Network-Calculus-Based Analysis of Power Management in Video Sensor Networks

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***Abstract*—This paper considers two important issues for video sensor networks: (1) timely delivery of captured video stream and (2) energy-efficient network design. Based on network calculus, it presents a unified analytical framework that is able to quantitatively weigh the tradeoff between these two factors. In particular, it derives the service curve, buffer and delay bound under single-hop and multi-hop scenarios for video sensor networks under power management. To the best of our knowledge, this is the first work that extends the network calculus theory to the domain of wireless network with the consideration of power management and wireless interference. Our analysis has been validated through experiments conducted on a video sensor network testbed.**

I. INTRODUCTION

The convergence of microelectronics and wireless communication leads to the emergence of wireless networks of sensor devices, which are capable of sensing, data processing and communication. Video sensor networks are equipped with video cameras which are capable of providing video surveillance in many application scenarios, such as remote health care and traffic control. Many challenges arise in the design of video sensor network due to the conflict between its requirement of video quality and the limited resource availability.

In this paper, we consider two critical issues for video sensor network: (1) timely delivery of captured video stream and (2) energy-efficient network design. The first goal, driven by the application needs, *e.g.*, video surveillance, targets to deliver the data acquired at a sensor node to the collection point in a timely fashion, or more strictly, within bounded delay. The second goal, driven by the resource scarcity of wireless nodes running on limited battery power, targets to maximize the network lifetime by carefully orchestrating the energy consumption of each node to the minimum degree.

Existing research on wireless (video) sensor network usually considers one of the two interdependent aspects in its design: the congestion and bandwidth management [1], [2], [3], [4], [5] and the power management [6], [7], [8], [9], [10], [11]. Though a few works consider the tradeoff between two factors [12], [13], [14]. However, there is no theoretical framework in the existing literature that provides an analytical study of the tradeoff between bandwidth and delay requirement and energy consumption, especially under bursty traffic and power management.

For example, in a simple video sensor network where two video sensor nodes A and B can both directly connect to the data sink C. The achievable bandwidth of the shared wireless medium is 1Mbps. Different solutions can be examined to explore the tradeoff between packet delay and power consumption. Enforcing power awareness in scheduling management, A and B alternatively transmit. When A is sleeping, B takes the entire 1Mbps bandwidth, and vice versa. Depending on the time quantum that A and B switch, large time quantum will reduce the switching overhead and save power accordingly at the cost of longer packet delay, while small time quantum will achieve the opposite. In the extreme case, with no power management, each node will always keep up and get itself 500Kbps bandwidth by sharing the wireless channel, hence achieves the minimum packet delay yet maximum energy consumption for unit traffic transmission.

Evidently, the goals of reducing packet delay and achieving energy efficiency are far from orthogonal, and actually contradictory from each other. This goal becomes even more challenging if we consider the bursty and non-uniform traffic in the video sensor networks. As such, we call for a unified framework that is able to quantitatively weigh the tradeoff of these two factors. Moreover, it should answer to the system objective (e.g., the packet delay bound) by setting the design parameter (e.g., maximum time quantum to meet the specified delay bound).

In light of such need, we propose an analytical framework to evaluate the tradeoff among video transmission requirements, buffer, delay under power consumption. Based on the previous results in network calculus [15], we investigate the service curve, buffer and delay bounds for both single-hop and multi-hop wireless network under power management. Such analytical results are important to guide the design of power management schedules that could minimize the energy consumption while providing bounded delay guarantee.

Although considerably deriving from the previous results in min-plus network calculus, our work is justified by the following unique contributions: (1) This work is the first one that considers the effect of power management on the service curve and provides close-form analytical results for buffer and delay bounds;(2) This work extends the network calculus analysis to the domain of wireless network where flows not only contend in the temporal domain but also spatial domain, and provides the basis of interference-aware delay analysis for wireless networks.

The rest of this paper is organized as follows. We present the system model in Sec II, the analysis of delay bound for single-hop wireless network in Sec III and multi-hop network in Sec IV. We evaluate our analysis in an experiment-based study in Sec V, and conclude the paper in Sec VI.

II. MODEL

A. System Model

We consider a wireless sensor network with a set of N video sensors, denoted by $\mathcal{N}$, and a data sink. Fig. 1 illustrates the architecture of one sensor node. As shown in the figure, a video camera is used as the sensor front. Motion of objects in observed area will be captured as video images and compressed into a video stream. The compressed data abstract the difference between every adjacent raw video frames. Therefore more 'severe' object movement will cause larger amount of compressed data flow. The compressed video stream will be sent to a buffer for transmission.

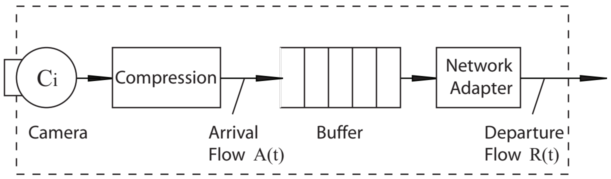

Fig. 1. Video Sensor Model.

In the following discussions, we call such compressed video stream *arrival flow*. In order to save energy, power management is adopted for the network adaptor, which periodically turns the adaptor into sleep. When awake, the network adaptor retrieves video packets from the buffer and transmit them in a FIFO fashion. The data stream transmitted from the network adaptor is called *departure flow*.

The video stream will be delivered from the video sensors to a data sink. In this paper, we consider both single-hop networks and multi-hop networks. For simplicity, we consider the achievable network capacity as C.

B. Traffic Model

The motion of objects in the surveillance area are random and bursty. which produces fluctuated traffic from arrival flows. To characterize such fluctuation, we model the arrival flow at node $i, i \in \mathcal{N}$ using its cumulative traffic $A_i(t)$, defined as the number of bits coming from the flow in time interval $[0, t]$ ($A_i(0) = 0$). To focus our discussion on the impact of power management on delay, we adopt a fluid model for the arrival flows. Thus $A_i(t)$ is a continuous increasing function defined on continuous time domain. Further, we assume that the arrival flow traffic A_i is constrained by a wide-sense increasing function α_i, *i.e.*,

$$A_i(t) - A_i(s) \leq \alpha_i(t - s); \forall s \leq t, t \geq 0 \quad (1)$$

$\alpha_i(t)$ is called the *arrival curve* of $A_i(t)$. In this paper, we assume affine arrival curves for all video sensors, which is defined by $\alpha_i(t) = a_i \cdot t + b_i$. Having a affine arrival curve $\alpha_i(t)$ allows a source to send b_i bits at once, but not more than a_i *bps* over the long run, which means with a maximum flow rate of a_i. Fig. 2 illustrates the relationship between the cumulative function $A_i(t)$ and the arrival curve $\alpha_i(t)$. Intuitively, for a randomly selected time period, the cumulative arrival function $A_i(t)$ always stays below the linear function defined by $\alpha_i(t) = a_i \cdot t + b_i$ within that time period.

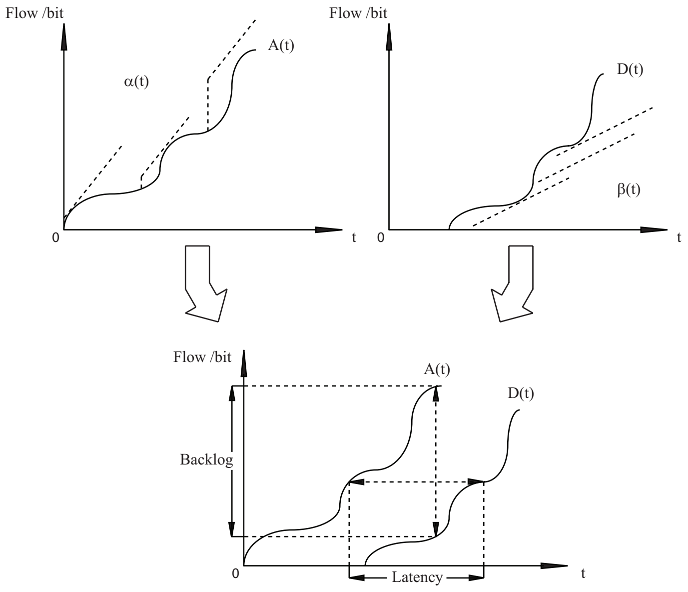

Fig. 2. Traffic Model.

Similarly, the departure flow from node i could also be characterized by a cumulative function $D_i(t)$, which is defined as the traffic volume departed from node i during time $[0, t]^1$. We further define *service curve* $\beta_i(t)$ of sensor node i as a wide-sense increasing function, with $\beta_i(0) = 0$ and

$$D_i(t) \geq \inf_{s \leq t}(A_i(s) + \beta_i(t - s)) \quad (2)$$

When $\beta_i(t)$ is a continuous function, the use of infimum could be avoided. For continuous function $A_i(t)$ the above definition could be simplified as follows.

$$D_i(t) - A_i(s) \geq \beta_i(t - s) \quad (3)$$

The relation between arrival flow $A_i(t)$, departure flow $D_i(t)$, arrival curve $\alpha_i(t)$, and departure curve $\beta_i(t)$ are illustrated in Fig. 2. For arrival flow $A_i(t)$, arrival curve $\alpha_i(t)$ serves as a piecewise upper bound for arrival flow rate; For departure flow $D_i(t)$, departure curve $\beta_i(t)$ serves as piecewise lower bound for service rate. Therefore, the vertical deviation between arrival flow $A_i(t)$ and departure flow $D_i(t)$ is the amount of backlogged flow data waiting to be transmitted, which should not exceed the buffer length of that sensor node. The horizontal deviation between arrival flow $A_i(t)$ and

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[1] Note that in network calculus [15], the arrival flow is typically denoted by $R(t)$ and the departure flow is denoted by $R^*(t)$.

departure flow $D_i(t)$ is the latency that would be experienced by a bit of video flow, if all the data arrived before it is served before it. Intuitively, the buffer length, and delay are bounded by their corresponding deviation between arrival curve $\alpha_i(t)$ and departure curve $\beta_i(t)$.

C. Power Management and Energy Model

We assume that in this sensor network, the power management scheme coordinates the sleeping cycle of each sensor node in a synchronized time division manner. The energy consumption will be contributed by three factors: data transmission, node sleeping, and slot switching. Denote the energy consumption rate of the three stages as E_{tx}, E_{sleep}, and E_{switch}, we have the unit energy consumption E_{unit} under single-hop wireless network scenario,

$$E_{unit} = (\frac{T_i}{T})E_{tx} + (\frac{T - T_i}{T})E_{sleep} + (\frac{1}{T})E_{switch} \tag{4}$$

Node i has a share of time T_i, and a whole round takes time T. For node i, during its transmission time slot, energy will be consumed with rate E_{tx}, and with rate E_{sleep} for the rest of the period T. Between the state change of transmission and sleep, energy consumption rate will be E_{switch}. The switching happens once every period for each node.

III. ANALYSIS FOR SINGLE-HOP WIRELESS NETWORK

We start with the simplest case of video sensor network – single-hop wireless network. In this case all sensor nodes could communicate with the data sink directly. The power management scheme coordinates the sleeping cycle of each sensor node in a synchronized time division manner with period T so that there is only one sensor node waking up at any time. We further assume that node i will wakes up for a time interval T_i and transmit. We will show later that, in order to control the packet delay, T_i should be chosen based on traffic arrival at sensor node i.

Now we proceed to analyze the delay experienced by the data flow from node i. First we study the service curve $\beta_i(t)$ of node i under the above power management scheme. Recall that C is the achievable capacity of the wireless network. Since only one node wakes up and transmit at a time, node i is able to transmit at rate C during its wake-up period, which leads to an average transmission rate of $\frac{C \cdot T_i}{T}$. Also node i will wait at most $T - T_i$ for its next turn. Thus we have the following results for service curve at node i. All the proofs in this paper are provided in our technical report [16] due to the space constraint.

Lemma 3.1 (Service Curve in Single-Hop Network): The service curve β_i for node i under synchronized time division power management with wake-up time T_i out of period T is given by the following rate-latency function with rate $\frac{C \cdot T_i}{T}$ and latency $T - T_i$.

$$\beta_i(\tau) = \frac{C \cdot T_i}{T}[\tau - (T - T_i)]^+ \tag{5}$$

At time t, the amount of data await in the buffer of node i is called *backlog* B_i, which can be considered as the difference between the cumulative function of arrival flow and departure flow $A_i(t) - D_i(t)$. Recall that the cumulative function of the arrival flow $A_i(t)$ is $\alpha_i - smooth$, with α_i as its arrival curve. Then the backlog at time t satisfies

Lemma 3.2 (Buffer Bound in Single-Hop Network):

$$B_i \leq \sup_{s \geq 0}\{\alpha_i(s) - \beta_i(s)\} \tag{6}$$

Such a backlog introduces a delay for the data stream. Formally we define the *virtual delay* at time t as

$$d_i(t) = \inf_{\tau \geq 0}\{A_i(t) \leq D_i(t + \tau)\} \tag{7}$$

which is the delay that would be experienced by a bit arriving at t if all bits are received before it are served before it.

Now we describe the latency at time t with the virtual delay $d_i(t)$.

Theorem 3.3 (Delay Bound for Single-hop Network): In a single-hop wireless sensor network under synchronized time-division power management, the delay for flow i is given by

$$d_i(t) = \inf\{\tau \geq 0 : A_i(t) \leq D_i(t + \tau)\}$$

The definition of $d_i(t)$ is the delay that would be experienced by a bit arriving at time t if all bits arrived before it are served before it. The intuition behind $d_i(t)$ is illustrated in Fig. 2. Because both arrival and departure cumulative function $A_i(t)$ and $D_i(t)$ are wide-sense increasing, virtual delay $d_i(t)$ can be considered as shifting $D_i(t)$ leftward, to the time point, at which $D_i(t)$ has the same value as $A_i(t)$, and $d_i(t)$ is the smallest value that $D_i(t)$ need to shift. This means that the departure flow $D_i(t)$ will cumulate to the same amount of bits as the arrival flow after a latency of at least $d_i(t)$.

This theorem establishes the relationship among delay bound (d_i), power management policy (by the choice of T_i), and the traffic arrival characteristic (from α_i). Thus we are able to select the appropriate power management parameters based on traffic arrival curve to minimize the energy consumption while providing the delay bound.

Here we consider the delay bound instead of other metrics as jitter explicitly. This is because if every packet in departure flow satisfies the delay bound, we may smooth out the delay jitter at the receiver side buffer with a corresponding playback delay.

IV. ANALYSIS FOR MULTI-HOP WIRELESS NETWORK

A multihop wireless video sensor network can be modeled as a graph $G = (\mathcal{N}, E)$. $E \subseteq 2^{\mathcal{N}}$ denotes the set of wireless links, which are formed by sensor nodes that are within the transmission range of each other. A wireless link $e \in E$ is represented by its end nodes i and j, *i.e.*, $e = \{i, j\}$.

Here we call a video stream from the video sensor to the data sink as an *end-to-end flows*. We denote the set of end-to-end flows as F. We also denote the set of flows passing through node i as F_i, $F_i \subseteq F$, and the set of nodes which send or forward flow f as $N(f)$. A single-hop video transmission in the flow f along a particular wireless link is referred to as a *subflow* of f. In this paper, we only consider the multi-hop wireless network without spatial reuse, which means all wireless links are mutually contending with each other. The analysis of multihop wireless network with spatial reuse is given in our technical report [16].

We now study the service curve, buffer and delay bound. In a video sensor network, the video streams are always delivered from the video sensors to the data sink. Thus we assume that the traffic only goes along one direction in any wireless link in the network. First, we consider the service curve at node $i \in \mathcal{N}$, which is awake for a time interval T_i in a period of T. Suppose node i has $F_i \subseteq F$ flows passing through, and the maximum packet size is L. Similar to the single-hop wireless network case, we have the following results:

Lemma 4.1 (Service Curve in Multi-hop Wireless Network): Assume fair scheduling of each flow $f \in F$ at node $i \in \mathcal{N}$. The service curve β_{if} under synchronized time division power management with wake-up time T_i out of period T, is given by the following rate-latency function with rate $\frac{C \cdot T_i}{|F_i| \cdot T}$ and maximum possible latency $T - T_i + L \cdot (|F_i - 1|)$.

$$\beta_{if}(\tau) = \frac{C \cdot T_i}{|F_i| \cdot T}[\tau - (T - T_i + L \cdot (|F_i| - 1))]^+ \quad (8)$$

As showing in Fig.3, flows of data stream are sent back to data sink though a concatenation of nodes. In this case, the concatenated bounds may be derived according to min-plus algebra. In min-plus algebra $(\mathbb{R} \cup \{+\infty\}, \wedge, +)$, where the ‘addition’ is $\wedge$ and the ‘multiplication’ is $+$. an ‘integral’ of function f becomes therefore

$$\int_0^t f(s)ds = \inf_{0 \le s \le t \;\; s \in \mathbb{R}} \{f(s)\} \quad (9)$$

the convolution of two functions β_1 and β_2 is the function

$$(\beta_1 \otimes \beta_2)(t) = \inf_{0 \le s \le t} \{\beta_1(t-s) + \beta_2(s)\} \quad (10)$$

Lemma 4.2: Assume a flow traverse two systems (nodes) $\mathcal{S}_1$ and $\mathcal{S}_2$ in sequence. If $\mathcal{S}_i$ offers a service curve of $\beta_i, i = 1, 2$ to the flow. Then the concatenation of the system offers a service curve of $\beta_1 \otimes \beta_2$ to the flow, which is the min-plus convolution of the two service curves.

From *Lemma 4.2*, we can intuitively derive

Theorem 4.3 (Service Curve with Concatenation): Assume a flow f traverse $|N(f)|$ systems $\mathcal{S}_i, i = 1, 2, ..., |N(f)|$ sequentially. If $\mathcal{S}_i$ offers a service curve of $\beta_i, i = 1, 2, ..., |N(f)|$ to the flow. Then the concatenation of the system offers a service curve of $\prod_{i=1}^{|N(f)|} \otimes \beta_i = \beta_1 \otimes \beta_2 \otimes ... \otimes \beta_{|N(f)|}$ to the flow, which is the iterated min-plus convolution of the $|N(f)|$ service curves.

Therefore, we have the concatenated departure flow from system $\mathcal{S}_{|N(f)|}$ as

$$D_{|N(f)|} = D_0 \prod_{i=1}^{|N(f)|} \otimes \beta_i = A_1 \prod_{i=1}^{|N(f)|} \otimes \beta_i \quad (11)$$

In which, D_0 is the departure flow from node 0, which is also arrival flow at node 0, A_0. $D_{|N(f)|}$ is the departure flow from node $|N(f)|$.

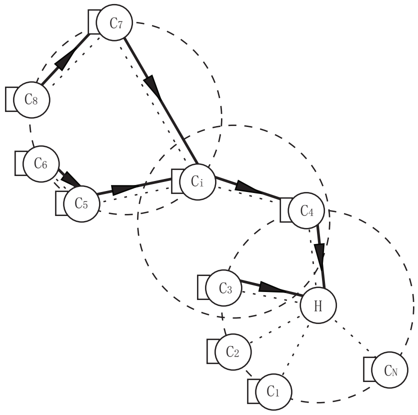

Fig. 3. Multi-Hop Scenario.

As video sensor network usually has only one data sink, we only consider the tree-structured concatenation here.

Theorem 4.4 (Delay Bound in Multi-Hop Network): Assume a flow traverse tree-like hierarchical systems $\mathcal{S}_{n,j}$ in sequence. If $\mathcal{S}_{n,j}$ offers a service curve of $\beta_{n,j}$ to the flow. Then the concatenation of the system offers a service curve of $\lambda[\bullet]$ to the flow, which is

$$\lambda[\bullet] = \sum_{j_{n-1}=1}^{N_{n-1}} [\sum_{j_{n-2}=1}^{N_{n-2}} [...[\sum_{j_0=1}^{N_0} \bullet] \otimes \beta_{1,j_1}] \otimes ...] \otimes \beta_{n-1,j_{n-1}}] \otimes \beta_{n,j_n} \quad (12)$$

V. EXPERIMENT

The experiment was carried out on a wireless video sensor platform. We use Stargate wireless testbed(XScale PXA255) as sensor node, with AmbiCom WL1100C-CF (802.11b) wireless network interface. The video sensor is Logitech Pro4000 camera, with USB connection, which connects to Stargate. The video stream is generated by a modified video capture application *vidcat* on Stargate. The captured video stream will serve as Arrival Flow (See Fig. 4) in our experiment. The Arrival Curve can be inferred with the maximum arrival flow rate. We generated the trace of Departure Flow (See Fig. 5)

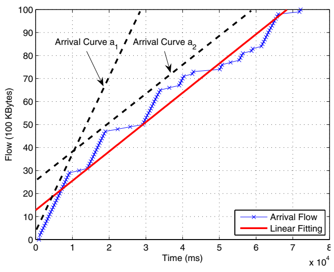

Fig. 4. Arrival Flow and Arrival Curve.

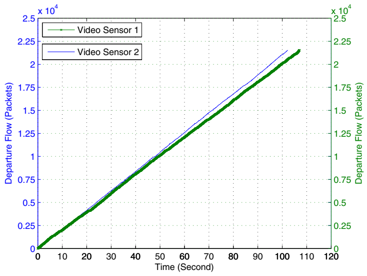

Fig. 5. Departure Flow in Single-hop Scenario with 2 nodes.

by logging packets received at video sensor nodes and data sink (Fedora FC6 Laptop).

We tested our system a single-hop wireless sensor network. In the single-hop case, two or four video sensor nodes constantly send out video streams and contend for the wireless channel. With two nodes in the single-hop scenario (Fig. 6) , the departure curve will surpass the arrival curve, which means the transmission ability may well handle all the arrival flow and no data will be backlogged. With four nodes in the single-hop scenario (Fig. 7) , arrival flow will be delayed (See Fig. 8) and backlogged (Fig. 9), but within the threshold of Delay Bound and Buffer Bound. By logging the packet departure time at video sensor node and arrival time at data sink, we also measured the end-to-end delay and backlog length in aforementioned scenarios. In Fig. 8, we get the delay of two single-hop nodes by measuring the horizontal deviation between arrival flow and departure flow in Fig. 7. Similarly, in Fig. 9, we get their backlog by measuring the vertical deviation between arrival flow and departure flow in Fig. 7.

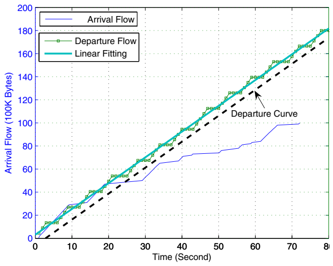

Fig. 6. Departure Flow and Departure Curve in Single-hop Scenario (2 Nodes with Arrival Curve in Background).

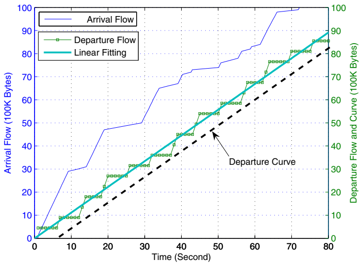

Fig. 7. Departure Flow and Departure Curve in Single-hop Scenario (4 Nodes with Arrival Curve in Background).

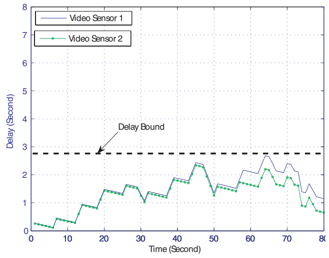

Fig. 8. Delay and Delay Bound in Single-hop Scenario (2 out of 4 Nodes)

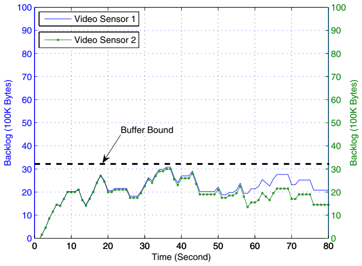

Fig. 9. Buffer and Buffer Bound in Single-hop Scenario (2 out of 4 Nodes)

VI. CONCLUSION

In this paper, we investigated the power management problem in the context of sleep/awake scheduling. We adopt a network calculus approach, through which we derived the service curve, buffer and delay bound under single-hop and multi-hop scenarios. Our analysis has been validated through experiments conducted on a video sensor network testbed. Our experiment results validate the existences of the optimal solution.

Further optimization on the energy consumption could be done by adjusting the scheduling algorithm subject to the service, buffer, and delay constraints. We can improve the energy model to relate scheduling variables with the three bounds. We can also solve the energy consumption minimization problem by formatting it as linear programming problem. Other improvements include formulating more realistic and complex contention model beside our current clique model, and implementing proper approximation algorithm to efficiently simplify it.

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