulators, i.e., the fact that they do not provide functionalities to emulate the continuous effects of signal propagation. To solve this problem, in this paper the channel is modeled based on measurements, made on real testbeds, so our simulator embeds data taken from experiments performed in a real scenario. The second contribution is the assessment of the impact of the modulation scheme on the performance of the PRIME protocol.

Keywords—Powerline communications; PRIME protocol; Performance evaluation; OMNeT Simulation.

I. INTRODUCTION AND RELATED WORK

Powerline Communications (PLCs) are promising candidates for automation applications such as smart homes integration, distributed generation plant management, advanced metering, that can benefit from the ability of transmitting data over already deployed power lines, without requiring new network infrastructures and thus reducing deployment costs.

PLC technologies can be classified into two classes [1], i.e., broadband and narrowband. Broadband PLCs are designed for Home Area Networks (HANs), operate in the frequency range [1.8–250] MHz and have a high data rate (up to several hundred megabits per second). On the contrary, narrowband PLCs are designed for Neighbor Area Networks (NANs), operate in the [3-500] KHz frequency range with a data rate from tens of kbps up to 500 kbps and can cover long distances without repeaters. The growing interest in narrowband multicarrier PLC technologies is leading industries to support protocols such as PRIME (PoweRline Intelligent Metering Evolution) [2] and PLC G3 [3]. Both operate in the CENELEC A-Band, from 3 kHz up to 95 kHz, that is reserved to electricity distributors and their licensees. The PRIME protocol is well suited for advanced metering infrastructure applications, which require a two-way communication between customer utility meters and utility companies for load monitoring and billing purposes, as it allows for long distance coverage. PRIME provides a hierarchical topology in which a Base Node is the network coordinator and is able to self-adapt to the network operating condition by means of dynamic promotion (and demotion) of the terminal nodes to the switch node role. The protocol supports three modulations (DBPSK, DQPSK and D8PKS) with or without Forward Error Correction.

Several works exists in literature which address PLCs and their application to energy management. In [8] and [9] clock synchronization protocols in narrowband PLCs are proposed, while in [10] an experimental characterization of latency over broadband PLCs in medium voltage networks is presented. The works [11] and [12] addressed the performance of the PRIME physical layer, while MAC-layer adaptive backoff algorithms for narrowband PLCs were investigated in [7]. In [14] a simple industrial automation system that tunnels Modbus commands over PRIME is proposed, while in [15] a measurement system based on a software-defined radio platform is presented.

This paper proposes a performance assessment of the Media Access Control layer of the PRIME protocol through OMNeT simulations in different scenarios. The aim is to assess the impact of the modulation scheme on the performance. To solve the problem that OMNeT is a discrete-event simulator and so it cannot emulate the continuous effect of signal propagation, here the channel is modeled based on measurements made on real testbeds. In particular, our simulator embeds the results of experimental measurements of the Bit Error Rate (BER) as a function of the Signal to Noise Ratio (SNR) performed on a real PLC network.

The paper is organized as follows. Sect.II provides an overview of the PRIME protocol, while Sect. III describes the characterization of the powerline channel model used in this work. Sect. IV addresses both the simulation setup and the simulation model here adopted, while Sect. V shows the performance obtained in two different scenarios. Finally Sect. VI concludes the paper and gives directions for future work.

II. PRIME PROTOCOL OVERVIEW

The PRIME protocol is supported by the PRIME Alliance and was published in October 2012 as Recommendation ITU-T G.9904 [4]. The protocol stack (shown in Fig. 1) is composed of three layers, i.e., the *Convergence Layer* (CL), the *Media Access Control* (MAC) layer and the *Physical* (PHY) layer.

The Convergence Layer classifies traffic associating it with its proper MAC connection. The CL maps any kind of traffic to be included in the *Mac Service Data Units* (MSDU), i.e. the primitives for MAC layer communication. The CL includes the *Common Part Convergence Sublayer* (CPCS), that provides generic services to the MAC Layer, such as segmentation and reassembly, and the *Service Specific Convergence Sublayer* (SSCS), that provides a mapping between the MSDUs and several communication profiles, such as, IPv4, IPv6, IEC-432, etc. The MAC layer is the core layer of PRIME and provides functionalities like connection management, channel access and network topology management. The Physical layer is in charge of transmitting and receiving the PDUs using the Orthogonal Frequency Division Multiplexing (OFDM) modulation.

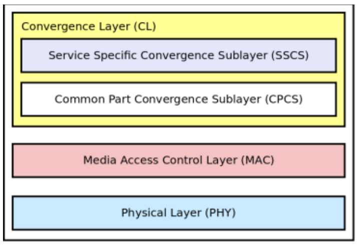

Fig. 1. PRIME Layers

A. *Physical Layer*

The PRIME PHY layer uses the frequency band from 41.992 kHz to 88.867 kHz, with an OFDM modulation in which the signal is loaded on 97 equally spaced subcarriers and transmitted in symbols of 2240 microseconds. Three modulations, i.e., DBPSK, DQPSK and D8PKS are provided, with the possibility of adding FEC. Table I shows the values of the raw data rate associated with each modulation schema [2].

TABLE I. RAW DATA RATES (Kb/s)

FEC	DBPSK	DQPSK	D8PSK
On	21.4	42.9	64.3
Off	42.9	85.7	128.6

B. *Media Access Control Layer*

The PRIME network is logically organized according to a tree topology, which consists of two kinds of nodes:

- Base Node (BN): This node is the root of the tree and the network coordinator and manages resources and connections. There is only one BN in the network, and such a node is in charge of generating a Beacon PDU that is used for node synchronization and discovery.
- Service Nodes (SNs): These nodes are the leaves and branch points of the logical topology. They can be promoted by the BN to become Switch nodes.

When the SNs are promoted by the BN and become Switch nodes, they also take the task of forwarding the traffic of the nodes that belong to their network branch. Switch nodes are also in charge of sending Beacon PDUs that are used for synchronization and discovery purposes.

The medium access policies assume that time is partitioned into slots, called MAC Frames (Fig. 2), which have a duration of 276 symbols and are cyclically repeated. The MAC Frame starts with a beacon transmitted by the BN. The MAC frame comprises three periods, i.e., the *Beacon Period* (BP), the *Shared Contention Period* (SCP) and the *Contention Free Period* (CFP). The BP is partitioned into slots of the same length (4 symbols). In the first slot, the Base Node transmits a Beacon PDU (BPDU) that is needed for node synchronization and discovery. Subsequent slots are allocated to Switch nodes for transmitting their BPDUs. Slot allocation is done during the promotion phase. Each BPDU contains the SubNetwork Address (SNA) of the transmitter node, the relevant level in the network, the duration of the BP, and the start symbol of the CFP. Switch nodes transmit this PDU to reach their child nodes and their transmission frequency can be lower than that of their parent nodes. According to PRIME specifications [2], to ensure the maximum possible node coverage and transmission success probability, the BPDU is always transmitted using the most robust modulation available, i.e. DBPSK with Forward Error Correction, and the highest transmission power (Maximal Output Level, MOL). When the BP has finished, the SCP starts. During the SCP, nodes transmit using a prioritized CSMA/CA algorithm with four priority levels.

Fig. 2. PRIME MAC Frame Structure

This algorithm calculates the backoff time (called *macSCPRBO)*, i.e., the amount of time to wait before querying the channel state and transmitting data [2], expressed as an integer that represents the corresponding number of symbols and defined as in (1)

$$macSCPRBO = random(0, \min((2^{(priority+txAttempts)} - 1), (scpLength/2))) \quad (1)$$

where priority is an integer from 0 to 3 that represents the priority of the transmitted data (being 0 the highest priority), txAttempts is a counter of the actual number of transmission attempts made to find the channel free and scpLength is the duration in symbols of the SCP. It is known that in CSMA/CA algorithms when the number of nodes that try to transmit at the same time is high, there is a high probability that the maximum number of attempts allowed before aborting the transmission of a PDU (maxTxAttempts) is reached. This behavior, already observed in other protocols such as the IEEE 802.11e [13], is also found in PRIME.

The Contention Free Period (CFP) is an optional period during which nodes can be allocated channel time to transmit or receive without contention. Allocation is made through an explicit request issued from the Service Nodes. In a multilevel network in which there are Service Nodes not directly connected to the Base Node, the latter shall allocate time in the CFP to all the intermediate Switch Nodes, so as to allow transmission without contention along the entire transit path followed by a PDU to reach the Service Nodes.

C. *MAC Procedures*

At the network startup, the Base Node periodically transmits its BPDU. A disconnected Service Node that receives the beacon may decide to join the network starting a registration procedure. If a SN does not receive any BPDU for a *macMinSwitchSearchTime*, it starts sending a Promotion Need PDU (PNPDU) to its neighbor nodes (the PNPDU can be sent either broadcast or to a Service Node). Disconnected SNs are not synchronized with the network, so they can send PNPDUs at any time with a high collision probability. Upon receiving a PNPDU, a Service Node starts the promotion procedure and requests the BN to be promoted to Switch Node. The Switch Node role is needed for routing. After the registration, all nodes can start the connection process to transmit to, or receive data from, the BN. Moreover, the PRIME specifications [2] provide direct connections for communication between Service Nodes. In this case, data are transmitted to the first common Switch Node, which forwards them to the destination.

III. POWERLINE CHANNEL

The Powerline channel is a very harsh and noisy medium, that is very difficult to model. Due to the time-varying behavior, noise, and multipath fading, each network segment has a different behavior [1]. Many studies have been made to characterize the channel. In [5] a parametric multipath model is proposed, whose frequency response *H(f)* is shown in (2),

$$H(f) = \sum_{i=1}^{N} g_i \cdot A(f, d_i) \cdot e^{-j2\pi f \tau_i} \quad (2)$$

where

- i is the index of the *i-th* path.
- N is the number of paths.
- g_i is the weighting factor for the *i-th* path.
- τ_i is the delay of the *i-th* path.
- $A(f,d_i)$ is the attenuation, which increases with both frequency (f) and path length (d), and is characterized by

$$A(f, d) = e^{-\alpha(f)d} \quad (3)$$

where $\alpha(f)$ is the attenuation factor and can be approximated in the form

$$\alpha(f) = a_0 + a_1 f^k \quad (4)$$

In (3) a_0, a_1 are the attenuation parameters and k is the exponent of the attenuation factor. From (2), (3) and (4), the final version of the frequency response is given as in (5) [5]

$$H(f) = \sum_{i=1}^{N} g_i \cdot e^{-(a_0 + a_1 f^k) d_i} \cdot e^{-j2\pi f \tau_i} \quad (5)$$

With this approach, in order to estimate the frequency response of the model, experimental measurements on the network segment under study are needed to find suitable values for the parameters in (5). To simplify the model, in [5] the concept of length profiles is proposed (i.e., attenuation profiles based on distance not considering the notches caused by the properties of the branches). With such a simplification, in (5) N and g are set to 1, while a0, a1, and k are determined from measurements [5]. The model in [5] is largely adopted in the literature [1][7] and is also suitable for our purposes, as here what is important is to assess whether the nodes ''hear'' each other and whether the exchanged data are correctly received or not. For this reason, in our simulation the signal attenuation was calculated based on length profiles, using (5).

IV. SIMULATION SETUP

The PRIME performance was evaluated using OMNeT++ [6], a widely-used discrete event simulator framework. Unfortunately, OMNeT++ does not provide functionalities to simulate the continuous behavior of signal propagation, i.e., modulation, noise and attenuation models. To overcome this problem, in our study we embed in the simulation model the results of measurements performed on a real testbed. What we assessed was, in particular, the Bit Error Rate (BER) as a function of the Signal to Noise Ratio (SNR). The measurements were made with the aim of obtaining real BER values to be associated to the various SNR values for all of the modulations foreseen in the PRIME specifications.

As mentioned before, the PRIME protocol supports three modulations, with additional FEC, which nodes select according to the channel noise conditions. For instance, DBPSK with FEC modulation is the most robust against noise, but has a low data rate (21.4 Kb/s), while D8PSK has a higher data rate, but is more error-prone.

A. Channel measurements

In order to perform the measurements of the BER as a function of the SNR, a suitable testbed, with two PRIME nodes, has been deployed. The testbed, which is shown in Fig. 3, included:

- A 200 meters long line segment;
- 5 connection points located 50m from each other;
- One signal generator (Agilent 33220A) used to inject Gaussian noise in the channel;
- One oscilloscope;
- 2 demo boards compliant with the PRIME protocol (EvalST7590).

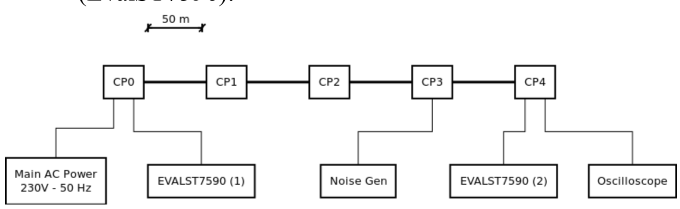

Fig. 3. Testbed diagram.

The measurements were taken in different noise scenarios and with different modulations, using a software, called PRIME GUI, provided by STMicroelectronics, that allows to communicate directly with the physical layer, disabling the upper layers. SNR is obtained using the *PHY_SNR.get/confirm* primitive, which returns a 3-bit value indicating the measured SNR of the last packet. The SNR ranges are mapped on eight values, as shown in Tab. II [2].

To evaluate the BER, a random payload of 377 bytes was transmitted. The received data were then compared with those transmitted to quantify the number of bits that experienced an error. For each measurement campaign, up to 100 Physical layer PDUs were transmitted, using all the power levels allowed and in various noise conditions.

TABLE II. SNR MAPPED VALUES

SNR (dB)	Mapped Value
SNR ≤ 0	0
0 < SNR ≤ 3	1
3 < SNR ≤ 6	2
6 < SNR ≤ 9	3
9 < SNR ≤ 12	4
12 < SNR ≤ 15	5
15 < SNR ≤ 18	6
SNR > 18	7

Figs.4 (a) and 4(b) plot the obtained BER versus the SNR for the three modulations provided by the PRIME specifications, with and without FEC, respectively. As shown in the graphs, the BER values decrease with increasing SNR values, but with significant differences between different modulations. For instance, the D8PSK without FEC suffers from the highest BER, showing BER values in the range of 4.687 x 10^{-5} with SNR=7 (i.e., for SNR values greater than 18 dB, as shown in Table II). Although combining D8PSK with FEC slightly improves the BER, there is still a BER in the order of 10^{-6} for SNR=6, whereas all the other modulation schemes with FEC show negligible BER values for SNR values greater than 5. In particular, the DBPSK with FEC outperforms all the other modulation schemes, as the BER becomes negligible for SNR values greater than 4. The values obtained from these measurements were fed into our simulation model, so as to use realistic (SNR, BER) pairs.

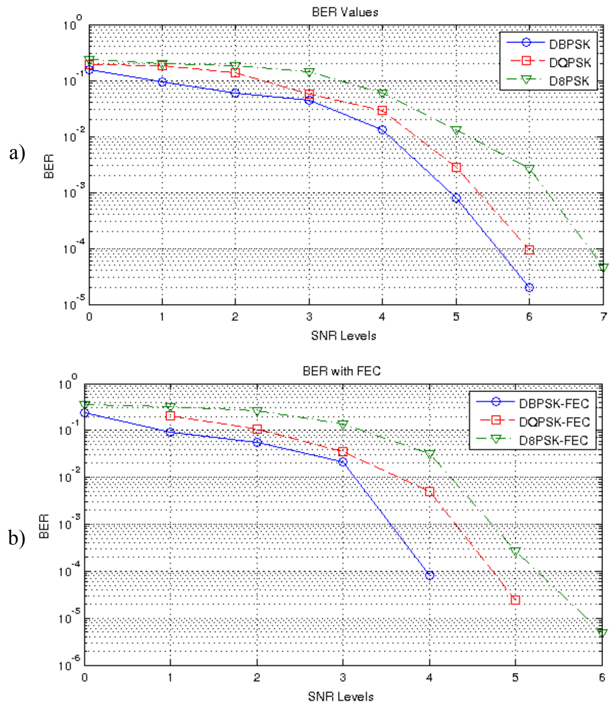

Fig. 4. BER measured values

B. Channel model

The implementation of a detailed channel model is beyond the scope of this paper, as our target here is only to evaluate the MAC layer behavior. However, an approximate channel model is needed to emulate the channel properties that have an impact on the MAC Layer, i.e., the nodes visibility and the BER. The simulated PLC channel is implemented as a module which contains the distances between nodes and the measured BER values for each modulation scheme obtained with our testbed. Signal attenuation is calculated for each node based on length profiles using formula (5), as proposed in [5]. Some of the activities that are generally performed at the physical layer (e.g., by transceivers), in the simulator are provided by the channel module. When a packet arrives, the channel module reads the transmitted power, calculates the attenuation, subtracts to it the noise level (both power signal and noise are expressed in dB) and then calculates errors, collisions, and delays. Finally, the channel module sends the packet to all the connected nodes.

C. PRIME node model

The PHY and MAC layers were modeled following the PRIME specifications [2]. In particular, the MAC Layer provides the following features: switching capability, Contention Free Period capability, and support for retransmission of control packets. As the aim of the paper is comparing the network performance obtained using each modulation schema, the PHY Robustness Management functionality [2] was not implemented. The PLC interface is composed of three simple modules, i.e., the PHYLayer, the CSMAModule, and the MACLayer module. The latter models the following processes: node promotion/demotion, node registration, connection establishment, and Keep-Alive. Finally, the NULLConvergence Sublayer was implemented, that performs a direct mapping on the MAC primitives, thus providing the MAC layer with a transparent path to upper layers [2].

V. SIMULATION SCENARIOS AND RESULTS

This section proposes an evaluation of the PRIME protocol obtained by OMNeT++ simulations in two different scenarios. In the first scenario, the performance of the different modulation schemes, in terms of throughput, packet delivery ratio and mean end-to-end delay, as a function of the number of nodes are compared. In the second scenario, the most robust modulation, i.e., DBPSK with FEC, is set, and the effect on the mean end-to-end delay of a two-level network under a varying workload is observed.

A. Modulation schemes comparison

Throughput is obtained as the overall number of packets received by the Base Node in a simulation run (i.e., in 1 hour) during which all the Service Nodes transmit periodic traffic to the BN. In this scenario all nodes are located 100m apart from each other. They periodically generate 32 byte data packets every 2s. In order to evaluate the protocol behavior, no noise is present, therefore the SNR is calculated considering only the transmitting power and the attenuation of the transmission medium. The network workload at the Application level is calculated as in (6),

$$workload = \frac{P_{size} \times (N-1)}{TxPeriod} \quad (6)$$

where P_{size} is the size of the generated packets (in bit) also including the overhead introduced from the MAC layer (13 bytes), N is the number of nodes (we use N-1 in the formula as the Base Node does not generate application workload), and *TxPeriod* is the packet generation period. We measured the MAC layer throughput. The simulation results are shown in Fig. 5.

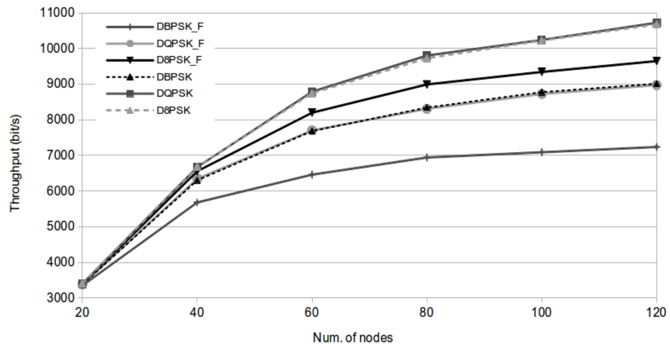

Fig. 5. Throughput vs. the number of nodes.

Throughput is strongly influenced by the CSMA/CA algorithm, as the bandwidth utilization efficiency, i.e., the ratio between the maximum throughput and the available bandwidth, is in the range of 33.82% (for DBPSK-FEC) and 8.30% (for D8PSK). Table III shows the generated workload for each simulation increasing the number of service nodes.

TABLE III. GENERATED WORKLOAD FOR EACH SIMULATION RUN

Num. of nodes	20	40	60	80	100	120
Workload (Kbit/s)	3.42	7.02	10.62	14.22	17.82	21.42

Fig. 6 shows the packet delivery ratio, i.e., the ratio between the number of correctly received packets and the number of generated packets.

In Fig.6 the DBPSK modulation with FEC largely outperforms the others, with more than 70% of correctly received packets under the highest workload. The second best result, that is slightly more than 50%, is achieved by DBPSK without FEC, that performs as well as DQPSK with FEC (in fact, in Fig.6 they overlap). Fig. 6 therefore provides quantitative evidence of the superiority of the slowest modulation over the others in terms of robustness. In order to compare the modulation schemes, the packet generation periods were set so as to maintain constant, i.e., "normalized", the ratio between the workload and the available bandwidth for each modulation, as in (7):

$$\frac{workload}{Bandwidth} = 0.0957 \quad (7)$$

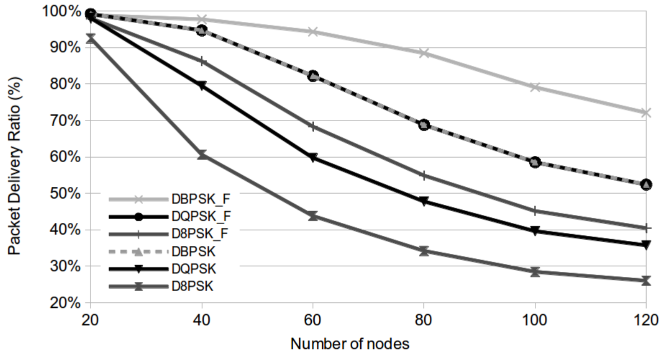

Fig. 6. Packet delivery ratio vs. the number of nodes.

Table IV shows the generation periods for each modulation scheme.

TABLE IV. GENERATION PERIOD FOR EACH MODULATION SCHEME

Modulation Scheme	TxPeriod
DBPSK-FEC	5s
DQPSK-FEC	2.49s
D8PSK-FEC	1.66s
DBPSK	2.49s
DQPSK	1.25s
D8PSK	0.83s

Fig. 7 shows that the bandwidth increase obtained changing the modulation scheme (e.g. from DPBSK-FEC to D8PSK) does not compensate for the number of packets dropped due to exceeding the maximum transmission attempts during the contention phase. Moreover, the figure shows that the number of collisions is not influenced by the modulation. In order to reduce packet loss both the maximum number of retransmissions allowed and the size of the contention window for the CSMA/CA algorithm should be increased.

We also assessed the end-to-end delay, here defined as the time taken by a packet from source to destination measured at the Application layer. In this test nodes transmit 64 byte data packets, with a period of 10s for the minimum workload of 1.17 Kbit/s (20 nodes) to the maximum of 8.56 Kbit/s (140 nodes). This choice is made to not overload the network, so as to allow high delivery ratio and avoid the network saturation when the number of nodes grows. Fig. 8 shows the mean end-to-end delays for each modulation scheme.

Fig. 8 shows that the largest delays are obtained by the DBPSK with FEC, while the other modulation schemes have quite close trends. Under the highest workload, the lowest mean delay (i.e. 0.073s) is obtained by the D8PSK modulation without FEC. It is worth noticing that the DQPSK without FEC

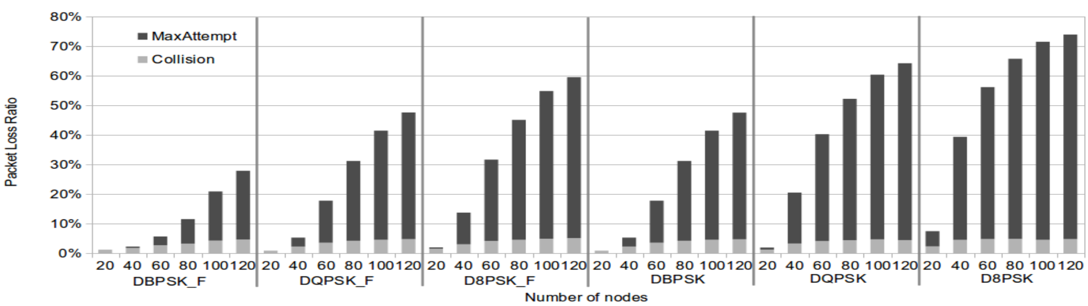

Fig. 7. Packet Loss Ratio (for each modulation scheme) vs. the number of nodes.

performs almost as well as the D8PSK. The mean delay obtained by all the other modulation schemes does not exceed the 0.146s.

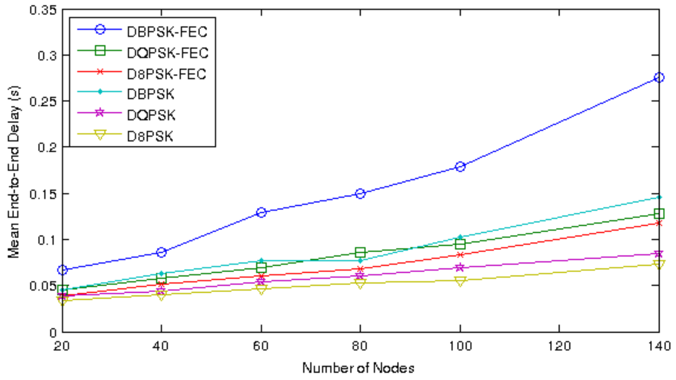

Fig. 8. End-to-End delay vs. the number of nodes.

B. *Two-level network*

In this simulation a realistic scenario of advanced metering application with a two-level network is evaluated. The network has the topology shown in Fig. 9.

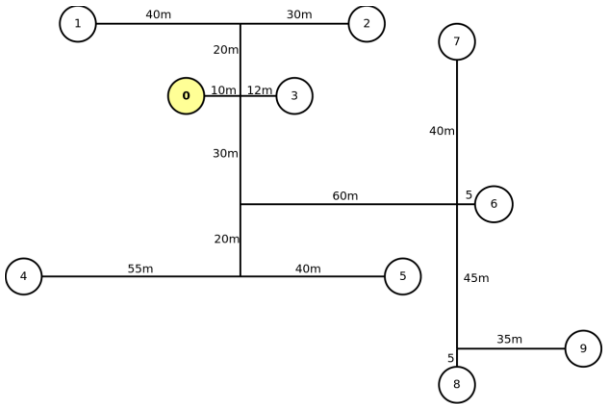

Fig. 9. Simulated Network Topology

All the Service Nodes periodically transmit 32 byte metering data to the Base Node, i.e. Node 0. In this scenario, Service Nodes 7, 8 and 9 are placed quite far from the Base Node and the noise level is set to 110 dBuV. This setting has been chosen to make sure that SNs 7, 8 and 9 do not receive any BPDU from the Base Node. As a result, they have to start a Promotion procedure that makes SN 6 promoted as switch. Consequently, SNs 7, 8, and 9 communicate with the BN through the Switch Node 6. In this scenario, three packet types are defined. They are: data packets, which contain sample data acquired by sensors; acknowledged control packets, that require retransmission if the transmitter does not receive an acknowledgement within a certain time; unacknowledged control packets, which do not need retransmission. In order to improve the network performance, these packets are transmitted with different priorities, as specified in Table V.

TABLE V. PACKET PRIORITY

Data Classes	Priority
Data Packet	3
Control Packet with ack	2
Control Packet without ack	1 (highest priority)

The results in this simulation refer to one hour of network operation. We evaluated the end-to-end delay using the DBPSK modulation scheme with FEC, which represents the worst option for end-to-end delay, as this modulation features the lowest data rate. Moreover, in our simulation we varied the transmission periods so as to decrease the network workload from 3.24 Kbit/s (with a 1s transmission period), to 324 bit/s (with 10s transmission period). Results are plotted in Fig. 10, which shows to what extent the mean delays in a multilevel network are higher than in a single level one, due to packet

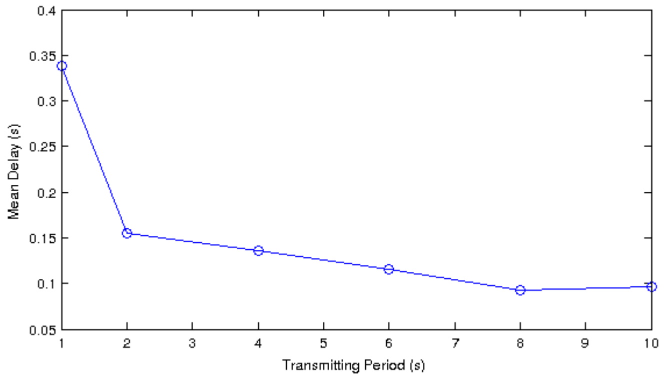

Fig. 10. Mean end-to-end delay

retransmissions from the Switch node. The delay significantly grows with transmission periods below 2s, as the duration of the contention period increases with the workload.

VI. CONCLUSIONS

This paper analyzed the performance of the PRIME protocol MAC layer, comparing the results obtained using the different modulations provided by the protocol specifications.

The contribution of the paper is twofold. The first contribution is an approach to overcome a well-known problem of discrete-event simulators, i.e., the fact that they do not provide functionalities to emulate the continuous effects of signal propagation. To solve this problem, in this paper the channel is modeled based on measurements, made on real testbeds, which provide the Bit Error Rate (BER) as a function of the SNR (Signal to Noise Ratio) for the different modulations provided by the PRIME protocol. To simulate the nodes visibility, signal attenuation was emulated using a model largely adopted in the literature which, once fed with real data, allows for quite accurately assessing the factors that impact on the MAC layer performance. The approach proposed in this paper can be also applied to other narrowband powerline protocols.

The second contribution of the paper is represented by the comparison results, which are useful to assess the worst and the best working conditions for the network as well as the impact of the modulation scheme on the performance, thus providing valuable insights for sizing the network and tuning the protocol parameters. Simulation results showed that under a high workload the MAC policies significantly affect the performance independently of the modulation scheme adopted.

In particular, our results showed that throughput is strongly affected by the CSMA/CA algorithm. While the best packet delivery results were obtained by the slowest modulation, which therefore proved to be the most robust one, the number of collisions does not depend on the modulation. Our results showed that a higher data rate is not enough to avoid the packet loss due to either collisions or too many failed transmission attempts. As a result, the only way to reduce packet loss is to increase both the contention window size for the CSMA/CA algorithm and the maximum number of retransmissions allowed. As far as delays are concerned, under the same (normalized) workload, no significant differences between the modulation schemes here considered were found.

Future work will therefore address improvements of the CSMA/CA algorithm, such as, dynamic adaptation of both the contention window size, like in [13], and the maximum number of retransmissions, and specific applications.

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