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Heterogeneous Networks for Smart Metering – Power Line and Radio Communication

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***Abstract*—In this paper, the radio wireless communication and the narrowband power line communication are analysed, simulated and experimentally verified for Smart Metering systems. This is followed by the proposal of a heterogeneous network, which consists of wireless radio transmission and narrowband power line communication (PLC). In rural and remote areas, due to the low population density and the poor familiarity with new technologies, the heterogeneous radio-PLC network offers a solution for smart grid and smart metering applications.**

***Index Terms*—Power distribution lines, Smart grids, radio communication, simulation, measurement.**

I. INTRODUCTION

The Smart Metering is considered as one of the important research field for the Smart Grid solution. For this field it is essential to have appropriate communication channels. There is no doubt that the Smart Grid will exploit multiple types of communication technologies, ranging from fibre optics to wireless and wireline.

Communications in Smart Grid networks from the data acquisition centre to energy meters can be carried out via a great variety of technologies. These technologies could be narrowband power line communication (NB-PLC), Universal Mobile Telecommunications System (UMTS), general packet radio service (GPRS), broadband PLC (BB-PLC), radio transmission or WiMAX. For the requirements of data transfer in Smart Grid applications, we have to consider all available resources and therefore we must focus on the suitability of using the above mentioned technologies in each specific case. Heterogeneous-hybrid networks, which combine wireless and wire communication technologies, should also be considered.

Among the various technologies for deploying the Smart Grid network, the heterogeneous-hybrid solution combines the ubiquitous power distribution grid with wireless technology to create and deliver a reliable, high-capacity and cost-effective access network that is nowadays in great demand [1], [2]. Therefore, the main objective of this paper is to make a comparison between a non-hybrid and a heterogeneous-hybrid network. In this paper, conclusions are obtained on the added value of a heterogeneous-hybrid network compared with the use of a single technology (PLC or radio).

The contribution of this paper is three-fold: First, the radio transmission for telemetry is analysed in simulation in terms of signal coverage. Second, data and loss rates measurements of narrowband power line modems are conducted. Third, radio transmission and power line communication are jointly considered as heterogeneous networks for future Smart Metering solutions.

II. ANALYSIS OF HETEROGENEOUS-HYBRID WIRELESS-PLC NETWORKS

One of the first attempts to combine wireless and wire technologies was introduced in [3]. The paper shows experimental advantages that can be obtained if the PLC is combined with Wi-Fi technology.

The hybrid network architecture incorporating a Broadband Wireless Access (BWA) system (e.g. IEEE 802.16 [4]) and PLC systems (e.g. HomePlug AV [5]) has recently been proposed in [6]. The PLC network is adopted to deliver medical data within a hospital building to avoid interference with medical devices and provide up to 200 Mbps throughput at the Physical Layer (PHY), while the BWA system is designated for communication between various hospital buildings.

A pilot wireless and broadband power line communication (W-BPLC) network was deployed in Larissa, a rural area in Greece in 2007. The hybrid W-BPLC network was adopted for the Smart grid solution to implement remote monitoring and control of irrigation pumps [7]. The BB-PLC technology was deployed due to the small population of the area, lack of telecommunication infrastructure and the high cost of a separate wireless solution. Access to the BB-PLC network was provided by the wireless Wi-Fi standard IEEE 802.11b/g.

PLC and radio transmission are severely affected in urban areas, as will be shown in the paper, therefore we consider only rural areas for our proposed heterogeneous network. The heterogeneous network in combination with narrowband

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PLC and radio network has not yet been sufficiently described in the literature. Only a few papers, e.g. [8], deal with heterogeneous networks for Smart Metering. These heterogeneous networks will be appropriate choice for devices in remote or rural areas, e.g., short-circuit current indicators located on power line poles. Therefore, this paper will focus on heterogeneous network for remote data acquisition from devices located in rural or remote areas. Also, the paper will show experimentally the advantage and disadvantage of single technology (PLC or radio). Subsequently, the paper will show the advantages that could be obtained if the PLC is joined with the radio technology.

III. EXPERIMENTAL RADIO NETWORK

Figure 1 shows an experimental radio network for remote data acquisition from Universal energy meters (MEg40^{+}) or indicators for indication of earthing and short circuits on high voltage (MEg61.4). More information about MEg40^{+} and MEg61.4 can be found in [9] and [10].

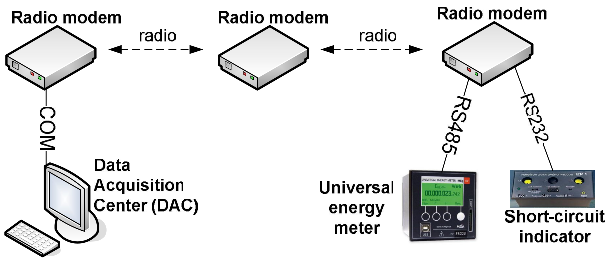

Fig. 1. Experimental radio network for remote data acquisition.

The following overview describes the location of measuring points, their GPS positions and measuring equipment already installed in these positions:

Measuring points:

– 49°34'2.238"N, 16°3'27.720"E / Nové Město na Moravě / MEg61.4

– 49°33'13.785"N, 16°4'24.703"E / Nové Město na Moravě 2 / MEg61.4

– 49°36'55.214"N, 15°55'49.019"E / Polnička / MEg61.4

– 49°39'0.401"N, 16°8'43.688"E / Daňkovice / MEg61.4

– 49°39'13.301"N, 16°8'12.500"E / Léčebna / MEg40

Data Acquisition Centre (DAC):

– MEgA - Measuring Power Apparatus, plc. Česká

All measuring points and DAC are located in the Czech Republic. The measuring points are mostly on power line poles and the devices installed on the poles are used for short-circuit current indication. More information about the measuring equipment already installed in measuring points can be found in [11].

Simulations of Radio Coverage

The simulation was realized by using the Radio Mobile software [12]. The simulation of signal coverage without/with repeater and the measurement of attenuation and path losses were performed on the experimental radio network.

1) Signal coverage without repeater

Figure 2 shows the signal coverage from the measuring point Léčebna (red) and DAC (green). The signal coverage shows that the measuring point Léčebna and DAC are not in direct line of visibility. The same situation with no direct visibility applies to the other measuring points from the experimental radio network.

Figure 3 shows the path profile of the route between Léčebna and DAC and the low value of the received signal level -131.4 dBm (e.g. the limit of the RipEX modem sensitivity is -113 dBm for a transmission rate of 10 kbps for BER 10^{-6} [13]). The path profile shows obstacles in the form of mountainous area, which causes a low value of the received signal level. Figure 3 also shows the results of attenuation: Forest (1 dB), Urban (1.4 dB) and Obstruction (47.8 dB). These attenuation values of Urban and Forest can be neglected in comparison with the attenuation caused by obstruction. The attenuation parameter Obstruction is caused by terrain, mountains or various objects.

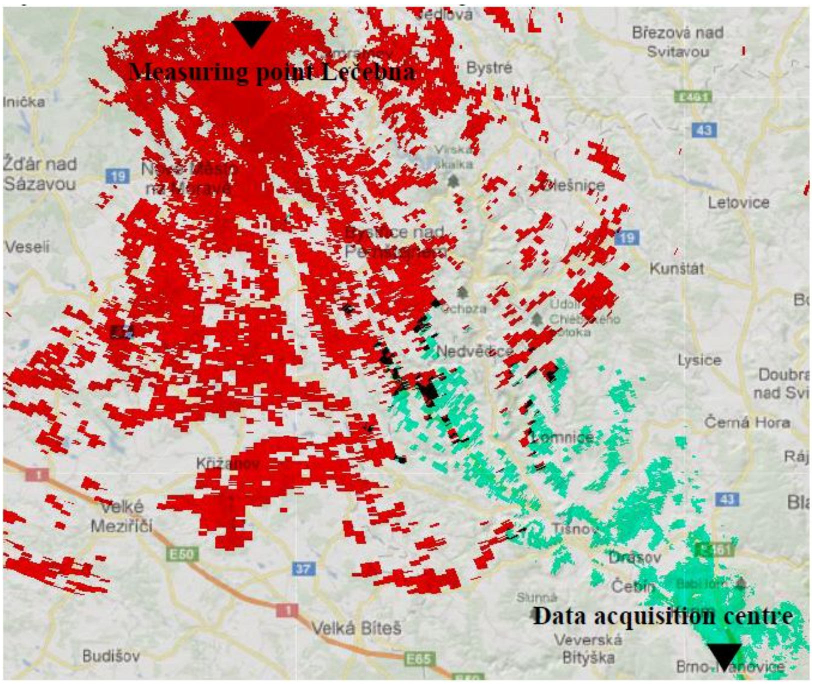

Fig. 2. Signal coverage without repeater.

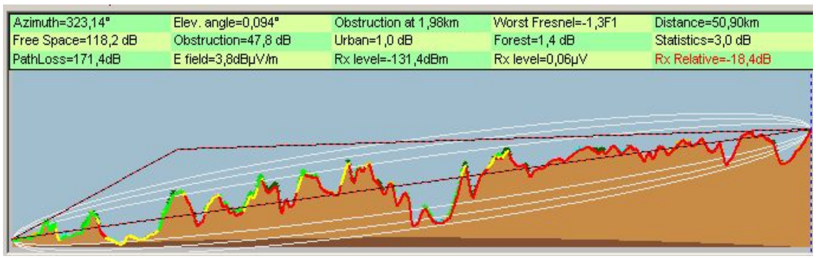

Fig. 3. Path profile.

1) Signal coverage with repeater

According to the results from the previous chapter, there is no direct visibility between the measurement points and DAC, therefore it is necessary to consider a repeater in the communication path.

TABLE I. REPEATER INFORMATION.

	Altitude [m]	Antenna height [m]	Antenna azimuth [°]	Distance in km from	
				Repeater	DAC
Nové Město 2	579	3.5	121	3.47	46.79
Repeater	659	20	132	-	42.67
DAC	303	6	312	42.67	-

To cover all measuring points, it was necessary to locate the repeater on the telecommunication pole with a height of 20 meters. The repeater coordinates were 49°32'29.848"N and 16°7'3.472"E. The Double Dipole antenna was considered for radio modems in the simulation. Table I provides information about the altitude, antenna height, azimuth and distances.

The measuring point Nové Město na Moravě 2 was chosen for the simulation of signal coverage with repeater. Figure 4 shows the path profile of the route between the measuring point Nové Město na Moravě 2 and the repeater. The problematic radio signal coverage of measurement points can be seen from the path profile. The signal did not spread over the hill.

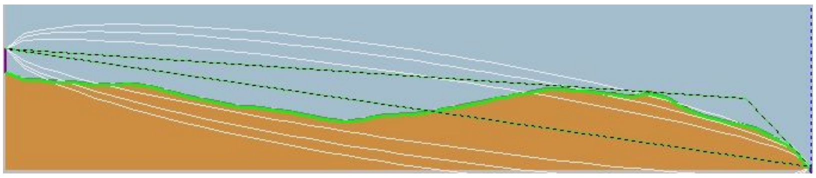

Fig. 4. Path profile-repeater and measuring point Nové Město na Moravě 2.

Table II shows the simulation results for particular frequencies.

TABLE II. REPEATER INFORMATION.

Frequency [MHz]	Power		repeater -> meas. point		meas. point -> repeater	
	[W]	[dBm]	*Rx level* [dBm]	*reserve* [dB]	*Rx level* [dBm]	*reserve* [dB]
490	1	30.000	-96.4	16.6	-105.4	7.6
	8	39.031	-97.4	15.6	-97.4	15.6
450	0.5	26.990	-95.7	17.3	-106.4	6.5
	6	37.782	-97.6	15.4	-106.7	15.4
416	0.3	24.771	-94.5	18.5	-106.7	6.3
	5	36.990	-97.3	15.7	-97.3	15.7
385	0.2	23.010	-93.8	19.2	-106.9	6.1
	4	36.021	-97.6	15.4	-97.6	15.4
350	0.2	23.010	-92.9	20.1	-104.7	8.3
	3	34.771	-97.9	15.1	-97.9	15.1
330	0.1	20.000	-92.1	20.9	-106.8	6.2
	3	34.771	-97.7	15.3	-97.7	15.3
310	0.1	20.000	-90.9	22.1	-105.7	7.3
	3	34.771	-97.4	15.6	-97.4	15.6
164	0.1	20.000	-82	31	-95	18
	2	33.010	-95.5	17.5	-95.5	17.5
144	0.1	20.000	-82.4	30.6	-95.4	17.6
	2	33.010	-94.3	18.7	-94.3	18.7

The results show information about the transmission power, level and reserve of the received signal from repeater to endpoint and vice versa for particular frequencies. A modem sensitivity of -113 dBm and a reserve of minimally 6 dB were considered (transmission power was adjusted to achieve the reserve).

1) Influence of antenna repeater height on coverage and signal level

Table III shows the simulation results of the influence of the antenna repeater height on signal strength at the end points, and vice versa. The measuring point Nové Město na Moravě 2 was considered, where the hill represented a problematic coverage of the measurement point (path profile in Fig. 4). The frequency 490 MHz was considered.

TABLE III. SIMULATION OF REPEATER HEIGHT.

Repeater height [m]	Power		repeater -> meas. point		meas. point -> repeater	
	[W]	[dBm]	*Rx level* [dBm]	*reserve* [dB]	*Rx level* [dBm]	*reserve* [dB]
20	1	30.000	-96.4	16.6	-105.4	7.6
	8	39.031	-97.4	15.6	-97.4	15.6
15	1	30.000	-97.3	15.7	-106.3	6.7
	8	39.031	-97.9	15.1	-97.9	15.1
10	1	30.000	-98.5	14.5	-107.6	5.4
	8	39.031	-98.3	14.7	-98.3	14.7
5	1	30.000	-101.4	11.6	-110.4	2.6
	8	39.031	-98.9	14.1	-98.9	14.1
1	1	30.000	-103.2	9.8	-112.2	0.8
	8	39.031	-122	-9	-122	-9

If we consider the -113 dBm modem sensitivity and the reserve of minimally 6 dB, the received signal level is below the sensitivity of the modem with an antenna height of 1 meter. When the antenna height was 10 meters, the received signal level was still below the reserve. The limits were fulfilled with an antenna height of 15 meters.

IV. NARROWBAND POWER LINE MODEMS FOR HETEROGENEOUS NETWORKS

The second part of the paper will focus on the NB-PLC and measurements with narrowband PLC modems for the Smart Metering applications.

Figure 5 shows a model of heterogeneous communication using PLC modems and other channels for Smart Metering solutions.

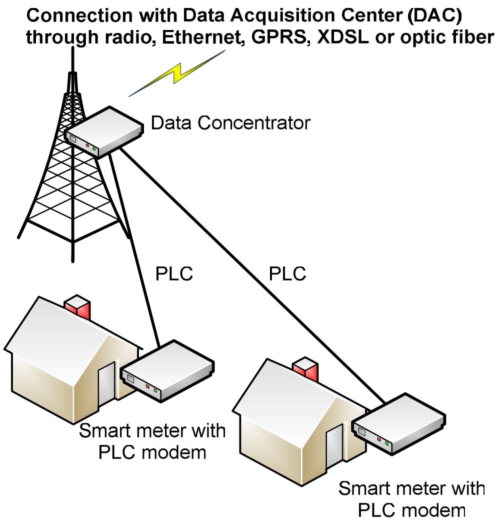

Fig. 5. Heterogeneous network with Power Line Communication.

PLC allows realizing two-way communication for the access part of network. Data from the Smart meter are sent via power lines to the concentrator located near the MV/LV transformer. From the transformer, the transport part of the network, data are forwarded using other technologies (wireless, GPRS, xDSL, fibre optic, etc.).

The BB-PLC offers high speed data communication [2], [14], but the communication ranges without repeaters are small (e.g. in the W-BPLC network in Larissa (Greece) [7] the BB-PLC units are placed and configured at distances of approximately 500 meters as repeaters). Therefore the BB-PLC for remote data acquisition from devices located in rural or remote areas was not considered.

The disadvantage of narrowband PLC (small data rates) is solved by using High Data Rate NB-PLC (HDR NB-PLC) standards which use the Orthogonal Frequency Division Multiplexing (OFDM). NB-PLC is nowadays gaining interest for Smart Metering applications because of the recent creation of two new standards IEEE 1901.2 and ITU-T G.hnem [1].

A. Measurement Setup

The vast majority of the literature considering narrowband PLC standards [15]–[19] introduces mainly simulation results or measurement results with various data rate limits and data ranges. Any extensive measurements are still missing. Data rates are sometimes chaotically presented on the physical layer together with data rates on the application layer; more information can be found in [20].

The most widespread narrowband PLC standards with high data rates are G3-PLC [21] and PRIME [22]. These standards offer data rates of hundreds of kilobits per second. New standards ITU G.hnem [23] and IEEE 1901.2 [24] offer data rates of several megabits per second, but these standards need to be validated via massive deployment and some evaluation kits are still missing. The first development kits for the evaluation of high-speed data rates of the IEEE 1901.2 standard are commercially available from Texas Instruments. But the solution with the IEEE 1901.2 standard from Texas Instruments (PLC kit TMDSPLCKITV4 [25]) is only for the ARIB frequency range (154 kHz to 403 kHz).

There is a concern that in the long run the data rates of narrowband PLC are not sufficient to fulfil the requirements of future Smart Grid solutions [1]. Therefore, the data and loss rates of the above mentioned PLC modems were measured for different topologies.

These narrowband power line modems were considered for heterogeneous network solutions:

– PLC module IC Yitran IT700,

– TMDSPLCKIT-V3: C2000 Power Line Modem Developer's Kit,

– SGCM-P40 module.

The PLC module IC Yitran IT700 uses the Yitran patented Differential Code Shift Keying (DCSK) modulation technique for extremely robust communication. The IT700 complies with the FCC, ARIB and CENELEC frequency bands regulations. More information can be found in [26].

TMDSPLCKIT-V3 is a PLC modem based on the C2000 TMS320F28069 control CARD and TI's advanced PLC analogue front end AFE031. This software based modem is from Texas Instruments. The modem is fully PRIME and G3-PLC compliant. More information can be found in [27].

The SGCM-P40 module is a power line communication evaluation tool based on the G3-PLC standard using the Maxim MAX2992 PLC modem and MAX 2991 AFE. More information can be found in [28].

B. Measurement of PLC Modem's Data and Loss Rates

Measurements were conducted in the CENELEC A frequency band [29]. The low voltage lines and CYKY 3x2.5 cables are considered.

Three measurement scenarios were considered. The scenarios were realized in indoor residential area. Based on length and topology, these scenarios were divided into three field test configurations:

– Small-size topology - inter-connected laboratories and a distance of 16 meters between Tx-Rx modems.

– Medium-size topology - laboratory and hall, a distance of 25 meters between Tx-Rx modems.

– Large-size topology - laboratory and hall, communication through switchgear and a distance of 45.5 meters between Tx-Rx modems.

The G3-PLC and PRIME standards with Robust Operation (ROBO) mode and D8PSK modulation were considered. ROBO for robustness and long-range communication and D8PSK for maximum data rate [20]. The results of the G3-PLC and PRIME standards were also compared with the DCSK modulation technique used in the

Yitran IT700 module. Table IV shows the results of data and loss rate measurements.

TABLE IV. DATA RATES OF NARROWBAND POWER LINE MODEMS.

Modem, standard and modulation	Loss rate in [%] Data rate in [kbps]	Topology size		
		Small-size	Medium-size	Large-size
Yitran, DCSK with ROBO	Loss rate	0	0	71.3
	Data rate	3.27	2.71	2.24
C2000,PRIME D8PSK	Loss rate	0	100	100
	Data rate	9.14	0	0
C2000, G3, ROBO	Loss rate	0	0	0
	Data rate	2.36	2.18	1.76
SGCM-P40, G3, ROBO	Loss rate	0	0	0
	Data rate	5.3	5.3	5.3
SGCM-P40, G3, D8PSK	Loss rate	0	2.1	100
	Data rate	43.39	43.39	0

From the measurement results in Table IV, the ROBO mode in comparison with other modulations enables communicating over a large distance or switchgear without resending or aborting communication. However, the ROBO mode reduces the channel’s effective data rate. The maximum application data rate was achieved by D8PSK modulation. Anyway, this modulation is easily influenced by noise and it is suitable only for a small communication range. For the G3-PLC standard, the hardware solution from Maxim as implemented in SGCM-P40 is better in terms of data rates than the software solution from Texas Instruments.

V. HETEROGENEOUS NETWORKS

The PLC-wireless module was designed to merge radio and PLC networks into a heterogeneous network for Smart Metering. Figure 6 shows the hybrid PLC-wireless module.

According to the results from the previous chapter, the solution of the PLC modem is based on the G3-PLC standard and Maxim chips (PLC modem MAX2992 and analog front-end MAX2991). The wireless solution is based on XBee PRO 868.

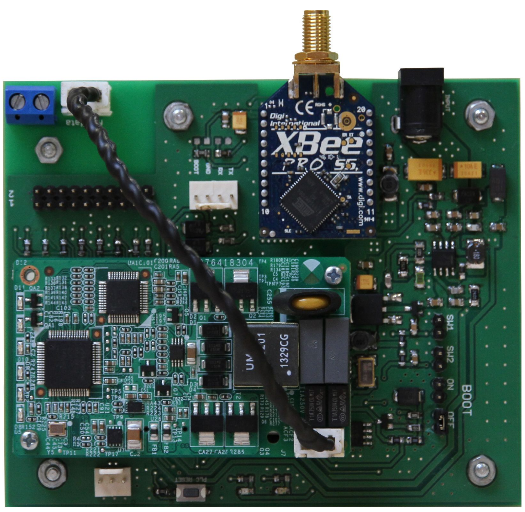

Fig. 6. Prototype of hybrid PLC-wireless module.

Figure 7 shows an experimental heterogeneous network. The experimental heterogeneous network shows a combination of radio and PLC transmission for remote on-line measurement from universal energy meters or short-circuit currents indicators.

The end-to-end performance of the heterogeneous network in Fig. 7 was verified by laboratory measurement using the MEg40$^+$ Universal energy meter, where the values of energies and recorded quantities are transferred through the heterogeneous network into DAC and shown on-line.

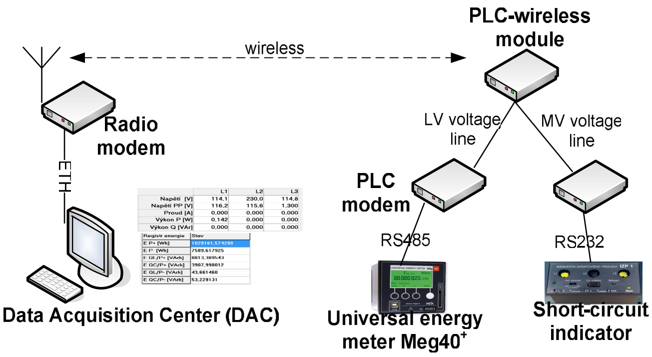

Fig. 7. Heterogeneous network – radio and PLC.

A. *Heterogeneous Network Planning and Design Steps*

When radio transmission is considered for particular areas, first the signal coverage and repeater position are verified by simulation. The simulation results show the performance and usability of the radio channel for particular areas. On the other hand, the simulation tools for PLC communication are available [30]–[32], but mainly for indoor channels or broadband communication. Therefore the usability of NB-PLC for outdoor channels has to be verified by experimental measurements.

The following measurements focus on data rate and communication range measurements using the PLC modem from hybrid PLC-wireless module.

An experimental scenario with vacant wiring without branches of 1 kilometre in length was considered.

Table V shows maximum data rates on the application layer for different modulations and for both frequency bands, CENELEC-A (35 kHz to 91 kHz) and FCC (145.3 kHz to 490 kHz). More information about modulation techniques can be found in [20]. The results in conditions without noise show a stability of communication and maximum data rates for all types of modulation.

TABLE V. DATA RATE COMPARISON FOR DIFFERENT MODULATIONS.

Modulation	CENELEC-A	FCC
ROBO	6.38	35.56
ATM	18.80	180.48
DBPSK	22.56	112.80
DQPSK	37.60	140.09
D8PSK	47.00	210.14

VI. DISCUSSION AND EVALUATION

The key questions when designing a heterogeneous wireless-PLC network are the following:

– *What is the primary motivation for the deployment of a wireless-PLC network?* Due to the necessity for repeaters, the solution based only on radio modems could be very expensive in rural or remote areas. The use of repeaters is necessary mainly due to the obstructions in form of mountains, buildings or forest in the signal path. A problematic area of radio transmission is also the weather; more information about the influence of weather on radio transmission can be found in [33]. Therefore the solution for the coverage of large, rural or remote areas is a heterogeneous-hybrid network, which combines various communication technologies.

– *Which PLC standards will be deployed for the Smart Metering issue?* PLC standardization moved from a lack of BB-PLC standards to the opposite extreme of having multiple non-interoperable technologies. A similar situation of multiple non-interoperable technologies is in HDR NB-PLC because of the new standards IEEE 1901.2 and ITU-T G.hnem and the already existing standards G3-PLC and PRIME. This situation leads to a confusion in deployments. The paper tries to show the area of usability for the G3-PLC and PRIME standards.

– *Which frequency band will be considered in Europe?* The_FCC frequency band is not allowed to be used in Europe, the communication needs to be CENELEC EN 50065-1 compliant. But according to ongoing activities within CENELEC regarding EMC regulations/standardization for frequencies of 150 - 500 kHz it is possible to expect changes in using the frequencies above the CENELEC band [34]. In the case of the G3-PLC standard and PLC-wireless module the configuration of frequency bands will be only the tone mask setting.

– *What is the advantage and disadvantage of using OFDM in the HDR NB-PLC standards?* The allocated frequency range in the OFDM technique is divided into a set of subcarriers and thanks to time orthogonality the subcarriers are not disturbed by each other. The standards based on this assumption are easily influenced by noise, especially narrowband noise. Our measurements show that the D8PSK, DQPSK and DBPSK modulations used in OFDM are easily influenced by noise. This problem will be solved by a larger distance between subcarriers, but this assumption will lead to lower data rates.

– *What is the best modulation in the G3-PLC standard for the Smart Metering issue?* The solution based on the G3-PLC standard with ROBO or ATM mode is suitable for applications requiring stable and reliable communication in contrast to applications requiring high data rate communication. The measurements show stable communication over distances of kilometres without the necessity for repeaters. The big advantage of the ATM mode against ROBO mode consists in estimating the signal-to-noise-ratio (SNR) of the received signal subcarriers and then adaptively selecting the usable tones and the optimum modulation. This feature is useful for environments with different SNR at different times (day/night). When the interference conditions and SNR are good, the ATM mode applies automatically multi-state modulation to achieve a high data rate.

VII. CONCLUSIONS

Information such as the effect of the height of repeater for radio network is not new, but the simulation conducted in this paper showed results for a specific rural area.

Heterogeneous smart grid networks supporting wireless radio transmission and power line-wired connectivity are a promising solution for future Smart Grids, especially for remote data acquisition.

The wireless radio network has some drawbacks in signal coverage while the power line communication solution has some drawbacks in the small communication distance, necessity for repeaters and impact of noise. Together they provide an appropriate solution for remote data acquisition by eliminating the drawbacks of particular technologies.

The paper introduced the experimental radio network and the simulation results showed a problematic situation with signal coverage and necessity for repeaters. The second part of the paper introduced possible narrowband power line communication standards and modems for the Smart metering applications. The last part of the paper introduced a solution combining radio and PLC communication for a heterogeneous network.

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