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Programmable Software-Defined Testbed for Visible Light UAV Networks: Architecture Design and Implementation

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***Abstract*—As of today, there has been increasing research on designing optimization algorithms and intelligent network control methods for visible light Unmanned Aerial Vehicles (UAV) networks to provide pervasive and broadband connections. For those theoretical analysis based algorithms, there is an urgent need to have a visible light UAV network platform that can help evaluate the proposed algorithms in real-world scenarios. However, to the best of our knowledge, there is currently no dedicated high data rate and flexible visible light UAV networking prototype. To bridge this gap, in this paper, we first design a novel programmable software-defined architecture for visible light UAV networking, including *control plane*, *network plane*, *signal processing chain and front-ends plane*, and *ground facility plane*. We then implement a prototype and conduct numerous experiments to validate the feasibility of visible-light UAV networks and further evaluate the system performance pertaining to achievable data rate and transmission distance. The real-time video streaming experimental results show that up to 550 kbps data rate and a maximum distance of 7 meters can be achieved.**

***Index Terms*—Visible Light Communication, Unmanned Aerial Vehicles, Wireless Networking**

I. Introduction

Unmanned Aerial Vehicles (UAVs) assisted networks [1] have been envisioned as an enabler for a diverse set of high-data-rate and reliable applications in 6G networks and next-generation Internet of Things (IoTs), such as flexible mobile base stations for big event and post-disaster rescue, smart agriculture, fire rescue in remote areas, etc., because of drones' high mobility, flexibility, adaptability, low-cost operations, and more. The foreseen wide adoption of UAV systems will pose a significant burden on the capacity of the underlying RF-based wireless networks. In this paper, we aim to explore new approaches that can enable high-data-rate UAV operations by exploring the visible-light spectrum as a promising alternative to traditional Radio Frequency (RF) communications to unlock almost 400 THz spectrum bandwidth [2].

In recent years, Visible Light Communication (VLC), as a promising technology to help alleviate the spectrum crunch in conventional RF communications, has attracted significant attention from researchers because of the following advantages [3]: (i) VLC relies on a large portion of the unregulated spectrum between 380 THz and 780 THz, while the RF communication's spectrum including the regulated portion is just between 30 kHz and 300 GHz; (ii) VLC has a higher data rate potential beneficial from the significantly larger bandwidth; (iii) VLC has no interference with the current wireless network, which makes deploying VLC and RF communication concurrently possible; (iv) VLC has a higher security level, due to the low penetration characteristics of light propagation; and (v) VLC technology uses low-complexity and inexpensive front-ends, such as Light-Emitted Diodes (LEDs) as transmitters and Photodetectors (PDs) as receivers. Moreover, the proliferation of LEDs will make the deployment of VLCs with LEDs as transceivers easier, thus accelerating its transition from the conceptual phase to real-world applications.

Most of the existing research on VLC focuses primarily on theoretical analysis and simulation-based performance evaluation, such as advanced modulation schemes and new multiple access control methods [4] [5] [6] [7] [8] [9]. More recently, a few works have been proposed on visible-light band wireless UAV networks to unlock the capacity in the air by designing intelligent network control algorithms [10] [11], with system challenges largely unexplored except several recent efforts [12] [13]. One of the main reasons is that, as of today, there are still no publicly available, software-defined, and open-source based platforms that allow researchers to verify their theoretical results in visible-light band wireless UAV networking by conducting rigorous testbed experiments. In this paper, we take a step toward filling this gap by proposing a universal broadband programmable software-defined testbed for visible light UAV networking. The main contributions of this work are as follows:

- We design a software-defined visible light UAV network architecture that can perform flight control and network reconfiguration over-the-air according to flight status and networking control parameters including link quality, remaining energy, access point association, delay requirement, etc.
- Based on the designed architecture, we develop a universal programmable software-defined testbed for visible light UAV networks composed of two UAVs, one equipped with a LED transmitter and another equipped

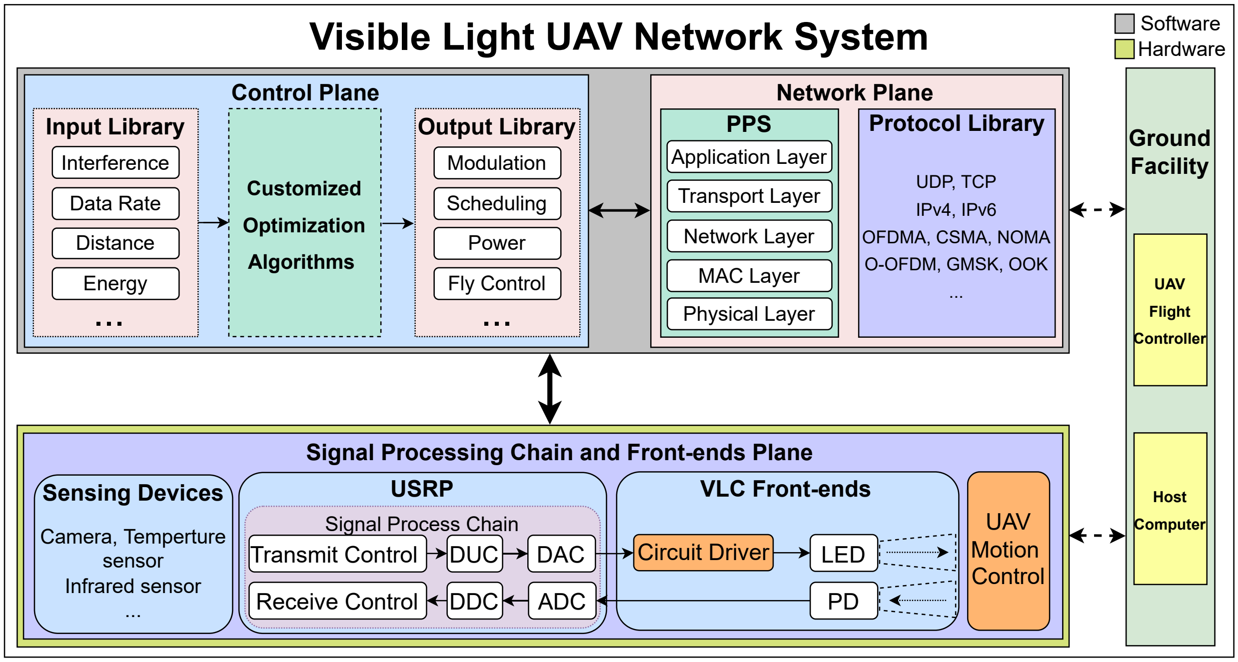


Fig. 1: Architecture of visible light UAV network

with a PD receiver, signal processing chains on Universal Software Radio Peripheral (USRPs), and real-time video streaming module.

- To validate the effectiveness of the developed prototype, we conduct extensive experiments in practical environments with respect to sunlight effect, distance effect, and power effect. Experimental results show that we can achieve 550 kbps data rate communication with distance up to 6.5 m - 7 m.

The rest of the paper is organized as follows. In Section II and Section III, we describe the overall architecture and prototype in detail. In Section IV, we conduct experiments to validate the effectiveness of the implemented prototype and discuss the results. Related works are discussed in Section V. Finally, we make the conclusions and envision future research directions in Section VI.

II. Architecture Design

The proposed architecture of the visible light UAV network is illustrated in Fig. 1. It includes four main modules: control plane to control the operation parameters, network plane to reconfigure the network, signal processing chain and front-ends plane to process the data, signal and UAV motion, and ground facility to monitor the system and control system manually. Next, we will discuss the main functionalities of each module.

A. Control Plane

The *Control plane* is designed to control and reconfigure the parameters of the *network plane*, *signal processing chain and front-ends plane*. It includes input and output libraries and customized optimization algorithms. The *Control plane* collects and stores in the input library the information received from the planes mentioned above such as data rate, signal interference levels, flight height, UAV location, modulation type, transportation layer protocol, and others. Then, with the received information, customized optimization algorithms can be designed, such as load balancing control, drone motion control, and medium access control, to optimize at network runtime the network operating parameters that will be stored in the output library and then be sent to corresponding planes for real-time networking reconfiguration.

B. Network Plane

As illustrated in Fig. 1, the *Network Plane* consists of a Programmable Protocol Stack (PPS) spanning from the physical layer up to the application layer, and a protocol library. The network state information at each protocol layer is sent to and stored in the *Control Plane*, used to determine the optimal network operating parameters pertaining to the received network state information.

Programmable Protocol Stack: PPS is designed in a modular way, i.e., designed with different optimizable parameters at each layer, thus making reconfiguration and networking control easier. For example, the physical layer can freely select modulation schemes from the protocol library to meet various requirements of different applications, such as desired data rate, achievable transmission range, and controllable interference levels. The Medium Access Control (MAC) layer can switch among different medium access control algorithms under different application scenarios. The network layer implements IPv4 and IPv6 to accommodate different types of routers[1]. The transport layer implements adaptive segmentation and flow control, with designed programmable

[1]Some networking devices can only support IPv4 and cannot be compatible with IPv6 [14].

parameters including transmission rate, congestion window size, packet size, among others. The application layer supports different applications with programmable sockets, such as video streaming, file transfer, etc.

Protocol Library: The protocol library is predefined with a protocol pool, which helps implement fast reconfiguration of each layer pertaining to protocols switching. Next, we will discuss in detail the modulation schemes, multiple access techniques, and transport layer protocols implemented in the protocol library.

At the physical layer, we will implement a number of widely used modulation schemes for VLC, such as On-Off keying (OOK) and Gaussian Minimum Shift Keying (GMSK) [15] [16] [17]. OOK uses 0s or 1s in the generated data bit stream to turn the LED on and off. In the *off* state, the LED is usually not completely turned off but with reduced light intensity. The advantages of OOK are its simplicity and ease of implementation. GMSK is a modulation method developed from Frequency-shift Keying (FSK) with a Gaussian minimum shift keying filter. The advantages of GMSK include higher spectral efficiency and simpler transceiver design. In the next step, we plan to implement Optical Orthogonal Frequency Division Multiplexing (O-OFDM) in the protocol library. This is motivated by the fact that O-OFDM can reduce the inter-symbol interference and does not require complex equalizer [4] and achieve high spectral efficiency compared to OOK and GMSK, thus resulting in high data rate.

At the Medium Access Control (MAC) layer, Orthogonal Frequency Division Multiple Access (OFDMA), Carrier Sense Multiple Access (CSMA), and Non-Orthogonal Multiple Access (NOMA) are implemented. OFDMA based multiple access in VLC is a natural extension utilizing OFDM for modulation in the physical layer, where different users are assigned separate sets of subcarriers for communicating. CSMA is a type of random channel access mechanism that has been used in IEEE 802.15.7 standard [18]. In recent years, NOMA has been proposed in VLC [5], allowing down-link transmissions in the same band at the same time where different users are distinguished by different power levels.

As mentioned earlier, IPv4 and IPv6 are implemented at the network layer to be compatible with different types of devices. At the transport layer, we will implement two popular protocols: Transport Control Protocol (TCP) and User Datagram Protocol (UDP) to enable reliable or best-effort transmission, respectively. Finally, at the application layer, different applications can be implemented, such as video streaming, data analysis, etc.

C. Signal Processing Chain and Front-ends Plane

Signal Processing Chain and Front-ends Plane interacts with the *Control Plane* and *Network Plane* to retrieve control parameters. The sensing devices, such as camera, temperature sensor, and infrared sensor, are also included in the architecture to capture desired data requested by the application layer in PPS. Signal Processing Chain for transmitting path and receiving path is implemented in USRP, including transmit control/receive control, Digital Up Converter (DUC)/ Digital Down Converter (DDC), and Digital-to-Analog Converter (DAC)/ Analog-to-Digital Converter (ADC). The generated/received bit stream is then sent to or received from the VLC front-ends, i.e., LED and PD, respectively. At the transmitter side, a circuit driver is implemented to convert the received voltage signal to current signal, and to drive the LED. The UAV motion control is also included to be responsible for UAV height and position adjustment according to the received control parameters.

D. Ground Facility

The *Ground Facility* is implemented to monitor the visible light UAV networks and provides an interface to users to manually adjust the parameters of the whole system in case of any fatal errors, such as, the UAV cannot operate normally based on the output of the customized optimization algorithms. The *Ground Facility* is optional, which is useful for the initial phase implementation of the system to monitor system behaviors and refine testbed functionalities. Currently, we use wired connection between the UAV and the *Ground Facility*. The next-step is to implement wireless connection, such as RF and VLC.

III. Prototype Implementation

The diagram of the developed prototype is shown in Fig. 2, including two laptops, two USRPs, circuit driver, and two UAVs endowed with visible light communication capability.

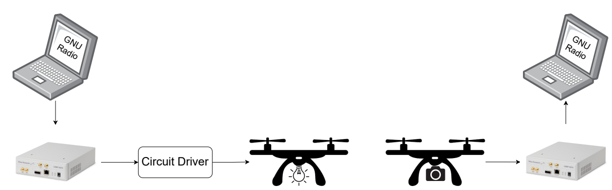


Fig. 2: Visible light UAV network prototype design

The *Control Plane* and *Network Plane* are implemented in GNU Radio using Python. GNU Radio [19] is a free and open-source software and provides signal processing modules used in Software-defined Radios (SDR) to implement wireless communication systems. In this work, the operating system runs on transmitter and receiver computer is Ubuntu 18.04. The Python version is 2.7 and the GNU Radio version is 3.7.14. OpenCV-python [20], an open-source computer vision processing library, is used to enable the real-time video streaming capability of the developed prototype. It allows real-time camera data acquisition at the transmitter side and real-time rendering at the receiver side.

The *Signal Processing Chain and Front-ends Plane* is implemented in hardware. Detailed implementation follows: (i) Signal Processing Chain is implemented on USRP N210 from Ettus [21] at the transmit and receiver sides, respectively. (ii) Circuit Driver [22] is built to drive the LED, which mainly consists of a bias-T and an operational amplifier. The bias-T is used to combine the modulated AC waveform from USRP

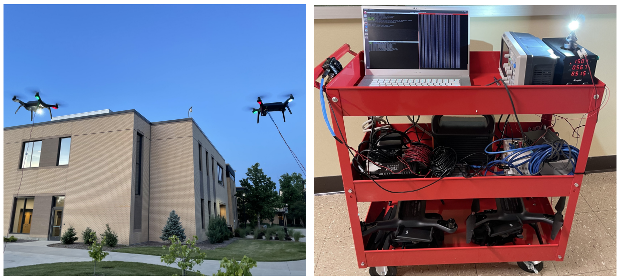


Fig. 3: Prototype and testing scenario

N210 and the DC bias that meets the minimum voltage requirements to light up the LED. And the operational amplifier is used to amplify the signal received from USRP. (iii) We use Fahren H11 Headlight Bulbs as the transmitter, and Thorlabs PDA100A2 as the receiver, which can detect light with wavelength ranging from 320 nm to 1100 nm. PDA100A2 features a built-in low-noise Transimpedance Amplifier (TIA) with switchable gain and it can support bandwidth from DC to 11 MHz. (iv) SOLO from 3D Robotics UAVs are used in our prototype, whose tall landing legs and detachable gimbal head make mounting LEDs and PDs relatively simple. (v) In the initial version of our prototype, customized optimization algorithms are not yet implemented. *Ground Facility* is used to configure the network control parameters and control the UAVs.

TABLE I: Prototype Parameters

OS	Ubuntu 18.04
Python	Version 2.7
GNU Radio	3.7
USRP	Ettus N210
Modulation	GMSK
Video Camera	Laptop Camera
Video Acquisition	OpenCV-python
Drone	3D Robotics SOLO
LED	LED Headlight Bulbs
Photo Detector(PD)	Thorlabs PDA100A2
LED Power	up to 60 Watts
LED Illumination	up to 12,000 LM
LED Color Temperature	6500k Cool White
LED FOV	Approx. 170 Degree
PD Responsivity	320-1100 nm
PD Bandwidth	11 MHz
PD FOV	180 Degree
Drone Height	Approx. 5 Meters

IV. Experiment Evaluation

In this section, we validate experimentally the effectiveness of the designed prototype. As shown in Fig. 3, we set up a two-node visible light UAV network and the detailed parameters are listed in Table I. Then, we conduct the following experiments to validate the feasibility and performance of the designed prototype under different settings pertaining to *Sunlight*, *Distance*, and *Power*.

A. Sunlight Effect

Experiments are designed to test the sunlight condition effect on the system performance of visible light UAV networks. We select a sunny day with clear sky and conduct

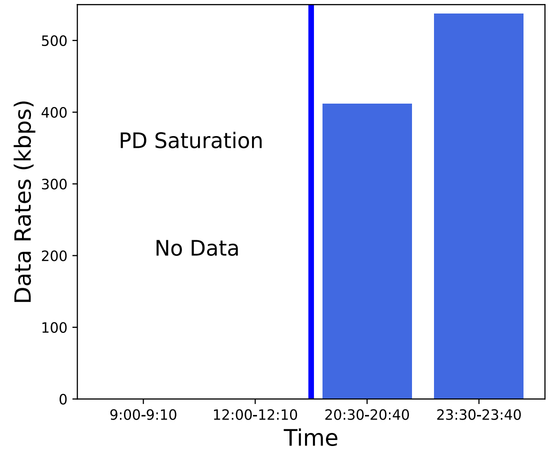


Fig. 4: Data rate vs sunlight condition

the experiments at around 9:00 am, 12:00 pm, 20:30 pm, and 23:30 pm. In each experiment, we obtain twelve data rate records. We calculate the average data rate after removing the largest and the smallest values. The UAV distance is fixed at around 2 m, and the power of the LED is set as 3.864 watts.

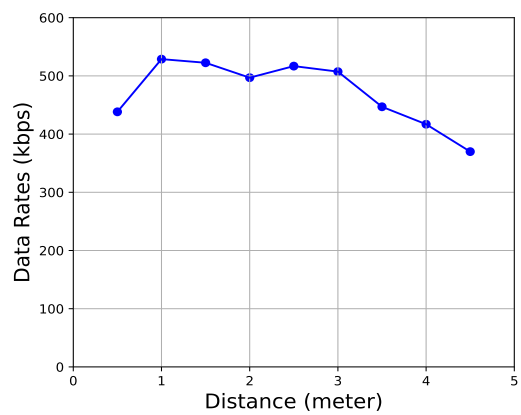
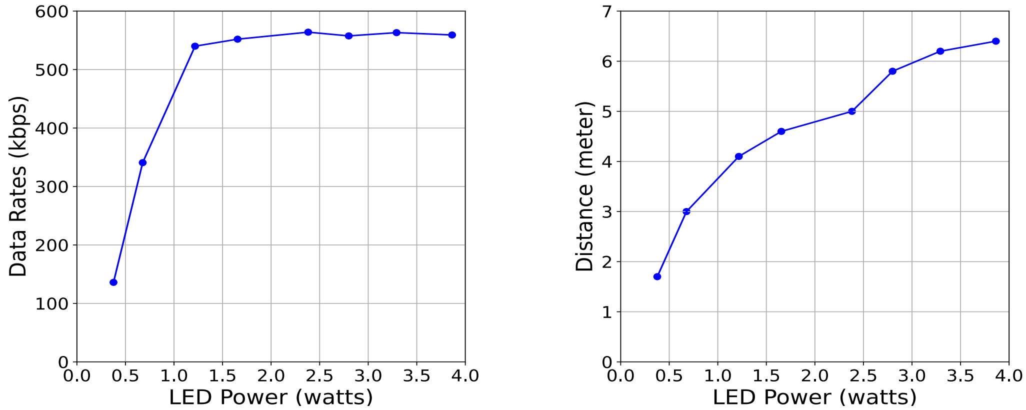


Fig. 5: Data rate vs distance

The result is shown in Fig. 4. Experiments at 9:00 am, and 12:00 pm cannot successfully establish visible light communication. This is because direct exposure to the sunlight causes saturation of the PD, thus resulting in unsuccessful signal reception. In our future work, we plan to mitigate the strong solar radiation effect by using various techniques, such as selective combining and optical bandpass blue filter as discussed in [23] [24] [25]. From Fig. 4, we can see that at sunset and night, we can set up reliable communication between two drones, with data rate 400 kbps and 550 kbps at 20:30 pm and 23:30 pm, respectively. We can also observe that the darker the testing environment is, the higher data rate is obtained.

B. Distance Effect

To test the distance effect on the achievable data rate, we conduct a set of experiments during 10:00 pm to 10:30 pm, with the power of the LED set as 3.864 watts also. We gradually increase the distance between the two UAVs



(a) (b)

Fig. 6: (a) Data rate and (b) distance vs LED power

from 0.5 m to 4.5 m by 0.5 m. We collect twelve data rate records for each distance and then calculate the average of the remaining records after removing the outliers (e.g., the largest and smallest ones). As shown in Fig. 5, the data rate fluctuates around 500 kbps within 3 meters due to unstable flight of drones, and gradually decreases as the distance is over 3 meters. We expect that until some distance, the data rate will drop to 0 kbps because of the limited transmission range of VLC.

C. LED Power Effect

LED power effect on data rate and transmission distance is evaluated in this part. We first evaluate the effect of power on the transmission data rate. We increase the input power of LED from 0.377 watts to 3.864 watts. As previous experiments, we obtain twelve data rate records for each LED power level at mid night, and then average the records after removing the maximum and minimum values. As shown in Fig. 6(a), the obtained data rate significantly increase from 110 kbps to 550 kbps as LED power increases from 0.377 watts to 1.2 watts. After 1.2 watts, the data rate stably stays at around 550 kbps, which is consistent with the results obtained in Fig. 4. Next, we conduct experiments to evaluate the LED power effect on transmission range. We set the transmission data rate at 320 kbps and increase the LED power from 0.377 watts to 3.865 watts. The recorded distance is the maximum distance between the two UAVs that can maintain the predefined data rate. The result is shown in Fig. 6(b), where we can see that the LED power greatly affects the transmission distance. As the LED power increases, the achieved transmission distance increase accordingly, with a trend of reaching a plateau, which will be further validated in our future work since the current maximum power of the LED is 3.865 watts in our testbed.

V. Related Work

In recent years, we have witnessed an increasing number of researchers focusing on VLC-related research to improve the data rate and transmission distance for single-link VLC systems. In [26], O-OFDM is proposed to meet the unipolar requirement of visible light signal, which can enable high-data-rate and low-interference communication. In [4], the authors analyze and compare the performance of ACO-OFDM, DCO-OFDM, and ADO-OFDM in terms of Bit Error Rate (BER) using simulation and find that ADO-OFDM requires less optical power to achieve the same performance compared with the other two schemes. The authors in [27] propose to apply DCO-OFDM for long-range communication in their developed vehicular VLC testbed. In addition to proposing advanced modulation methods to boost data rate of VLC systems, a number of works have focused on designing new multiple access schemes to improve the throughput of the overal system [5] [6] [7] [8] [9]. Among these works, NOMA has attracted significant attention from researchers because of its higher date rate potential compared to OFDMA [28]. More recently, Reconfigurable Intelligent Surface (RIS) has been envisioned as a novel technology that can help overcome the shortcomings of limited transmission range of visible-light link and intermittent link availability due to blockage [29] [30] [31] [32].

With the advancement of VLC technology, a diverse set of VLC-based applications have been proposed, such as smart health [33], modernized military [34], indoor positioning [35], intelligent transportation [36] [37] [38], etc. Among these, visible light UAV networking has obtained increasing attention from researchers. In [10] and [11], the authors design optimized network control algorithms to improve the achievable data rate of visible light UAV networks. While in [12] [13], the authors make efforts to design a camera based visible light UAV platform, where very low data rate achieved, i.e., 20 bps and 5 kbps, respectively, which cannot meet the broadband requirements of most applications mentioned above.

VI. Conclusion

In this paper, we propose a programmable software-defined visible light UAV network architecture and implement the prototype. We also conduct extensive experiments to validate the effectiveness of the developed prototype and investigate the performance of the visible-light UAV networks with respect to data rate and transmission range. We also encounter some challenges in our experiments, such as solar radiation caused PD saturation, wired connected *Ground Facility* to the

UAVs resulting in strong electromagnetic interference from ten-meter-long SMA wires, etc. These problems will affect the system performance. Therefore, in our future work, we plan to mount a lightweight computing processor along with USRP on UAVs to mitigate the inconvenience casued by wired connected *Ground Facility*. Besides, as discussed in Sec. III, strong solar radiation from the sun saturates the PD resulting in unsuccessful VLC transmission between UAVs, which requires practical solutions to enable the deployment of visible light UAV networks to be functional during daytime. We will also plan to set up more than two UAVs to help test networking-related algorithms, such as medium access control, resource allocation, among others.

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