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Analysis of the Perfect Nulling Technique in ACO-OFDM for DHT Hybrid PLC-VLC System in Impulsive Noise

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Abstract —In this paper, we investigate the performance of the discrete Hartley transform (DHT) hybrid Power Line Communication - Visible Light Communication (PLC-VLC) system based on asymmetrically clipped optical - orthogonal frequency division multiplexing (ACO-OFDM) in impulsive noise, when the Perfect Nulling technique is utilized to analyze the combating of impulsive noise in the system. ACO-OFDM is a multicarrier modulation technique used in communications systems to allow for high data rates while adding robustness to the system. In this work, we derive the theoretical bit error rate (BER) error floor expression which enables us to calculate the error floor introduced into the system due to the nulling of data samples affected by impulsive noise, which we then compare to the simulated BER error floor. Results from this work show that the simulated BER error floor values are approximately the same as the theoretical BER error floor values with insignificant differences. The simulated BER error floor values confirmed the theoretical expression for the BER error floor derived in this work.

Index Terms—DHT, PLC-VLC, ACO-OFDM

I. INTRODUCTION

Due to data traffic jamming in the currently existing communication systems, researchers have shifted their interest to exploit new technologies, which allow high speed, robust and reliable communication. Power Line Communication (PLC) and Visible Light Communication (VLC) are some of the technologies that has been studied over the past years with intent to reduce data congestion and solve the problem of 'hard to reach' nodes [1]. In lately published work, it has been evident that when the two technologies, that is the PLC and VLC, they offer high end secure communication, high power efficiency due to their low energy consumption as well as reasonable deployment costs [2]. PLC has gained a lot of popularity due to the increased demand of high-speed internet connectivity. The need to Eliminate Electromagnetic Interference (EMI) in institutions like hospitals [3], [4], capability to enable communication with nodes that are hard to reach where radio frequency (RF) signal suffers from high levels attenuation [5], makes PLC a conducive technology and competitor to other existing communication systems. Some of the applications of PLC include automatic meter reading, home networking, internet access, and home automation [6]. VLC has also emerged as an appealing complement technology due to the wide use of light emitting diodes (LEDs) as well as an upgrade of other existing communication systems for fast internet connections [7], [8]. VLC paves way for a new prospect for future communication due to the vast bandwidth it possesses. VLC also offers less threat to human health as compared to RF in places like mines and hospitals, and its duality in providing both light and communication services makes it indispensable [4]. PLC and VLC have their own fragilities, which can be scaled down by cascading PLC and VLC systems. Hybrid PLC-VLC systems have gained considerable amount of research attention due to their robustness, high-speed communication and the fact that both technologies could be implemented via Orthogonal Frequency Division Multiplexing (OFDM) [9]-[11].

Intensive research is already being undertaken to exploit the possibility of implementing the hybrid PLC-VLC systems in real world. The first cascaded PLC-VLC system prototype was first proposed back in the early 2000s [21], and the proposed system utilized single carrier binary phase shift keying (SC-BPSK) modulation which made the system to suffer from low data transmission rates. As a result of higher demands of higher data transmission rates, J. Song *et al* [22], presented a cost effective indoor broadband communication system implemented by cascading the PLC and VLC technologies. The broadcasting system proposed in [22] used Quadrature Amplitude Modulation (QAM) with OFDM for modulation in order to achieve higher data rates. Authors in [12] presented a hybrid PLC-VLC system based on OFDM where the performance of four pilot-based channel estimation algorithms are compared. Results in [12] indicate that the Singular Value Decomposition (SVD) combined with Linear Interpolation gave the best performance. It has been shown in literature that the PLC and VLC technologies can be integrated with the existing RF spectrum to form a hybrid PLC/RF/VLC system that is energy efficient and suitable for indoor communication [13]. Work in [14] presents the a hybrid power line communication multiple-input multiple-output visible

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light communication system (PLC-MIMO-VLC) system, where they analyzed the performance of the system under two different conditions, namely, line-of-sight (LOS) and LOS with first reflection(L-R1) signals in the MIMO VLC channel. The results in [14] revealed that it is possible to integrate the two technologies, however, the scenario in which the signal was added with the reflected signal gave the worst performance due to the noise introduced by the reflected signal. In addition, several manuscripts have been proposed for the integration of PLC system with other wireless technologies for various applications. Authors in [19] proposed a hybrid PLC/VLC/RF system for wireless communication under several realizations and the obtained results revealed a substantial improvement in performance in comparison to the already existing RF spectrum. The proposed PLC/VLC/RF system in [19] utilized the already existing RF spectrum and managed to minimize the power consumption required during data transmission while returning the quality of service required. It is interesting to note that the hybrid PLC/VLC system are also an ideal candidate in the design of 5G communication system. Authors in [20] demonstrated that the two independent PLC and VLC technologies can be integrated via discrete wavelet transform (DWT) in the implementation of a 5G network and the results showed that the PLC and VLC technologies have a huge potential for future generation communication systems.

ACO-OFDM is one of the popular modulation techniques being utilized in hybrid PLC-VLC systems. This technique has been vastly used in both wired and wireless communication systems [15]. In the intensity modulated direct detected (IM/DD) OFDM systems, the transmitted data must be real-valued and positive to be successfully integrated with VLC, which is achieved by applying the ACO-OFDM technique [10], [11]. The transmitted data can be made real-valued by utilizing the Hermitian symmetry coupled with IFFT block [16] or by using the Hartley transform [17]. Authors in [17] used the modified nulling technique to mitigate impulsive noise in a DHT hybrid PLC-VLC system based on ACO-OFDM. The nulling technique in [17] utilized a nulling threshold value to determine the positive data samples affected by impulsive noise and clips them to zero. The negative data samples affected by impulsive noise were taken care of by ACO negative nulling. The utilization of the Perfect nulling technique to analyze the combating of impulsive noise in the DHT hybrid PLC-VLC system based on ACO-OFDM has not yet been studied. Perfect nulling in this paper refers to an impulse noise nulling technique where perfect knowledge of the locations of impulse noise in the time domain is assumed.

In this paper, we propose to mitigate impulsive noise in a DHT hybrid PLC-VLC system based on ACO-OFDM and analyze the system with the help of the perfect nulling technique. The use of the perfect nulling technique introduces an error floor in the system as a result of nulling data samples affected by impulsive noise. Therefore, in this paper, we will compare the simulated BER error floor to the theoretical BER error floor in the communication system to check the validity of our results.

This paper is organized as follows. Section II gives a brief description of the components of the block diagram of the DHT hybrid PLC-VLC system based on ACO-OFDM, where the perfect nulling technique is utilized to combat impulsive noise. Section III covers signal analysis of the hybrid system and noise models used to corrupt the information signal. Subsequently, Section IV covers simulation results of the simulated DHT hybrid PLC-VLC system based ACO-OFDM and compare them to the theoretical BER of the system. The paper will be concluded in Section V.

II. IM/DD OFDM SYSTEM

A. ACO-OFDM

In an ACO-OFDM system, data is constrained to be unipolar by clipping the negative symbols of the signal to zero [10], [15]. The ACO-OFDM technique transmit data on half of the available subcarriers. Effective data is carried on odd subcarriers only, hence reducing the spectral efficiency of the system to nearly 50%.

B. Impulsive Noise and Awgn

In this paper, we investigate the performance of the hybrid PLC-VLC system in the presence of added white gaussian noise (AWGN) and impulsive noise. AWGN is a background noise usually caused by the environment where the system is located. In a PLC-VLC channel, sources may include sunlight, lightning, and thermal noise generated by circuit components. AWGN has a variance given by

$$\lambda^2{}_G = \frac{N_o}{2} \tag{1}$$

where N_o is the noise power density and its divided by 2 to indicate a double-sided spectral density. Impulsive noise is also added to the PLC channel of the hybrid PLC-VLC system. Impulsive noise occurs instantaneously introducing sharp peaks with normally higher amplitude than the information signal and has a variance which is expressed by

$$\lambda^2{}_I = K\frac{\lambda^2{}_G}{P} \tag{2}$$

where is K the strength of the impulsive noise and P is the probability of occurrence of impulsive noise.

Fig. 1 shows the proposed block diagram of the DHT hybrid PLC-VLC system based on ACO-OFDM where the perfect nulling technique is utilized to mitigate impulsive noise.

III. SIGNAL ANALYSIS IN ACO-OFDM SCHEME

In this Subsection, we briefly describe the signal processing in the DHT hybrid PLC-VLC system based on

ACO-OFDM system where the impulsive noise is mitigated via perfect nulling. In Fig. 1, (^) represent the noisy version of the original signal. From this point onwards, we shall refer the DHT hybrid PLC-VLC system based on ACO-OFDM as the ACO-OFDM hybrid PLC-VLC system.

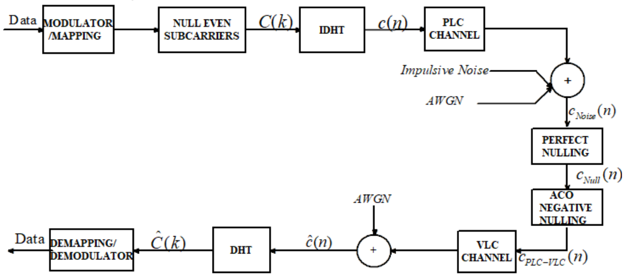

Fig. 1. DHT hybrid PLC-VLC system based on ACO-OFDM

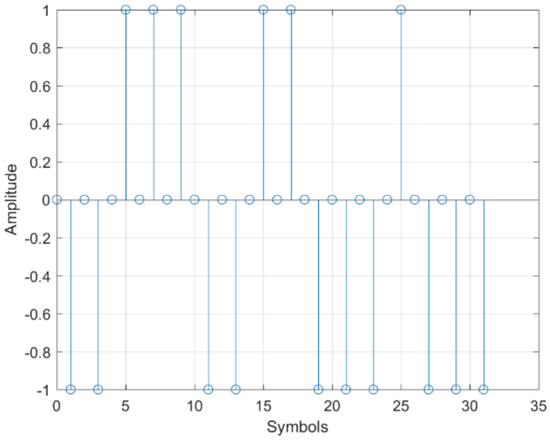

Fig. 2. Nulling even subcarriers.

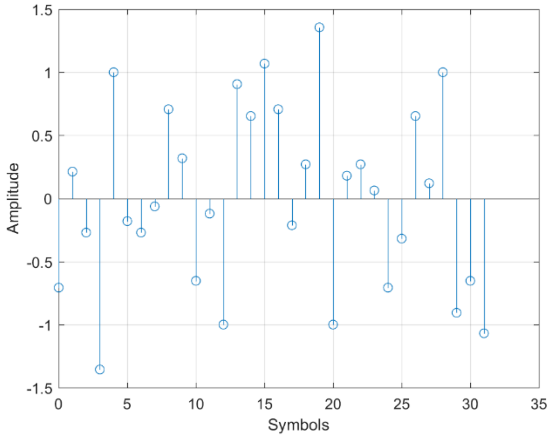

Fig. 3. IDHT output signal (real-valued data).

Fig. 1 shows a block diagram of the ACO-OFDM hybrid PLC-VLC system in impulsive noise. Binary Data is randomly generated and is mapped by a binary phase shift keying (BPSK) modulator to produce a signal that is then nulled on even subcarrier positions as part of the ACO-OFDM signal processing. For clarity, N = 32 data samples will be used for signal analysis and discrete signal plots in this Subsection. For the PLC channel to be successfully integrated with the VLC channel, the VLC input data is constrained to be real-valued. The inverse discrete Hartley transform (IDHT) block is utilized at the transmitter to ensure that its output signal, *c(n)*, is real-valued. The utilization of the ACO-OFDM modulation technique results in a reduction in spectral efficiency since useful data is only carried on odd subcarriers. Fig. 2 shows the data samples after nulling the even subcarriers. After nulling the even subcarriers, the signal is sent to the IDHT block to ensure that its output is real-valued. Figs. 3 and 4 shows the real-valued and imaginary data output of the IDHT block, respectively. The real-valued signal, *c(n)*, from Fig. 1 is then fed to the PLC channel where it gets corrupted by AWGN and impulsive noise, generating a noisy signal $c_{Noise}(n)$ with increased amplitudes as shown in Fig. 5.

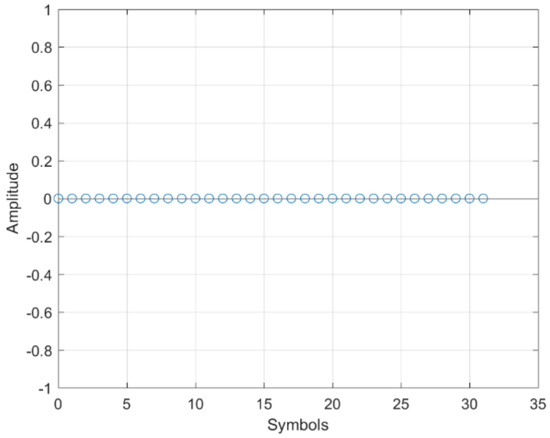

Fig. 4. IDHT output (imaginary).

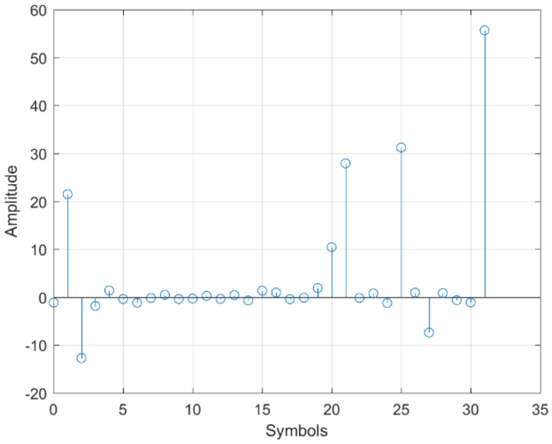

Fig. 5. Noisy signal.

The impulsive noise used in this paper is modelled as Middleton Class A due to its simple probability density function and it is widely used in PLC impulsive noise [18]. The addition of impulsive noise to the signal introduces unwanted disturbance, hence distorting the signal. In this paper, we shall use the Perfect nulling technique to combat impulsive noise from the signal. A perfect nulling system refers to a system that has perfect knowledge of the location of the impulsive noise samples and nulls all the samples exactly where impulse noise occurred.

In this case, the perfect nulling technique identifies all data samples (both positive and negative) affected by impulsive noise and clips them to zero. Fig. 6 shows the data samples after perfect nulling, with all the samples at which impulsive noise was located clipped to zero.

The clipped data samples are marked in ‘red’ in Fig. 6. The resulting signal then goes through ACO negative nulling, a procedure which involves the nulling of all negative samples to ensure that data send to the VLC channel is positive. Fig. 7 shows the data samples after asymmetrically clipped optical (ACO) negative nulling. The negative samples marked in ‘red’ in Fig. 7 represent the data samples that were affected by impulsive noise and got clipped to zero as well as the negative data samples that have been clipped to zero as a result of ACO negative nulling. Now that the signal is real-valued and positive, it is then sent to the VLC channel where is further corrupted with AWGN, then demodulated to recover the data samples.

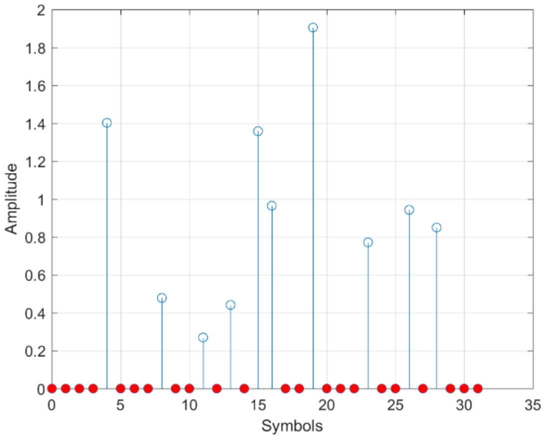

Fig. 6. Signal after perfect nulling.

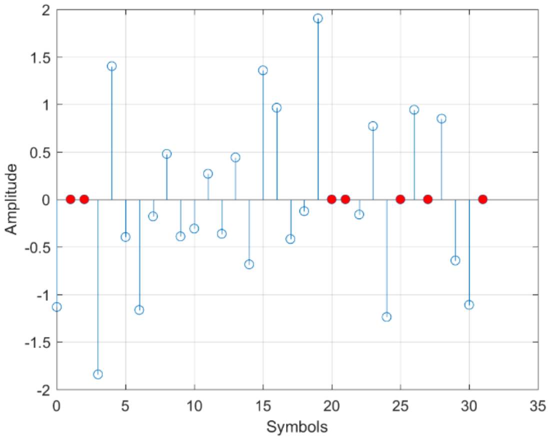

Fig. 7. Unipolar signal.

IV. SIMULATION RESULTS AND DISCUSSION

In this Subsection, we discuss and analyze the performance of the ACO-OFDM hybrid PLC-VLC system in the presence of impulsive noise. In this work, we will vary the probability of impulsive noise, *P*, and investigate its effect on the BER performance of the system. The impulsive noise power, *K*, is will be fixed at *K*=100. Throughout these simulations, the curve labelled “AWGN” represents the performance of the system in the system in AWGN only. The curve labeled “E_b/N_o” on the x-axis of the plots represents the signal to noise ratio (SNR) of the signal. For simulations in this Subsection, a sample size of $N = 1024$ was utilized.

Fig. 8 shows the performance of the ACO-OFDM hybrid PLC VLC system in impulsive noise where the perfect nulling technique is utilized to combat impulsive noise. The impulsive noise power *K* is held constant at $K = 100$, while the impulsive noise probability, *P*, is varied. *K* was held constant in these simulations since it was determined prior through simulations that its value does not have any effect on the BER performance of the system. This is because all the data samples affected by impulsive noise will be clipped to zero, rendering the impulsive noise power ineffective.

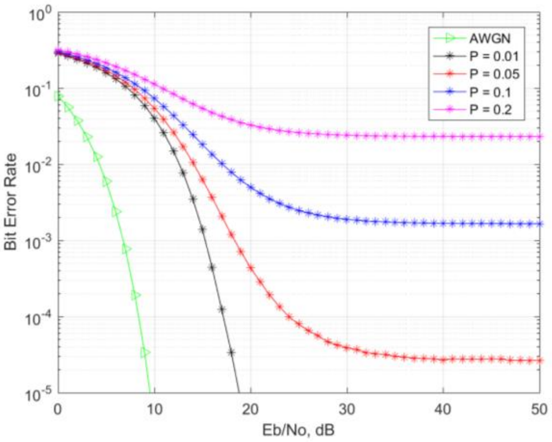

Fig. 8. Performance of the ACO-OFDM hybrid PLC-VLC system with perfect nulling, K =100, P = {0.01, 0.05, 0.1. 0.2}.

It can be observed from Fig. 8 that the best performance of the system is achieved when the probability of occurrence of impulsive noise is low, in this case, at $P = 0.01$. As the *P* is increased, the performance of the system starts to deteriorate. As expected, we notice the worst performance of the system when *P* is high, this is because more data samples will be affected by impulsive noise and gets clipped to zero, losing a large part of the signal. The curves in Fig. 8 from $P = 0.05$ to $P = 0.2$ share a common trend at high SNR, all of them possess an error floor. The curve for $P = 0.01$, that is at very low *P*, has no error floor since a negligible number of data samples will be affected by impulsive noise, therefore less or no data samples will be clipped to zero as a result of perfect nulling. The error floor represented in the curves in Fig. 8 is due to the nulling of data samples affected by impulsive noise.

Next, we will derive the general expression of the theoretical BER that allows us to calculate the error floor presented in Fig. 8 and compare it to the simulated values. The signal to noise ration of a digital communication system can be expressed as $SNR = E_b \backslash N_o$, where E_b is the bit energy (or symbol energy in the case of one bit per symbol) and No is the background noise power. In a system corrupted with impulsive noise, where impulsive noise is mitigated via the nulling technique, the SNR of the received signal takes a different form which is be represented by

$$SNR = \frac{E_b}{N} \tag{3}$$

where $N = N_o + pN_I$, and E_b is the symbol energy.

However, since at the receiver, the demodulator for ACO-OFDM decides between symbols 0 and +1 instead of the originally transmitted -1 and +1, the symbol energy is halved into $E_b/2$. In addition, nulling of impulse noise, that occurs with probability *p*, is performed at the receiver before demodulation. The nulling removes part of the signal energy, related to the probability of nulls (linked to the probability of impulse noise occurrence *p*), which is pE_b. This equates to nulling noise $E_N = pE_b$. Therefore the new SNR, with nulling, is given by

$$SNR_{null} = \frac{E_b}{N + E_N} = \frac{E_b}{N + pE_b}.$$

The term pE_b represent the energy of the nulled data symbols. As the bit energy E_b increases, it reaches a point where $N_o + pN_I << E_b$ such that the new expression for SNR is expressed as

$$SNR_{null} \approx \frac{E_b}{0 + pE_b}$$

$$\approx \frac{E_b}{pE_b}.$$

$$\therefore SNR_{null} = \frac{1}{p}. \tag{4}$$

The expression in (4) allows us to calculate the BER error floor introduced into the system as a result of nulling data samples affected by impulsive noise in Fig. 3. Now we will compare the theoretical error floor to the simulated error floor for the ACO-OFDM hybrid PLC-VLC system in Fig. 3.

As stated earlier, the decision behavior of the ACO-OFDM system follows frequency shift keying (FSK) since it decides between symbols 0 (for bit 0) and +1 (for bit 1) instead of -1 and +1, even though the transmitted symbols were initially -1 and +1, we end up making a decision between 0 and +1. From literature, the BER expression for such a modulation that decides between 0 and +1 is given by

$$BER = erfc\left(\sqrt{\frac{E_b}{2N}}\right) ?= erfc\left(\sqrt{0.5*\left(\frac{E_b}{N}\right)}\right)$$

$$= erfc\left(\sqrt{\left(0.5*\left(SNR\right)\right)}\right),$$

where $SNR = \frac{E_b}{N} = \frac{1}{p}$,

for very high E_b values. Therefore, the theoretical expression describing the error floor in our system is given by

$$BER = ?erfc\left(\sqrt{\left(0.5*\left(\frac{1}{p}\right)\right)}\right). \tag{5}$$

Table I shows a comparison of theoretical BER vs simulated BER at SNR = 40dB, for the case of perfect nulling for the ACO-OFDM hybrid PLC-VLC system with impulsive noise. The calculated error floor at 40dB is approximately the same as the simulated error floor for respective impulsive noise probability applied. The theoretical values were calculated from the expression given in (5) while the simulated results were obtained from the graph in Fig. 3.

TABLE I: THEORETICAL BER VS SIMULATED BER FOR THE ACO-OFDM HYBRID PLC-VLC SYSTEM

SNR = 40 dB	**Theoretical BER**	**Simulated BER**
P = 0.2	0.0253	0.02323
P = 0.1	0.0016	0.001672
P = 0.05	7.744×10^{-6}	2.936×10^{-5}

The results in Table I show that the theoretical and simulated BER values are close to each, with negligible differences. These values verify the theoretical expression for the BER error floor given in (5).

V. CONCLUSION

This paper analyzed the performance of DHT hybrid PLC-VLC system implemented via ACO-OFDM in impulsive noise perfect knowledge of the locations of impulse noise in the time domain is assumed and nulling was performed on the impulse noise locations. This was termed, perfect nulling. Results obtained from this work suggest that the *Perfect nulling* technique can be successfully utilized to analyze the combating of impulsive noise in the proposed DHT hybrid PLC-VLC system based on ACO-OFDM, however, *Perfect nulling* introduces an error floor when the probability of impulsive noise in the channel is high. We also managed to derive a theoretical expression that estimates the error floor when the channel is corrupted with higher frequency of impulsive noise, which can be used to obtain BER calculations of the proposed system without simulation. To confirm the validity of the derived expression in (5), we demonstrated that the theoretical error floor obtained using the expression in (5) for the ACO hybrid PLC-VLC system is approximately the same as the simulated error floor for the same system. In addition, the simulation results obtained in this work revealed that the proposed system performs much better when the system is exposed to low levels of the impulsive noise probability, otherwise the opposite is true.

CONFLICT OF INTEREST

The authors declare no conflict of interest

AUTHORS CONTRIBUTION

Irvine Mapfumo: -The student contacted the research. -Analyzed the data with the help of the supervisor. -Wrote the paper. -approved the final version.

Prof. Thokozani Shongwe: Supervised the research work. -Helped in data analysis. -approved the final version of the work.

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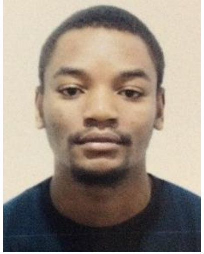

Irvine Mapfumo received the B.Eng. degree in electrical and electronics engineering from the University of Swaziland. He is currently pursuing the M.Eng. degree in Telecommunications with the Department of Electrical and Electronics engineering, at the University of Johannesburg, South Africa. His research interests include Power Line Communication (PLC), Visible light communication (VLC) and signal processing. He is a recipient of the 2019/20 University of Johannesburg Global Excellence Stature (GES) award, which was awarded to him to carry out his master's research at the University of Johannesburg. In 2017, he received the best student award in Electronics engineering at the University of Swaziland.

Thokozani Shongwe received the B. Eng degree in Electronic engineering from the University of Swaziland, Swaziland, in 2004 and the M. Eng degree in Telecommunications Engineering from the University of the Witwatersrand, South Africa, in 2006 and the D. Eng degree from the University of Johannesburg, South Africa, in 2014. He is currently an Associate Professor at the University of Johannesburg, department of electrical and electronic engineering Technology. He is a recipient of the 2014 University of Johannesburg Global Excellence Stature (GES) award, which was awarded to him to carry out his postdoctoral research at the University of Johannesburg. In 2016, Prof T. Shongwe was a recipient of the TWAS-DFG Cooperation Visits Programme funding to do research in Germany.

Other awards that he has received in the past are: the post-graduate merit award scholarship to pursue his master's degree at the University of the Witwatersrand in 2005, which is awarded on a merit basis; In the year 2012, Prof. Shongwe (and his co-authors) received an award of the best student paper at the IEEE ISPLC 2012 (power line communications conference) in Beijing, China. Prof T. Shongwe's research fields are in Digital Communications and Error Correcting Coding. His research interests are in power-line communications; cognitive radio; smart grid; visible light communications; Machine Learning and Artificial Intelligence.