32 Gbit/s 60 GHz Millimeter-Wave Wireless Communications using Orbital-Angular-Momentum and Polarization Mulitplexing

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***Abstract*—This paper reports an experimental demonstration of a 32 Gbit/s wireless link using orbital angular momentum (OAM) and polarization multiplexing in the millimeter-wave regime at 60 GHz. Two different OAM channels (*l*= +1 and +3) on each of the two polarizations are spatially multiplexed and each channel carries 2 Gbaud signals with 16-QAM modulation. Spiral phase plates are used to generate 60 GHz OAM beams. The bit-error rates (BER) of 4 channels are measured and the raw BERs are below 3.8×10^{-3}. The distance of the link is about 2.5 meters.**

Keywords—Orbital angular monmentum; millimeter wave; OAM multiplexing.

I. INTRODUCTION

Spatial division multiplexing has the potential to increase the total link capacity and the spectral efficiency in wireless communications [1,2]. One of the approach is to multiplex spatially orthogonal spatial modes. Each spatial mode carries an independent data stream and is spatially orthogonal to all other spatial modes, such that efficient spatial multiplexing and demultiplexing can be performed at the transmitter and receiver, respectively.

One approach of spatial multiplexing in wireless communications that has received a fair amount of recent interest is the use of orbital angular momentum (OAM) of electromagnetic (EM) waves [3]. OAM is associated with the "twist" of the phase front of a propagating EM wave. The wavefront phase of an OAM beam could change from 0 to $2\pi l$ azimuthally, in which l is known as the OAM number that can be any integer of either negative, zero or positive value. The OAM beam with l=0 is also known as the Gaussian beam. Each OAM beam with $l\neq0$ has a doughnut-shaped intensity profile and the beam size grows with the increase of l. Note that OAM is distinct from the circular polarization states. In the ideal case each OAM beam is spatially orthogonal to (that is, distinguisha-ble from) all other OAM beams with different OAM numbers when they propagate along the same axis. The OAM beams have thus been suggested for spatial multiplexing because their orthogonality enables multiple beams of different OAM numbers to be multiplexed together and subsequently demultiplexed with negligible crosstalk among them [4]. Each OAM beam can carry an independent data stream at the same carrier frequency, and therefore the total link rate equals the data rate of the single channel multiplied by the total number of multiplexed OAM beams.

OAM has been demonstrated for RF and millimeter-wave (mm-wave) wireless communications [5-8]. A 32 Gbit/s link that multiplexed 8 OAM channels has been demonstrated at the frequency of 28 GHz [6]. A system that combined OAM multiplexing and traditional spatial multiplexing using multiple pairs of apertures has been demonstrated to achieve a 16 Gbit/s link [7]. 4 Gbit/s data transmission over a single orbital angular momentum (OAM) has been demonstrated at 60 GHz [8]. Recently, wireless communications at 60 GHz frequency band is attractive because the unlicensed bandwidth [9,10], less absorption in the air [11,12], and less beam divergence due to the higher carrier frequency. Especially, the property of less divergence is favorable for OAM communications because one of the challenges of OAM communications is that the OAM beams diverge faster than the regular Gaussian beam and has less power at the very center. Operating at a higher carrier frequency will help increase the propagation distance, the SNR of the channels, and the number of multiplexed OAM channels [5]. It may also decrease the size of the components and lead to more compact transmitter and receiver.

Contributions: In this paper, we demonstrate a mm-wave communication link using OAM multiplexing at 60 GHz. We multiplexed 4 channels of 2 OAM numbers (l=+1 and l=+3) and two polarizations (X- and Y- polarizations) to achieve a capacity of 32-Gbit/s. Each channel carries a 2 Gbaud 16 QAM signal. We used the spiral phase plates made of high-density polyethylene (HDPE) to generate and demultiplex the OAM beams. A 50/50 beam splitter is used to multiplex the four OAM channels. As this is a proof-of-principle experiment, the transmission distance is about 2.5 meters in the lab. We demonstrate that crosstalk is low, allowing a decoding of the spatial streams *without* further processing by interference cancellers (BLAST-like structures) or maximum-likelihood detectors [12].

II. GENERATION OF 60 GHZ MILLIMETER OAM BEAMS

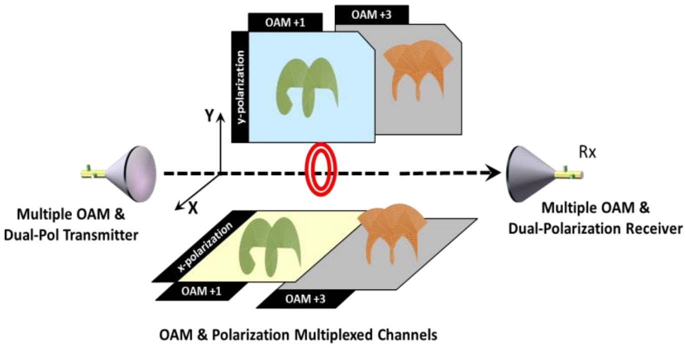


Figure 1. Concept of 60 GHz mm-wave wireless communications using OAM and polarization multiplexing techniques. The multiplexed OAM beams propagate through a single pair of apertures and could be demultiplexed with low crosstalk and recovered without further signal processing to cancel the channel interference.

Figure 1 shows the concept of the 60 GHz wireless communications using 4 OAM channels of OAM numbers of l=+1 and l=+3 on both polarizations. We start with the Gaussian-like beams of l=0 emitted by standard mm-wave dual-polarization lensed horn antennae. Figure 2 shows the comparison of the power loss for 28 GHz and 60 GHz carrier frequency for different OAM beams. We can see that as the OAM number increases, the difference between the 28 GHz and 60 GHz also increases. This means that higher carrier frequency can reduce the propagation loss for OAM beams and this effect is more significant for higher order OAM beams.

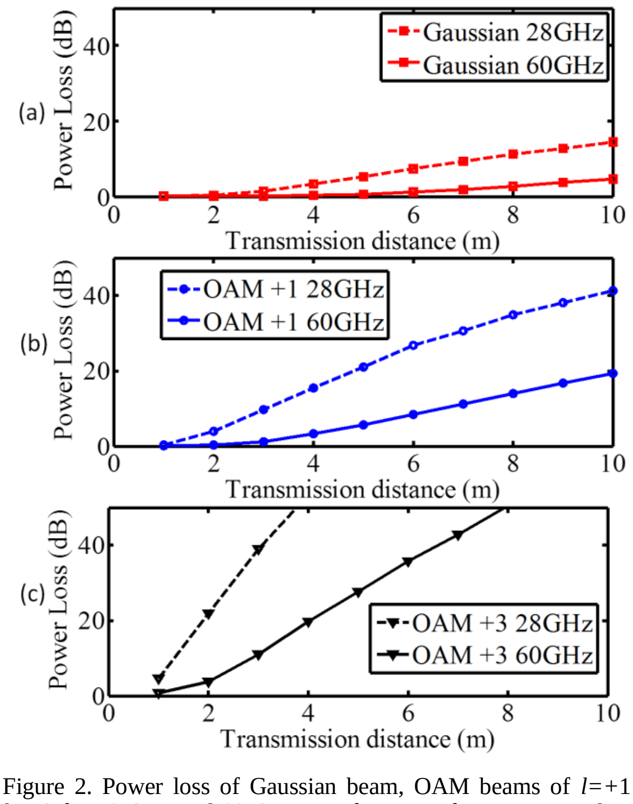


Figure 2. Power loss of Gaussian beam, OAM beams of l=+1 and l=+3 for 28 GHz and 60 GHz as a function of transmission distance.

The diameter of the Gaussian beam at Tx is 15 cm. The diameter of Tx and Rx is 30 cm. The OAM beam is generated by passing the Gaussian beam through the Spiral Phase Plate.

The antennae used in the experiment have an aperture diameter of 15 cm and a Gain of 30 dB. The lensed horn antenna and the intensity of the emitted 60 GHz mm-wave beam are shown in Fig. 2(a). A SPP is placed in front of the antenna to convert the Gaussian-like beam into an OAM beam. The spiral surface induces different phase shifts in different parts of the input Gaussian beam. When the height difference of the spiral plate $\Delta h = l\lambda/(n-1)$, in which n is the refractive index of the plate material, λ is the wavelength of the millimeter wave and l is the OAM charge number, the transmitted beam becomes an OAM beam of charge number l [13]. Reversely, a spiral plate that has an inverse spiral surface can convert an OAM beam back into a Gaussian beam. The spiral phase plates are made of high-density polyethylene (HDPE) which has a refractive index of 1.52 at 60 GHz. Thus, to generate the l=±1 and l=±3 OAM beams the designed height differences are Δh_1=±9.52 mm and Δh_3=28.62 mm, respectively. The diameter of the spiral plates in our experiment is 30 cm, which is larger than the aperture of the horn antenna we use to create the Gaussian beam. The spiral plates were fabricated by a precise Computer Numeric Control (CNC) machine process.

Figures 3 (b) and (c) show the measured intensity of the OAM beams which are generated by the Gaussian beam passing through the SPPs, and the interferogram of the OAM beams generated by interfere them with a Gaussian-like beam with l=0. The image is recorded by a probe antenna with a small aperture diameter of 0.2 cm that is connected to an electrical spectrum analyzer. The probe antenna is attached to a two-dimensional (X-Y) linear translation stage with a scanning resolution of 1 cm and a transversal coverage of 60 by 60 cm. Figs. 3 (b) and (c) confirm the ring-shaped intensity profile of the generated OAM beams. The spiral phases of the OAM beams were deduced from the interferogram and the numbers of rotating arms indicate that the OAM values l are +1 and +3.

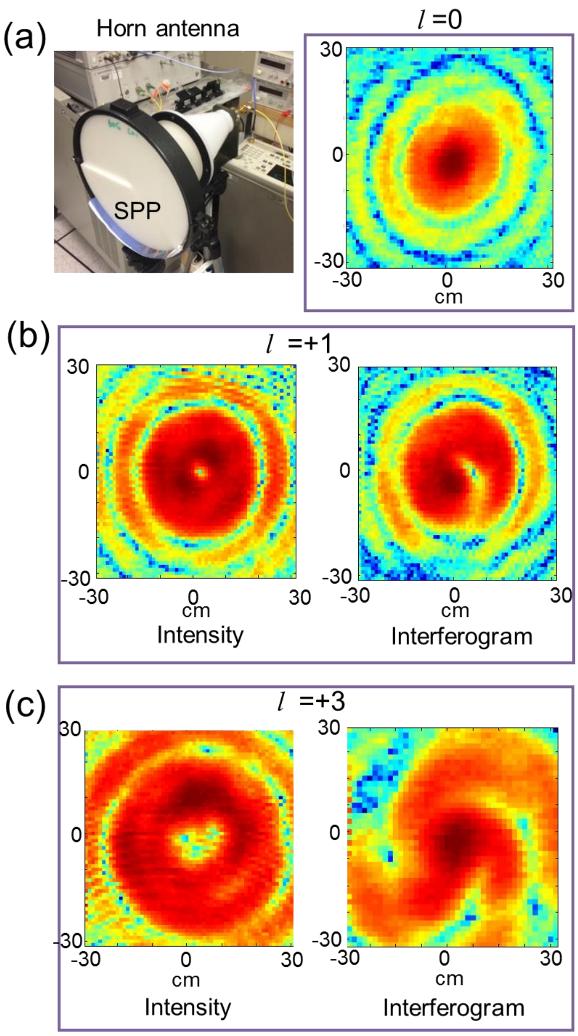


Figure 3 (a) Lensed-horn antenna and spiral phase plate to generate OAM beams and the intensity of emitted Gaussian-like beam from the lensed-horn antenna. (b) Measured intensity and interferogram of the OAM beam of *l*=+1. (c) Measured intensity and interferogram of the OAM beam of *l*=+3.

III. Multiplexing and Demultiplexing OAM Beams

The dual-pol horn lensed antenna emits two Gaussian-like beams on both X- and Y- polarizations. The generated 60 GHz OAM beams are combined by a designed beam splitter [6]. The beam splitter is a 2-dimenional array of metal rectangles on a dielectric substrate, which can be fabricated by using standard PCB techniques. The size of the rectangle unit is 1 mm by 0.5 mm, and the period of the array is 1.25 mm in both X and Y direction. These parameters are designed to have a 50/50 transmission-reflection ratio when the incoming beam is incident on the surface with an angle of 45 degrees. The designed parameters are based on the simulation by using Finite-Difference-Time-Domain method (FDTD) [14]. Figure 4 shows the diagram and photo of the experimental setup for multiplexing and demultiplexing OAM beams. At the transmitter side, 2 lensed-horn antennae and two spiral phase plates of *l*=+1 and *l*=+3 are used to generate 4 OAM beams with 2 OAM numbers on both polarization states. A beam splitter is used to combine these four beams. Since OAM and polarization are orthogonal domains of multiplexing, we can combine them to achieve higher transmission capacity and spectral efficiency. At the receiver side, we demultiplexed one of the OAM beams at a time. A SPP with *l*=-1 (or *l*=-3) is used to convert the OAM beams of *l*=+1 (or *l*=+3) on two polarizations back to a Gaussian-like beams with *l*=0, while the other ones remained as OAM beams with *l*=+2 (or -2). Another lensed horn antenna is used to receive the signal carried by the converted Gaussian beam, and the antenna receives little energy from the other OAM beams. Fig. 4 (b) shows the photo of the experimental setup. The link distance between the beam splitter and the demulitplexing SPP is 2.5 m.

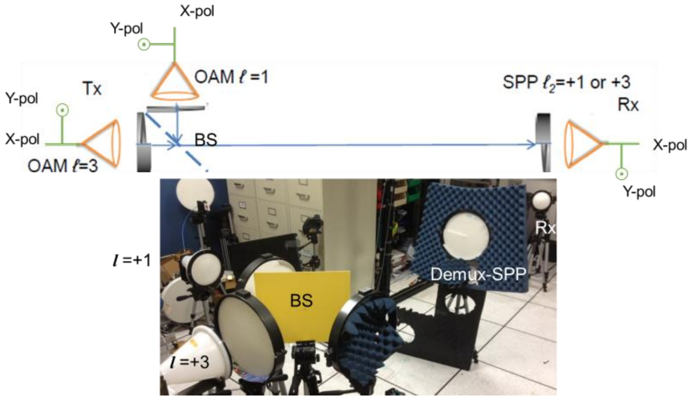


Figure 4. 4 OAM channels (*l*=+1 and *l*=+3 on both X- and Y-polarizations) are multiplexed by using two dual-polarization antennae, two spiral phase plates, and a 50/50 beam splitter (BS). At the receiver side, a demultiplexing SPP is used to demultiplex one of the multiplexed OAM channels one at a time, and then an Rx lensed horn antenna is used to receive the Gaussian-like beam for detection. The distance between the BS and the demultiplexing SPP (Demux-SPP) is 2.5 m.

IV. Demonstration of 32-Gbit/s Link using 2 Orbital-Angular-Momentum Channels on each of the 2 Polarizations

A. 16-QAM signal generation and detection

Figure 5 shows the transmitter and receiver to generate and detect 2 Gbaud 16-QAM signal. A 15 GHz clock signal is generated from a RF oscillator as the input of an X4 frequency multiplier to generate a 60 GHz clock signal. An IQ mixer takes the 60 GHz clock signal as LO and two independent IF signal waveforms from the arbitrary waveform generator to generate the 2 Gbaud 16 QAM signal at 60 GHz carrier frequency. The length of PRBS signal is 2^{15}-1. The output 16 QAM signal is amplified by an amplifier, and then split into 4 paths by using a 4-way power divider. Four cables of different lengths connect the four outputs of the power divider to four dual-pol antenna inputs. The lengths of the cables and the positions of the antennae ensure that the signals on 4 different channels have time delays among them and the signal are decorrelated.

At the receiver, the signal is received by a horn lensed antenna and then is amplified by a low noise amplifier (LNA).

A down-conversion mixer is followed to mix the 60 GHz signal with a 50 GHz clock signal. The output is 10 GHz signal. Then an 80 Gsample/s real-time oscilloscope with an analog bandwidth of 32 GHz is used to faithfully capture the waveform of the 10 GHz signal. Finally, the recorded signal ($2x10^6$ sampled points corresponding to $4x10^5$ bits for 2 Gbaud/s 16-QAM signal) is processed offline to recover the 16-QAM signal and calculate the SNR and BER. Attenuators are placed before the real-time oscilloscope to vary the signal-to-noise ratio (SNR).

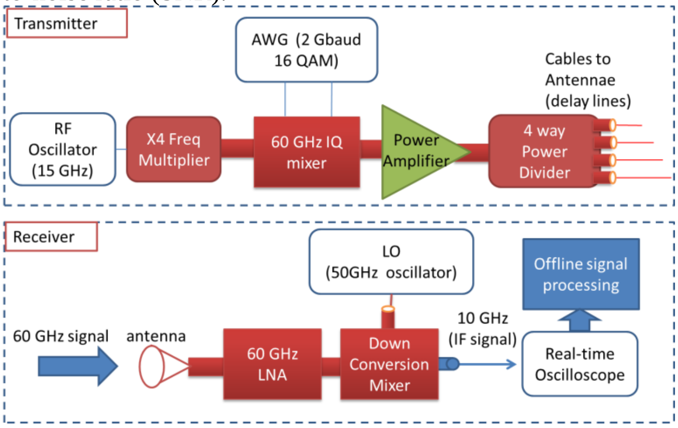


Figure 5. Transmitter and receiver of 2 Gbaud 16-QAM signal used in the OAM communication link. Transmitter: AWG: arbitrary waveform generator. Receiver: detection of 2 Gbaud/s 16-QAM by using LNA, down-conversion mixer and 80 GSample/s real-time oscilloscope followed by offline processing.

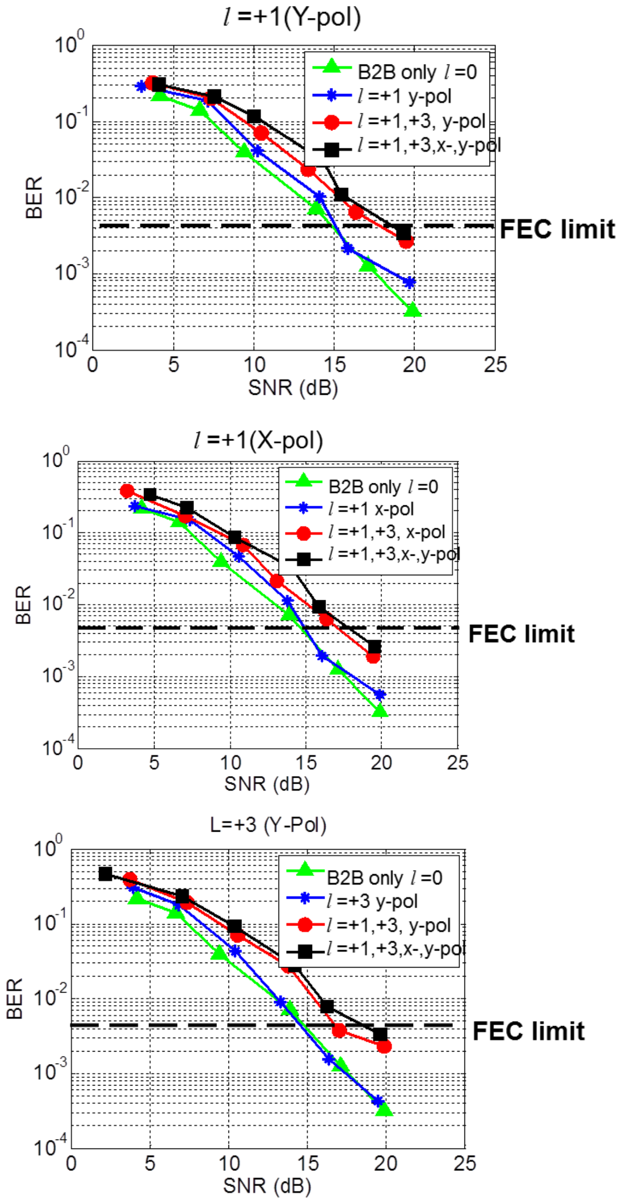
B. *Crosstalk and Bit-error rate measurement of 8 OAM channels*

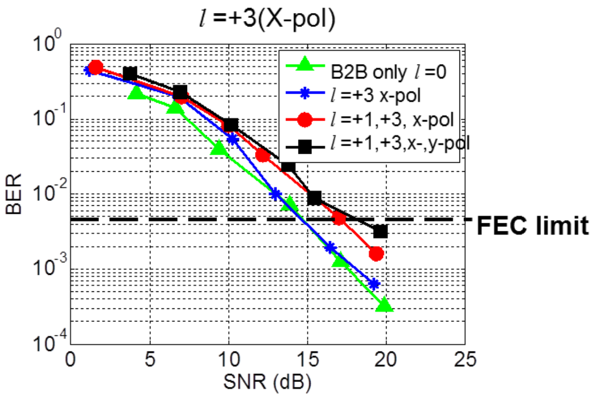
Ideally, there should be no crosstalk from one OAM channel to others. However, in the implementation of OAM communications, the imperfections of OAM generation, multiplexing, demultiplexing and setup misalignment may result in the channel crosstalk of certain level. The crosstalk for a specific OAM channel l_1 can be measured by $P_{l\neq l1}/P_{l=l1}$, where $P_{l\neq l1}$ is the received power when all other channels are transmitted on except channel ℓ_1, and $P_{l=l1}$ is the received power on channel ℓ_1 when only channel l_1 is transmitted.

OAM / Pol	l =+1	l =+3
X-polarization (single-pol case)	-19.2 dB	-18.5 dB
Y-polarization (single-pol case)	-18.6 dB	-19.1 dB
X-polarization (dual-pol case)	-19 dB	-18.2 dB
Y-polarization (dual-pol case)	-18.4 dB	-18.7 dB

Table 1 Crosstalk of OAM channels measured at f=60 GHz. Single-pol case: 2 channels of 2 different OAM numbers on X-polarization. Dual-pol case: 4 channels of 2 different OAM numbers on both polarizations.

The first row of Table 1 shows the measured crosstalk of the 2 OAM channels on the X-polarization without the other two channels on the Y-polarization. The second row shows the measured crosstalk of the 2 OAM channels on the Y-polarization without the other two channels on the X-polarization. The third and fourth rows of show the crosstalk from the all the other 3 OAM channels on both polarizations. We found that the crosstalk for all the channels is less than -18 dB.





Figures 6. BER measurement of 2 Gbaud/s 16-QAM signal on a single Gaussian beam (B2B only l=0), a single OAM channel on a single OAM channel, 2 OAM channels on X-polarizations or Y-polarizations, and 4 OAM channels on both X-and Y- polarizations.

Figures 6 show the BER measurement of the OAM channels. For each OAM charge number, we measured the BER when there is no crosstalk from other channels (blue star), when there is crosstalk from other OAM channels on the same polarization (red circle) and when there is crosstalk from the other 3 OAM channels on both polarizations (black square). We also measure BER for the baseline case when only the Gaussian beam is used in the link (B2B only l=0). We see that the power penalty of each OAM number in the single-pol case is lower than that of either polarization in the dual-pol case due to the fact that each channel in single-pol case experiences lower crosstalk. It is clear that each channel is able to achieve a raw BER below the 3.8×10^{-3} forward error correction (FEC) limit, which is a level that enables very low packet error rates to be achieved by the use of appropriate FEC codes (e.g., concatenated RS-Convolution code [15]). As an example, in Fig. 7 we show the constellations for OAM charge number l=+1 when the SNR is 20 dB.

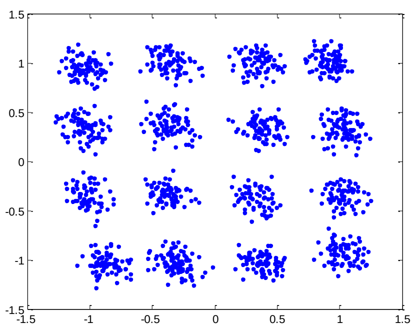


Figure 7. Constellation of OAM channel of charge number l=+3 when SNR is 20 dB.

V. SUMMARY

We demonstrate OAM multiplexing of 4 OAM channels to achieve a capacity of 32-Gbit/s in a wireless communication link at 60 GHz. Each channel carries 2 Gbaud 16-QAM signal riding over the same carrier frequency. Two different OAM beams of charge number l=+1 and +3 on each of the two linear polarization states are used. Spiral phase plates and beam splitter have been used to multiplex and demultiplex. OAM multiplexing communication operating at higher mm-wave frequency could reduce the divergence of OAM beams and may help extend the distance of link and reduce the size of the components.

ACKNOWLEDGMENT

This work was supported by the Intel Labs University Research Office and NxGen Partners.

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