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A Performance of MAC Layer Over Error-prone Channel in The IEEE 802.11ac

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***Abstract* –A MAC (Medium Access Control) layer throughput is evaluated over error-prone channel in the IEEE 802.11ac-based wireless LAN. In this evaluation, DCF (Distributed Coordination Function) protocol and A-MPDU (MAC Protocol Data Unit Aggregation) scheme are used. Using theoretical analysis method, the MAC saturation throughput is evaluated with the PER (Packet Error Rate) on the condition that the number of station, transmission probability, the number of parallel beams and the number of frames in each A-MPDU are variables. When the PER is 10^{-2} and the number of aggregated MPDUs in each A-MPDU is 20, it is identified that the MAC layer throughput of IEEE 802.11ac can be maximally attained up to a 92.8% of physical transmission rate in this evaluation.**

***Keywords*–Wireless LAN, MAC, Throughput, CSMA/CA, DCF, IEEE 802.11ac.**

I. Introduction

Over the past few years, wireless LAN have been deployed rapidly across enterprises, homes, public sectors and service providers due to mobility, flexibility, interoperability and cost-effective deployment. It is expected that wireless LAN have emerged as a promising network for future IP applications. When wireless channel experiences fading, bit errors occur and its performance decreases largely. Also, with the limited frequency resources, designing an effective MAC protocol is a hot challenge. The legacy IEEE 802.11b and 802.11g/a specification provide up to 11 and 54 Mbps data rates, respectively. They employs a CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) protocol with binary exponential back-off as the MAC protocol. IEEE 802.11n allows coexistence with IEEE 802.11b/g/a legacy devices[1]. It delivers a theoretical maximum throughput of 600 Mbps at physical layer and has maximum data throughput of at least 100 Mbps as measured at the MAC SAP (Service Access Point). IEEE 802.11ac is an amendment to IEEE 802.11 for very high throughput (VHT) operation in frequency bands below 6 GHz, excluding 2.4 GHz (i.e., unlicensed bands at 5 GHz band) [2]. The previous researches have been executed on the DCF performance over wireless LAN[3]. In case of IEEE 802.11n, the throughput performance at the MAC layer can be improved by aggregating several frames before transmission[4]. Frame aggregation not only reduces the transmission time for preamble and frame headers, but also reduces the waiting time during CSMA/CA random backoff period for successive frame transmissions. Under error-prone channels, corrupting a large aggregated frame may waste a long period of channel time and lead to a lower MAC efficiency. The previous paper analyzed the IEEE 802.11b/g/a/n MAC performance for wireless LAN with error-free and error-prone channel[3, 5-7]. Papers related to IEEE 802.11ac also analyzed MAC throughput, but did not consider error-prone environment that is applied to most wireless LAN[8-11]. So, this paper extends the previous IEEE 802.11ac performance researches and analyzes the IEEE 802.11ac MAC performance for wireless LAN under the error-prone channel environment. In Section 2, IEEE 802.11ac PHY and MAC layer are reviewed. In Section 3 and Section 4, saturation throughput with bit errors appearing in the wireless channel are numerically analyzed and evaluated. In Section 5, it is concluded with remarks.

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II. IEEE 802.11ac WLAN

A basic block of IEEE 802.11 wireless LAN consists of a set of station and an AP (Access Point), which constitutes a BSS (Basic Service Set). As shown in Fig. 1, when a higher layer pushes a user packet down to the MAC layer as a MAC-SDU (MSDU), the MAC layer header (M-HDR) and trailer (FCS) are added before and after the MSDU, respectively and form a MAC-PDU (MPDU). The PHY (Physical) layer is again divided into a PLCP (Physical Layer Convergence Protocol) sub-layer and a PMD (Physical Medium Dependent) sub-layer. Similarly the PLCP preamble and PLCP header (P-HDR) are attached to the MPDU at the PLCP sub-layer. Different IFS (Inter Frame Space)s are added depending on the type of MPDU.

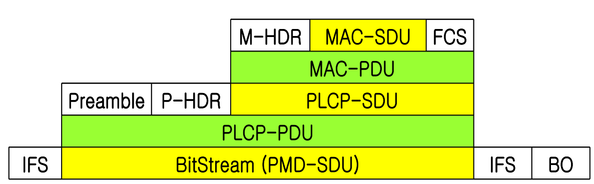


Figure 1. Protocol stack of physical and MAC layer

Plurality of IEEE 802.11b/g/n devices are currently operating at 2.4 GHz, crowding the channels and causing bandwidth crunch and higher signal interference. IEEE 802.11ac supports 40 MHz, 80 MHz, and 160 MHz channel bandwidth compared to only 20 MHz and 40 MHz supported by IEEE 802.11n[12]. The 160 MHz channel bandwidth is composed of two 80 MHz channels that may or may not be contiguous. The 80 MHz and 40 MHz channels are composed of two contiguous 40 MHz and 20 MHz channels, respectively. The support of 40 MHz and 80 MHz channel bandwidth is mandatory while support of 160 MHz and 80 + 80 MHz is optional. The IEEE 802.11ac supports up to 8 spatial streams compared to the maximum 4 in IEEE 802.11n. IEEE 802.11ac supports multi-user MIMO (MU-MIMO) as well as single-user MIMO (SU-MIMO). SU-MIMO is a method by which an AP can transmit multiple independent streams at the same time to a single device. MU-MIMO is a technique by which the AP can transmit multiple independent streams at the same time to multiple devices. In IEEE 802.11ac, MU-MIMO system supports four users with up to four spatial streams per user with the total number of spatial streams not exceeding eight. Data for transmission is divided into independent data streams to be transmitted through multiple antennas. This is known as spatial multiplexing.

According to IEEE 802.11ac, the PHY data subcarriers are modulated using binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (QAM), 64-QAM, and 256-QAM. Note that 256-QAM is not supported by IEEE 802.11n. FEC (Forward Error Correction) coding is used with coding rates of 1/2, 2/3, 3/4, and 5/6. Use of BCC (Binary Convolutional Coding) is mandatory, but LDPC (Low-Density Parity-Check Coding) is optional. IEEE 802.11ac is backward compatible with IEEE 802.11n at 5 GHz ensuring the interoperability of IEEE 802.11ac and the already deployed 802.11n devices[12].

IEEE 802.11 MAC protocol supports the DCF and the PCF (Point Coordination Function)[4]. The DCF uses the CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) mechanism for contention-based access, while the PCF provides contention-free access. The two modes are used alternately in time. IEEE 802.11 MAC protocol defines five timing intervals. Two of them are the SIFS (Short InterFrame Space) and the slot time that are determined by the physical layer. The other three intervals are the PIFS (Priority InterFrame Space), DIFS (Distributed InterFrame Space) and EIFS (Extended InterFrame Space) that are defined based on the above two intervals. But the PCF is restricted to infrastructure network configurations. IEEE 802.11 DCF stations access the channel via a basic access method or the four-way handshaking access method with an additional RTS/CTS message exchange as shown in Fig. 2 and Fig. 3. In the basic access method, the CSMA mechanism is applied. Stations wait for the channel to be idle for a DIFS period of time and then execute backoff for data transmission. Stations choose a random number between 0 and CW (Contention Window) -1 with equal probability as a

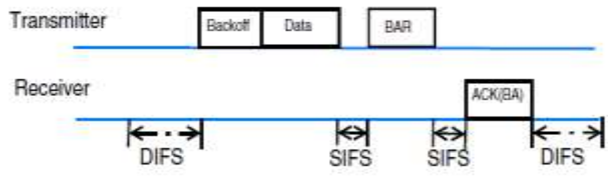


Figure 2. Basic access scheme[10]

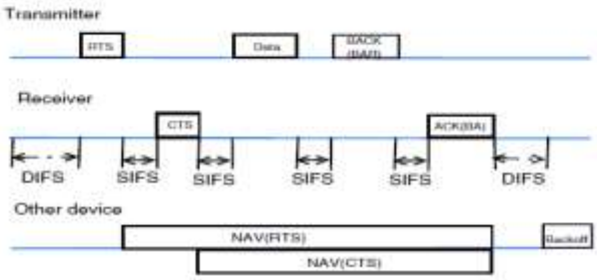


Figure 3. RTS/CTS access scheme[10]

backoff timer. When the backoff timer reaches zero, the data frame is transmitted. The receiver replies an ACK message upon successfully receiving a data packet. In the four-way handshaking access method, when the backoff timer of station reaches zero, the station first transmits a RTS frame. Upon receiving the RTS frame, the receiver replies with a CTS frame after a SIFS period. Once the RTS/CTS is exchanged successfully, the sender then transmits its data frame. The RTS and CTS frames carry a duration field, information of time interval to transmit the packet. Any station receiving RTS or CTS frames can read the duration field information. That information is then used to update a NAV (Network Allocation Vector) value that indicates to each station the amount of time that remains before the channel will become idle. Therefore, a station detecting the RTS and CTS frames suitably delays further transmission, and thus avoids collision. The NAV is thus referred to as a virtual carrier sensing mechanism. The main purpose of the RTS/CTS handshaking is to resolve the so-called hidden node problem. In IEEE 802.11ac, the sending STA will firstly send Block Acknowledgment Request (BAR) after Short Interframe Space (SIFS) period, then receiver responds with a Block Acknowledgment (BA) frame. If BA is not received by the sending STA, it will start its back-off procedure and double its current CW unless $CW = CW_{max}$. If BA is received or maximum retry limits is reached, the CW is always reset.

In the RTS/CTS mechanism, besides following the above mentioned basic access scheme, the sending STA will send a special RTS frame after medium is sensed to be free for a DIFS period. When the receiver receives the RTS frame, after a SIFS period it will respond with CTS frame. The transmission is started by sending station only if the CTS frame have been received correctly. During the RTS/CTS exchange period, the other contending STAs also read the information of RTS/CTS frames and update their Network Allocation Vector (NAV) containing the information of which period the medium remains captured.

III. Analysis of DCF Throughput

This section derives numerically MAC throughput in the IEEE 802.11ac wireless LAN over the error-prone channel. The back-off procedure of the DCF protocol is modeled as a discrete-time, two-dimensional Markov chain. Fig. 4 shows the Bianchi's Markov chain model for the back-off window size. We define $W = CW_{min}$. Let m, the maximum back-off stage, be such value that $CW_{max} = 2^m W$. We also define $W_i = 2^i W$, where $i \in (0,m)$ is called the back-off stage. We consider the stochastic process representing the back-off stage (0,...,m) of the station at time t. p is the probability that a transmission is collided or unsuccessfully executed. Station starts transmission in a generic time slot with probability τ, and the transmission suffers from the collision with probability p. The number of stations n is assumed to be fixed and each station always has packets for transmission. In other words, we operate in saturation conditions, the transmission queue of each station is assumed to be always nonempty. Hence τ and p can be expressed as

$$\tau = \frac{2(1-2p)}{(1-2p)(W_0+1)+pW_0(1-(2p)^m)}$$
$$\mathrm{p} = 1-(1-\tau)^{n-1} \tag{1}$$

Where n is the number of contending stations, $W_0 = W_{min}$ and m is the maximum increasing factor. The transmission probability τ and collision probability p can be calculated by solving the nonlinear equations of (1) numerically using fixed point iteration technique. It can be proved that the system has unique solutions[3].

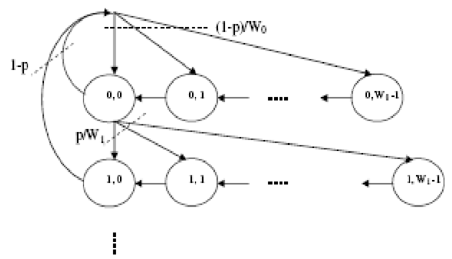


Figure 4. Markov chain model for the backoff window size

We define a variable P_c which is the probability that a back off occurs in a station due to bit errors in packets. We further assume that bit errors randomly appear in the packets. Performance evaluation of 802.11 networks has been investigated by other researchers. Out of such works Bianchi model appears to be the most widely cited. IEEE 802.11 network is considered as a discrete-time system which contains multiple generic slots[3]. A generic slot may contains an empty slot, a collision, or a successful transmission. The backoff procedure of the DCF protocol is modeled as a dircrete-time, two-dimensional Markov chain.

Let S be the normalized system throughput, defined as the fraction of time in which the channel is used to successfully transmit payload bits[5].

P_{tr} is the probability that there is at least one transmission in the considered slot time. Since n stations contend on the channel and each transmits with probability τ, we get

$$P_{tr} = 1-(1-\tau)^n \tag{2}$$

P_s is the probability that a transmission successfully occurs on the channel and is given by the probability that exactly one station transmits on the channel, conditioned on the fact that at least one station transmits.

$$P_s = \frac{n\tau(1-\tau)^{n-1}(1-P_c)}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1}(1-P_c)}{1-(1-\tau)^n} \tag{3}$$

We consider the MU-RTS/CTS scheme and A-MPDU scheme in deriving the saturation throughput. There are benefits of employing the MU-RTS/CTS scheme. It eliminates the need of executing the ECFB (Explicit Compressed FeedBack) protocol periodically. It reduces the collision time because the length of RTS is much shorter than that of A-MPDU. The data sender can also obtain CSI(Channel State Information) by estimating the training sequence included in MU-CTSs. The saturation throughput S can be calculated as follows[5,9].

$$\mathrm{S} = \frac{P_s P_{tr} N_f N_b L}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c} \tag{4}$$

Where T_s is the average time the channel is sensed busy because of a successful transmission, and T_c is the average time the channel is sensed busy by each station during a collision. σ is the duration of an empty slot time.

$$T_s = T_{RTS} + T_{SIFS} + N_b(T_{MU-CTS} + T_{SIFS}) + T_{A-MPDU} + T_{SIFS} + T_{B-ACK} + T_{AIFS} + \sigma$$
$$T_c = T_{RTS} + T_{SIFS} + T_{MU-CTS} + T_{AIFS} + \sigma \tag{5}$$

The duration of each frame transmission can be calculated as shown in equation (6), where $T_{VHT}(M)$ = (36+4M)μs are the duration of the IEEE 802.11ac PHY preamble. The number of VHT-LTF is proportional to the number of antenna M. Table 1 shows physical and MAC layer parameters of IEEE 802.11ac–based wireless LAN[9].

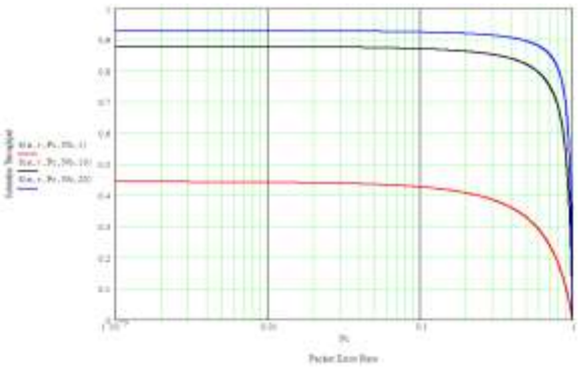
$$T_{A-MPDU} = T_{VHT}(M) + \left\lceil \frac{L_{service}+N_f(L_{MAC}+L+L_{delimiter})+L_{tail}}{N_s N_{DBPS}} \right\rceil T_{symbol}$$
$$T_{RTS} = T_{VHT}(M) + \left\lceil \frac{L_{service}+L_{RTS}+L_{tail}}{N_{DBPS}} \right\rceil T_{symbol} \tag{6}$$
$$T_{MU-CTS} = T_{VHT}(M) + \left\lceil \frac{L_{service}+L_{MU-CTS}+L_{tail}}{N_{DBPS}} \right\rceil T_{symbol}$$
$$T_{B-ACK} = T_{VHT}(M) + \left\lceil \frac{L_{service}+L_{B-ACK}+L_{tail}}{N_{DBPS}} \right\rceil T_{symbol}$$

TABLE I. IEEE 802.11ac Parameters

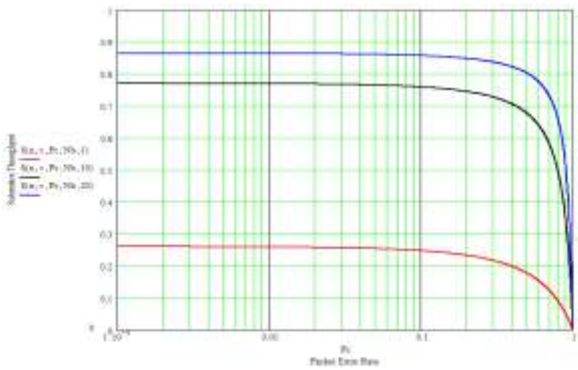
Parameter	Explanation
P_c	Packet error rate
T	Packet transmission probability
P	Probability that a transmission is collided or unsuccessfully executed.
n	Number of stations
P_s	Probability that a transmission successfully occurs on the channel
N_f	The number of aggregated MPDUs in each A-MPDU
N_b	The number of beam
N_s	The number of spatial streams in each beam
L	Frame payload size
N_{ES}	The number of BCC encoder
T_{RTS}	RTS frame transmission time
$T_{MU\text{-}CTS}$	CTS frame transmission time
$T_{A\text{-}MPDU}$	A-MPDU transmission time
$T_{B\text{-}ACK}$	Block ACK frame transmission time
M	The number of antenna
T_{SIFS}	SIFS time
σ	Slot time
T_{AIFS}	AIFS time
$L_{service}$	The length of the service field
L_{MAC}	The length of a MAC header
$L_{delimiter}$	The length of the MPDU delimiter
L_{tail}	The length of the tail field
L_{RTS}	The length of RTS
$L_{MU\text{-}CTS}$	The length of MU-CTS
$L_{B\text{-}ACK}$	The length of B-ACK
N_{DBPS}	The number of data bits in a symbol
T_{symbol}	The symbol duration
CW_{min}	Minimum backoff window size
CW_{max}	Maximum backoff window size

IV. Numerical Results

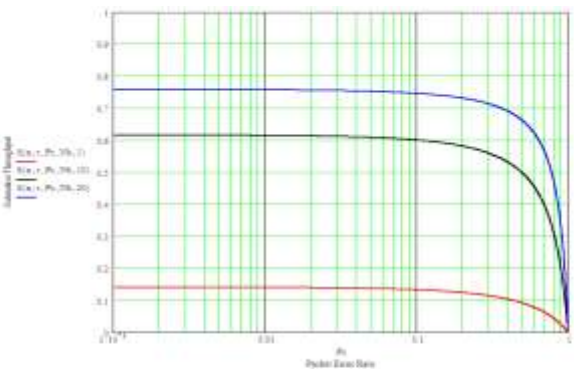
This section evaluated DCF throughput of the IEEE 802.11ac-based wireless LAN for one, four and eight spatial streams, as shown in Fig. 5. $S(n, \tau, P_c, N_b, N_f)$ shows DCF throughput performance over the error-prone channel. Fig. 5(a) shows DCF throughput on the condition that the channel bandwidth is 20 MHz, modulation scheme is 256-QAM, code rate is 3/4, guard interval is 800 ns, the number of BCC encoder is 1 and physical data rate is 78 Mbps. Fig. 5(b) shows DCF throughput on the condition that the channel bandwidth is 40 MHz, modulation scheme is 256-QAM, code rate is 5/6, guard interval is 800 ns, the number of BCC encoder is 1 and physical data rate is 180 Mbps. Fig. 5(c) shows DCF throughput on the condition that the channel bandwidth is 80 MHz, modulation scheme is 256-QAM, code rate is 5/6, guard interval is 800 ns, the number of BCC encoder is 1 and physical data rate is 390 Mbps. Fig. 5(d) shows DCF throughput on the condition that the channel bandwidth is 160 MHz, modulation scheme is 256-QAM, code rate is 5/6, guard interval is 800 ns, the number of BCC encoder is 2 and physical data rate is 780 Mbps. Fig. 5(e) and Fig. 5(f) have the same conditions as Fig. 5(d) with the exception of N_{ES} and data rate. When the packet error rate is 10^{-2} and the number of aggregated MPDUs in each A-MPDU is 20, It is identified that A MAC efficiency of IEEE 802.11ac can be attained up to 92.8% of physical data rate as shown in Fig. 5(a). With the same conditions mentioned above, Fig. 5(b) shows that a MAC efficiency can be attained up to 86.4% of physical data rate, and Fig. 5(c) shows that a MAC efficiency can be attained up to 75.7% of physical data rate. Fig 5(d) shows that it can be attained up to 61.5% of physical data rate. Fig 5(e) shows that it can be attained up to 37.4% of physical data rate and Fig 5(f) shows that it can be attained up to 20.1% of physical data rate.



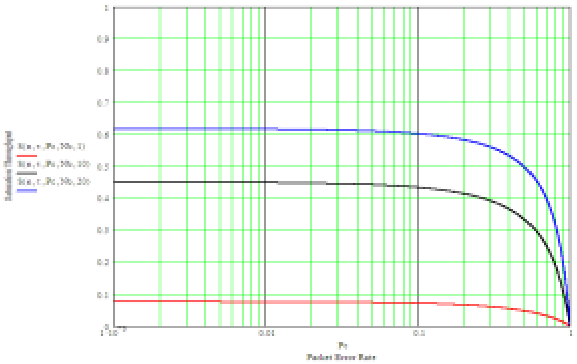
(a) Channel bandwidth = 20MHz, code rate = 3/4, modulation=256-QAM, N_{ES}=1, data rate=78Mbps



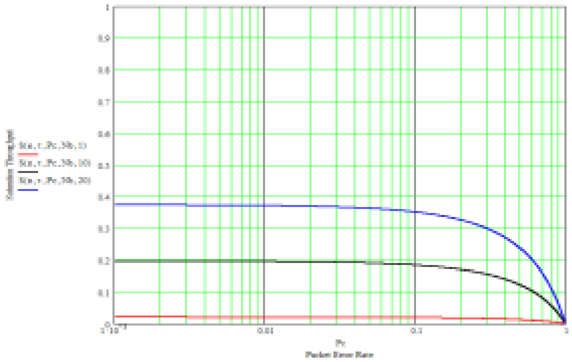
(b) Channel bandwidth = 40MHz, code rate = 5/6, modulation=256-QAM,N_{ES}=1, data rate=180Mbps



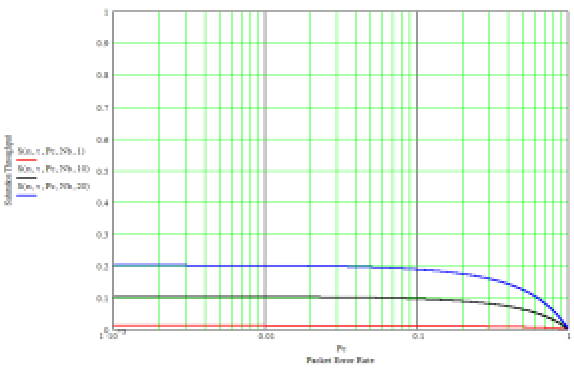
(c) Channel bandwidth = 80MHz, code rate = 5/6, modulation=256-QAM, N_{ES}=1, data rate=390Mbps



(d) Channel bandwidth = 160MHz, code rate = 5/6, modulation=256-QAM, N_{ES}=2, data rate=780Mbps



(e) Channel bandwidth = 160MHz, code rate = 5/6, modulation=256-QAM, N_{ES}=6, data rate= 3,120Mbps



(f) Channel bandwidth = 160MHz, code rate = 5/6, modulation=256-QAM, N_{ES}=12, data rate= 6,240Mbps

Figure 5. DCF throughput in IEEE 802.11ac

V. Conclusions

The DCF saturation throughput was derived and analyzed over error-prone channel in the IEEE 802.11ac-based wireless LAN. In evaluating DCF saturation throughput, DCF protocol and A-MPDU scheme were used. Packet error rate, the number of stations, the number of frames, frame payload size and transmission probability are used as the parameters. In this evaluation, it is identified that MAC efficiency of IEEE 802.11ac is attained up to the 92.8% of physical data rate when the packet error rate is 10^{-2} and the number of aggregated MPDUs in each A-MPDU is 20. Also, it is identified that the higher the data rate is, the worse a MAC efficiency is. In the following research, a MAC efficiency will be evaluated according to the number of aggregated MPDUs in each A-MPDU.

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