Simple and Low-Cost PLC Modem for IoT Applications

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***Abstract*—We present in this paper a simple and low-cost Power Line Communication (PLC) modem for Internet of Things (IoT) applications. The proposed modem implements a simple on-off-keying (OOK) modulation/demodulation with only discrete electronic components, not requiring complex ICs, such as processing units. It uses the ground and neutral wires as a channel communication, eliminating the need for complex isolation circuitry. To improve its robustness to noise, the developed PLC modem includes an automatic receiver gain adjustment and a transmitter sweep carrier frequency algorithm. Laboratory tests show that the developed PLC modem is capable of transmitting data at 9,600 bps with no errors if the noise spectral density in the power line is below 111 nV_{RMS}^2/Hz in the bandwidth of 150 kHz to 500 kHz. The system was also evaluated in a residential power network, where it presented a bit error rate below 1.21%. Due to its low cost, the developed PLC modem is suitable for low data rate IoT applications such as energy consumption monitoring, appliance monitoring and control, environmental monitoring (temperature, humidity, luminosity), security monitoring (presence sensors), etc.**

***Index Terms*—Internet of things, IoT, Modem, PLC, Power line communication.**

I. INTRODUCTION

Internet of Things (IoT) is a network of cloud-connected devices capable of obtaining information from the environment, and, in some cases, actuate on it. Due to the possibilities of IoT in our modern, increasingly connected society, this emerging concept has drawn attention from academics and industries. Recent works have proposed IoT solutions in different areas, such as intelligent transportation systems, smart grids, smart home, urban lighting, waste management and environmental monitoring [1], [2]. One important application of IoT is in resource management of smart homes, where IoT can be employed to control and monitoring energy, water, gas, and other resources [3].

A vital part of any IoT device is its communication system, since hardware and protocols are required for robust and secure communication between the connected devices and the database. Additionally, an important requirement for IoT communication is to have the lowest cost possible, allowing it to be applied in simple and inexpensive devices, such as smart meters, lights, and simple appliances, such as coffee makers [4].

Wireless communication systems are usually employed in IoT due its easy installation. Examples of wireless technologies used in IoT include ZigBee, 6LoWPAN, LoRaWAN, Bluetooth, Wi-Fi and Z-wave [3], [5], [6]. Although wireless communication is usually a good solution for IoT systems, it presents an important inconvenient: the radio signal is attenuated by obstacles, often requiring the use of repeaters [7], [8]. This characteristic makes wireless networks more complex, expensive, and difficult to install and maintain.

One alternative to the wireless technologies in IoT is Power Line Communication (PLC) [3], [6]. PLC uses the existing electrical wiring to transmit digital signals between devices attached to the power line. The main advantage of PLC is its low cost, since it does not require the installation of a communication infrastructure. Furthermore, PLC is not subjected to interference due to obstacles, such as walls and furniture, or other communication links, such as radio frequency (Wi-Fi, Bluetooth, ZigBee). These features make PLC, in many cases, the best solution for IoT applications [6], [9].

However, there are still some challenges to allow proper communication in power lines. For instance, since the power network was not designed for data transmission, it is electromagnetically noisy, harsh, and difficult to model [10] – [12]. Furthermore, there is a concern about interferences between PLC and the appliances connected to the power line, as well as with wireless systems that work in the same frequency band. To avoid these problems, standards were created to define PLC bands, such as the Europeans EN 50065: 3 – 148.5 kHz and IEEE 1901.2: 148.5 – 500 kHz, the American 9 – 490/500 kHz, and the Japanese ARIB STD T-84: 10 – 450 kHz [13].

Recent works reporting the development of PLC modems focus mainly in increasing the transmission data rate and improving robustness to noise. In the work proposed by DS Kim *et al.* [14], the authors presented a broadband PLC modem based on adaptive signal detection techniques. The proposed modem employs chirped spread spectrum (CSS) and implements a lookup table to achieve a collision protocol (CSMA/CA). The proposed system is capable of transmitting

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information at 50 meters with an error of approximately 10% in a power line with ordinary household appliances, such as microwave oven, vacuum cleaner, electric dryer, and other electronic devices. However, the proposed system requires RAM memory, direct digital synthesis (DDS), and a digital-to-analog converter (DAC), which are relatively expensive components. In general, the higher the complexity of the broadband modems, the higher their cost, which makes them unsuitable for low-cost PLC applications.

Y. T. Hwang *et al.* [15] implemented a narrowband PLC transceiver in a Field Programmable Gate Array (FPGA). The proposed transceiver adopts a 2-level modulation scheme consisting of *m*-ary bi-orthogonal keying (MBOK) for direct-sequence spread spectrum (DSSS) and frequency shift keying (FSK) to overcome the noise effects in power line channel and to guarantee the multiple channel access (CDMA). The first modulation level ensures the multiple channel access and the data spreading (MBOK + DSSS). The second level is responsible to insert the spread information in the power line. The system allows data rates up to 100 kbps. Although the proposed modem employs a narrowband PLC, it requires an FPGA, which is still an expensive solution for digital signal processing and, hence, unsuitable for low-cost PLC modems.

Y. F. Chen *et al.* [16] proposed an architecture of spread spectrum PLC transceiver developed in FPGA that also uses MBOK modulation. In this implementation, similarly as in the system described in [14], the first modulation level of MBOK is responsible for multiple channel access and data spreading. On the other hand, unlike the implementation proposed in [15], the second level of modulation is not adopted. The developed PLC modem achieves a transmission rate up to 128 kbps.

In [17], B. Tiru and P. Boruah developed a PLC modem based on a digital signal processor (DSP) that implements an echo canceller and enables a dual carrier frequency transmission through amplitude modulation. Although it can be considered simple, the proposed modem requires a DSP to perform digital signal processing, which increases its cost.

Despite the good performance of PLC modems discussed so far, their complexity makes them unsuitable for low-cost IoT implementations. These modems are usually based on complex modulation techniques that require DAC, FPGA, DDS, DSP, and RAM memory or other additional components that increase the system cost.

Many IoT devices, such as smart meters and presence sensors, do not require high data rate communication. Based on that, S. Barker *et al.* [9] proposed a narrowband PLC for low-cost home automation based on the Insteon protocol, which combines PLC and radio frequency (RF) techniques for home automation solutions. The PLC modem proposed is based on phase-shift keying (PSK) modulation and performs synchronized transmissions at the zero crossings of the power line signal. The baud rate for this protocol is limited to 2,880 bps. No further details of the hardware, protocol implementations, and performance were reported.

Considering the demand for inexpensive, low data rate PLC modems for simple IoT devices, we propose in this work a novel low-cost narrowband PLC modem for residential applications. Three design solutions were fundamental to achieve a low cost: (i) full implementation of the modulation and demodulation electronic circuitry with inexpensive components: transistors, resistors, capacitors, and inductors; (ii) implementation of simple communication protocols – not requiring digital processor neither complex filter; and (iii) communication through neutral and ground wires – eliminating the need for complex isolation circuitry.

II. THE PROPOSED LOW-COST PLC MODEM

The proposed PLC modem employs a simple transceiver based on communication through neutral-ground wires. The ground and neutral conductors were chosen because there is no load between them, resulting in lower voltage drop of the coupled signal than in phase-neutral or in phase-ground. Furthermore, the noise levels between neutral-ground are often lower than those between phase-neutral. Another practical advantage of using neutral-ground communication is that the coupling circuit is simpler, since there is no significant voltage between those wires, eliminating the need for complex and expensive isolation circuitry.

In the proposed PLC modem, the modulation and demodulation were fully implemented in hardware with inexpensive discrete components, in contrast to previously discussed solutions that employed FPGA or DSP. The block diagram of the proposed PLC modem is shown in Fig. 1.

The modem was connected to an embedded processor unit (a low-cost microcontroller – MCU) through universal asynchronous receiver-transmitter (UART) bus. Although the processor unit is not part of the modem proposed, it was used to provide a square wave modulation carrier, and two digital signals to control the gain of the receiver amplifier.

A pulse width modulation (PWM) module, which is embedded in most modern microcontrollers, was employed to generate the modulation carrier. Furthermore, to improve the noise robustness of the proposed modem, a set of simple algorithms to control the gain of the receiver amplifier and the frequency of the modulation carrier were implemented in the processor unit. Those algorithms run once during the system setup, not requiring further power processing from the embedded system.

A. Transmitter

The transmitter circuit, shown in Fig. 2, is composed by a modulator, a bandpass filter, and a power line coupler.

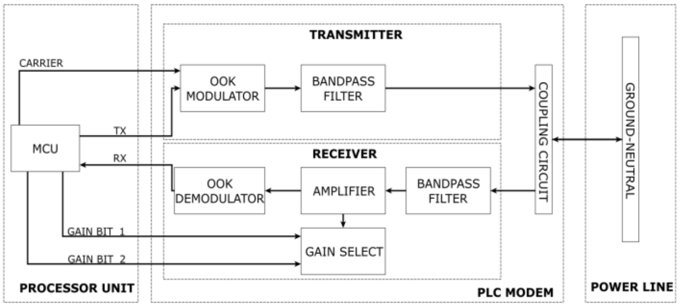

Fig. 1. Block diagram of the proposed PLC modem.

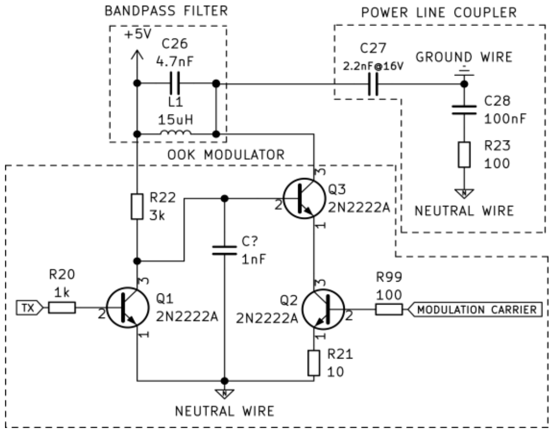

Fig. 2. Transmitter circuitry of the proposed PLC modem.

Since the transceiver was designed for low data rate communication, there was no need for large bandwidth, neither complex modulation scheme, allowing for the development of a cost-effective narrowband PLC modem. The developed transmitter implements OOK modulation, which is a simple form of amplitude-shift-keying modulation where the digital data is represented by the presence (bit zero) or absence (bit one) of modulation carrier (square wave signal). This type of modulation is ideal for low-speed PLC transceivers since it does not require complex signal processing and can be implemented with few discrete components.

The modulator operation is explained as follows: when the modulating signal (TX) is low (0 V), the transistor Q1 is cut-off and, hence, the voltage drop in the base-emitter junction of transistor Q3 is saturated. The transistor Q2 acts as a high-speed switch controlled by the high-frequency carrier. In this situation (TX low), the high-frequency carrier signal appears in the Q3 collector. When TX signal is high (3.3 V), the transistor Q1 is saturated, the transistor Q3 is cut-off, and the collector of the transistor Q2 is floating. Therefore, there is no influence of the high-frequency switching (modulation carrier) when the modulation is in high level. Thus, the modulator outputs the carrier signal when the transmitted data is a binary zero (0), and a low level is output when the data sent is a binary one (1).

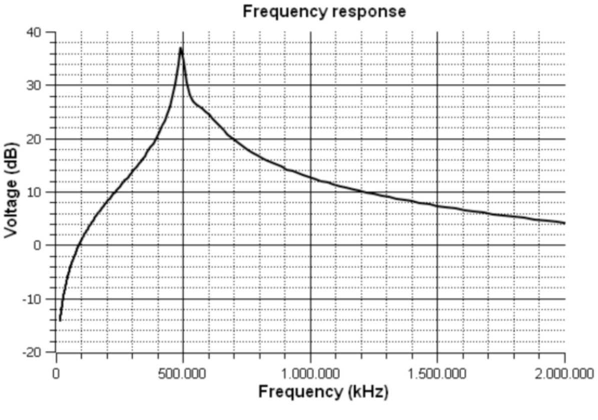

Fig. 3. Frequency response of the bandpass filter of the PLC transceiver.

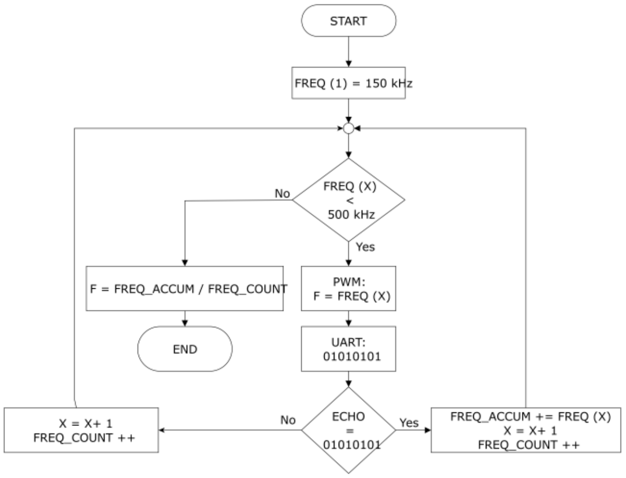

Fig. 4. Algorithm to identify the effective bandpass frequency of the PLC filter.

Since the transceiver operates with a simple OOK modulation, it requires only a bandpass filter at the fundamental frequency of the carrier signal. The bandpass filter was implemented with a simple resonant circuit, composed by a 15-μH inductor (L1) and a 4.7-nF capacitor (C26), resulting in a resonance frequency of 492 kHz, as shown in Fig. 3.

However, it is important to notice that the distributed impedance between neutral and ground wires of the power line modifies the bandpass frequency. Since this impedance depends on the specific installation, it is not possible to predict the real bandpass frequency of the PLC modem installed. To solve this problem, we proposed and implemented a frequency sweep algorithm to examine the power line frequency response and choose the best frequency for the modulation carrier signal.

The sweep-frequency algorithm, which is schematically shown in Fig. 4, was implemented in the processor unit that communicates with the PLC modem.

This simple algorithm sweeps the frequency (FREQ(X)) of the modulation signal from 150 kHz to 500 kHz, in which X represents the index in a lookup table of frequency. In each modulation frequency (F), the bit sequence “01010101” is sent through the transmitter and its corresponding echo (ECHO) received are compared. If there are no errors in the received packet, the successful frequency index value is stored (FREQ_ACCUM). The next frequency is selected from the lookup table by incrementing the index X, and the overall transmit counter (FREQ_COUNT) is also incremented. Finally, the algorithm selects the modulation carrier signal that outputs the highest mean frequency to which it was possible to receive the echo of the transmitted bit sequence with no errors. The resolution of the carrier frequency sweep algorithm depends on the performance of the PWM module in the MCU.

The filtered signal is injected into the power line by a coupling circuitry composed by a low-voltage ceramic capacitor and a resistor. A 2.2-nF capacitor (C27), also with low-voltage isolation (16 V), acts as a high impedance to 60-Hz signals, as well as a low impedance to the modulation signal (150 kHz to 500 kHz), isolating and protecting the transceiver from any residual voltage difference from the electric installation. A 100-nF capacitor (C28) and a 100-Ω resistor (R23) act as a low impedance between ground and neutral for

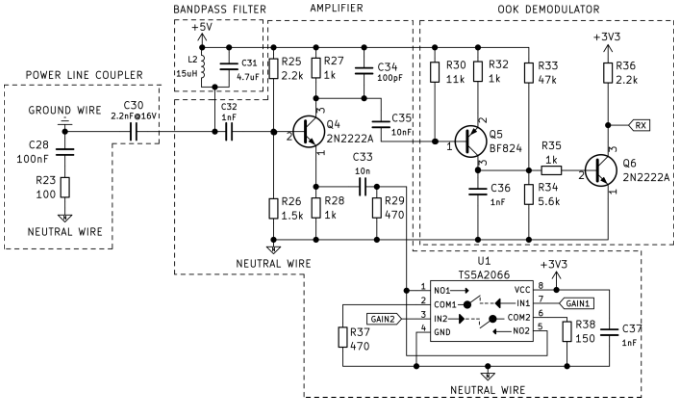

Fig. 5. Receiver circuitry of the proposed PLC modem.

the modulated signal, and act as a high impedance for low frequency signals, allowing for the proper insertion of the modulated signal in the powerline. Compared to the usual PLC power coupling circuits, such as those presented in [15], [17], and [18] that require several ICs and transformers, the solution proposed in this work is considerable simpler and cheaper.

B. Receiver

The modem receiver circuitry, which is shown in Fig. 5, is composed by a bandpass filter, an amplifier with adjustable gain, and a demodulation circuitry. The power line coupler and bandpass filter circuits are the same as in the transmitter.

The transistor-based amplifier of the receiver was designed to allow adjustable gain. Its circuitry is based on discrete transistor amplifier in the common emitter configuration. Its gain is defined by

$$A_V = -\frac{R_{27}}{\frac{V_T}{I_C} + (R_{28} \,//\, R_{29})} \tag{1}$$

where, R_{27} is the collector resistor, R_{28} and R_{29} are the emitter resistors, $V_T \approx 25$ mV is the transistor thermal voltage at 25 °C, and I_C is the collector current. The receiver circuitry also contains a dual single-pole single-throw (SPST) analog switch (TS5A2066, Texas Instruments) that selects one among four equivalent resistances ($R_{28}//R_{29}$, $R_{28}//R_{29}//R_{37}$, $R_{28}//R_{29}//R_{38}$, $R_{28}//R_{29}//R_{37}//R_{38}$). It was found experimentally that the best gain of the receiver for most installations was between 2 and 8. Therefore, the resistors were chosen to result in gains of 2, 4, 6 and 8 V/V.

Because noise increases with higher gain values of the receiver amplifier, the gain should be adjusted in an optimal value to allow for the correct recognition of the modulation carrier signal, but not high enough to cause the recognition of the line noise as a binary zero. Since the communication channel noise and attenuation levels depend on the local power network, it is necessary to configure the gain to each specific installation. To configure the gain of the receiver amplifier automatically, we proposed and implemented a simple adjustable gain algorithm that selects the highest gain that allows for the reception of information from a transmitter with no errors. Using the selected gain, it is possible to overcome channel attenuation without problems due to the noise level.

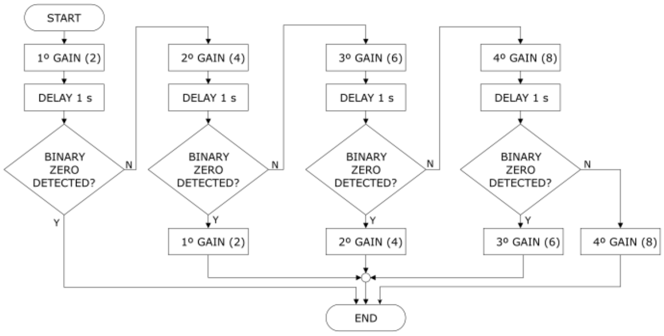

Fig. 6. Algorithm to select the receiver gain based on power line noise.

The proposed algorithm, which is shown schematically in Fig. 6, was implemented in the processor that communicates with the modem.

The algorithm starts with the minimum gain and increases up to the maximum value. At each gain, the algorithm verifies if the receiver circuit has a noise level capable to saturate Q6 transistor, making the processor recognize a bit zero in the UART RX pin. Each gain is tested within one second, and if a binary zero is identified, the gain is too high, then the previous gain is selected (if it is in the lowest gain, this gain is selected). This algorithm should run only when the system is installed, not requiring processing power during the operation of the embedded system. More robust algorithms can be proposed, including, for instance, a continuous control of the receiver gain during the operation, which is capable of compensating variations in the noise with time. However, these algorithms would require more processing time and message exchanges between the transceivers.

To recover the information, we designed a simple demodulation circuitry (Fig. 5) based on envelope detection composed by a PNP transistor (Q5), a capacitor (C36), and resistors (R30, R32, R33 and R34). This circuitry is basically an active low-pass filter. At the end of the circuitry, resistors R35 and R36, and transistor Q6 (acting as switch) are responsible for converting the absence of modulation carrier to a binary one (3.3 V), and the presence of the carrier, to a binary zero (0 V).

As demonstrated in the description of the transceiver, we propose in this work a system that can be implemented with low-cost discrete components, such as resistors, capacitors, transistors, and an analog switch (TS5A2066), which is the only IC employed, with a cost of less than one dollar for the components, including the PCB. Additionally, it is possible to further reduce the cost of the proposed modem by replacing the IC with discrete transistors.

III. EXPERIMENTAL RESULTS

To evaluate the proposed PLC modem independently of any specific electrical installation, some experiments were performed using a pair of wires disconnected of the power line as the communication channel, similarly as in [15]. Additionally, to evaluate the feasibility and performance of the system under real conditions, we also evaluated the modem in real residential installation.

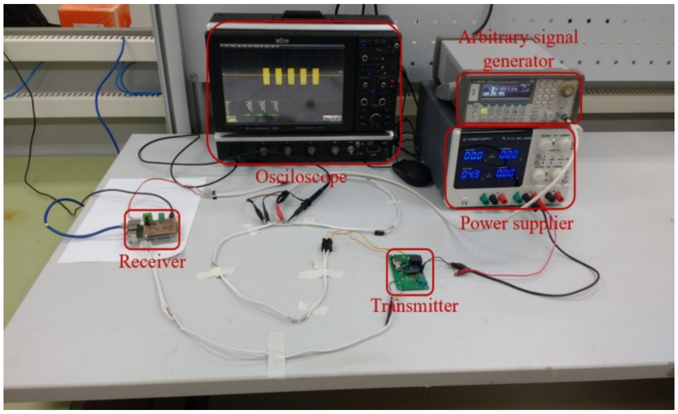

Fig. 7. Experimental setup for the bench tests.

A. Bench Tests

Fig. 7 shows a picture of the bench setup used to evaluate the proposed modem. In this setup, the communication channel is composed by pair of cables 1.5-m long, 2-mm in diameter disconnected of the power line. A second 45-cm long cable was used for synchronization of the transmitter and receiver. An arbitrary signal generator (Agilent 33220A) was used to inject noise signals in the channel. An oscilloscope Lecroy WaveRunner 604zi was used to measure the noise spectral density, following the recommendations described in [19].

Two PLC modules were connected in the channel, one operating as the transmitter, the other as the receiver. The transmitter is based on a simple 16-bit microcontroller from Texas Instruments [20], and the receiver is based on a Raspberry Pi 3 platform [21]. This setup is often found in home automation, where a simple microcontroller-based module is employed to acquire information from the environment and actuate on it, and the Raspberry Pi-based module is used as the concentrator or web server. The transmitter was configured to send a package of 5,000 bytes with the content (in binary) of “01010101”, resulting in 40,000 bits with a baud rate of 9,600 bps.

To evaluate the performance of the proposed modem with the adjustable receiver gain algorithm, it was configured a carrier frequency of 500 kHz (approximately the resonance frequency) with additive white Gaussian noise in the channel. The noise added to the signal was a uniform white noise bandlimited in 9 MHz with spectral density varying from 14 to 574 nV_{RMS}^2/Hz. Additionally, since the proposed modem is band limited, mainly the noise in the band of the carrier influences the performance of the system.

The adjustable receiver gain algorithm was executed before running the tests for each noise spectral density value. The results of this experiment are presented in Table I. Fig. 8 shows the bit error as a function of noise spectral density.

These results show that the proposed PLC modem presented good performance even when operating in noisy channels, with no errors when the noise level was below 111 nV_{RMS}^2/Hz. Additionally, even in environments with noise levels as high as 444 nV_{RMS}^2/Hz, the modem presented acceptable performance, with a bit error of 4.54%. Furthermore, it was observed that the bit error grows exponentially with noise, as it can be seen in Fig. 8. Therefore, the adjustable receiver gain algorithm worked as expected, decreasing the gain to the lowest value for noise levels above 111 nV_{RMS}^2/Hz, and increasing the gain up to the maximum value for spectral densities under 14 nV_{RMS}^2/Hz.

TABLE I
RESULTS OF THE ADJUSTABLE RECEIVER GAIN ALGORITHM

Receiver Gain (V/V)	Noise spectral density (nV_{RMS}^2/Hz)	Bit error rate (%)
8	14	0.00
6	18	0.00
4	28	0.00
2	111	0.00
2	250	0.19
2	340	1.37
2	444	4.54
2	574	17.67

Although the proposed PLC modem presented higher error rates than the ones proposed in [14], [15] and [16], it is considerably simpler since it does not require complex modulation schemes, RAM memory, DDS, DAC and/or FPGA, making it ideal for low-cost applications. Furthermore, compared to the narrowband PLC for home automation based in the Insteon protocol reported in [9], the PLC modem proposed in this work is considerably simpler, does not require isolation circuitry and transmitter synchronization, and it is capable to work with higher data rates.

B. Real Power Line Tests

The developed PLC modems were also tested in a residential installation with typical appliances connected to power line, such as televisions, computers, lamps, set-top boxes, refrigerator, ACs, washing machine, electric shower, broadcast devices, etc. The modems were subjected to the noise present in the residential power network, allowing for the evaluation of the frequency sweep algorithm. The tests performed with the modems connected to the mains were similar to the bench tests: a pair of modems were installed in the mains, one operating as the transmitter (connected to the microcontroller), and the other as the receiver (connected to a Raspberry Pi 3). The transmitter was again configured to send a package of 5,000 bytes with the content (in binary) of “01010101”, resulting in 40,000 bits with

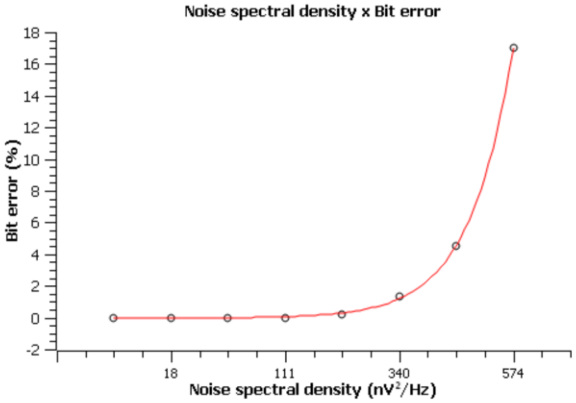

Fig. 8. Exponential behavior of bit error as a function of noise spectral density.

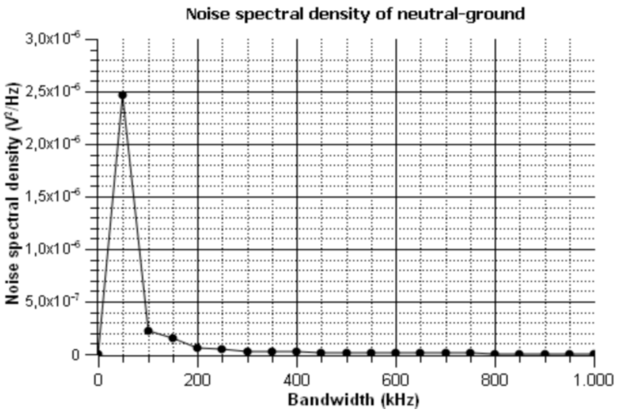

Fig. 9. Noise spectral density of the network.

TABLE II

COMPARISON BETWEEN THE SOLUTION PROPOSED FOR PLC

Ref.	Processor	Bandwidth	Transmission Rate	Coupling	Channel
[9]	Raspberry Pi	Narrowband	2,800 bps	-	Phase-Neutral
[14]	RAM/ DDS/ DAC	Broadband	-	Transformer	-
[15]	FPGA	Narrowband	100 kbps	-	-
[16]	FPGA	Broadband	128 kbps	-	Phase-Neutral
[17]	DSP	Narrowband	33 kbps	Transformer	Phase-Neutral
This work	None	Narrowband	9,600 bps	Capacitor	Neutral-Ground

baud rate of 9,600 bps. The performance of the system was also evaluated by counting the number of bit errors received.

Two measurements were taken, one with the modules distant 3 m from each other, and the other with the modules 20 m apart. Measurements of the noise spectral density of the residential power line were performed using the same oscilloscope employed in the bench tests, and the results are shown in Fig. 9.

As we can observe in Fig. 9, though there is a peak of noise in 50 kHz, the noise spectral density in the bandwidth of 150 – 500 kHz was below 10 nV_{RMS}^2/Hz, which allowed the adjustable gain algorithm to set the receiver gain to the maximum value (8 V/V). This test also showed that the sweep carrier frequency algorithm worked as expected, selecting the frequency of 224 kHz to compensate for the impedance of that specific power line. The results indicate that the proposed PLC modem can be employed successfully in real installations, presenting low bit error rates (below 1.21%) in different situations.

To make the contributions of our work clearer, Table II shows the key features that differentiate the proposed modem from others reported in the literature. The solution proposed in this work is the only one that employs neutral and ground wires as the communication channel. Furthermore, this unique feature allows for the use of a simple coupling circuitry, in opposition to the solutions that require transformers to isolate and inject the signal into the mains. Additionally, despite its low transmission rate, our solution is adequate for simple applications, such as monitoring electric power consumption, occupancy, temperature, and humidity.

The proposed modem can also be applied to the agricultural industry, for example, in monitoring systems for poultry production or grain storage systems. Considering that Latin America and the Caribbean are among the world's largest producers of poultry meat and that poultry production requires constant monitoring of temperature, humidity, water, and feed availability, the proposed low-speed PLC modem is adequate to handle the data traffic needed. Furthermore, since no additional communication infrastructure is necessary, the low-cost PLC system proposed shows robustness and good coverage area, presenting itself as an alternative solution to wireless communications. Grain storage systems, which also require continuous monitoring of temperature and moisture content, would also greatly benefit from the use of the proposed PLC modem because wireless technology is often impracticable in these systems due to the number of obstacles found inside large silos.

IV. CONCLUSION

In this work, we presented a simple and low-cost PLC modem for low data rate IoT applications. The low-cost feature of the proposed modem was achieved by using neutral and ground conductors as the communication channel, as well as implementing a simple OOK modulation with demodulation in hardware.

One of the key features of the proposed PLC modem is the use of neutral and ground wires as the communication channel, which allowed the design and successful implementation of a simple and inexpensive power line coupling circuitry. Furthermore, the choice for an OOK modulation allowed for a simpler and cost-effective design of modulator and demodulator circuits using low-cost discrete electronic components.

The algorithms implemented to automatically adjust the gain of the receiver amplifier and to sweep the carrier frequency improved the robustness of the system, allowing for a good performance in real installations with different attenuation and noise. Additionally, the circuitry that implements the adjustable gain is simple, low-cost, and does not require processing time after the system setup.

The results achieved in laboratory tests showed that the proposed PLC modem is capable of transmitting data at 9,600 bps with no errors if the noise spectral density is below 111 nV_{RMS}^2/Hz in the bandwidth of 150 kHz to 500 kHz. The system was also evaluated in a residential power network, where it presented a bit error rate below 1.21%.

The proposed PLC modem is an ideal solution for low-cost IoT devices that require low baud rate communications. It can be employed in any home appliance controller, such as ACs, microwaves, as well as in resource management systems, such as in smart energy meters.

For future work, we propose to define optimized network topologies, packet formats, and network protocols. Additionally, an application-specific integrated circuit (ASIC) can be developed to implement the proposed modem and further reduce its cost in large-scale production.

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REFERENCES

[1] G. Bedi, G. K. Venayagamoorthy, R. Singh, R. R. Brooks, and K.-C. Wang, “Review of Internet of Things (IoT) in Electric Power and Energy Systems,” *IEEE Internet Things J.*, vol. 5, no. 2, pp. 847–870, 2018.

[2] D. Minoli, K. Sohraby, and B. Occhiogrosso, “IoT Considerations, Requirements, and Architectures for Smart Buildings – Energy Optimization and Next Generation Building Management Systems,” *IEEE Internet Things J.*, vol. 4, no. 1, pp. 269–283, 2017.

[3] Q. “A Comprehensive Review of Smart Energy Meters in Intelligent Energy Networks,” *IEEE Internet Things J.*, vol. PP, no. 99, pp. 1–1, 2015.

[4] E. Spano, S. Di Pascoli, and G. Iannaccone, “Internet-of-things infrastructure as a platform for distributed measurement applications,” *Conf. Rec. - IEEE Instrum. Meas. Technol. Conf.*, vol. 2015-July, pp. 1927–1932, 2015.

[5] M. Rizzi, P. Ferrari, A. Flammini, and E. Sisinni, “Evaluation of the IoT LoRaWAN Solution for Distributed Measurement Applications,” *IEEE Trans. Instrum. Meas.*, vol. 66, no. 12, pp. 3340–3349, 2017.

[6] M. Oliveira Leme, F. Trojan, A. C. Francisco, and A. A. Paula Xavier, “Digital Energy Management for Houses and Small Industries Based on a Low-cost Hardware,” *IEEE Lat. Am. Trans.*, vol. 14, no. 10, pp. 4275–4278, 2016.

[7] H. Ghayvat, S. C. Mukhopadhyay, and X. Gui, “Issues and mitigation of interference, attenuation and direction of arrival in IEEE 802.15.4/ZigBee to wireless sensors and networks based smart building,” *Meas. J. Int. Meas. Confed.*, vol. 86, pp. 209–226, 2016.

[8] S. Shoaib, X. Chen, and I. Llewellyn, “Increasing the Effective Range of Smart Meter Home Area Network,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, pp. 2898–2901, 2017.

[9] S. Barker, D. Irwin, and P. Shenoy, “Pervasive Energy Monitoring and Control Through Low-Bandwidth Power Line Communication,” *IEEE Internet Things J.*, vol. 4, no. 5, pp. 1349–1359, 2017.

[10] H Gassara, F Rouissi, A Ghazel, “Statistical Characterization of the Indoor Low-Voltage Narrowband Power Line Communication Channel,” *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 1, pp. 123–131, 2013.

[11] D. Chariag, D. Guezgouz, J. C. Le Bunetel, and Y. Raingeaud, “Modeling and simulation of temporal variation of channel and noise in indoor power-line network,” *IEEE Trans. Power Deliv.*, vol. 27, no. 4, pp. 1800–1808, 2012.

[12] T. R. Oliveira, A. A. M. Picorone, S. L. Netto, and M. V. Ribeiro, “Characterization of Brazilian in-home power line channels for data communication,” *Electr. Power Syst. Res.*, vol. 150, pp. 188–197, 2017.

[13] C. Cano, A. Pittolo, D. Malone, L. Lampe, A. M. Tonello, and A. Dabak, “State-of-the-art in Power Line Communications from the Applications to the Medium,” vol. 8716, no. c, pp. 1–19, 2016, doi: 10.1109/JSAC.2016.2566018.

[14] D. S. Kim, S. Y. Lee, K. Y. Wang, J. C. Choi, and D. J. Chung, “A power line communication modem based on adaptively received signal detection for networked home appliances,” *IEEE Trans. Consum. Electron.*, vol. 53, no. 3, pp. 864–870, 2007.

[15] Y. T. Hwang and S. W. Chen, “Hardware efficient design for narrow band power line communication modem,” *IEEE Reg. 10 Annu. Int. Conf. Proceedings/TENCON*, pp. 508–512, 2011.

[16] Y. F. Chen and T. D. Chiueh, “Baseband transceiver design of a 128-Kbps power-line modem for household applications,” *IEEE Trans. Power Deliv.*, vol. 17, no. 2, pp. 338–344, 2002.

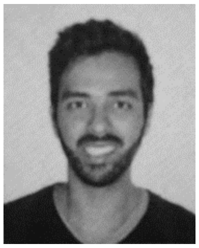
[17] B. Tiru and P. Boruah, “Design and Testing of a Suitable Transceiver for Full Duplex Communication in Indoor Power Line,” *IETE J. Res.*, vol. 56, no. 5, p. 286, 2010.

[18] C.-H. Wang, C.-Y. Chen, and T.-P. Sun, “Circuit implementation of OOK modulation for low-speed power line communication using X10 standard,” pp. 248–453, 2011.

[19] “Noise Measurements Using a Teledyne LeCroy Oscilloscope,” 2013.

[20] T. Instruments, “MIXED SIGNAL MICROCONTROLLER 1 MSP430AFE2x3 MSP430AFE2x2 MSP430AFE2x1,” 2011.

[21] R. Pi, “Raspberry Pi Compute Module (CM1) Raspberry Pi Compute Module 3 (CM3) Raspberry Pi Compute Module 3 Lite (CM3L),” vol. 3, no. October, pp. 0–21, 2016.



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