Impulsive Noise Evaluation on PLC-VLC based on DCO-OFDM

M. D. Kubjana[∓], A. R. Ndjiongue[⁎] & T. Shongwe[∓]
[∓] Department of Electrical and Electronic Engineering Technology,
[∓] P.O. Box 17011, Doornfontein, 2028
[⁎] Department of Electrical and Electronic Science,
[⁎] P.O. Box 524, Auckland Park, 2006
[∓,⁎] University of Johannesburg, South Africa
{201181931@student.uj.ac.za,{arrichard,tshongwe}@uj.ac.za}

***Abstract*—Power line communications (PLC) and visible light communications (VLC) are two emerging communication technologies which have several similarities. Among them, the advantage related to cost effectiveness is considered as strong research motivation. These two technologies are also characterized by the fact that each one of them barely form a complete communication system without the need of other supporting technologies. In this paper, based on the positive aspect of VLC technology, we exploit the Hermitian symmetry to design an hybrid system combining PLC and VLC technologies using orthogonal frequency division multiplexing (OFDM). A DC biased optical OFDM (DCO-OFDM), employed in VLC, is investigated when combined with PSK-OFDM (used in PLC). In the hybrid PLC-VLC system proposed in this paper, we exploit the inherent clipping feature of DCO-OFDM to combat impulsive noise found in the PLC channel, where the optimal combination of the DC bias level for optical communication, DC and impulse noise clipping threshold, T_c are investigated through simulations. We also exploit the fact that both DCO-OFDM and PSK-OFDM employ the FFT, to simplify the system.**

***Index Terms*—PLC-VLC integration, OFDM, DCO-OFDM.**

I. INTRODUCTION

The demand for indoors broadband distribution for both wireless and wired communication systems has motivated the research into complementary networks [1]. There has been great success in achieving such alternative methods for both wired and wireless communication namely, power-line communication (PLC) [2] and visible light communication (VLC) [3], [4]. In [5], research has proven that the PLC system has the potential for data transmission at a high and low information rate. Despite the fact that power-line communication takes advantage of the existing AC power transmission cabling (infrastructure) as a communication channel, a stand-alone PLC system does not support the ability to broadcast data over wide area [6], this means that PLC can mainly be used for indoor applications. In most cases of applications that uses PLC system, their performance during transmission gets limited by noise, inter-symbol interference (ISI) and attenuation [7].

The VLC system exploits the existing light infrastructure as a medium for communication based on energy efficient light-emitting diodes (LEDs), data transmission is achieved by modulating the information signal on the brightness of the LEDs. The concept of VLC has encouraged lighting industries to adapt the LED technology not only for lighting purposes but also for data transmission, where light is used as a carrier and the information is conveyed through varying the illumination intensity. Due to the fact that PLC and VLC share the same AC electric power infrastructure, the integration of both yields a simple and low-cost communication technology that require minimal changes to an existing infrastructure. In addition, VLC networks have the ability to provide coverage over a wide area based on indoor applications [6]. PLC is considered as a backbone for the link of these communication channels.

Various ways are proposed in the literature to combine PLC and VLC. Combinations of PLC and VLC are proposed in [8], [9], [10] in an amplify and forward scenario using PSK and CSK. In [7], cascaded PLC-VLC channel using OFDM and CSK Techniques is proposed. In this system, OFDM is used on the PLC channel and the OFDM signal is passed through VLC channel. The results obtained show that the performance of the system in PLC-VLC cascaded channel is influenced by the bad channel. In [11], [12], channel and noise models are proposed for PLC and similarly for VLC in [13], [14], with the PLC channel having impulsive noise and VLC channel having shot noise. The noise in both the systems is modeled using Poisson distribution. A PLC channel is combined with a system of white LEDs using binary phase shift keying (BPSK) in [15]. In [16], spread frequency shift keying (SFSK) is used on the PLC link and On-off keying (OOK) is used on the VLC link for applications that require low data rate to create interface between the PLC and VLC channel. In [17], the integration of PLC and VLC systems based on indoor applications is analyzed, and the authors highlighted OFDM with emphasis on multiple inputs and multiple outputs (MIMO).

The signals in the PLC channel are bipolar and complex and need to be converted to real and positive to realize the integration with VLC channel. In this paper, we show how impulse noise from PLC affects a VLC system which is based on DC-biased optical OFDM (DCO-OFDM). The effects of impulsive noise on the VLC channel is

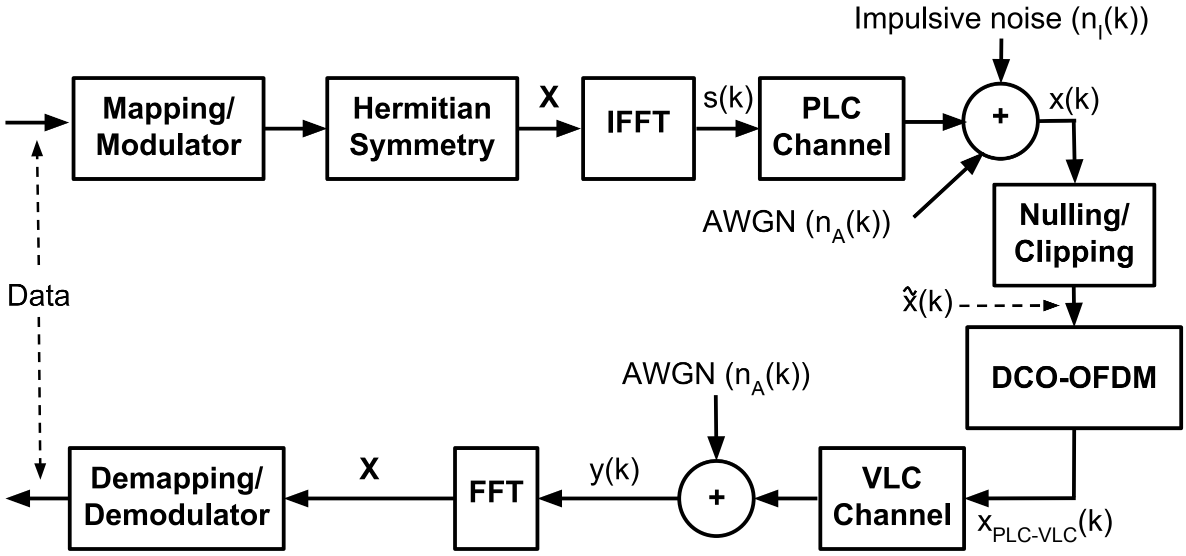

Fig. 1. Hybrid PLC-VLC system model based on DCO-OFDM.

investigated. The nulling and clipping of impulsive noise to mitigate its effects on the VLC channel will be analyzed in terms of system performance. In DCO-OFDM, the signal is made positive by adding a DC bias before transmission. In most cases a moderate DC bias is normally used and the remaining negative peaks are clipped at zero. We therefore take advantage of this inherent clipping/nulling mechanism, that already exist in the DCO-OFDM, to combat impulsive noise. In addition, the proposed PLC-VLC communication system is simplified because we make use of the OFDM modulation (and demodulation) only once instead of using it for each channel (PLC and VLC).

The rest of this paper is organized as follows. In Section II the system model is presented, and brief overview of DCO-OFDM. The performance of DCO-OFDM in PLC-VLC channels with consideration of impulsive noise is investigated through simulations in Section III. Conclusion and remarks are provided in Section IV.

II. SYSTEM DESCRIPTION

This section describes a functional communication model of the proposed technique based on DC-biased optical OFDM (DCO-OFDM) for integration of PLC and VLC channels as shown in Fig 1. In this system the transmitted PLC OFDM signal is corrupted by impulsive noise and additive white Gaussian noise (AWGN) and similarly in the VLC channel the OFDM signal is affected by only AWGN. In this paper upper cases are used to denote signal in the discrete frequency domain and lower cases to represent signal in the time domain.

A. PLC OFDM

OFDM is a special form of multi-carrier modulation based on frequency division multiplexing (FDM) system obtained by using orthogonal sub-carriers. Multi-carrier systems allow for the split of information to be transmitted into multiple smaller chunks and independently, this means total data rates can be divided and transmitted into number of sub-carriers [18]. The bipolar OFDM signal consists of N data symbols represented by $X = [X_0, X_1, \ldots, X_{N-1}]$, in a block of OFDM with N sub-carriers. The input data is modulated using binary phase shift keying (BPSK) or quadrature amplitude modulation (QAM) grouped in blocks of N parallel symbols. The IFFT operation on X yields a time domain signal represented by a vector $s(k) = [s_0(k), s_1(k), s_2(k), , s_{N-1}(k)]$. This time domain signal is passed through digital to analogue converter and it gets corrupted by noise. In this paper we consider two types of noise, namely impulsive noise modeled as Middleton Class A noise and AWGN.

B. IMPULSIVE NOISE

The Middleton Class A noise model is the most famous statistical noise model for impulsive noise based on Poisson-Gaussian model. It is used in communications system to model the effects of impulsive noise [19]. The Poisson process is used to model the probability of occurrence of an impulse noise event, and the Gaussian process is used to model the distribution amplitude of the impulsive noise. The effective variance of Class A noise model is given by $\delta_I^2 = K\delta_g^2/A$ [19], where δ_I^2 is the variance of the impulsive noise and δ_g^2 is the variance of the background noise (AWGN). $\delta_g^2 = No/2$, where the parameter No represents the two-sided power spectral density of the background noise. K represents the average power of the impulsive noise given and the parameter A represents the density of impulses.

C. SIGNAL ANALYSIS OF PLC DCO-OFDM

Data symbols are carried on about half of the sub-carriers in DCO-OFDM. The input signal, $X =$

$[X_0, X_1, \ldots, X_{N-1}]$, to the inverse fast Fourier transform (IFFT) is constrained to have Hermitian symmetry property as given by,

$$X_m = X^*_{N-m}, \text{for } 0 < m < N/2. \tag{1}$$

The use of Hermitian symmetry is to ensure that the signal at the output of the IFFT is real not complex. To satisfy the Hermitian symmetry condition, the components X_0 and $X_{N/2}$ in (1) are set to zero, $X_0 = X_{N/2} = 0$. The k^{th} time domain output of $s(k)$, is given by,

$$s(k) = \frac{1}{N}\sum_{m=0}^{N-1} X_m e^{\frac{j2\pi km}{N}}, \text{for } 0 < k < N-1,$$

where N represents the number of sub-carriers on the IFFT and X_m represents the m^{th} sub-carriers of signal X. In practice, for large values of N the signal $s(k)$ can be modeled as Gaussian random noise with zero mean and variance,

$$\delta^2 = E\{s^2(k)\}.$$

Due to Hermitian constraint the number of data carrying sub-carriers is $(N2)/2$. The signal $s(k)$ is now transmitted over PLC channel and gets corrupted by background noise modeled as AWGN $n_A(t)$ and impulsive noise $n_I(t)$ modeled using Middleton Class A noise model, the resulting signal transmitted over PLC is given by,

$$x(k) = s(k) + n_I(k) + n_A(k). \tag{2}$$

- Combating impulsive noise

To mitigate the effects of impulsive noise contribution on the PLC channel, in this paper we propose to use two most common techniques known to deal with impulsive noise. Where the first approach is to null the PLC OFDM signal and secondly to clip the signal based on the threshold T_c. In consideration of the signal $x(k)$ in (2), after nulling and clipping the signal is then be denoted by (3) and (4) respectively,

$$\tilde{x}(k) = \begin{cases} x(k), x(k) \le T_c \\ 0, x(k) > T_c, \end{cases} \tag{3}$$

and

$$\tilde{x}(k) = \begin{cases} x(k), x(k) \le T_c \\ T_c, x(k) > T_c. \end{cases} \tag{4}$$

It is worth noting that the traditional nulling or clipping mechanism identifies signal samples that are larger than T_c or smaller than $-T_c$, and then null or clip them. This means clipping both negative and positive samples of the signal that exceed T_c. In (3) and (4), only positive samples greater than T_c are clipped or nulled. The reason for this is because the DC bias in the DCO-OFDM will take care of any negative samples regardless of whether they were affected by impulse noise or not. This DC bias effect is explained in the next subsection.

D. DCO-OFDM

In this section we will not give the full explanation of DCO-OFDM, we only mention the parameters of DCO-OFDM that will be used in this paper. A DC bias gets added to the signal $\tilde{x}(k)$, and the required DC bias to ensure non-negativity is equal to the absolute maximum negative amplitude of the signal $\tilde{x}(k)$. However, since OFDM signal have a very high peak-to-average power ratio (PAPR) this will mean a high DC bias will be required to guarantee non-negativity resulting in high chances of signal distortion. In order to avoid excessive use of DC bias and minimize the useful optical power, the possible approach is to use a DC bias denoted by B_{DC}, which is proportional to the square root of the electrical power ($\sqrt{\delta^2}$), such that

$$B_{DC} = \alpha\delta, \tag{5}$$

where α represents a clipping factor or a proportionality constant and δ^2 is the variance of $s(k)$. The DC bias level in dB is given by $DC = 10\log_{10}(\alpha^2 + 1)$. The DC biased time signal $x_{B_{DC}}(k)$, is then given by

$$x_{B_{DC}}(k) = \tilde{x}(k) + B_{DC}. \tag{6}$$

Any remaining negative peaks after addition of B_{DC} will be clipped at zero to ensure that only positive time domain signal appear at the optical transmitter input. This clipping results in clipping noise represented as $nc(B_{DC})$. The resulting PLC-VLC channel model based on DCO-OFDM is therefore expressed as,

$$x_{PLC-VLC}(k) = \tilde{x}(k) + B_{DC} + n_c(B_{DC}). \tag{7}$$

The clipping noise, $n_c(B_{DC})$ decreases when B_{DC} increases, such that for high values of B_{DC} (7) can be approximated by (6). Since the optical power (P_{opt}) is proportional to the electrical power (P_{elec}) of the OFDM signal, for DCO-OFDM, the SNR in the electrical domain and the SNR in the optical domain are related by the clipping factor α in (5) as follows [20]:

$$\frac{E_{bopt}}{No} = \frac{\alpha}{1+\alpha^2}\frac{E_{belec}}{No}, \tag{8}$$

where E_{bopt} and E_{belec} are the energy per bit corresponding to optical power and electrical power, respectively. N_o is the two-sided power spectral density for AWGN.

III. RESULTS AND DISCUSSION

Prior to presenting and discussing the results, it is important to discuss the relationship between the clipping/nulling threshold, T_c for impulse noise and the DC bias, B_{DC} for the DCO-OFDM signal, and how the values for T_c and B_{DC} were chosen. The acceptable DC bias values for an AWGN channel were given in [20]. In this work we experimented with the DC bias values in [20] when AWGN and IN are present in the channel, and found that those values are not optimal or acceptable for our proposed communication system. It therefore became important to find an optimal DC bias for impulse noise, and also an appropriate clipping threshold, T_c. The DC bias (B_{DC}

and T_c have to be chosen such that they complement each other to give the best performance, in terms of bit error rate. The simulation results that will be presented in this paper will demonstrate the best combination of T_c and B_{DC} (as DC) for the PLC-VLC system proposed in Figure 1. In the simulations, different values of T_c and DC were experimented on, with different impulse noise scenarios, and the best combinations of T_c and DC values were presented. For all similations in this paper, it should be noted that after applying a DC level bias to offset the signal, then the threshold T_c was applied to identify samples above T_c, and these samples were then set to zero (nulling) as demonstrated in (3).

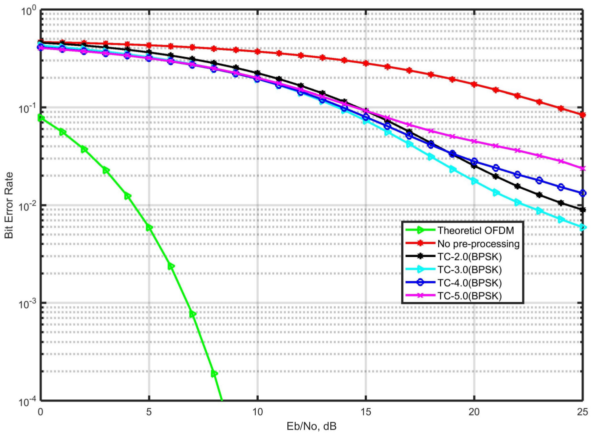

Fig. 2. Performance of a hybrid PLC-VLC based DCO-OFDM (BPSK): $DC = 4$, $A = 0.1$, $K = 10$ and $T_c = \{2, 3, 4, 5\}$.

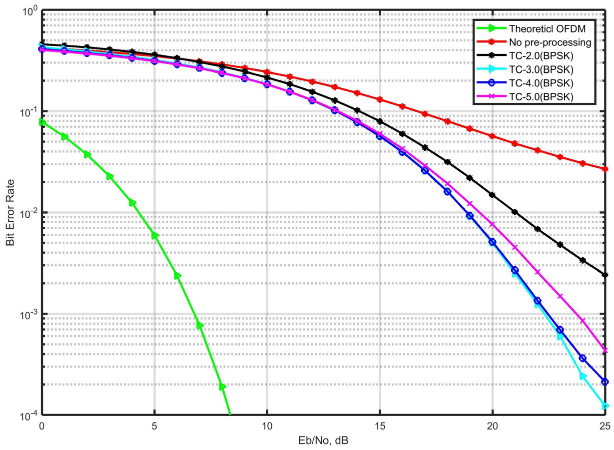

Fig. 3. Performance of a hybrid PLC-VLC based DCO-OFDM (BPSK): $DC = 4$, $A = 0.01$, $K = 10$ and $T_c = \{2, 3, 4, 5\}$.

The results can be explained in groups as follows. Figs. 2 and 3 show a case where the DC bias is $DC = 4$ dB, $K = 10$, and various values of T_c. These two figures demonstrate that as the T_c value is increase from a small value of 2, the performance improves until it is at its best at $T_c = 3$. Beyond $T_c = 3$, the performance begins to degrade. In the simulations we started off with the value of a DC bias of $DC = 4$ dB because it was found, through simulations, to be optimal for one case of IN and AWGN. This value of $DC = 4$ dB will be tested for different scenarios of impulse noise and against other values of DC bias. In Fig. 2, the probability of impulse noise is $A = 0.1$, while in Fig. 3, $A = 0.01$. This difference in the impulse noise probability is evident from the results, where the performance in Fig. 3 is better than that of Fig. 2. The common property presented by Figs. 2 and 3 is that a value of $T_c = 3$ results in the best performance, and any values of T_c that are further away from 3 result in performance degradation.

In Figs. 4 and 5, the parameters are the same as in Figs. 2 and 3, except that the impulse noise power is increased to $K = 100$. Again, the lower the probability the better the performance, and the $T_c = 3$ is the best threshold for nulling impulsive noise.

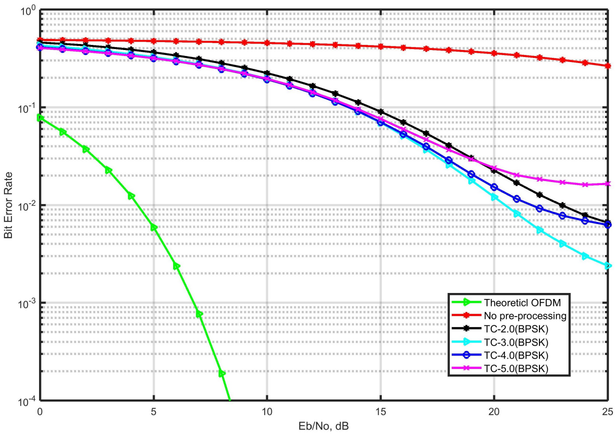

Fig. 4. Performance of a hybrid PLC-VLC based DCO-OFDM (BPSK): $DC = 4$, $A = 0.1$, $K = 100$ and $T_c = \{2, 3, 4, 5\}$.

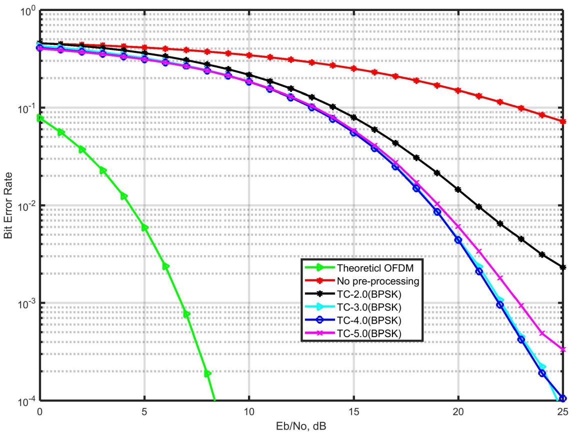

Fig. 5. Performance of a hybrid PLC-VLC based DCO-OFDM (BPSK): $DC = 4$, $A = 0.01$, $K = 100$ and $T_c = \{2, 3, 4, 5\}$.

The next set of figures (Figs. 6 and 7) show similar performance to Figs. 2 to 5, but now the nulling threshold is fixed to $T_c = 3$ because it was the best threshold for the

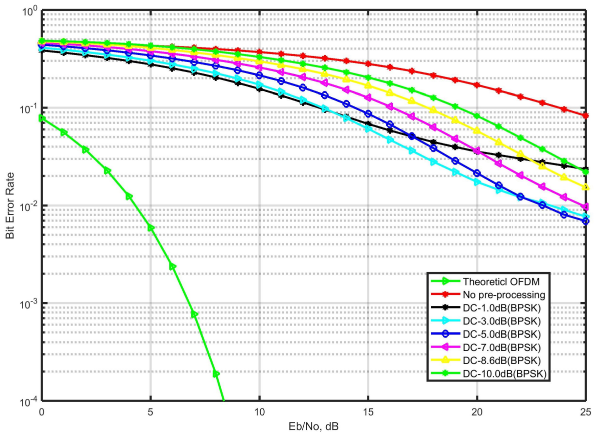

Fig. 6. Performance of a hybrid PLC-VLC based DCO-OFDM (BPSK): $T_c = 3$, $A = 0.1$, $K = 10$ and $DC = \{1.0, 3.0, 5.0, 7.0, 8.6, 10.0\}(dB)$.

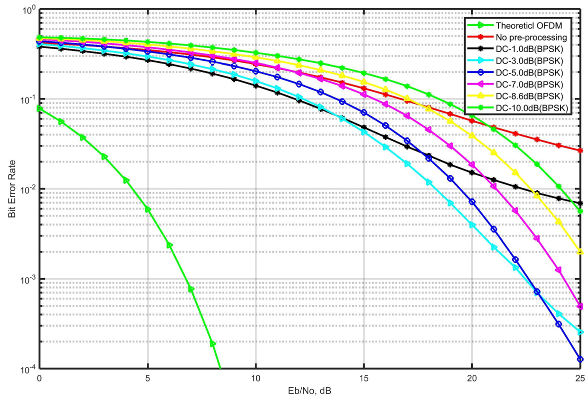

Fig. 7. Performance of a hybrid PLC-VLC based DCO-OFDM (BPSK): $T_c = 3$, $A = 0.01$, $K = 10$ and $DC = \{1.0, 3.0, 5.0, 7.0, 8.6, 10.0\}(dB)$.

previous results (Figs. 2 to 5). In Figs. 6 and 7, the DC bias, DC is varied. The performance results show that the best DC bias is $DC = 3 - 5$ dB.

It is clear from the results that the bit error performance is more depended on the probability of impulse noise, A than on the power of the impulse noise, K. The reason for the low dependence on the impulse noise power is that once the impulse noise amplitudes are detected using the threshold T_c, they are nulled, rendering the power of the impulse noise ineffective. However, the number of nulls created by the nulling operation depend on the parameter A. An increase in A results in an increase in the number of nulls in the signal. It is also seen in all the graphs that for a given DC level bias, there is a corresponding optimal T_c value, in this case ($DC = 4$ dB and $T_c = 3$). It should be remembered that DC bias pushes the signal from the bottom and clips any remaining negative samples, while the T_c is used to clip any samples of the signal from the top and null any samples above T_c. This means that when the signal is nulled/clipped from the top and then pushed up by the DC bias it requires a certain value of T_c to clip it from the top, in relation to the DC bias. This T_c value should be such that it is not too low compare to the DC value in order avoid increased clipping noise. At the same time, this value of T_c should not be too large compared to the DC value otherwise it will allow most of the impulse noise into the system.

IV. CONCLUSION

This paper presents simulations results of impulsive noise evaluation to be used in PLC-VLC communication systems based on DCO-OFDM. The performance of the system is limited by impulsive noise when looking at its components, A and K. The large probability of noise occurrence, A results in an increased number of null operations to be performed on the OFDM signal hence increasing the clipping noise, $n_c(B_{DC})$. The BER indicates that the performance of the system is less dependent on the impulsive noise power, K. This is because once the impulsive noise amplitudes are detected using the threshold T_c, they are nulled, resulting in the power of the impulsive noise being ineffective. Likewise, the DC bias also limits the performance of the system. A larger DC bias results in the increase in power required, while a lower DC bias increases clipping noise, $n_c(B_{DC})$.

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