

Data Rate Profiles of Coded/Uncoded Power Line Channel With Single-Carrier/Multicarrier Modulation Techniques

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Abstract – The power-line communication (PLC) technique involves sending information through an electrical conductor for a commercial or domestic purpose. Lately, electronic means of communication have gained popularity for the transfer of information. Conversely, there is an increased requirement for more transmission media, like the use of power line as a communication channel for remote data delivery. This paper focuses on determining the data rate profile achievable using the single-carrier/multicarrier modulation techniques with Reed-Solomon concatenated convolutional (RS-CC) codes for data transmission through a power line channel. In this investigation, MATLAB/SIMULINK was used to explore a low-voltage power line as a communication channel for high data transmission rate. Data transmission was accomplished by utilizing a parametric model of a power line channel with the different kinds of noise considered in the simulation. In the designed power-line communication (PLC) system, single-carrier modulation offered a maximum of 14.4 Mbps reduction in the data rate when the uncoded 64-quadrature amplitude modulation (QAM) was compared to coded 64-QAM with 1/2 forward error correction (FEC). In the OFDM power-line communication (PLC) system, the decrease in the data rate was maximal at 39 Mbps when the uncoded 16-QAM was contrasted with the 16-QAM having 1/2 FEC. It was evident that the increased code rate of the PLC system using single-carrier and OFDM modulation implied increased data rate profiles.

Keywords – Channel; Data rate; Forward error correction (FEC); Multicarrier; Power line; Reed-Solomon concatenated convolutional code; Single-carrier.

I. INTRODUCTION

Man once relied on the use of fires, beacons, smoke signals, horns and communication drums to send messages but this was limited to a small geographic space. However, the need to transmit information over a long distance gave rise to electronic means of communication. The advancement of electronic communication has likewise made a road for various transmission technologies to be utilized depending to a great extent on cost and need.

The power-line communication (PLC) technique involves sending information through an electrical conductor for commercial or domestic purpose [1]. It is a ‘no new wire’ networking solution equipped for conveying data dependably to remote areas [2], [3]. This technique, much the same as some other communication technologies, require a transmitter to modulate the information before transmission, a channel through which the message signal is passed through and a receiver that will demodulate the data being transmitted. Lately,

electronic means of communication has gained popularity for the transfer of information. . Conversely, there is an increased requirement for more transmission media, like the use of power line as a communication channel for remote data delivery. This technology is used in smart grids, traffic light control and home automation [4]. In accordance with [5], noise in the power line channel includes background noise, narrow-band noise and impulsive noise, all of which could impact data transmission.

The channel was modelled by modifying the transfer function of the low voltage line as adapted from [6]. The adapted power-line communication (PLC) channel was subjected to various types of noise and a flexible coding scheme was introduced to add some extra bits in the actual data for error detection and correction. The data rate improved as the code rate and the modulation format increased. In this paper, the power line channel was modelled and transmission was achieved using single-carrier modulation and orthogonal frequency division multiplexing (OFDM) as a multicarrier modulation technique. The Reed-Solomon concatenated code was chosen for error correction and detection due to its robustness [7]. The different data rates achievable amid the transmission of data through the modelled channel were gotten and presented in a graph.

II. METHODOLOGY

The focus of this paper is to determine the data rate profile achievable using the single-carrier/multicarrier modulation techniques with Reed-Solomon concatenated convolutional (RS-CC) codes for data transmission through a power line channel. In this investigation, MATLAB/SIMULINK was used to explore a low-voltage power line as a communication channel for high data transmission rate. This was achieved by contrasting single-carrier and multicarrier modulation techniques with Reed-Solomon concatenated convolutional codes (RS-CC) to rectify the negative impact of the noise introduced at the receiver. The modelled power line channel, the transmitter and the receiver was first simulated using a single-carrier modulation technique.

For a comparative study, the message signal was transmitted using orthogonal frequency division multiplexing (OFDM) and the achievable data rate during data transmission was gotten at the end of the simulation. Figure 1 shows the block diagram for an Orthogonal Frequency Division Multiplexing (OFDM) PLC system.

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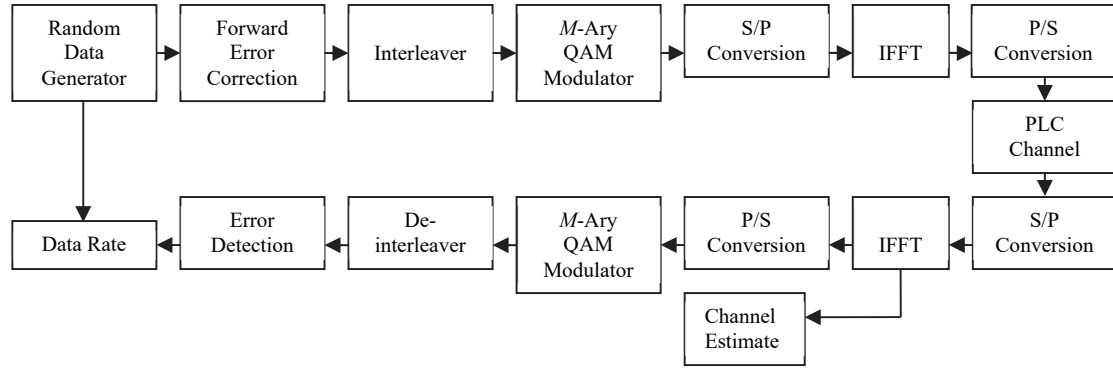


Fig. 1. An OFDM PLC system. Adapted from [8], [9].

A random binary sequence was generated and converted from serial to parallel format before being modulated in the OFDM PLC system. The inverse fast Fourier transform (IFFT) was carried out on the modulated signal to find the time waveform of the message signal [10]. A cyclic prefix was added by copying a percentage of the OFDM symbol and prepending it to the serially transmitted signal. The original binary sequence was recovered after cyclic prefix removal, serial-to-parallel conversion, IFFT, error correction and demodulation. The simulation of the PLC system was done by means of MATLAB/SIMULINK and implemented in blocks.

The single-carrier PLC system used one (1) sample per frame, whereas in the orthogonal frequency multiplexing (OFDM) transmission, 864 samples per frame were used. The power line communication system was simulated by using single-carrier modulation, in which a randomly generated binary sequence was made to pass through a BPSK, QPSK, 16-QAM or 64-QAM modulator before it was coupled into the modelled channel. The transmitted binary sequence was recovered through demodulation at the receiver.

The simulation used a Bernoulli binary block to generate random bits consisting of integer 1 and 0 with probability of 0.5. At the encoder stage, the reed-solomon code was concatenated with a convolutional code implemented with a viterbi encoder block with poly2trellis (7, [133 171])) for encoding the generated data. The output from this block was used to evaluate the data rate of the PLC system. Figure 2 illustrates the single carrier PLC system comprised of input binary sequence, error detection and correction, modulator/demodulator and power line channel.

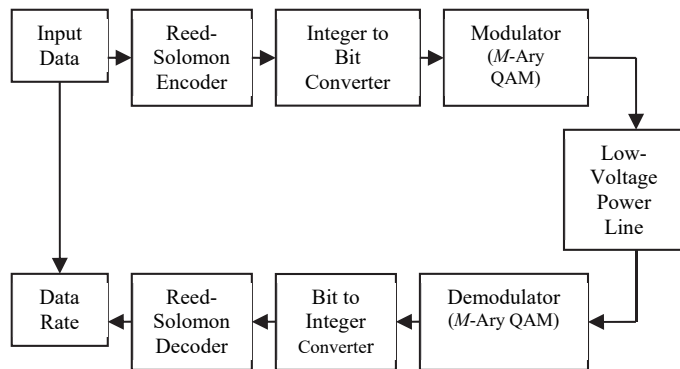


Fig. 2. Single-carrier modulated PLC system [8]

A. The Low-Voltage Line Model

As indicated by [11], the most well-known conductor materials in the Nigerian cable industry are copper and aluminium; however, over the years, copper cables have dominated the market, with the exception for bare Overhead All Aluminum Conductor (AAC) and service cables. The investigation of the low-voltage line presumed the outdoor and the indoor low-voltage lines operating at 220 V [12]. Figure 3 below shows a power line network having one branch. Line AD represents the outdoor low-voltage line, line BC represents the indoor low-voltage line, node B represents a distribution box or a point connecting the outdoor low-voltage line to the indoor (domestic) low-voltage line and node C represents the connected load. The outdoor low-voltage line, AD, was modelled as an AAC conductor, whereas the indoor low-voltage line was modelled as a copper conductor for domestic use.

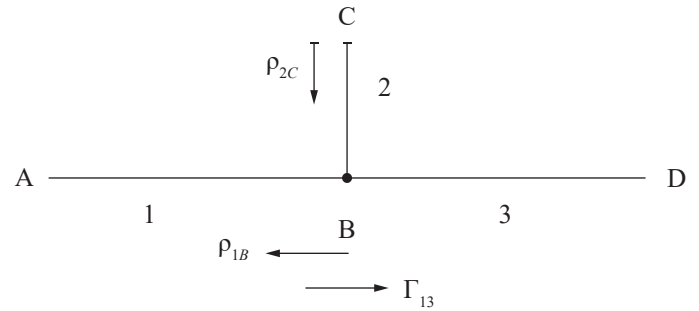


Fig. 3. Data transmission through a single-tap power line channel [5].

The outdoor low-voltage line represented by line AD was an AAC conductor of 50 mm² sectional area with radius per conductor a equal to 0.0015 m and with the distance between two conductors d equal to 0.009 m. In this study, the low voltage channel was modelled with a branch uniformly distributed along line AD with the distance of the receiver from the transmitter kept constant at 1200 m. The length of the branch was kept at 20 m and equal spacing is maintained along the line in the simulation. The parameters used were gotten from Table I.

TABLE I

OVERHEAD ALL ALUMINUM CONDUCTOR (AAC) CHARACTERISTICS FOR DIFFERENT SECTIONAL AREAS [13], [14]

Nominal section area, mm ²	Conductor diameter, mm	Overall diameter, mm	Maximum DC resistance at 20 °C
16	1.70	5.10	1.8020
25	2.15	6.45	1.1270
35	2.50	7.50	0.8332
50	3.00	9.00	0.5786

For two wires located in free space, the estimations of L_i and C_i can be expressed as [11]:

$$L_i = \frac{\mu_0}{\pi} \cosh^{-1} \left(\frac{d}{2a} \right) \quad (1),$$

$$C_i = \frac{\epsilon_0 \pi}{\cosh^{-1} \left(\frac{d}{2a} \right)} \quad (2),$$

where, a is the radius, d is the distance between two conductors, μ_0 is the permeability of the free space and ϵ_0 is the permittivity of the free space equal to 8.8541878 pF/m as presented in [9]. In this manner, the per-unit length parameters of the AOHL conductor, which corresponds to line AD in Figure 3, were calculated to obtain L_1 as 0.65474 $\mu\text{H/m}$ and C_1 as 0.16994 pF/m. The indoor low-voltage line represented by line BC was a cable of 2.5 mm² sectional area, which had a characteristic impedance of 234 Ω , a relative permittivity of 1.52, an inductance L_2 of 0.96 $\mu\text{H/m}$ and a capacitance C_2 of 17.5 pF/m as presented in Table II.

TABLE II

INDOOR POWER LINE CABLE CHARACTERISTICS FOR DIFFERENT CABLE SECTIONS [13], [14]

Cable type	0	1	2	3	4
Sections, mm ²	1.5	2.5	4.0	6.0	10.0
Relative permittivity ϵ_{eq}	1.45	1.52	1.56	1.73	2.00
Characteristic impedance Z_0 , Ω	270	234	209	178	143
Capacitance C , pF/m	15.0	17.5	20.0	25.0	33.0
Inductance L , $\mu\text{H/m}$	1.08	0.96	0.87	0.78	0.68

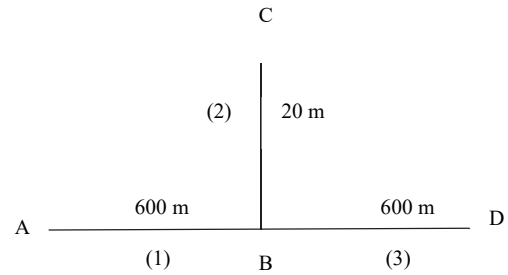
The characteristic impedance Z_i is expressed as [15]:

$$Z_i = \sqrt{\frac{R + j\omega L_i}{G + j\omega C_i}} \quad (3),$$

where R is the resistance per unit length of the wire, C is the capacitance per unit length of the line, L is the inductance per unit length of the line, G is the conductance per unit length of the wire and ω is the angular frequency in rad/s.

The characteristic impedance of line AB is represented as Z_1 while the characteristic impedance of line BC is represented as Z_2 , where it is assumed that the load impedance, Z_L , is equal to source impedance Z_S and matched with Z_1 at 50 Ω while Z_2 is obtained from the datasheet of the cable. It is crucial to factor in the impedance of the line because waves moving in a direction when energy is supplied by a source at one point of the line is made to pass through the line but not dissipated along the power line channel [16].

The lengths of the power lines used for this study are 600 m for line AB, 20 m for line BC and 600 m for line BD. For the purpose of this investigation, parameters such as the effect of the length of cable from the transmitter, the length of the



branch, the number of branches, load impedance and characteristic impedance were kept constant and the channel response was obtained and plotted.

Fig. 4. Multipath power line channel with single branch showing length.

In Figure 4, point A represents the source of the signal inserted through the channel and point D is the receiving end of that same signal across the line. The signal to be transmitted is subjected to multipath propagation due to mismatched impedance at point B causing reflections [17]. However, the signal generated at point A which is meant to be transmitted to point D would take the following paths:

- i) A-1-3-D at 1200 m;
- ii) A-1-1-A at 1220 m;
- iii) A-1-2-B-3-D at 1240 m;
- iv) A-1-2-B-1-A at 1260 m.

As shown above, there were four (4) different paths that the signal transmitted from A to D took for a transmission line with only one branch (single-tap transmission line). Therefore, the power of the received signal and the bit error rate (BER) depends upon the path followed and the length of that path. The delay (τ_i) introduced by this multipath propagation was determined by [18]:

$$\tau_i = \frac{d_i \sqrt{\epsilon_r}}{c_0} = \frac{d_i}{v_p} \quad (4),$$

where d_i is the length of the i -th path, c_0 is the speed of light, ϵ_r is the dielectric constant of the insulating material and v_p denotes the velocity of propagation. The model used for this study to investigate the frequency response $H(f)$ of the low-voltage power line channel was adapted from [5], which made it easier to parametrically model the channel and is expressed as follows:

$$H(f) = \sum_{i=1}^N g_i(f) A(f_i, d) e^{-j2\pi f \tau_i}; \quad (5)$$

$$A(f_i, d) = \exp\left(-\sqrt{(R + j\omega L)(G + j\omega C)}\right) d_i; \quad (6)$$

$$g_i = \Gamma_{12} \rho_{2C}^{(i-1)} \rho_{2D}^{(i-2)} \tau_{2C}^{(i-1)}; \quad (7)$$

where τ_i is the delay in the i -th path, g_i is the weighting factor of the i -th path, d_i is the distance between two conductors in meters f is the applied frequency band of 100 kHz to 30 MHz, the $A(f_i, d)$ part of the equation is the attenuation portion whereas the $e^{-j2\pi f \tau_i}$ part of the equation is the delay portion, Γ_{12} is the transmission factor of transmission lines (TLs) 1 to 2, Γ_{2C} is the transmission factor of transmission line (TL) represented with (2) in Fig. 4, ρ_{12} is the reflection factor at C. The weighting factor g_i of the i -th path was obtained from the transmission factors Γ_{12} and Γ_{2C} of the signal flow path expressed as follows [5]:

$$g_1 = \Gamma_{12}; \quad (8)$$

$$g_2 = \Gamma_{12} \rho_{12} \Gamma_{23}; \quad (9)$$

$$g_3 = \Gamma_{12} \rho_{2C}^2 \rho_{2D} \Gamma_{23}; \quad (10)$$

$$g_4 = \Gamma_{12} \rho_{2C}^3 \rho_{2D}^2 \Gamma_{23}; \quad (11)$$

where the parametric estimations of i , g_i and d_i for the modelled multipath channel were obtained with the spread velocity v_p as 1.5×10^8 m/s, Γ_{13} is the transmission factor of transmission lines (TLs) 1 to 3, Γ_{12} is the transmission factor of transmission line (TL) 1 to 2, Γ_{23} is the transmission factor of transmission lines (TLs) 2 to 3, ρ_{2C} is the reflection factor of TL 2 to C. The transmission factors were obtained as follows [5]:

$$\Gamma_{13} = 1 + \rho_{13}; \quad (12)$$

$$\Gamma_{12} = 1 + \rho_{12}; \quad (13)$$

$$\Gamma_{23} = 1 + \rho_{23}. \quad (14)$$

The values of the reflection factor of the i -th path are expressed as follows [5]:

$$\rho_{13} = \frac{Z_2 \parallel Z_3 - Z_1}{Z_2 \parallel Z_3 + Z_1}; \quad (15)$$

$$\rho_{12} = \frac{Z_2 \parallel Z_3 - Z_1}{Z_2 \parallel Z_3 + Z_1}; \quad (16)$$

$$\rho_{23} = \frac{Z_3 \parallel Z_1 - Z_2}{Z_3 \parallel Z_1 + Z_2}; \quad (17)$$

$$\rho_{2C} = \frac{Z_{L2} - Z_2}{Z_{L2} + Z_2}; \quad (18)$$

$$\rho_{2B} = \rho_{23}; \quad (19)$$

$$\rho_{1B} = \rho_{13} = \rho_{12}; \quad (20)$$

where, ρ_{1B} is the reflection factor of TL 1 to B, ρ_{2B} is the reflection factor of TL 2 to B.

B. Data Rate

A change in the channel state persisting for a fixed period of time was described in terms of symbols and the number of such changes to the symbols across the low-voltage line is described using a digitally modulated signal referred to as symbol rate, f_s , and measured in symbols per second [7].

$$f_s = \frac{1}{T_s} \quad (21),$$

where T_s is the symbol duration.

In a single-carrier PLC system, the term 'data rate' (R) refers to the number of bits transported per second for N bits conveyed per symbol and can be calculated as follows [6]:

$$R = f_s \log_2 M \quad (22),$$

where M is the number of distinct messages that can be sent. In an OFDM PLC system, the number of bits transported per second, termed data rate, is expressed as follows [6]:

$$\text{Data Rate} = N_{\text{dataSC}} b_m \frac{C_r}{T_s}; \quad (23)$$

$$T_s = T_b + T_g; \quad (24)$$

$$T_g = \frac{T_b}{8}; \quad (25)$$

$$T_b = \frac{N_{\text{fft}}}{F_s}; \quad (26)$$

$$F_s = n \cdot BW; \quad (27)$$

where N_{dataSC} is the number of data sub-carriers, b_m stands for the coded bits/sub-carrier, C_r is the code rate, T_s is the symbol time with or without the cyclic prefix, T_g is the guard time, T_b is the bit period, F_s is the sample rate, N_{fft} is the size of the fast Fourier transform (FFT) and BW is the bandwidth.

III. RESULTS AND DISCUSSION

At the input stage of the transmission process, the message signal was generated using the Bernoulli block that produced random binary numbers using the Bernoulli distribution with a probability p and $1 - p$ to produce a '0' and a '1', respectively. At the modulator stage, the single-carrier modulation technique used only one carrier to modulate the message signal transmitted, thereby making implementation much easier and simpler than at the stage of multicarrier modulation, where the data to be transmitted were modulated with each of the 256 carriers and encoded with a previous symbol before being mapped to a M -ary quadrature amplitude modulation (QAM) format.

The IFFT stage is unique to the OFDM-PLC system because the 256 carriers used are defined in complex conjugate pairs that are symmetric about the Nyquist frequency to produce the real-time signal. However, this stage is not present in the single-carrier modulation technique. Here, the required spectrum was worked out by obtaining the corresponding time usage form, using the IFFT block in SIMULINK. Although, the cyclic

prefix (CP) reduces the data throughput, the value of the cyclic prefix was cautiously selected to be not more than an eighth of the OFDM symbols' time ($T_b/8$) to maintain the efficiency of the PLC system. The CP helped to minimize the inter-symbol interference (ISI) resulting from multipath delays.

The transmitted signal was distorted and needed channel coding to maintain its integrity at the receiver. The transmitted data symbols on each sub-carrier were received with a scaling amplitude and a rotation in phase provided by the channel. This was caused by disturbance in the channel by impulse noise, coloured background noise and narrow-band noise due to the effect of variation in the connected loads, variation in the length of branches and the influence of interference from amplitude modulation (AM) broadcasting stations. The transmitted signal belonged to a modulation constellation format through the method of M -QAM choices. The channel showed some amount of non-linearity from disturbances that affected the symmetry of the transmitted signal constellation. The result presented in Figure 5 shows the influence of the channel modelled while the message signal was transmitted in time domain just after passing through the power line channel.

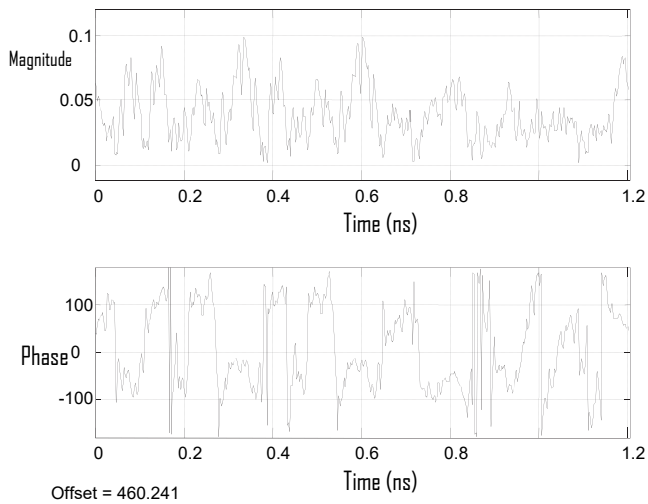
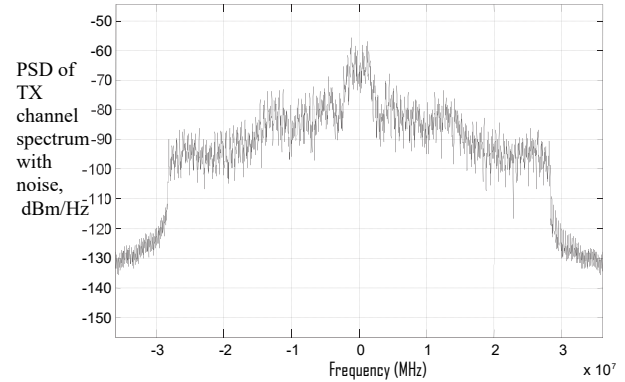


Fig. 5. Time response of a message signal after passing through the power line channel.

The model allowed the signal-to-noise ratio to be varied or controlled by adding a known amount of white noise to the transmitted message signal. It was observed that the frequency-selective channel as adapted from Zimmermann and Dostert's model has a power spectral density shown in Figure 6 at an oscilloscope span of 72 MHz.



RBW: 70.31 kHz, NFFT: 1537, span: 72 MHz, CF: 0 Hz

Fig. 6. PSD of transmitted signal when passing through the PLC channel with noise.

Power line cables are highly sensitive to external noises from radio frequency devices and electromechanical equipment if they are without electromagnetic shielding. The designed PLC system is disturbed by noise consisting of coloured background noise, narrow-band noise and impulsive noise. It was modelled and factored into the channel during the simulation. The coloured background noise has a low power spectral density (PSD) and is caused by connected appliances operating at low power. Impulsive noise is mainly caused by switching power supplies synchronously with the main cycle in the form of spikes. The noise caused by the ingress from radio broadcasting stations represents the narrow-band noise which is an amplitude-modulated sine wave. It was modelled as a sine wave block, which generates a multi-channel complex sinusoidal signal f at 50 Hz.

The path parameters as presented in Table III show the weighting factors of each path followed by the signal as a result of a single branch connected to the direct path AD as simulated in MATLAB.

TABLE III

PATH PARAMETERS FOR PLC CHANNEL WITH ONE BRANCH

i	1	2	3	4
g_i	0.667	0.2879	-0.062	0.013
d_i, m	1200	1220	1240	11 260

Furthermore, the number of possible paths, N , became fifteen (15) when the power line had two branches. The attenuation parameters and path parameters of the modelled channel are shown in Table IV. The weighting factors were tabulated after obtaining them from the transmission and reflection factors.

TABLE IV

PATH PARAMETERS FOR PLC CHANNEL MODELLED WITH TWO BRANCHES

Path parameters															
i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
g_i	0.0290	0.0430	0.0103	-0.0580	-0.0450	-0.0400	0.0380	-0.0380	-0.0710	-0.0350	0.0650	-0.0550	-0.0420	-0.0590	0.0490
d_i, m	90	102	113	143	148	200	260	322	411	490	567	740	960	1130	1200

The modelled frequency response of the power line channel with one branch and two branches is presented in Figure 7, showing that the channel was subjected to frequency-selective fading and multipath signal propagation in the frequency and time domain respectively. It also depicts that higher attenuation occurred at higher frequencies and attenuation increased with increasing distance from the transmitter to the receiver.

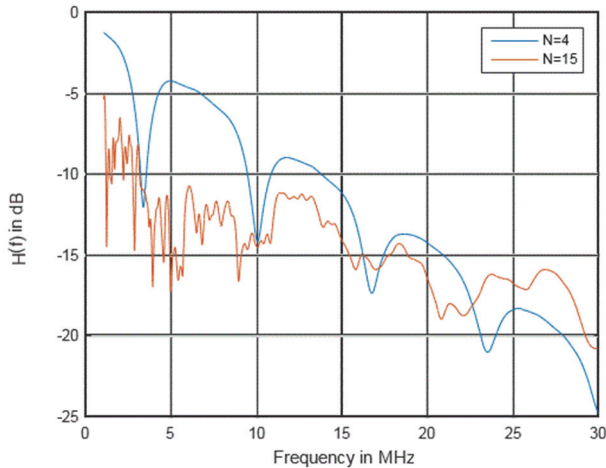


Fig. 7. PLC Frequency response magnitude plot for N number of possible paths as 4 and 15 representing single-tap and double-tap lines.

There was a reduction in the data rate by using the Reed-Solomon concatenated code on a modulation scheme; however, the channel coding technique used in this work still remains useful when transmitting digital signals over power line channels with limited bands.

Figure 8 shows the data rate of the PLC system designed for both single-carrier and OFDM being a multicarrier modulation technique. The result shows that the data rate increases along with the increase in the number of symbols mapped to 1 bit in the case of both single-carrier and OFDM modulation techniques.

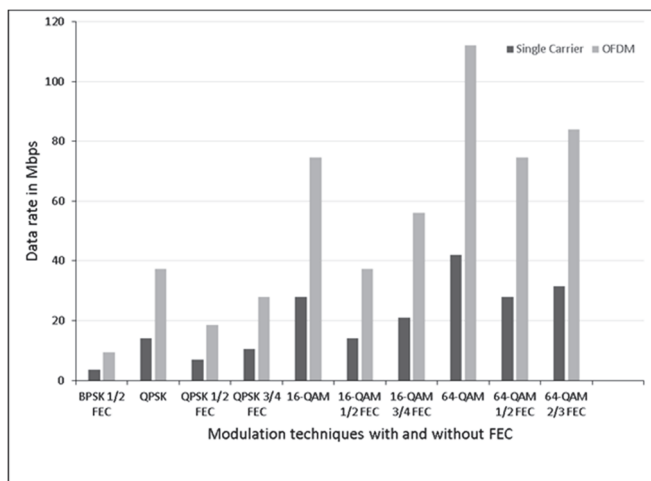


Fig. 8. Data rate profiles using single-carrier and OFDM modulation

In the case of single-carrier modulation, the reduction in the data rate was maximal at 14.4 Mbps when comparing the uncoded 64-QAM to the 64-QAM with 1/2 FEC. In OFDM,

the reduction in the data rate was maximal at 39 Mbps when comparing the uncoded 16-QAM and the 16-QAM with 1/2 FEC. It is evident from our result that both for single-carrier and OFDM modulation techniques, irrespective of whether it is the case of BPSK, QPSK, 16-QAM or 64-QAM, the more the code rate of forward error correction (FEC) for a particular modulation technique, the more data rate was achieved.

IV. CONCLUSION

When faster data rates are required, the 16-QAM and 64-QAM modulation technique offered a data rate above 14 Mbps across the PLC channel. The simulation results also showed that the Reed-Solomon concatenated convolutional code performs better than other encoding techniques in the implementation of a PLC system because of the flexibility introduced to the code rate and its ability to correct both burst errors and errors due to background noise.

It was discovered that a poor choice of modulation and anti-error coding technique can significantly affect the data rate of the resulting signal at the receiver of a PLC system. Finally, QPSK modulation was the least susceptible to interference, reaching the lowest transmission speed of 8 Mbps, whereas 64-QAM proved to be the most susceptible to interference but allowed the highest transmission speed, 54 Mbps.

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