Ensuring the Quality-of-Service of Tactile Internet

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Abstract—Tactile internet requires ultra-low latency and ultra-high reliability, which bring new challenges to the design of mobile systems. In this paper, we study how much resources are required to ensure the short end-to-end (E2E) delay and high reliability by taking a vehicle communication system as an example, where the E2E delay includes both queueing delay and transmission delay, and the reliability is captured by the packet loss caused by queueing delay violation, packet error induced by finite blocklength channel codes, and packets dropping due to deep channel fading. To this end, we optimize the bandwidth allocation among multiple users to minimize the average transmit power required to ensure the queueing delay and its violation probability of each packet, and analyze the maximal transmit power required to guarantee the E2E delay and the reliability. Simulation and numerical results validate our analysis and show the required maximal transmit power, bandwidth, and number of antennas to ensure the extremely stringent quality of service.

I. INTRODUCTION

Guaranteeing the quality of service (QoS) in terms of ultra-low latency and ultra-high reliability is another frontier to be considered in the fifth generation (5G) cellular networks, in addition to the high throughput, low cost and massive connections [1,2]. With the 1 ms end-to-end (E2E) delay [3] and 0.001%~0.00001% packet loss probability [1,2], a new breakthrough enabling unprecedented mobile applications, tactile internet, becomes viable [1].

Recent research efforts focus on the air interface technologies to satisfy the extremely stringent QoS requirements. To ensure the ultra-low latency, a short frame structure was proposed for orthogonal frequency division multiple (OFDM) system in [4]. With non-orthogonal waveform, the length of each frame can be further shortened [3]. To reduce the transmission delay, the resource allocation needs to be updated more rapidly, say, by using much shorter transmit time interval (TTI) [3,4]. To ensure the ultra-high reliability in conveying the short frame or packet under fading channels, except exploiting multiple links [5], channel coding appropriate for short code block is also important. Fortunately, the results in [6] indicate that it is possible to guarantee very low error probability with short blocklength channel codes, at the expense of data rate reduction. In fact, by using Polar codes [7], the delays caused by transmission, signal processing and coding can be reduced. However, in this context the queueing delay is overlooked in the existing literature. This does not mean that the queueing delay is negligible. The results in [8] show that when the average queueing delay approaches to the channel coherence time, the average transmit power may become infinite. This implies that the queueing delay may become the bottleneck for ensuring the E2E delay for tactile internet.

A typical scenario for ultra-low latency and ultra-high reliability communications is road safety applications [1]. In state-of-the-art communication systems, the achievable delays over vehicle-to-vehicle links and vehicle-to-infrastructure links are more than 10 ms [9–11], which miss the target of the tactile internet at least one order of magnitude.

In this paper, we take vehicle collision avoidance as an example application to show how to guarantee the QoS requirements of the tactile internet. We consider a system that multiple users (i.e., vehicles) are served by a roadside base station (BS). For the E2E delay, we consider both queueing delay and uplink (UL)/downlink (DL) transmission delay. For the reliability, we consider the packet loss and packet error caused by finite blocklength channel coding, queueing delay violation and packet dropping. We consider the typical scenario where the queueing delay is shorter than the channel coherence time, and analyze the transmit power required to guarantee the E2E delay and the packet dropping probability. To reveal how much resources are necessary to ensure the QoS, we optimize bandwidth allocation among multiple users based on the average channel gains. Simulation and numerical results validate our analysis, and illustrate the maximal transmit power, bandwidth, and the number of transmit antennas required to guarantee the ultra-low latency and ultra-high reliability.

II. SYSTEM MODEL

Consider a vehicle communication system, which is a typical application of ultra-low latency and ultra-high reliability. A roadside BS with $N_t$ antennas serves $K$ single antenna users located in its cell. Each user (i.e., vehicle) transmits its safety messages (e.g. speed and location [10]) with short packets to the BS, and is interested in the safety messages from its nearby users. After receiving the packets, the BS sorts the messages from nearby users for each user and then transmits these messages to the target user. Since the interference among users causes severe deterioration in QoS, we consider frequency division multiple access, where the bandwidth is allocated to each user based on the average channel gains of the users. Denote the bandwidth allocated to the $k$th user as $W_k$.

A. Channel and Signal Models

Consider time division duplexing (TDD), where each frame consists of a DL and an UL transmission phase. The duration of each frame and the duration for DL transmission phase are
denoted as $T_f$ and $T_D$, respectively. To reduce transmission delay for low latency service, a short frame structure was proposed in [4] for TDD OFDM system, and the TTI equals to the frame duration, where $T_f = 0.16$ ms [4].

We consider block fading channel, which remains constant within each block and changes independently among the blocks. The duration of each block is denoted as $T_c$, which is assumed to be dividable by $T_f$, i.e., $T_c = N_cT_f$. When the number of users is large, the bandwidth allocated to each user is less than the coherent bandwidth of the channel, hence we assume flat fading channel. For the $k$th user, denote the average channel gain as $\alpha_k$, and the spatial channel vector in the $n$th frame as $h_k(n) \in \mathbb{C}^{N_t \times 1}$, whose elements are independent and identically Gaussian distributed with zero mean and unit variance. With perfect knowledge of $\alpha_k$ and $h_k(n)$ at both the BS and the user, the maximal number of packets that can be transmitted (also called service rate in the sequel) to the $k$th user in the $n$th frame can be expressed as

$$s_k(n) = \frac{\Phi T_D W_k}{u} \log_2 \left( 1 + \frac{\alpha_k P_k^c(n) g_k(n)}{N_0 W_k} \right) \text{(packets/frame)}, \quad (1)$$

where $u$ is the size of each packet, $P_k^c(n)$ is the transmit power allocated to the $k$th user in the $n$th frame, $N_0$ is the single-sided noise spectral density, $g_k(n) = |h_k(n)|^2 \Phi h_k(n)$. $^H$ denotes the conjugate transpose, and $\Phi \in \{0, 1\}$ is the gap between channel capacity and data rate achieved by finite blocklength codes under given error probability $\varepsilon_c$ [6]. For example, in additive white Gaussian noise channel, when $\varepsilon_c = 10^{-6}$, the blocklength is 200, and the signal-to-noise ratio is 20 dB, $\Phi \approx 0.9$ [6].

### B. Queuing Model

Consider a discrete-time queueing model. In the $n$th frame, the number of packets sent from the $k$th user is denoted as $a_k(n)$. The $k$th user requests the packets sent from its nearby users, whose indices are included in a set $A_k$, and the cardinality of this user index set is $|A_k|$. As illustrated in Fig. 1, $A_k = \{k - l, ..., k - 1, k + 1, ..., k + m\}$. After decoded the packets from the $K$ users, the BS first sorts the interesting packets for every user and then buffers each packet in the queue of its target users. Then, the number of packets waited in the queue for the $k$th user at the beginning of the $n + 1$th frame can be expressed as

$$Q_k(n + 1) = \max\{Q_k(n) - s_k(n), 0\} + \sum_{i \in A_k} a_i(n). \quad (2)$$

### C. QoS Requirement

The QoS requirement is characterized by an end-to-end (E2E) delay bound of each packet, $D_{\text{max}}$, and a packet loss and error probability, $\varepsilon_D$. The E2E delay is very short (say 1 ms [1]), which includes the transmission delays in both UL and DL transmission phases and the queueing delay in the buffer of the BS. Since the packet size of the tactile service is small (e.g., $u \leq 100$ bytes), UL and DL transmission of each packet can be finished within a frame [4]. In other words, the transmission delay of each packet is less than the frame duration. Then, the maximal queueing delay is $D_k^q = D_{\text{max}} - T_f$. Denote the queueing delay violation probability of the $k$th user as $\varepsilon_k^q$. Then, the requirement imposed on the queueing delay is $(D_k^q, \varepsilon_k^q)$, where $\varepsilon_k^q < \varepsilon_D$.

### III. Resources Required to Ensure the QoS

In this paper, we consider channel-dependent resource allocation. The policy depending on both channel information and queue status will be investigated in future work. In this section, we first study the transmit power required to ensure the QoS of the $k$th user over Rayleigh fading channels, from which we can provide useful insight into the required resource to guarantee the QoS. Then, we derive the packet dropping probability, and study the maximal transmit power that is required to control the probability into an acceptable level. Finally, we optimize the bandwidth allocation among multiple users based on their average channel gains.

#### A. Required Transmit Power for the $k$th User

For a 1 ms of E2E delay [1] and 0.16 ms of frame duration (i.e., a TTI as proposed in [4]), $D_{\text{max}} >> T_f$. Then, effective bandwidth can be used to optimize resource allocation [12]. For stationary packets arrival process $\{\sum_{i \in A_k} a_i(n), n = 1, 2, ...,\}$, the effective bandwidth can be expressed as [12]

$$E_k^B(\theta_k) = \lim_{N \to \infty} \frac{1}{N \theta_k} \ln \left\{ E \left[ \exp \left( \theta_k \sum_{n=1}^{N} \sum_{i \in A_k} a_i(n) \right) \right] \right\} \text{ (packets/frame)}, \quad (3)$$

where $\theta_k$ is the QoS exponent. When the $k$th user is served by a constant rate equal to $E_k^B(\theta_k)$, the steady state queueing delay violation probability of the packets can be approximated as [13]

$$\Pr\{D^q_k(\infty) > D_k^q(\max)\} \approx \eta_k \exp\{-\theta_k E_k^B(\theta_k) D_k^q(\max)\}, \quad (4)$$

where $\eta_k$ is the buffer non-empty probability. Since $\eta_k \leq 1$,

$$\Pr\{D^q_k(\infty) > D_k^q(\max)\} \leq \exp\{-\theta_k E_k^B(\theta_k) D_k^q(\max)\}. \quad (5)$$

If the right hand side of (5) satisfies

$$\exp\{-\theta_k E_k^B(\theta_k) D_k^q(\max)\} = \varepsilon_k^q, \quad (6)$$

![Fig. 1. Queueing model at the BS.](image-url)
then \((D^u_{\text{max}}, \varepsilon^u_k)\) can be satisfied. From (6), we can obtain \(\theta_k\) for a given arrival process with known \(E^u_k(\theta_k)\), which is used for resource allocation to ensure \((D^u_{\text{max}}, \varepsilon^u_k)\). Later, we will validate with simulation that the QoS can be guaranteed by using the approximated upper bound in (5).

There are two kinds of safety messages generated by each user, the periodic messages and the event-driven messages [10]. The aggregation of the packet arrival processes from |\(A_k\) users for the \(k\)th user (i.e., \(\sum_{i\in A_k} a_i(n)\) in (2)) can be modelled as a Poisson process with average packet arrival rate \(\lambda_k\) [10]. For Poisson arrival process with average packet arrival rate \(\lambda_k\), the effective bandwidth can be obtained as

\[
E^u_k(\theta_k) = \frac{\lambda_k}{\theta_k} \left( e^{\theta_k} - 1 \right) \text{ (packets/frame)},
\]

(7)

For the users with typical velocities of \(30 \sim 120\) km/h, the channel coherence time under carrier frequency of \(2\) GHz is around \(1.1 \sim 4.5\) ms, which is larger than \(D^u_{\text{max}}\) (i.e., \(T_c > D^u_{\text{max}}\)). Since the channel gain remains constant within \(N_t\) consecutive TTIs, \(s_k(n)\) is constant within each block of channel fading. In order to guarantee \((D^u_{\text{max}}, \varepsilon^u_k)\), the minimal constant service rate of the \(k\)th user should satisfy [12]

\[
s_k(n) = E^u_k(\theta_k).
\]

(8)

**Remark:** For the considered scenario of tactical internet, it is possible that \(T_c < D^u_{\text{max}}\) (e.g., the users move even faster or the carrier frequency is higher). To ensure \((D^u_{\text{max}}, \varepsilon^u_k)\) in this case, effective capacity [13] should be equal to the effective bandwidth, which requires less resource than satisfy (8).

Substituting (1) into (8), the transmit power required to ensure \((D^u_{\text{max}}, \varepsilon^u_k)\) can be obtained as

\[
P^u_k(n) = \frac{N_0 W_k}{\alpha_k g_k(n)} \left[ \frac{a^{u_k}}{2 \frac{\sqrt{D^u_{\text{max}}}}{\text{Ray}}(x)} - 1 \right].
\]

(9)

The required average transmit power can be derived as

\[
E[P^u_k(n)] = \frac{N_0 W_k}{\alpha_k} \left[ \frac{a^{u_k}}{2 \frac{\sqrt{D^u_{\text{max}}}}{\text{Ray}}(x)} - 1 \right] \int_{0}^{\infty} x f(x) dx,
\]

(10)

where \(f(x)\) is the probability density function (pdf) of \(g_k(n)\). When \(N_t = 1\), \(f(x) = e^{-x}\) for Rayleigh fading. Since \(\int_{0}^{\infty} \frac{x}{x} e^{-x} dx \to \infty\), the average transmit power is infinite. When \(N_t > 1\), \(g_k(n)\) follows the Wishart distribution [14], whose pdf is

\[
f(x) = \frac{1}{(N_t - 1)!} x^{N_t - 1} e^{-x}.
\]

(11)

Substituting (11) into (10), the required average transmit power can be derived as

\[
E[P^u_k(n)] = \frac{N_0 W_k}{\alpha_k (N_t - 1)} \left[ \frac{a^{u_k}}{2 \frac{\sqrt{D^u_{\text{max}}}}{\text{Ray}}(x)} - 1 \right].
\]

(12)

This implies that \((D^u_{\text{max}}, \varepsilon^u_k)\) can be guaranteed with finite average transmit power by multiple transmit antennas.

However, the pdf in (11) indicates that the channel could be in deep fading though with a low probability. This indicates that if there is a maximal transmit power constraint \(P^\text{max}\) for the \(k\)th user, the required transmit power in (9) may exceed \(P^\text{max}\) when the channel is in deep fading, where the packets cannot be transmitted without error at rate \(s_k(n) = E^u_k(\theta_k)\). If the packets depart the queue at rate \(E^u_k(\theta_k)\), then \((D^u_{\text{max}}, \varepsilon^u_k)\) can be guaranteed. Since the error-free data rate \(s_k(n)\) may be less than \(E^u_k(\theta_k)\), some packets have to be dropped. In order to ensure the high reliability, we need to control the packet dropping probability.

Similar to the *time averaged delivery ratio* in [15], we define average packet dropping probability as the ratio of the average number of lost packets to the average number of arrived packets, which is

\[
e^p_k = \frac{E(N_{\text{loss}})}{E \left[ \sum_{i\in A_k} a_i(n) \right]},
\]

(13)

where \(N_{\text{loss}}\) is the number of packets that are dropped during a channel fading block.

To satisfy the E2E delay with probability \(1 - \epsilon_D\), \(e^p_k\) should satisfy \(e^p_k + e^q_k \leq \epsilon_D\). Here, \(1 - e^p_k - e^q_k - e^c\) is the probability that the packets can be transmitted without error to the \(k\)th user with E2E delay less than \(D^u_{\text{max}}\) and \(e^c\) is the average packet error probability of certain codes.\(^1\)

In what follows, we find \(P^\text{max}\) that is required to guarantee \(e^p_k \leq \epsilon_D - e^c - e^q_k\).

Define \(g_{\text{min}} \triangleq \frac{C}{e^q_k}\), where \(C = \frac{N_0 W_k}{\alpha_k} \left[ \frac{a^{u_k}}{2 \frac{\sqrt{D^u_{\text{max}}}}{\text{Ray}}(x)} - 1 \right]\).

When \(g_k(n) < g_{\text{min}}\), \(P^u_k(n)\) in (9) exceeds \(P^\text{max}\), and the BS serves the user with \(P^\text{max}\). The service rate with \(P^u_k(n) = P^\text{max}\) is \(s^\text{max}_k[g_k(n)] \triangleq \frac{\sqrt{D^u_{\text{max}}}}{a_k} \log_2 \left[ 1 + \frac{a_k P^\text{max}_k[g_k(n)]}{N_0 W_k} \right]\). Then, \(N_{\text{loss}} = \left( N_c \left( E^u_k(\theta_k) - s^\text{max}_k[g_k(n)] \right) \right)^x\), where \((x)^x\) is the minimal integer that is larger than \(x\). Since \(E(N_{\text{loss}}) = \int_{0}^{g_{\text{min}}} N_{\text{loss}} f(x) dx\), we have

\[
e^p_k = \frac{1}{N_c \alpha_k} \int_{0}^{g_{\text{min}}} \left( N_c \left[ E^u_k(\theta_k) - s^\text{max}_k(x) \right] \right)^x f(x) dx.
\]

(14)

Because \(g_{\text{min}}\) and \(E^u_k(\theta_k) - s^\text{max}_k(x)\), \(\forall x \in (0, \infty)\) decrease with \(P^\text{max}\), and \(e^p_k\) in (14) also reduces with \(P^\text{max}\), the maximal transmit power for the \(k\)th user that are required to satisfy \(e^p_k \leq \epsilon_D - e^c - e^q_k\) can be obtained numerically.

**B. Bandwidth Allocation among Different Users**

To find the required resources to ensure the QoS of multiple users, in the sequel we optimize the bandwidth allocation based on the average channel gains. To this end, we find \(W_k\), \(k = 1, ..., K\) to minimize the sum of the average transmit power required for the BS to guarantee \((D^u_{\text{max}}, \varepsilon^u_k)\) (which is given in (12)) for \(k = 1, ..., K\). Since the bandwidth allocation is independent of instantaneous channel, it cannot be used to control \(e^p_k\). The optimal bandwidth allocation can be obtained

\(^1\)We set packet size as the amount of data in one block of the codes in [6].

Then, the packet error probability is equal to the block error probability.
from the following problem,
\[\min_{W_k, k=1,\ldots,K} \sum_{k=1}^{K} \mathbb{E}[P_k(n)]\]
\[\text{s.t.} \sum_{k=1}^{K} W_k \leq W_{\text{max}}.\]  

(15)

From (12) we can derive \(dE[P_k(n)]\) as follows,
\[\frac{N_0}{\alpha_k (N_t - 1)} \left( \frac{\alpha_k}{\alpha_k (N_t - 1)} \ln 2 \right) \leq \frac{u E_k^B (\theta_k) \ln 2}{T_D W_k} \right) - 1,\]

(16)

from which we can further derive that
\[d^2E[P_k(n)] = \frac{N_0}{\alpha_k (N_t - 1)} \left( \frac{\alpha_k}{\alpha_k (N_t - 1)} \ln 2 \right) \leq \frac{u E_k^B (\theta_k) \ln 2}{T_D W_k} > 0.\]

Hence, \(\mathbb{E}[P_k(n)]\) is convex in \(W_k\). Therefore, problem (15) is a convex programming, which can be solved numerically with interior method [16].

IV. SIMULATION AND NUMERICAL RESULTS

In this section, we first validate the analysis via simulation. Then, we show the resources required to guarantee the E2E QoS requirement \((D_{\text{max}}, \varepsilon_D)\) with numerical results.

![Simulation scenario](image)

We consider an eight-lane two-direction highway scenario in urban area. The users (i.e., vehicles) uniformly located in the eight lanes are served by the roadside BSs with distance 400 m. The path loss model is \(10 \log_{10} \alpha_k = 35.3 + 3.6 \log_{10} d_k\), where \(d_k\) is the distance between a BS and the \(k\)th user in meters. Each vehicle requests safe messages from other vehicles with distances less than 100 m. The vehicles in the edge of the cell may request the safe messages from vehicles in adjacent cells. We assume that the BSs are connected with fiber backhaul. Then, the BS in the adjacent cell can forward the received messages to the BS who serves the user requesting the messages. The packet delay caused by fiber backhaul is around \(D_B = 0.1\) ms [17]. When a vehicle requests packets from adjacent cells, \(D_B\) is also counted in the E2E delay, i.e., \(D_{\text{max}}^2 + D_B + T_f \leq D_{\text{max}}\), where \(T_f\) exceeds the transmission delay of one packet. Although different values of \(\varepsilon_k^0, \varepsilon_k^1\) and \(\varepsilon_k\) will result in different resource requirements, we set \(\varepsilon_k^0 = \varepsilon_k^1 = \varepsilon_D = \varepsilon_D/3\) for simplicity, where the requirement on \(\varepsilon_D\) is reflected in \(\Phi\). The parameters to be used in the sequel are listed in Table I, unless otherwise specified.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>List of Simulation Parameters [2, 3, 6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-to-end delay (D_{\text{max}})</td>
<td>1 ms</td>
</tr>
<tr>
<td>Frame duration (T_f)</td>
<td>0.1 ms</td>
</tr>
<tr>
<td>Duration of DL phase (T_D)</td>
<td>0.05 ms</td>
</tr>
<tr>
<td>Width of each lane</td>
<td>4 m</td>
</tr>
<tr>
<td>Length of each vehicle</td>
<td>5 m</td>
</tr>
<tr>
<td>Packet size (m)</td>
<td>20 bytes</td>
</tr>
<tr>
<td>Data rate gap (\Phi)</td>
<td>0.9</td>
</tr>
<tr>
<td>Single-sided noise spectral density (N_0)</td>
<td>-173 dBm/Hz</td>
</tr>
</tbody>
</table>

To validate that the queueing delay \((D_{\text{max}}^k, \varepsilon_k^0)\) can be satisfied with the optimized policy, we show the complementary cumulative distribution function (CCDF) of delay (i.e., \(\Pr\{D_k(\infty) > D_{\text{th}}\}, \forall D_{\text{th}} \in [0, D_{\text{max}}]\}) for the packets to the \(k\)th user, which are obtained by computing the queueing delay of the packets during \(10^6\) frames. The distance between two vehicles in each lane (shown in Fig. 2) is \(d_u = 10\) m, hence the \(k\)th user requests the messages from \(|A_k| = 103\) nearby vehicles. Since the packets depart the queue at rate \(s_k(n) = E_k^B(\theta_k)\), when a packet arrives at the queue with length \(Q_k(n)\), the queueing delay is \(Q_k(n)/E_k^B(\theta_k)\) (frames).

![CCDF of queueing delay](image)

The curves in Fig. 3 are not very smooth, because the approximation in (4) is not very accurate for the short delay bound \(D_{\text{max}}^k\). Nonetheless, the right hand side of (5) is always an upper bound of the queueing delay violation probability, because when \(D_{\text{max}}^k\) is small, \(\eta_k \ll 1\) (around 0.3 in Fig. 3). We can see that the queueing delay requirement \((D_{\text{max}}^k, \varepsilon_k^0)\) is satisfied for different packet arrival rates (e.g., when the packet arrival rate from each UL user is 20 packets/s, \(\lambda_k = 20 |A_k| T_f\) packets/frame).

In the following, we illustrate the resource required by one BS for DL transmission, where we set \(d_u = 15\) m,
and the results are similar for the other BSs. Given maximal bandwidth, the bandwidth allocation among different users is obtained by solving problem (15). With the optimized $W_k$ to ensure $(D_{\text{req}}, \epsilon_k^p)$, $P_{\text{req}}^{\text{max}}$ required to guarantee $\epsilon_k^p$ can be obtained from (14) by using bisection method [16]. Then, the maximal transmit power required at the BS to ensure QoS for all the $K$ users is $P_{\text{req}}^{\text{max}} = \sum_{k=1}^{K} P_{k}^{\text{max}}$.

The relations between the required maximal transmit power and maximal bandwidth with different $N_t$ are provided in Fig. 4. We can see that when $N_t = 4$ and $W_{\text{max}} = 22.5$ MHz, $P_{\text{req}}^{\text{max}} \leq 40$ W (i.e., 46 dBm), which is a typical value of maximal transmit power of a macro BS. In order to improve spectral efficiency or reduce the maximal transmit power with maximal bandwidth of a macro BS. In order to improve E2E delay and reliability requirement of tactile internet.

Simulation and numerical results validated our analysis, and illustrated the maximal transmit power, bandwidth, and the transmit antennas required to guarantee the stringent QoS requirement of tactile internet.

**V. CONCLUSION**

In this paper, we studied how to guarantee the ultra-low E2E delay and ultra-high reliability requirement of tactile internet by taking vehicle collision avoidance system as an example. For the E2E delay, we considered both queuing delay and UL/DL transmission delay. For the reliability, we considered the packet loss and packet error caused by finite blocklength channel coding, queuing delay violation and packet dropping. We optimized bandwidth allocation among multiple users required to ensure the queuing delay and its violation probability of each user, and analyzed the maximal transmit power required to ensure the E2E delay and reliability. Simulation and numerical results validated our analysis, and illustrated the maximal transmit power, bandwidth, and the transmit antennas required to guarantee the stringent QoS requirement of tactile internet.

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