Performance Evaluation of Hybrid Optical OFDM-Based VLC Schemes in LOS and NLOS Indoor Optical Wireless Channels

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Abstract. The demand for high speed, high data rate and dependable communication drives the optical OFDM technique to be an attractive method owing to its broad spectrum property. In this paper, hybrid optical OFDM is evaluated and discussed for LOS and NLOS channel models. The perfect signal shaping characterized by optimal biasing and scaling at the transmitter/receiver sides within the optical power limitations plays a significant role in system performance. Consequently, the minimum needed energy bit/noise bit (Eb/N0) to preserve a required bit-error rate is achieved for a selected multi-layer modulation system and a specified variety of optical power limitations. Simulation results demonstrated the minimisation of the BER could be obtained by reducing the ambient noise vai adopting an extra process stage at the receiver, notably, at the transmitter side. The outcomes were presented in terms of two channels. Upon utilising the identical bit rate of all scenarios we have found that the equalization could enhance the overall system performance with MMSE values outperforming the ZF equalizer by SNR of 5 dB at the target BER of 10^{-3}.

INTRODUCTION

Due to imminent the spectrum crisis, the most promising candidate technologies are systems based on optical wireless communication (OWC) [1]. The current radiofrequency (RF) besides wired techniques, for instance, Wi-Fi, WiMax and WLAN provide mobility and flexibility yet it is experiencing a bandwidth bottleneck. In several applications, high data throughput capability is more necessary than mobility. Therefore, the OWC method deems a complementary alternative to RF techniques [2]. Compared to the RF, Visible light communication (VLC) offers various advantages such as immunity against electromagnetic interference, security protection and consuming low energy [3]. Among these merits, several applications such as non-orthogonal multiple access (NOMA) which is part of 5G enabling in terms of VLC [4], cognitive radio (CR) [5], and millimetre waves (mm-waves) [6, 7].

The most common application concerning optical technologies is the short-range transmission represented by indoor optical wireless. Intrinsically, it has gained momentum through extensive research and globally evolution, notably, in the last few years, decade [8, 9]. The wide visible spectrum offers an unrestricted bandwidth at optical frequency worldwide. Examples of such applications are Voice over IP (VoIP), streaming video and music, and network-attached storage (NAS). Besides that, several applications where the utilisation of RF is imprudent, for instance, hospitals as well as aeroplane cabinets. One advantage of the optical signal is that it has the ability to penetrate through the glass but not for opaque surfaces. This feature provides security to the users confined in the room [10].

Multi-carrier modulation schemes are introduced for OWC [11, 12, 13] to promote the system performance in terms of throughput via multi modulation order (M-QAM), benefitting from the feature of the orthogonality between subcarriers. In this regard, techniques, in particular, Long Term Evolution (LTE) and WiFi are implemented in accordance with OFDM systems in the physical layer attributed to several reasons, for example, the use of the simple one-tap- equalization technique at the frequency domain channel estimation, resistance to inter-symbol interference (ISI), and supported high data rate. It is notoriously known that the complex signal of OFDM applied in RF is unable to apply in the OWC system until modified to unipolar due to the nature of light characteristics.

Although extensive research has been carried out on indoor optical wireless communication, no single study exists that investigated such a system called HOOK-ACO optical system. Therefore, the aim is to investigate the performance of a hybrid optical OFDM system called hybrid ON-OFF Keying asymmetrically clipped optical OFDM (HOOK-ACO-OFDM) and analysis its performance to different QAM levels applied in both LOS and NLOS channels in terms of BER and two equalization methods. The channel DC bias is examined, and the BER performance is studied.

All of these objectives are met through an extensive computer Matlab simulations run with 10^4 iterations (R2015b). The rest of the paper is organized as follows. The section presents the channel impulse response besides the hybrid system model. The section explains the performance evaluation and system measurements. Finally, the concluding remarks are presented in the last section .

OVERALL SYSTEM MODEL

Indoor Optical Wireless Channel

A simple channel impulse response reflections model of indoor optical wireless communication conditions can be represented by $h(t)$ or through $\int_{-\infty}^{\infty} h(t)e^{-j2\pi ft}$ as a baseband frequency response $H(f)$ [14, 15]. Considering the noise, the received signal take the form of

$$y(t) = \Re.x(t) * h(t) + n(t), \tag{1}$$

wherein y(t) represents photo-current detection, $x(t)$ denotes the intensity of propagated illuminance signal, $\Re$ stands for responsivity of the detector, and $n(t)$ signifies the Additive White Gaussian Noise (AWGN) as an equivalent to thermal noise and surrounding light. It is well known that the electric signal can not be adopted directly in an optical system since the transmitted signal $x(t)$ is basically in the form of light intensity, a positive signal, that is to say ($x(t) \geq 0$), therefore, the propagated signal at the transmitter is the average power (P_t) represented by

$$P_t = \lim_{T\to\infty} \int_{-T}^{T} x(t)\, dt, \tag{2}$$

Instead of applying $|x(t)|^2$ which is suitable for amplitude calculations, the signal captured at the receiver side takes the form of intensity signal as follows

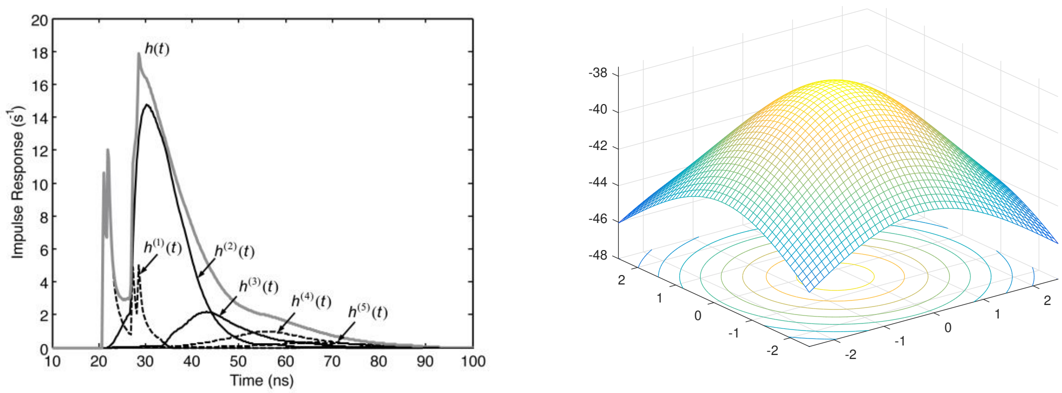
$$P = H(0)\, P_t, \tag{3}$$

wherein $H(0)$ signifies the channel DC gain or $H(0) = \int_{\infty}^{\infty} h(t)\, dt$.

In this research, the method reported in [15, 16] is adopted for simulating the channel impulse response based on an indoor wireless environment considering the multi-reflections phenomena. Such an approach subdivides a room into multiple zones of reflectors so that the impulse response is constructed by accumulating all the contributions from multi-path reflections k^{th}, $h^{(k)}(t),\ k = 1,\ 2,\ 3, \ldots$. It is worth mentioning that an approach introduced later [17] aims to decrease the calculation time needed to precisely formed the indoor impulse response-based optical propagation. In this work, the method stated in [17] with aid of [18] is employed in implementing the indoor channel impulse response.

The dimensions' room is $6 \times 6 \times 5\ m^3$ for length, width, and height, respectively. The resolution of room surface discretization is determined by 0.2 m and is postulated to have multi-path reflection (diffusion channel) as show in Fig. 1 [19, 20].

A Lambertian radiation pattern was postulated according to the radiated power per unit solid angle relative to the cosine of the angle concerning the sender. Also, we assumed that the effective received area is equivalent to 1.5 cm^2 with the light incidence detection angle lower than 90° relative to the receiver location [14]. Note that the coefficients of transmitter and receiver adopted in this research are identical to [14]. It has been reported that the five multi-path reflections are sufficiently enough for constructing the impulse response of indoor patterns. Therefore, it was adopted



(a) Channel impulse response of a typical diffuse channel.

(b) Power distribution within a room with dimensions of $6 \times 6 \times 5$ for length, width, and height, respectively

FIGURE 1: Channel impulse response of a typical diffuse channel.

five multi-reflection paths [17]. From fig. 1a, it can be noticed that the first path (LOS) captured by the receiver has the lowest time arrival equal to 28 ns with incident power of -30dBm, however, the other reflected path takes a long time depending on trajectory length. Since the 4^{th}, $h^4(t)$ and $5^{th}, h^5(t)$ paths take a longer time to arrive, then their power values are closed to zero. Also, the transmission delay for all other trajectories was between 28ns up to 65ns as illustrated in Table I.

TABLE I: NLOS channel model.

No. of Reflections Path	Impulse Response [S^{-1}]	Delay [ns]	Received Power [dBm]
$h(t)(LOS)$	18	28	-30
$h^1(t)$	14.4	31	-31
$h^2(t)$	7	43	-33
$h^3(t)$	2.1	55	-37
$h^4(t)$	0.9	55	-47
$h^5(t)$	0.2	65	-60

Through our simulation procedures, 185 various paths were generated via positioning the light-emitting diode (LED transmitter) in various positions inside the room area. In this vein, the Photo Detector diode (PD-receiver) was positioned in the room centre at 1 m over the ground level with an upward point. As illustrated in Figure 1a, the LED is positioned at the top of the room and pointed downward. That is to say, there will be a line of sight (LOS) channel besides the diffusion pattern. Additionally, in the case of the light being blocked by an object (shadowing condition) meaning the absence of the LOS trajectory, in other words, $h(0)(t)$. Figure 1b depicts the channel impulse response of a typical diffuse channel adopted in this study.

System Description of Hybrid Optical OFDM

High computational complexity of the hybrid systems makes it hard to support multiple services with different qualities-of-service (QoS). However, these hybrid schemes have superior power and spectral efficiency compared to the conventional optical OFDM. In what follows, is a brief description of the hybrid optical OFDM system built in according to the parameters listed in Table II.

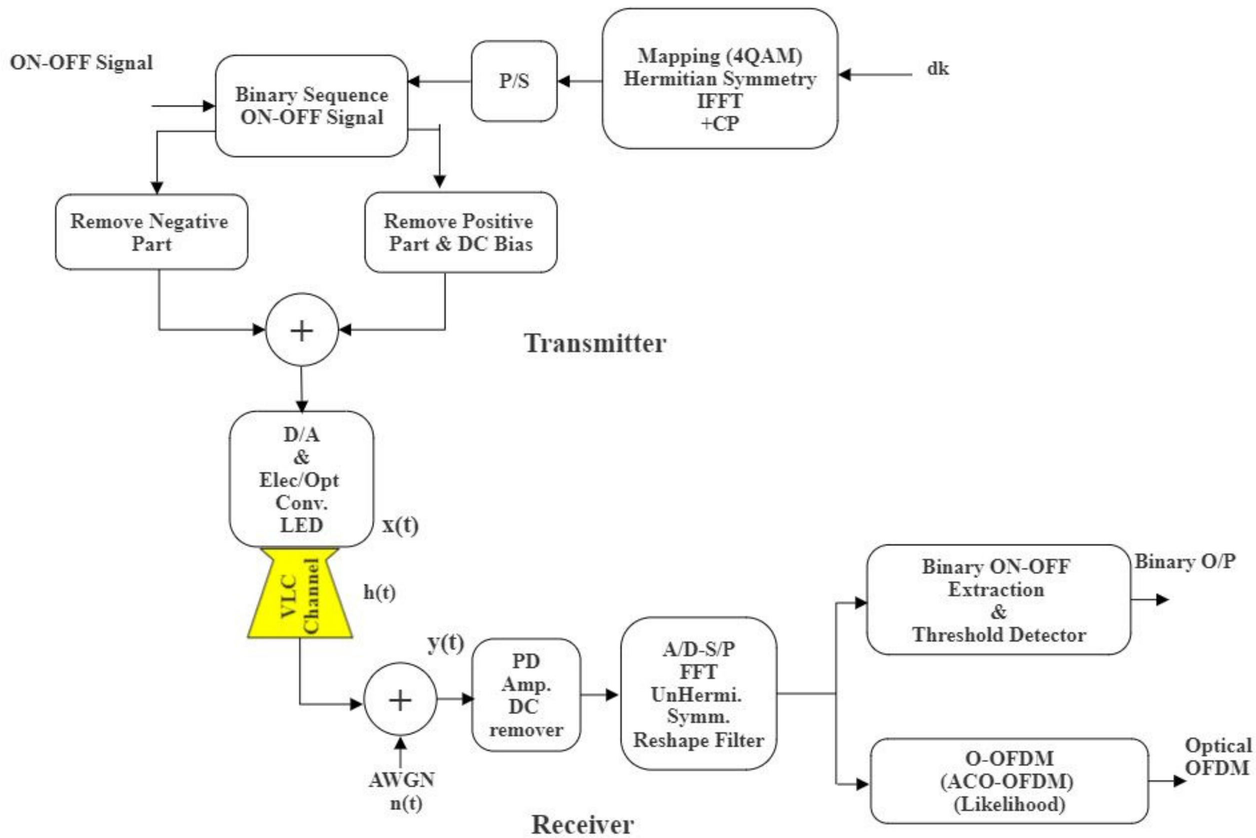


FIGURE 2: System model under investigation.

TABLE II: Hybrid optical OFDM system parameters.

Subcarrier Modulation	4, 16, 64, 256, 1024 QAM
Number of IFFT points N	64
Cycle prefix	8
Number of bit errors for each E_b/N_0	10^4
Number of T_x bits for each E_b/N_0	10^7
Number of Tx OFDM symbols per iteration	10^4
Bandwidth	20MHz
(Energy bit/Noise bit) ratio	$0 \leq E_b/N_0 \leq 25$

Transmitter

It starts with the generation of a random data d_k which is then mapped to a 4QAM constellation. Hermitian symmetry is applied to ensure the real signal at the IFFT output is obtained. Next is appending the cyclic prefix to combat with ISI and ICI. After P/S converting, an OOK signal is used to control the output and it takes the following mathematical expression [21]

$$D_{binary,n} = \begin{cases} DC_{bias}, & \text{Binary is "}ON\text{"}, \\ 0, & \text{Binary is "}OFF\text{"}, \end{cases} \tag{4}$$

where DC_{bias} is a DC value. Depending on the control signal, the ACO-OFDM and negative ACO-OFDM (NACO-OFDM) are generated as

$$D_{N,n} = \begin{cases} D_{NACO,n}, & \text{binary is "}ON\text{"}, \\ D_{ACO,n}, & \text{Binary is "}OFF\text{"}, \end{cases} \tag{5}$$

where $D_{N,n}$ indicates the mixed ACO-OFDM and NACO-OFDM signals. It is worth in mention that the OOK data signal and ACO-OFDM are synchronized. The overall transmitted signal of the HOOK-ACO-OFDM system in time domain gives the expression [21]:

$$D_{td,n} = \lfloor D_{N,n} + D_{binary,n} \rfloor . \tag{6}$$

Since intensity modulation schemes, as in wireless optical systems, do not up-convert the transmitted signal to any carrier frequency, this is not necessary. A DAC is applied to the transmitted signal followed by LPF process and then the electric signal is converted to optical equivalent signal, thereafter amplified before it is feed to the power LED.

Receiver

The received optical signal $y(t)$, which is detected using photodiode (PD), is firstly amplified (assuming ideal amplifier) and then passed through converter to convert the PD current into a voltage (optical-to-electrical-converter (O/E)). Thereafter, the DC value is removed before passing the signal through the LPF (anti-alias filter). It is essential to first estimate the channel and, within the whole demodulator block, apply channel equalization after removing the cyclic prefix and S/P conversion.Next, the Rx part performs the full OFDM receive chain. That is to say, the first step is to remove the CP, then takes the FFT, apply frequency-domain equalisation (using the vector of the channel gains estimated in the previous step), perform QAM decisions and ultimately generate the vector of detect bits. Finally, the Hermitian symmetry is removed before detection the signals.

PERFORMANCE EVALUATION AND SYSTEM MEASURES

DC Bias Effect

Figure 3 introduce the effect of the bias value on a hybrid 4QAM level optical system. As the results show, low DC bias leads to non-linear distortion which turns into BER deterioration. On the other hand, high DC bias and high DC level result in non-linear clipping distortion at the receiver side. Thus, the optimal value of the DC level depends on how much-transmitted power needs to fulfil the required BER and also relies on the clipping ratio.

Bit Error Rate Performance

Figures 4a,b illustrate the BER performance between the results already existing in [21] and our evaluation process. It can be said that although the clipping noise presents an extra distortion leading to deterioration in the system's BER it can mitigate this noise by adopting a dynamic clipping ratio and filter shaping process according to the noise level at the receiver and/or a digital pre-distortion device can be used to alleviate the non-linear distortion. Consequently, the hybrid and ACO OFDM systems' BER values are almost close to the ACO-OFDM model for two constellation levels 4QAM, and 16QAM as shown in Figure 4b.

Figure 5a shows the performance of the system under investigation. The AWGN scenario is considered for demonstrating the system work as in [21]. It is axioms that to achieve a target BER=10^{-3}, it is required to increase the E_b/N_0 as the modulation level increase for both scenarios of AWGN notably LOS environment.

In this vein, an NLOS channel model is also considered in this work. Figure 5b demonstrates the BER performance of the system under investigation. It can be observed that for 4QAM and 16QAM, the target BER=10^{-3} needs to be achieved at 25 and 30 dB, respectively. Moreover, for 64QAM, 256QAM, and 1024QAM, the results proved that it

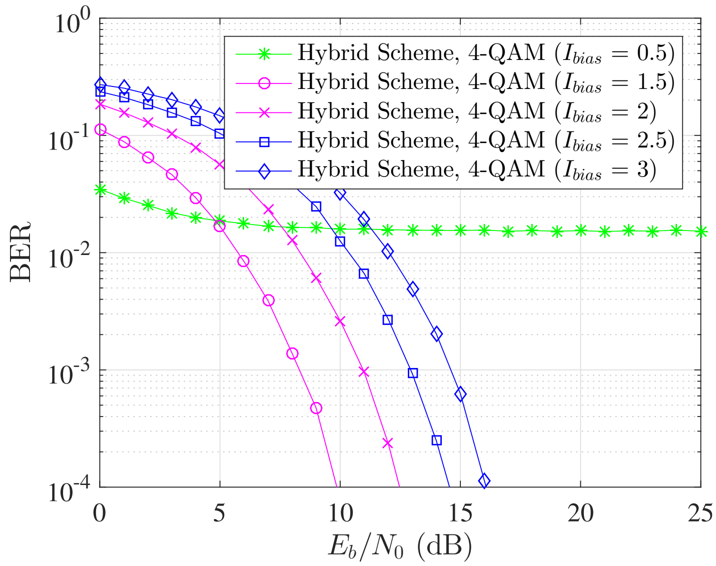
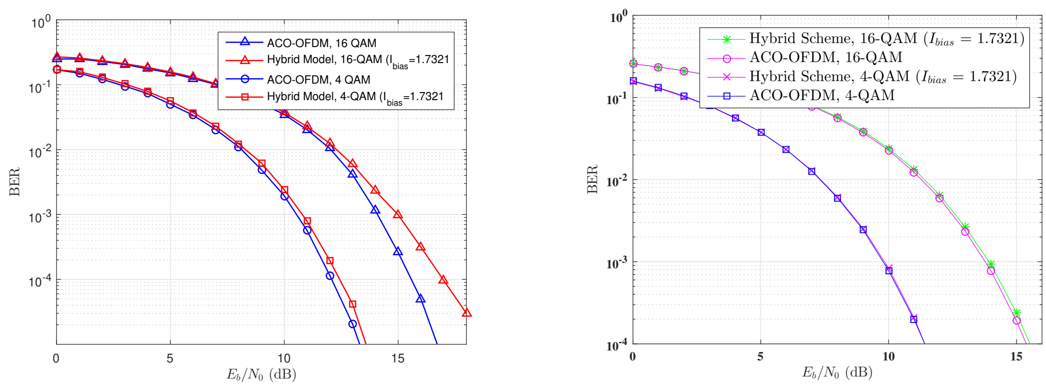


FIGURE 3: Impact of different DC bias values I_{bias} on system performance.



(a) The BER performance versus E_b/N_0 [21]

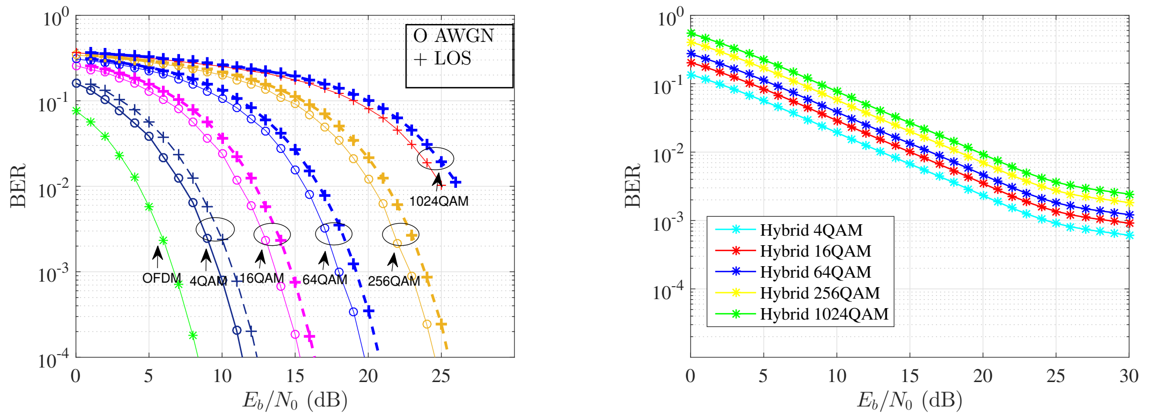
(b) Enhanced BER performance versus E_b/N_0

FIGURE 4: BER evaluation for AWGN channel.

may be hard to obtain the target BER as the performance turned to be flat at $E_b/N_0 \geq 30\ dB$. Consequently, more powerful techniques are required to integrate to fulfil the system target BER, for instance, coding technologies, and beamforming at more complexity.

Performance in term of BER for ZF , MMSE

Figure 6 illustrates the performance of Single-tap zero forcing (ZF) and minimum mean-squared error equalization (MMSE) for the system applying with 4QAM. Simulation outcomes are exhibited for illustrating the effect of powerful equalizer algorithms. It can be seen that the equalizer process enhances the BER despite the additional complexity of the system so that the MMSE outperforms the ZF by about 5 dB at target BER=10^{-3}.



(a) BER Performance of AWGN against LOS channel model (No ISI). [21]

(b) BER Performance of AWGN against NLOS channel model.

FIGURE 5: BER evaluation for LOS and NLOS channel.

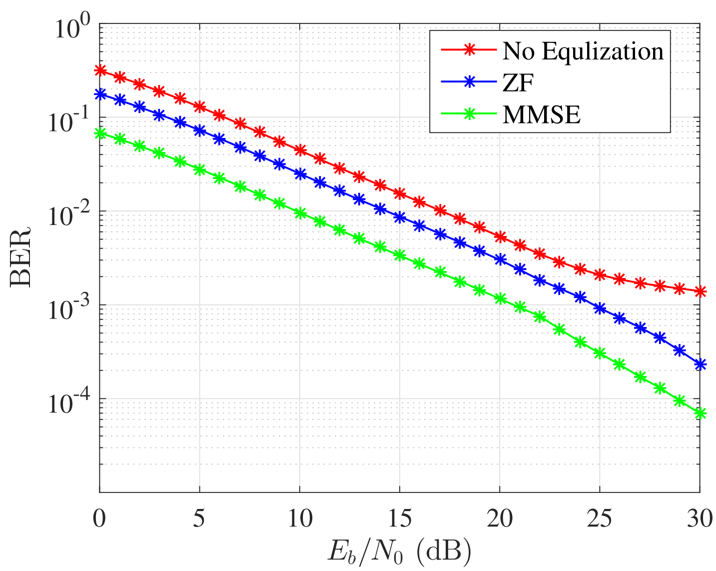


FIGURE 6: Performance of BER for ZF and MMSE Equalizer with 4QAM modulation.

CONCLUSION

Hybrid optical OFDM for indoor optical wireless communication system is evaluated in this paper. Simulation results were provided and discussed to illustrate the performance of LOS and NLOS channel model. We have shown how to minimize the the BER through reducing the ambient noise by adopted the extra process stage at the receiver. The outcomes were presented in terms of two channels. Upon utilizing the identical bit rate of all scenarios we have found that the equalization could enhance the overall system performance with MMSE values outperforms the ZF equalizer. Finally, the results afford clear insight for the scientific researcher and designer to deal with the factors of these environments that influence the indoor optical communication and the ability to increase the communication distance with satisfying reliability.

ACKNOWLEDGMENTS

I am gratefully acknowledge University of Technology for the support of this research.

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