Permutation Coding with Differential Quinary Phase Shift Keying for Power Line Communication

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***Abstract*—Permutation coding (PC) has been known to be effective in combating power line channel impairments, when used in concatenation with other channel coding schemes like convolutional or Reed Solomon (RS) codes, using FSK, PSK or DPSK as the modulator. We hereby report the development of a modified DPSK modulator, called differential quinary PSK (DQuiPSK), with only 5 constellations, to improve the performance of permutation coded DPSK-OFDM modulation for power line communication (PLC) purposes. This combination is, therefore, termed an RS-PC-DQuiPSK-OFDM scheme, with RS being used as an outer code. To implement this over power line, universal software radio peripherals, which are software defined radio hardware, originally designed for radio communications, were used together with narrowband coupling circuits, to interface with the power line. Simulations and practical implementation results show the strength and competitive performance of our scheme over the conventional convolutional coded D8PSK-OFDM scheme specified in the narrowband PLC standard.**

***Index Terms*—Channel coding, OFDM modulation, Permutation Coding, PLC G3, Power Line Communication, PRIME, Quinary Phase Shift Keying, Software Defined Radio.**

I. Introduction

The existing power lines, which are meant for both outdoor and indoor power distribution, have been broadly used to function as a communication medium in power line communication (PLC). As such, with PLC, data transmission for various applications such as electric vehicle-to-charging stations, AMR (automatic meter reading) in smart-grid infrastructure), internet access, home networking and indoor communications, can now be made cost effective. However, noise and attenuation, in form of narrowband interference (NBI), additive white Gaussian noise (AWGN), impulsive noise (IN), and frequency selective fading, are the major setbacks in PLC. These make the channel very unstable and hostile to data transmission [1], [2], [3]. PRIME and PLC G3, the two narrowband PLC (NBPLC) standards, have identified orthogonal frequency division multiplexing (OFDM) to be more robust against most of the above named PLC channel impairments, and MDPSK (M-ary differential phase shift keying) is specified as the constellation mapper for this OFDM scheme [4], [5]. In order to contribute to the development of these standards, we hereby report the development of a less-complex, but robust coded MDPSK-OFDM algorithm, termed RS-PC-DQuiPSK-OFDM scheme, where DQuiPSK stands for differential quinary PSK with 5 constellations, as proposed in this work. Due to the coding rate involved, this scheme is more suitable for wide area applications, especially for low speed telemetry in Smart Grids (SG). In SG, NBPLC is widely useful for load management applications and AMR, since these applications can operate at several thousand bits per seconds [6]. Hence, by mitigating against the incessant PLC noise, using a simplistic approach, as done in this study, we, invariably, contribute to the SG technology in general.

Some literature have reported the uniqueness of differential modulation schemes in a number of PLC channel conditions [4], [7], [8]. As regards combining permutation coding (PC) with modulation schemes, there is no work on a combined PC-DPSK-OFDM scheme, but a number of literature have reported the use of PC with ordinary PSK-OFDM [9]. As shall be discovered in this paper, a simple algorithm, which entails constraining the output of the conventional DPSK modulator to the PC codeword length (which is 5 in this regard), helps in improving the performance of PC coded MDPSK scheme in combating the PLC channel associated impairments. To the best of our knowledge, this is the first time a scheme like this is reported.

For the essence of evaluation, by simulation, we first make a comparison between the conventional RS-convolutional coded D8PSK-OFDM (i.e., RS-CC-D8PSK-OFDM), denoted as Scheme A, RS-PC-D8PSK-OFDM, denoted as Scheme B and the proposed RS-PC-DQuiPSK-OFDM, denoted as Scheme C. For practical comparisons, all the three schemes were, in turn, implemented, using USRPs (universal software radio peripherals), which are SDR (software defined radio) based modems, originally meant for wireless communications. With SDR, various radio communication systems can be practically evaluated, without difficulties. This is because, SDR gives room for digital signal processing in the software domain. Digital signal processing algorithms and other param-

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eters such as interpolation, decimation and centre frequency can be adjusted a multiple of times, without any physical change in the entire hardware architecture. USRPs are manufactured by Ettus Research, and can be adapted for power line communications, by the use of appropriate coupling circuits.

Section II of this paper contains some background into some important components of the proposed scheme. Here, a brief introduction into forward error correction coding schemes is provided, with emphasis laid on PC, after which we discuss the new DQuiPSK mapper. MDPSK-OFDM, as a communication system, is then presented in Section III. This is where all the three schemes, A, B, and C are fully defined. Section IV contains the description of the implementation setup for this work. We display some of our simulation and experimental results in Section V, before giving a concise summary and conclusion of the work done in Section VI.

II. General Background

A. Forward Error correction coding

Forward error correction coding (FEC), otherwise known as channel coding, is the process of mathematically manipulating digital information, in order to mitigate against the channel impairments [10]. CC, PC and RS codes are the FEC types considered in this report. We provide a brief introduction to only PC in this sub-section, since it is our FEC code of interest. In-depth studies on CC and RS can be accessed in [2] and [10].

1) Permutation coding: Permutation coding is the representation of binary data in non binary sequence of codewords, each containing M non repetitive symbols. Permutation block coding and permutation arrays have been known for some time, as reported in [11] and [12]. Due to the complexity in constructing a long block permutation code, together with the lack of a general decoding algorithm for such codes, Ferreira, Vinck, Swart and de Beer [1] came up with a concept called the permutation trellis code (PTC), which entails the mapping of n-tuples binary CC unto non binary M-tuples PC symbols. In this regard, the CC is considered an outer code, while the PC is an inner code. Equation (1) depicts a typical PTC mapping, where two CC bits (i.e., $n = 2$), are mapped unto four PC symbols (i.e., $M = 4$).

$$(00, 01, 10, 11) \rightarrow (0123, 1230, 2301, 3102) \tag{1}$$

In PTC system, the expressions $E_{\text{detec}} = d_{\min} - 1$ and $E_{\text{correct}} = (d_{\min} - 1)/2$ respectively define the amount of detectable and correctable symbol errors, where $d_{\min}$, called the minimum distance, defines the minimum (least) possible distance between any two codewords [2]. In general, PC can be defined, based on the distance mapping property, as $Q\ (M, n, \delta)$, where δ is a small integer that indicates the mapping type. If $\delta > 0$, it defines a DIM (distance increasing mapping), where the PC's $d_{\min}$ is always larger than the outer code's $d_{\min}$. For DRM (distance reducing mapping), the PC's $d_{\min}$ is less than that of outer code, and $\delta < 0$. With DCM (distance conserving mapping), the PC's $d_{\min}$ is at least as large as that of outer code, and $\delta = 0$. A $Q\ (5, 5, 0)$ DCM mapping has been used in this report, for schemes B and C. The codewords used have been adopted from the codebook presented in [1] and they are as represented in (2).

$$\left\{\begin{array}{llllll} 51234 & 51243 & 51324 & 51342 & 51423 & 51432 \\ 52134 & 52314 & 52143 & 52341 & 53214 & 53241 \\ 53421 & 53412 & 53124 & 53142 & 41325 & 41352 \\ 41523 & 41532 & 41235 & 41253 & 42135 & 42153 \\ 42315 & 42351 & 43125 & 43215 & 43152 & 43521 \\ 43512 & 43251 & & & & \end{array}\right\} \tag{2}$$

An examplary mapping, using the above codewords, is as shown in (3), where 5 bits are mapped unto their corresponding 5 PC symbols.

$$(00000, 00001, 00010) \rightarrow (51234, 51243, 51324) \tag{3}$$

In order to recover the encoded bits, the received codewords are compared with all the codewords in memory, using Hamming distance. The codeword with the nearest distance from the received word is selected as the correct codeword. After this, the corresponding bits to this codeword can be obtained, using a reverse mapping, such as presented in (3).

In-depth studies into the capability of PC in combating PLC noise are reported in [1], [9], [13], [14] and [15].

B. Differential Quinary phase shift keying

MDPSK modulation is more or less the same as the normal MPSK modulation, except that in MDPSK, every successive symbol is derived from the previously mapped symbol. From the mapping representation adopted in (2) above, 5 outer code bits are mapped unto 5 PC symbols (with each symbol taken between numbers 1 and 5). In order to map such symbols into constellations, the applicable conventional constellation mapper, in an MDPSK system, is the 8DPSK mapper. This means only 5, out of the 8 available constellations, will be used by the PC symbols. In effect, there is probability that 3 non transmitted symbols feature in the received symbols, due to channel corruption. Due to this effect, the term quinary DPSK was conceived, by devising an algorithm which constrains the MDPSK constellations to 5. With this, all the 5 constellations are evenly spaced on the constellation graph. This causes the Euclidean distance between adjacent symbols to be larger than that of the conventional 8DPSK mapper, the effect of which is an improved BER (bit error rate) performance, as shall be later revealed in our simulation results. As a means of comparison, the PSK constellations needed for mapping the differentially encoded D8PSK and DQuiPSK integers are presented in Fig. 1. Deeper studies on the general MDPSK algorithm can be found in [10] and [16].

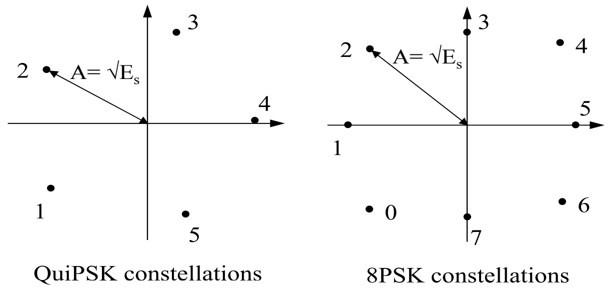

Figure 1. Typical QuiPSK and 8PSK constellations for mapping differentially encoded DQuiPSK and D8PSK symbols.

III. THE MDPSK-OFDM SYSTEM

An OFDM system is a multi-carrier digital modulation process that uses the conventional single carrier modulators for its constellation mapping. Fig. 2 clearly depicts what an OFDM transceiver does in processing digital signals. The upper part of the figure is the transmitter. The data to be transmitted is first pre-processed with CRC (cyclic redundancy check) and FEC, and then transformed by constellation mapper in the frequency domain, which, in this regard, is MDPSK modulator, depending on the bit rate of interest. This results into a set of complex baseband symbols. A serial to parallel converter (or a demultiplexer) splits the incoming stream of complex data into parallel streams. The resulting data stream is then mapped or modulated unto OFDM symbols, by computing their IFFT (inverse fast Fourier transform), based on the number of sub-carriers required. At this stage, pilot tones, preambles and paddings (if necessary) are inserted into the parallel data. These insertions are needed by the receiver to perform synchronization, so as to avoid ISI (inter-symbol interference) and ICI (inter-carrier interference). After this, cyclic prefixing is done. This is needed by the receiver to also prevent ISI. The resulting OFDM symbols are then multiplexed into serial format, by the help of a parallel to serial converter and further up-converted into analogue format, by using DAC (digital to analogue converter). A composite of the complex baseband signal is then formed, after being used to modulate a carrier of high frequency, to be sent through the communication channel.

In the context of this work, the proposed concatenated coding and modulation schemes are respectively introduced in the CRC & FEC Coding and Modulation blocks shown in Fig. 2. The receiver, typified in the lower part of Fig. 2, operates by making the received complex baseband signal go through a reverse process of the transmitter.

For the purpose of evaluation, we have designed and implemented three different concatenated coded modulation schemes (A, B and C), all using a binary $(32, 24)$ RS code as their outer codes, with $24/32$ as the coding rate. Scheme A is the conventional RS-CC-D8PSK-OFDM coded modulation scheme specified by the NBPLC standard (PLC G3) [5]. A $1/2$ rate CC is used here, with a constraint length of 7. Here, the D8PSK mapper used maps 3 CC bits unto the corresponding decimal symbols, before directly modulating them unto their complex basebands. The bit rate for the D8PSK is 3 bits per symbol. In effect, the CC-D8PSK has a combined rate of $3/2$. Scheme B is an RS-PC-D8PSK-OFDM scheme, which is the foundational coded modulation scheme for the proposed scheme C. The PC employed here is a Q $(5, 5, 0)$ DCM PC. The PC codewords used were obtained from [1]. Since we map 5 RS bits unto 5 decimal PC symbols, which are directly modulated, the concatenated PC-D8PSK scheme here has a combined rate of $5/5$, which is 1 bit per symbol. Scheme C is the proposed RS-PC-DQuiPSK-OFDM scheme, which employs the use of the new DQuiPSK mapper described in Sub-section II-B. It uses the same PC system as in scheme B. The difference between this scheme and scheme B, is the DQuiPSK used in place of the D8PSK. Both Schemes thus have the same combined rates.

By calculation, the effective ratio of the rates of all the three schemes is $R_A : R_B : R_C$ = 1.5 : 1 : 1. Since scheme A is of higher rate, this has been compensated for in the simulation and implementation work done, for ensuring fair comparisons.

IV. THE IMPLEMENTATION SETUP

We have recently reported an NBPLC channel modelling, using USRP and PSK modulation in [17]. The same experimental setup used therein has been used here as well. Since SDR system is software-based, the only difference in the set up is the signal processing algorithms, which are basically implemented in the software domain. This is what makes the practical comparisons of all the three schemes easy. Nothing needs to be altered in the hardware setup, except the software algorithms involved for each scheme. The schematic of the experimental setup is presented in Fig. 3. The topology is 7 m long and it has 4 load points. An isolated 230 V uninterrupted power supply (UPS) was used to power the entire topology, while the supply to the two USRPs is from another dedicated UPS source (not shown in the figure, to make it conspicuous). The USRP hardware at the left hand side of the topology was configured as the transmitter (Tx). Its radio frequency (RF) output port is connected to a PLC coupling circuit (bandpass filter), which in turn injects the transmitted signal into the PLC channel. The USRP at the right hand side of the topology was configured as the receiver (Rx). Its input port is connected to the Rx coupling circuit (also a bandpass filter). This Rx coupling circuit receives the transmitted signal from the PLC channel and couples it to the RF input of the receiving USRP.

A. Input data description

For the simulation work, a 5376 random bit sequence, generated by the "*randi*" MATLAB function, is used as the input data for all the three schemes compared. For the practical work, a paragraph of 91 words, composed of 649 characters (as

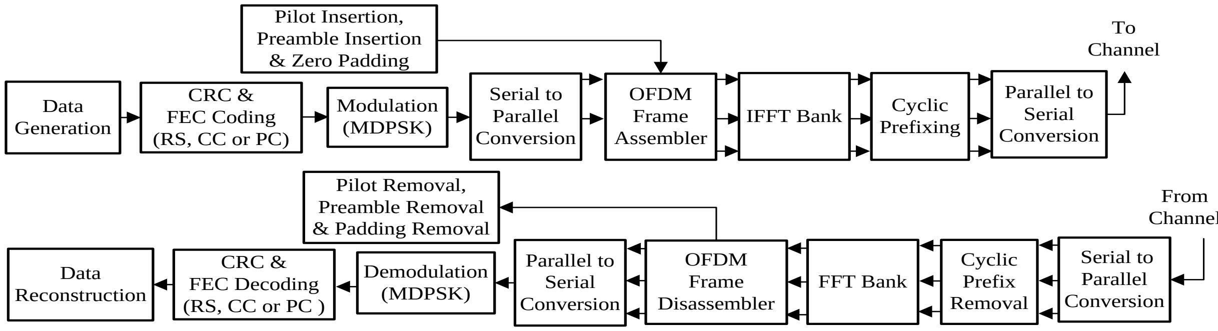

Figure 2. A typical block diagram of an OFDM transceiver.

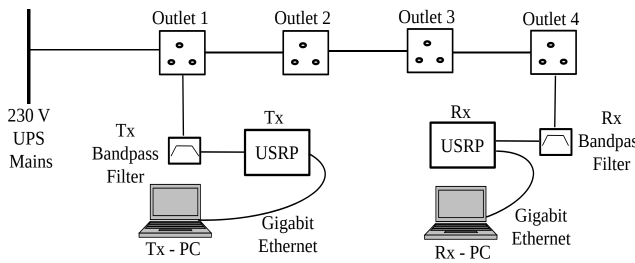

Figure 3. The schematic of the experimental setup.

shown in Fig. 4), was used to represent the binary input data to the three models implemented. Each character in the paragraph was converted to its corresponding binary format, which is 7 bits long. The resulting bit stream is what serves as the binary input to the models. After decoding the received bit streams, the transmitted paragraph was reconstructed by mapping each block of 7 bits unto its corresponding character. As such, the achieved quality of service (QoS) can, therefore, be used as the touchstone for evaluating the performances of the three schemes implemented. Apart from the centre frequency (which is now 145 kHz) and the signal processing algorithms used, all other software and hardware configuration parameters employed in this work are the same as what were used in [17]. For emphasis' sake, some of the important parameters include the sampling frequency (0.2 MHz), decimation and interpolation factors (1e8/sampling frequency), and the USRP daughterboards (LFTX & LFRX).

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Figure 4. The transmitted paragraph.

V. RESULTS

The simulation and measurement results obtained by comparing the three different schemes A, B and C described in Section III are presented here. The disparities in the coding rates have been compensated for in the E_b/N_o computations (for the simulation work). For practical comparisons, the coding rate compensation could have been very easy to accomplish, by simply adjusting the transmitting USRP's gain parameter (in DB). However, this parameter is non tunable in the LFTX daughterboard used [17]. As such, the transmit gain of the transmitter was manipulated in the software domain, immediately after the signal processing, so as to compensate for the coding rate disparities. In order to ascertain the compensation, a spectrum analyzer (SA) was used to monitor the manipulated transmit gain, by directly tapping the incoming signal to the RF input of the receiving USRP port and coupling it unto the the SA's input. With this, the level of the received signal could be monitored, as the gain was being varied in the software environment.

A. Simulation results

Four different channel conditions associated with PLC are used to evaluate the three schemes. The first channel condition considered is an ordinary AWGN channel, while the the second and the third channel conditions are a combined AWGN+IN and combined AWGN+NBI channels, respectively. All the three different noise types are combined in the fourth channel condition (i.e., AWGN+IN+NBI). The Markov model used to define IN in [2] is what we used for our IN channel model. Here, a parameter, T which defines the relationship between the IN PSD σ^2_{IN} and that of AWGN, σ^2_{AWGN}, is used to define the strength of IN in the system. This relationship is defined as $T = \sigma^2_{\text{IN}}/\sigma^2_{\text{AWGN}}$. For our simulation work, three instances of T (i.e., $0.2, 0.1$ and 0.04) have been considered. Also, we have adopted the NBI model described by Papilaya, Shongwe, Vinck and Ferreira in [9] in our NBI channel condition. In this NBI model, a parameter designated as P is used to define the probability of NBI featuring in an OFDM system, in the frequency domain. In our work, three instances of this probability (i.e., $P = 2.5\%$, $P = 6.5\%$ and $P = 12.5\%$) are used to evaluate all the three schemes compared. Details about these noise models can be accessed in [9] and [2]. Fig. 5 through 8 respectively show the results of the simulated schemes A, B and C, considering all the channel conditions described above.

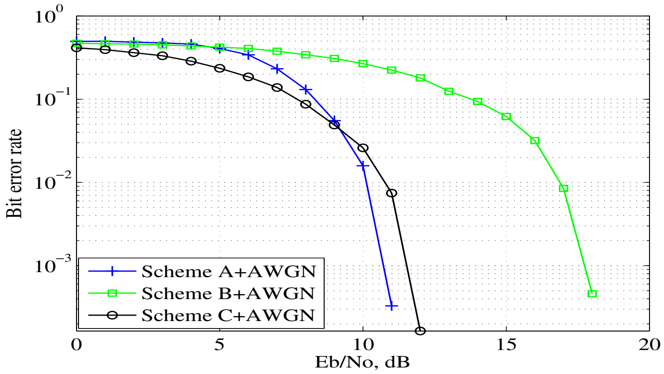

Figure 5. Bit error rate curve for schemes A, B and C, with AWGN.

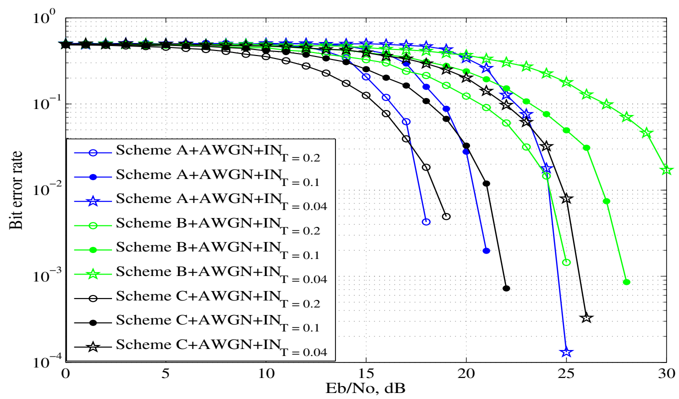

Figure 6. Bit error rate curve for schemes A, B and C, with AWGN+IN.

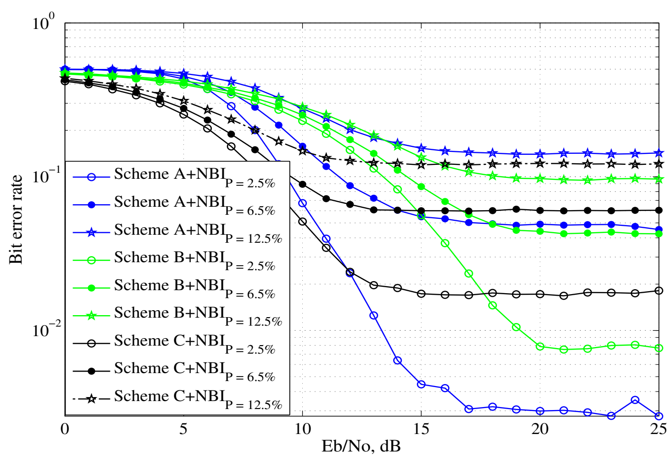

Figure 7. Bit error rate curve for schemes A, B and C, with AWGN+NBI.

With only AWGN, the proposed scheme, C is seen to outperform the other schemes at extremely low E_b/N_o values, followed by B. However, there is a crossing at $E_b/N_o = 9$dB, where A turns out being slightly better than C, with B being the worst (Fig. 5). With AWGN+IN channel, at all values of $T = 0.2,\ 0.1$ and 0.04, the proposed scheme, C is still the best performing scheme at low E_b/N_o values, but there are crossings at higer E_b/N_o values (i.e., at 17 dB for T = 0.2, 20 dB for T = 0.1 and 23 dB for T = 0.04), where

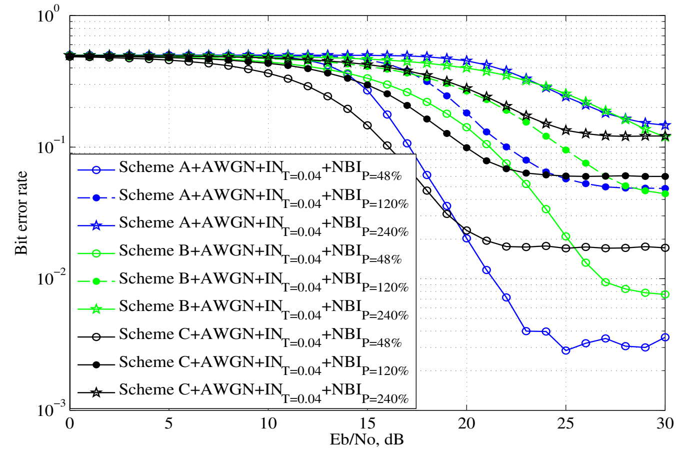

Figure 8. Bit error rate curve for schemes A, B and C, with AWGN+IN+NBI.

A slightly performs better than C (Fig. 6). Scheme B has a relatively competitive performance with A at low E_b/N_o values, but its worst performance becomes evident at higher E_b/N_o values. For the AWGN+NBI channel condition (Fig. 7), C remains the best performing scheme at lower E_b/N_o values, but there are crossings at higher E_b/N_o values, where B turns out being the best, followed by A, except at NBI probability of 2.5%, where A outperforms B at barely every E_b/N_o values. Similar pattern of performances are observable in the overall AWGN+IN+NBI channel condition, with the exception that none of the schemes can outperform C until after $E_b/N_o \approx 20$ dB. For this condition, the value of T is fixed at 0.04. Until NBI probability of 6.5%, C remains relatively the least performing scheme at high E_b/N_o, before attaining close competition with B at $P > 6.5\%$. At this value of $P > 6.5\%$, performances of schemes B and C justify the importance of PC in the presence of intense frequency disturbance (NBI) in the PLC channel.

The outcome of the simulation results shows the strength of the proposed scheme. Despite the complexity involved in the CC algorithm, A can only perform slightly better than the proposed scheme at very high E_b/N_o values. More so, there is a limit to which the transmit signal power can be increased in a PLC system [18], [19], [20]. Owing to this fact, the proposed scheme should be preferred above others, due to its performance at low E_b/N_o values. In terms of implementation, C stands better chance, due to the less-complex algorithm involved in PC.

B. Experimental results

For practical evaluation, the topology presented in Fig. 3 was setup for each of the three schemes considered. PLC channels, naturally, are unstable. However, in our experiment, we created a loading condition, to further make the channel more unstable, so as to observe the strength of the proposed scheme. As such, outlets 2 and 4 in the topology were used to power two additional computers, with a flickering 100 W

(a)

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(b)

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Figure 9. The received paragraphs using schemes (a) A, (b) B and (c) C.

incandescent light bulb connected to outlet 3. Fig. 9(a) to 9(c) display the results of the comparisons made between the three schemes under this channel loading condition. Schemes A and C successfully received the transmitted paragraph, without noticeable visual errors (Fig. 9(a) and 9(c)). Scheme B also received the transmitted paragraph, but with some noticeable errors (9(b)). This implies that the new DQuiPSK algorithm introduced in C has actually helped the RS-PC-D8PSK-OFDM to withstand the harsh channel conditions. This is what makes the use of PC with MDPSK modulations worthwhile.

VI. CONCLUSION

A special MDPSK modulator named DQuiPSK that assists the use of a DCM PC in a conventional D8PSK-OFDM system has been presented. The DQuiPSK modulator algorithm constrains the modulator's constellations to only 5, which is the exact PC codeword length considered. This thus improves its capability to handle unwanted errors to some extent. The implementation hardware used are two USRPs, originally meant for radio communications. The channel of communication in the presented work is a 230 V power line. At both simulation and practical levels, the proposed scheme showed better performance, when compared with an RS-PC-D8PSK-OFDM scheme, and a competitive performance with an RS-CC-D8PSK-OFDM scheme. Because the PC algorithm in the proposed scheme is less-complex, compared to the scheme involving CC, the proposed scheme stands better chance, in terms of easy implementation. Although PC have been proven to be robust, when used with other modulators like MFSK, its use with an MDPSK modulator would not have been worthwhile, if not for the sake of such modified modulator as presented here. It is, however, pertinent to note that the performance of a PLC system also depends on the quality of the coupling circuits used.

REFERENCES

[1] H. C. Ferreira, A. J. H. Vinck, T. G. Swart, and I. de Beer, "Permutation trellis codes," *Communications, IEEE Transactions on*, vol. 53, no. 11, pp. 1782–1789, Nov 2005.

[2] H. C. Ferreira, H. M. Grové, O. Hooijen, and A. J. Han Vinck, "Power line communication," *Wiley Encyclopedia of Electrical and Electronics Engineering*, 2001.

[3] T. G. Swart, "Distance-preserving mappings and trellis codes with permutation sequences," Ph.D. dissertation, Dept. Elect. Eng. Sci., Univ. Johannesburg, 2008.

[4] *PRIME Technology, whitepaper: PHY, MAC and Convergence layers*, 21st ed., 2008.

[5] eRDF, (2013, Jun.). *PLC G3 Physical Layer Specification*.

[6] L. Cheng and H. C. Ferreira, "Time-diversity permutation coding scheme for narrow-band power-line channels," in *Power Line Communications and Its Applications (ISPLC), 2012 16th IEEE International Symposium on*, March 2012, pp. 120–125.

[7] M. Wetz, W. G. Teich, and J. Lindner, "OFDM-MFSK with differentially encoded phases for robust transmission over fast fading channels," in *11th International OFDM-Workshop*, Aug. 2006.

[8] A. Pinomaa, H. Baumgartner, J. Ahola, and A. Kosonen, "Utilization of software-defined radio in power line communication between motor and frequency converter," in *Power Line Communications and Its Applications (ISPLC), 2010 IEEE International Symposium on*, March 2010, pp. 172–177.

[9] V. N. Papilaya, T. Shongwe, A. J. H. Vinck, and H. C. Ferreira, "Selected subcarriers QPSK-OFDM transmission schemes to combat frequency disturbances," in *Power Line Communications and Its Applications (ISPLC), 2012 16th IEEE International Symposium on*, March 2012, pp. 200–205.

[10] B. Sklar and P. M. Grant, *Digital Communications: Fundamentals and Applications*. Englewood Cliffs; NJ: Prentice Hall, 1988.

[11] D. Slepian, "Permutation modulation," *Proceedings of the IEEE*, vol. 53, no. 3, pp. 228–236, March 1965.

[12] M. Deza and T. Huang, "Metrics on permutations, a survey," *Journal of Combinatorics, Information and System Sciences*, vol. 23, no. 1–4, pp. 173–185, 1998.

[13] A. J. H. Vinck, "Coded modulation for power line communications," *AEU International Journal of Electronics and Communications*, vol. 54, no. 1, pp. 45–49, Jan 2000.

[14] A. J. H. Vinck and J. Häring, "Coding and modulation for power-line communications," in *Power Line Communications and Its Applications (ISPLC), 2000 IEEE International Symposium on*. IEEE, 2000, pp. 265–271.

[15] T. G. Swart, I. De Beer, H. C. Ferreira, and A. J. H. Vinck, "Simulation results for permutation trellis codes using M-ary FSK," in *Power Line Communications and Its Applications, 2005 International Symposium on*. IEEE, 2005, pp. 317–321.

[16] P. G. Lin, *OFDM simulation in MATLAB*. California Politechnic State University, 2010.

[17] A. Familua, K. Ogunyanda, T. Swart, H. Ferreira, R. Van Olst, and L. Cheng, "Narrowband PLC Channel Modeling using USRP and PSK Modulations," in *Power Line Communications and Its Applications (ISPLC), 2014 IEEE International Symposium on*, April 2014.

[18] CENELEC, "50065 part 1: Signalling on low voltage electrical installations in the frequency range 3 kHz to 148.5 kHz, general requirments, frequency bands and electromagnetic disturbances," 1992.

[19] International Electrotechnical Commission, "Electromagnetic compatibility (EMC) - part 4: Testing and measurement techniques," *Standard EN 61000*, 1995.

[20] A. Mengi, "On combined coding and modulation," Ph.D. dissertation, Universität Duisburg-Essen, Fakultät für Ingenieurwissenschaften» Ingenieurwissenschaften-Campus Duisburg» Abteilung Informatik und Angewandte Kognitionswissenschaft» Mathematische Methoden der Datenübertragung, 2010.