Exploiting SCTP Multistreaming to Reduce Energy Consumption of Multiple TCP Flows over a WLAN

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Abstract. The energy efficiency of a wireless client is an important issue for wireless network environments. A common strategy for energy saving in wireless network devices is to remain in sleep mode when data are not being transmitted or received. However, when multiple TCP flows are established from a wireless client, determination and control of sleep timings are difficult. In addition, frequent state transitions between active and sleep modes consume energy, resulting in a reduction in energy efficiency. In this paper, we propose an energy-efficient method for multiple TCP flows in wireless LAN (WLAN) environments. The proposed method is termed SCTP tunneling, and aggregates multiple TCP flows into a single SCTP association between a wireless client and access point to control packet transmission and reception timings. Furthermore, SCTP tunneling lengthens sleep time by transmitting and receiving multiple packets in a bursty fashion. In this study, we construct a mathematical model of the energy consumed by SCTP tunneling to assess its energy efficiency. Through numerical examples, we show that the proposed method can reduce energy consumption by up to 69%.

Key words: Transmission Control Protocol (TCP), Stream Control Transmission Protocol (SCTP), wireless LAN, energy efficiency

1 Introduction

There is a great deal of interest in reducing the energy consumed through wireless communication. For energy saving in media access control (MAC) layer protocols, the IEEE 802.11 standard defines a power saving mode (PSM) [1], as opposed to the mode under normal operation, which is referred to as the continuously active mode (CAM). Although PSM can considerably reduce energy consumption, it can also degrade network performance characteristics such as throughput and latency [2].

Several researchers have proposed energy-efficient methods for wireless LANs (WLANs) [2–7]. Some of these methods [2–4] achieve high energy efficiency by mainly modifying MAC protocols, whereas the others [5–7] are energy-efficient solutions for specific applications. In contrast, we aim to derive a generalized transport-layer solution for energy saving without modifying the applications or MAC protocols.

In a typical environment where mobile devices are utilized, multiple TCP connections are established for concurrently running applications. In such a case, determination and control of sleep timings by the wireless client are difficult because packets of each TCP flow are transmitted and received independently. Moreover, this uncoordinated behavior produces frequent state transitions between the active and sleep modes of a wireless network interface (WNI), which consumes extra energy, and results in the reduction of energy efficiency.

To overcome these issues, we propose an energy-efficient method for TCP data transfer over a WLAN in this paper. The key concept of the proposed method is that aggregate TCP packets are transmitted and received in a bursty fashion (known as *burst transmission*) to lengthen the idle time in which a WNI can enter sleep mode. To this end, the proposed method exploits stream control transport protocol (SCTP) [8] for TCP data transfer over a WLAN. We call this method *SCTP tunneling*. An SCTP association is established between a wireless client and an access point (AP), and all packets of TCP flows at the wireless client are aggregated into the association by means of SCTP multistreaming. Main contribution to save energy of SCTP tunneling is to reduce the number of state transitions between active and sleep modes, which is one factor of energy consumption, by burst transmission at transport-layer level. In practical cases, SCTP tunneling is used by combining it with sleep mechanisms at MAC-level such as PSM or automatic power save delivery (APSD) [1]. Note that energy wasted due to the behavior at MAC-level (e.g. frame collisions, overhearing, etc.) is out of scope of this work because it should be solved at MAC-level.

We derive an energy consumption model for SCTP tunneling to assess the potential gain in energy efficiency by its application. This model is based on our previous energy consumption model for a single TCP flow in a WLAN [9, 10], and focuses on both the frame exchanges of an IEEE 802.11 MAC and the detailed behavior of TCP congestion control mechanisms. [9] presented an energy consumption model for TCP data transfer over a WLAN, which was then extended to accommodate burst transmission in [10]. From the numerical results of the current model, we demonstrate the energy efficiency of SCTP tunneling for various aggregate throughputs of TCP flows.

2 SCTP Tunneling

The key concept of SCTP tunneling is that TCP packets of multiple flows at a wireless client are aggregated, and are transmitted or received in a bursty fashion to lengthen idle time in which the client can sleep during multiple TCP data transfer. Packet aggregation is realized by using SCTP, and thereby the transmission and reception timings are controlled with burst transmission.

2.1 TCP Flow Aggregation Using SCTP

SCTP is a connection-oriented transport protocol providing a service similar to TCP. In contrast to the stream-oriented nature of TCP, however, SCTP is message-oriented, and this feature is utilized in SCTP tunneling. Another feature of SCTP is multistreaming, which enables streams of user messages from multiple upper-layer applications to be multiplexed into a single SCTP association.

In SCTP tunneling, an SCTP association is established between a wireless client and an AP, as shown in Fig. 1. All packets of multiple TCP flows (e.g., the three flows in Fig. 1) are sent by SCTP tunneling, and each TCP flow is distinguished as a single

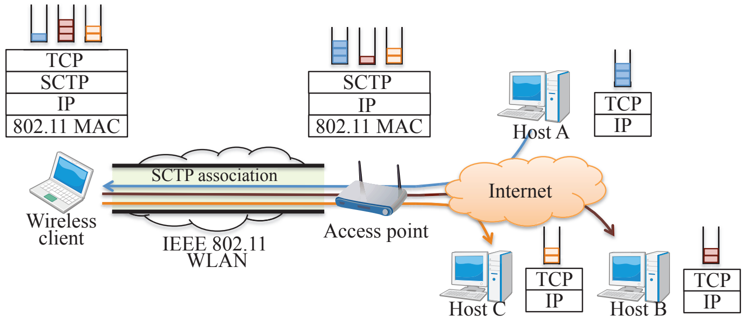

Fig. 1. SCTP tunneling in WLAN environment

stream in the SCTP association through multistreaming. Note that SCTP tunneling can also be applicable to UDP flows. A TCP packet generated in a wireless client is encapsulated in an SCTP-DATA chunk and enqueued in a transmission queue of the SCTP association. When a new SCTP packet can be transmitted, an SCTP-DATA chunk is dequeued from the transmission queue and is placed in a single SCTP packet. Transmission of the SCTP packet then obeys SCTP congestion control mechanisms. Once the SCTP packet is received by an AP, the packet is decapsulated and the original TCP packet is forwarded to its destination. At this time, SCTP at the AP generates an SCTP-SACK chunk to acknowledge receipt of the SCTP-DATA chunk. This SCTP-SACK chunk may piggyback with other SCTP-DATA chunks to the client. Data transmission from the AP to the client is conducted in a similar way to the above sequence.

By this method multiple TCP flows are aggregated, and thus the transmission and reception timings of multiple TCP packets can be controlled.

2.2 Burst Transmission

To lengthen the idle time in which a wireless client sleeps, SCTP tunneling employs burst transmission of SCTP packets by means of a delayed ACK mechanism applicable to SCTP. Figure 2 shows packet sequences of a wireless client during SCTP tunneling with and without burst transmission. If m SCTP packets are sent by burst transmission, these packets are transmitted and received consecutively by setting the delayed ACK parameter to m. In this case, once an SCTP has received m SCTP packets, in which the last packet contains an SCTP-SACK chunk, new m packets can be sent simultaneously. Upon receiving the SCTP packets including the SCTP-SACK chunk, another SCTP can consecutively send m new SCTP packets. By this mechanism, burst transmission can be realized. Note that an SCTP-SACK chunk piggybacks with an SCTP-DATA chunk in the mth SCTP packet. When the delayed ACK timer has expired, an SCTP packet containing an SCTP-SACK chunk is transmitted immediately. In the proposed method, we assume that the wireless client informs an AP of the value of m when establishing an SCTP association.

To send SCTP packets in bursts, SCTP tunneling buffers SCTP packets at the tunnel inlet until m TCP packets arrive, which results in an additional delay for each TCP

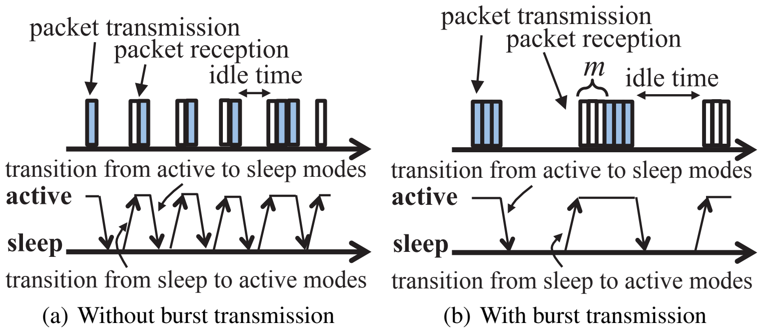

Fig. 2. Packet sequences of wireless client during SCTP tunneling

packet. Here, by using the average number of SCTP packets sent per unit time, R_{sctp}, the average buffering delay at the tunnel inlet is calculated as

$$D = \frac{m-1}{2} \frac{1}{R_{sctp}}. \tag{1}$$

SCTP tunneling thus enables a wireless client to save energy by sleeping during the idle time lengthened by burst transmission. In this paper, *ideal sleeping* is assumed when assessing the energy efficiency gained by SCTP tunneling. Ideal sleep implies that a WNI knows both the transmission and reception schedules of SCTP packets such that it can sleep and wake up with exact timing.

3 Energy Consumption Model

In this section, we construct an energy consumption model for SCTP tunneling. This model consists of two parts: a MAC-level submodel (Subsection 3.2) and an SCTP-level submodel (Subection 3.3). The assumptions for deriving these models are first described in Subection 3.1, after which the submodels are outlined.

3.1 Assumptions

The environment here is a WLAN in which a single SCTP association is established between a wireless client and an AP. Multiple TCP upstream and downstream flows are generated in the wireless client by applications. We assume that the average throughputs of TCP flows are given.

Suppose that at the hardware level the WNI has four communication modes — *transmit*, *receive*, *idle* or *listen*, and *sleep* [11]. Each of these modes has a different power consumption denoted by P^t, P^r, P^l, and P^s, respectively. Furthermore, the WNI consumes power when transiting between active and sleep modes, and we define P^{as} and P^{sa} as the power consumption when changing from and to active mode, respectively. The durations of these power consumptions are then denoted T^{as} and T^{sa}, respectively.

Other assumptions are as follows.

- The probability of transmission failures at MAC-level is given.
- RTS/CTS mechanisms are used by the wireless client when transmitting a frame to an AP, whereas and AP does not utilize RTS/CTS when transmitting a frame to the wireless client.
- Although values of the delayed ACK timer may affect performance, this effect is not considered here. Note that when the delayed ACK timer expires, SCTP-SACK packets are delayed up to the value of the timer, which result in longer RTT of the corresponding SCTP packets.

3.2 Modeling Energy Consumption of Frame Exchanges in IEEE 802.11 MAC

Due to space limitations, we omit the calculation process of expected times for a wireless client to send and receive one data frame, defined as $E[T^t]$ and $E[T^r]$, respectively, and the corresponding energy consumptions, denoted by $E[J^t]$ and $E[J^r]$, respectively. As a result, $E[T^t]$ and $E[T^r]$ are derived as follows:

$$E[T^t] = \sum_{i=1}^{N+1} \sum_{j=1}^{i} T^t(j)Q(i),\ E[T^r] = \sum_{i=1}^{N+1} \sum_{j=1}^{i} T^r(j)Q(i) \tag{2}$$

where N is a maximum number of data frame retransmissions, $T^t(i)$ and $T^r(i)$ are the average time by the wireless client to send and receive one data frame for the ith transmission, respectively, and $Q(i)$ is the probability that a data frame is transmitted i times. $T^t(i)$ and $T^r(i)$ are calculated as

$$T^t(i) = 3T_{SIFS} + T_{DIFS} + T^{BO}(i) + 4\tau + T_{RTS} + T_{DATA}^{client} + T_{CTS} + T_{ACK}, \tag{3}$$

$$T^r(i) = T_{SIFS} + T_{DIFS} + T^{BO}(i) + 2\tau + T_{DATA}^{AP} + T_{ACK} \tag{4}$$

where T_{SIFS} is the short interframe space (SIFS), T_{DIFS} is the distributed interframe space (DIFS), T_{RTS} is the transmission duration of the RTS frame, T_{CTS} is a transmission duration of the CTS frame, T_{DATA}^{client} and T_{DATA}^{AP} are transmission and reception duration of a data frame, respectively, T_{ACK} is reception duration of an ACK frame, $T^{BO}(i)$ is the average backoff time of the ith transmission after $(i-1)$ consecutive transmission failures, and τ is the radio propagation delay. $Q(i)$ is given by

$$Q(i) = \begin{cases} q^{i-1}(1-q) & \text{if } i \le N \\ q^N & \text{if } i = N+1. \end{cases} \tag{5}$$

where q denotes the probability of transmission failure at MAC level.

Similarly, $E[J^t]$ and $E[J^r]$ are calculated as follows:

$$E[J^t] = \sum_{i=1}^{N+1} \sum_{j=1}^{i} J^t(j)Q(i),\ E[J^r] = \sum_{i=1}^{N+1} \sum_{j=1}^{i} J^r(j)Q(i) \tag{6}$$

where $J^t(i)$ and $J^r(i)$ are the energy consumptions for the ith data frame transmission and reception after $(i-1)$ failures, respectively. $J^t(i)$ and $J^r(i)$ are derived as

$$J^t(i) = P^l(3T_{SIFS} + T_{DIFS} + T^{BO}(i) + 4\tau) + P^t(T_{RTS} + T_{DATA}^{client}) + P^r(T_{CTS} + T_{ACK}), \tag{7}$$

$$J^r(i) = P^l(T_{SIFS} + T_{DIFS} + T^{BO}(i) + 2\tau) + P^t T_{ACK} + P^r T_{DATA}^{AP}. \tag{8}$$

3.3 Modeling Energy Consumption of SCTP Tunneling

The congestion control mechanisms for an SCTP association are the same as those in TCP. Therefore, we can regard the behavior of SCTP congestion control mechanisms as being that for a single TCP flow. As a result, the energy consumption model for SCTP tunneling is formulated based on that for a single TCP flow in [9, 10]. Specifically, we determine the energy consumption per unit time (i.e., the power consumption) for a WNI of the wireless client.

The behavior of congestion control mechanisms can be divided to two phases: the initial slow start phase and the congestion avoidance phase. As a simplification, the effects of slow start phase are not considered here because their contribution is considered sufficiently small [9, 10]. The congestion avoidance phase can further be divided into two periods: a triple duplicate (TD) period, which is the duration between two packet loss events detected by triple duplicate TCP-ACK packets; and a timeout (TO) period, which is the duration of a retransmission timeout (RTO) sequence. According to our previous studies [9, 10], the power consumption for a WNI of the wireless client is given by

$$P = \frac{J^{TD} + Q(E[W])J^{TO}}{E[A] + Q(E[W])E[Z^{TO}]} \tag{9}$$

where J^{TD} is the expected energy consumption of a TD period, J^{TO} is the expected energy consumption of a TO period, $Q(w)$ is the probability that a packet loss is detected by an RTO as a function of window size w, and $E[W]$ is the expected window size when the first packet loss occurs. J^{TD} and J^{TO} are as functions of Eqs. (2) and (6). Finally, $E[A]$ and $E[Z^{TO}]$ are the expected duration of TD and TO periods, respectively. Equations for J^{TD}, J^{TO}, $Q(w)$, $E[W]$, $E[A]$, and $E[Z^{TO}]$ were derived in [9, 10].

However, in [9, 10] $E[A]$ is calculated under the assumption that congestion control behavior is dependent on the average round trip time (RTT) of a TCP connection, whereas in SCTP tunneling this behavior is determined by the arrival rate of TCP packets. Due to space limitations, we omit the calculation process of $E[A]$. Using the the average number of SCTP packets sent per unit time through a single direction of SCTP tunneling, R_{sctp} (packet/s), $E[A]$ is calculated as

$$E[A] = \left(\frac{1-p}{p} + \frac{3}{2}E[W]\right)\frac{1}{R_{sctp}} \tag{10}$$

where p is the probability of packet drop events at the SCTP level, which is given by $p = q^{N+1}$. R_{sctp} is calculated as $R_{sctp} = \min\left(R, R_{sctp}^{max}\right)$ where R is the arrival rate of TCP packets (packet/s) and R_{sctp}^{max} is the maximum throughput (packet/s) achieved by the SCTP tunneling, which is given by $R_{sctp}^{max} = 1/(E[T^t] + E[T^r])$.

Table 1. WLAN parameters

Name	Value	Name	Value
Data rate	54 Mbps	PLCP preamble	16 μs
Slot time	9 μs	MAC header	24 B
SIFS	16 μs	LLC header	8 B
DIFS	34 μs	CW_{min}	15
		CW_{max}	1023

Table 2. Power consumption of Atheros AR5004 [12] and parameters of state transitions [2, 13]

P^t	P^r	P^l	P^s	P^{as}	P^{sa}	T^{as}	T^{sa}
1.4 W	0.9 W	0.8 W	0.016 W	0.8 W	1.4 W	1 μs	1 ms

4 Numerical Results and Discussion

4.1 Parameter Settings

We consider an IEEE 802.11a WLAN in which multiple upstream and downstream TCP flows are established between a wireless client and wired hosts (Fig. 1). The WLAN parameters of IEEE 802.11a are summarized in Table 1. To calculate τ, we assume that the wireless client is located 4 m from the AP. From a data sheet for a WNI implemented by using the Atheros AR5004 chip [12] and measurement studies [2,13], we set parameters of power consumption to the values listed in Table 2. The TCP-DATA and TCP-ACK packet sizes are set to 1500 B and 40 B, respectively. The maximum number of frame retransmissions is set to $N = 7$.

4.2 Numerical Results

Figure 3 shows the power consumption results in the case that only upstream TCP flows exist when $q = 0.1$, 0.2, and 0.5. Here, we evaluate the performance of CAM and sleeping with burst transmission for $m = 1$, 2, and 5. Note that $m = 1$ signifies sleeping without burst transmission, while $m > 1$ is sleeping with burst transmission. In this figure, the x-axis represents the aggregate throughput of upstream TCP flows, where the average throughput of each TCP flow is 150 KB/s. The results when upstream and downstream TCP flows coexist show a similar trend to Fig. 3. Moreover, changes in q have little effect on the power consumption.

From Fig. 3, we observe that the power consumption when utilizing CAM is increased by an increase in the aggregate throughput of upstream TCP flows. As the aggregate throughput grows, the duration of packet transmission and reception increases and the idle time decreases. When sleeping is employed, the power consumption is considerably reduced regardless of the value of m. The power consumption is increased for large aggregate throughput, whereas the increase rate of power consumption is low at high m values. For instance, when the aggregate throughput of upstream TCP flows

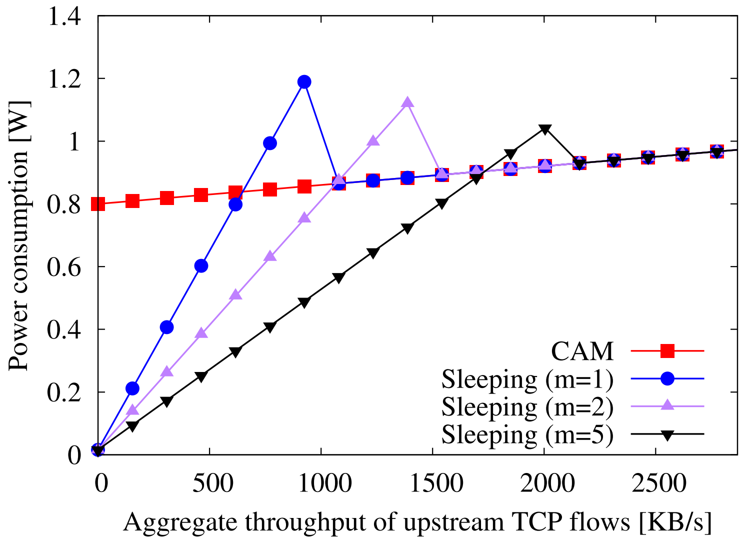

Fig. 3. Power consumption as a function of aggregate throughput of upstream TCP flows when $q = 0.1$ ($p = 1.00 \times 10^{-8}$)

is about 500 KB/s in Fig 3, sleeping without burst transmission reduces power consumption by 27% compared with CAM. In contrast, the reduction is around 69% for sleeping with $m = 5$ because the smaller number of state transitions resulting from burst transmission has a large impact on energy reduction.

If aggregate throughput is further increased, the power consumption when using sleeping eventually surpasses the consumption for CAM, and approaches that without sleeping. The power consumption required for state transitions exceeds the reduction realized by sleeping since the idle time is short. Note that such a situation can be avoided by staying in active mode when the idle time is insufficient.

Fig. 4 shows the power consumption ratio, obtained by dividing the power consumption when using sleeping by that when using CAM, for various m values and $q = 0.1$. Energy efficiency is high when the ratio is small. The corresponding average buffering delay which is calculated by Eq. (1) is presented in Fig. 5.

As m increases, the power consumption ratio converges to a constant value, whereas the average buffering delay increases linearly. In contrast, as the aggregate throughput of TCP flows increases, the reduction rate of power consumption is high, whereas the increase rate of the delay is low. The trade-off between energy efficiency and buffering delay is also observed from Figs. 4 and 5. With increased aggregate throughput, the energy reduction gained by sleeping becomes large compared with the increase of average buffering delay from sleeping. For example, if 5 ms of additional buffering delay is considered acceptable by a user or application, we can set $m = 2$ and obtain a 35% reduction in power consumption compared with $m = 1$ when the aggregate TCP throughput is 200 KB/s. When the aggregate TCP throughput is 1 MB/s, we obtain a 64% reduction compared with $m = 1$ in power consumption by setting $m = 8$.

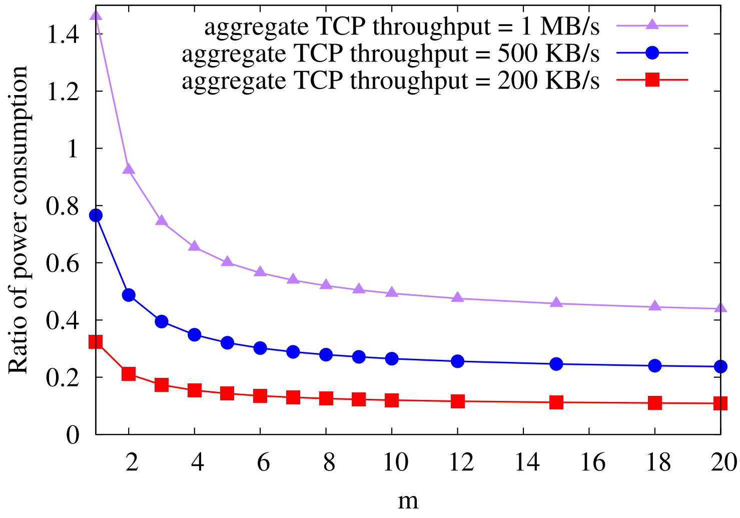

Fig. 4. Power consumption ratio for various m values and $q = 0.1$

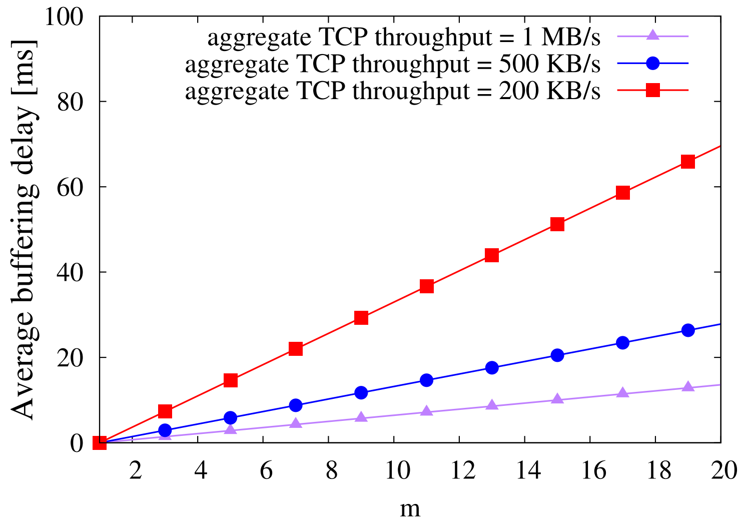

Fig. 5. Average buffering delay for various m values and $q = 0.1$

5 Conclusion

We have proposed an energy-efficient method for TCP data transfer over a WLAN, termed SCTP tunneling. We also formulated an energy consumption model of SCTP tunneling to assess its energy efficiency. Numerical results of the model show that the power consumption of SCTP tunneling is predominantly determined by the aggregate throughput of TCP flows, while burst transmission can considerably reduce power consumption with increasing moderate delay.

In the future, we plan to implement the SCTP tunneling on commercial WLAN APs and wireless clients with power saving mode such as PSM and APSD.

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