Uplink Adaptive Multimedia Delivery (UAMD) Scheme for Video Sensor Network

Bao Nguyen Trinh[1], Liam Murphy[2] and Gabriel-Miro Muntean[3]

Abstract— **Lately Video Sensor Networks (VSN) are increasingly being used in the context of smart cities, smart homes, for environment monitoring, surveillance, etc. In such systems, due to limitations in the video sensor node resources, the most important factor is energy efficiency. Sensing, processing and transmitting are the main contributors to energy consumption in a video sensor node. Among these, wireless transmissions play a dominant role. An effective way for reducing energy consumption is to adjust the active time duration of node's radio transmission. However, this method has the main drawback that affects streaming quality in terms of throughput and delay. So, one of the big challenges when designing an energy-aware VSN is the trade-off between energy consumption and video streaming quality.**

This paper proposes an Uplink Adaptive Multimedia Delivery (UAMD) scheme that dynamically adjusts the wake-up/sleep duration of video sensor nodes based on the node remaining battery levels and network traffic conditions. The UAMD algorithm employs a utility function in the decision on duty cycle adjustment process. Simulation results show how UAMD achieves good balance between energy consumption and throughput in comparison with other duty-cycle-based schemes.

I. Introduction

Wireless Sensor Network (WSN) and in particular Video Sensor Network (VSN) systems have been deployed in many aspects of our life, for instance, smart cities for traffic monitoring [1], [2], in smart homes for environment monitoring and security [3], in entertainment for video summarization [4], and in diverse situations for surveillance [5]. Such systems usually use a video compression technique, such as: H.264/AVC [6] or H.265/HEVC [7] as video coding standard. In these applications, multimedia content including video and audio at diverse quality levels are sensed and transmitted from video sensor nodes to sink nodes or gateways. VSNs play a key role in many Internet of Things (IoT) deployments [8]. An analysis from Cisco estimates that in 2020, there will be around 50 billion devices connected to the Internet and about 75% of the total traffic will be video [9]. Although in recent years, there has been a huge increase in the hardware platform development for sensor devices, the improvement in battery capacity is still far behind. For example, lithium ion is considered as the best battery technology, but its energy density is increasing only 5% per year [10]. In this context, it is clear that one of the most important aspect in any IoT system is battery life time and its optimisation.

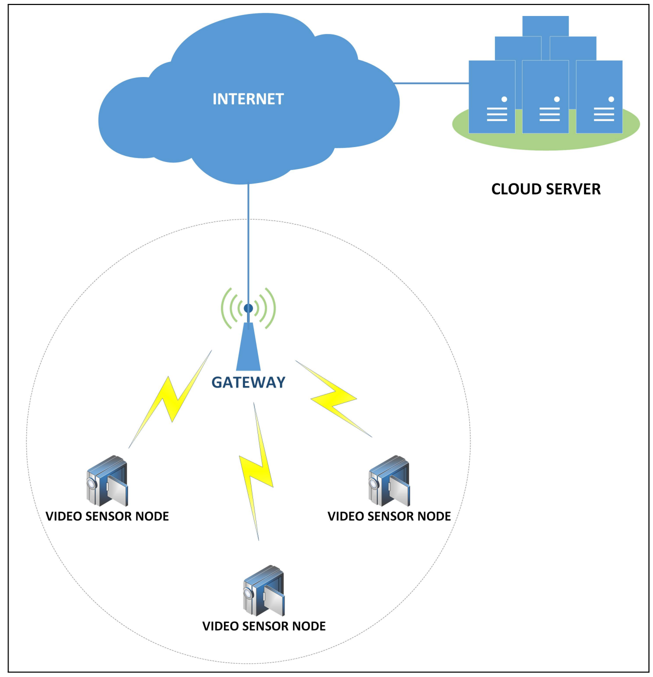

Fig. 1. A generic Video Sensor Network

A typical architecture of a video sensor network is illustrated in Fig. 1 [11]. This type of sensor network is equipped with tiny camera sensor nodes, embedded processors, and wireless tranceivers. The video sensor nodes communicate with an aggregation node (or also called Gateway) or with each other via wireless links supported by wireless technologies from the IEEE 802.11 family (i.e. WiFi), cellular (e.g. LTE) or IEEE 802.15 family (e.g. 6LowPan), etc.

In general, energy consumption in a sensor node is mostly due to the radio communications [12]. This is highly dependent on the MAC layer solutions, so improvement of these solutions is considered as fundamental in operational improvement of any energy-aware system such as a VSN. One prominent method for such improvement is to adjust the sensor node duty cycle. In such a scheme, sensor node's transmission part dynamically switches between on and off states. The energy consumption of sensor nodes are high

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when they are in an *on* state. When nodes are switched *off*, they save energy. These solutions are especially important for video sensor nodes where the energy consumption is higher than in comparison with other scalar sensors. However, there is a trade-off when using duty-cycle schemes. If the sleep period increases, the transmission delay and throughput is affected, so it is necessary to build schemes such that both energy efficiency and delivery quality are considered and balanced.

Different from previous works on duty cycle, this works introduces the Uplink Adaptive Multimedia Delivery (UAMD) scheme which balances the energy consumption of the video sensor node by adjusting its operation based on the remaining battery level and the video throughput. The contributions of this paper can be summarized as follows:

- A novel battery-throughput utility function which balances the influence of remaining battery level and delivery throughput on video delivery.
- A new scheme UAMD is proposed for dynamically adjusting the duty cycle of a video sensor node. UAMD uses the newly proposed utility function in its decision making to maintain the balance between energy consumption and video delivery throughput.
- Simulation results show how by using the UAMD scheme, the battery lifetime increases whereas the throughput and associated video streaming quality is maintained at good levels.

The rest of this paper is organized as follows: section II discusses related works from the literature on VSN including some adaptive duty-cycle adjustment and battery-aware schemes. In section III UAMD - the proposed solution is described in terms of its block-level architecture and proposed algorithm. The simulation-based testing of UAMD and its results are included in section IV and V. Finally, conclusions are drawn and future works directions are indicated in section VI.

II. Related Works

In relation to our work, next some research solutions on the following topics are discussed: 1) adaptive video delivery over wireless networks, 2) adaptive adjustment of duty-cycle of sensor nodes, and 3) battery-aware schemes for multimedia delivery.

In [13], the authors made use of a utility function in network selection when choosing the best solution for video transmission to mobile devices. The video configuration, e.g., bit rate, frame rate, are adapted based on the utility value achieved from proposed utility function. In another work, diverse solutions for the trade-off between the encoding complexity and communication power consumption in a VSN are investigated in [14]. The same work also proposes several algorithms to reduce the power consumption in VSNs in different uses cases.

There are many works which aim at improving the transmitting operation of WSN, especially focusing on the adjustment of wake up/sleep time (or also called duty cycle) of radio transmission [15]. Among these, S-MAC [16] can be seen as the seminal work in studying the WSN duty cycle. The idea of S-MAC is to improve the operation of the classic IEEE 802.11 standard Power Save Mechanism (PSM) [17]. S-MAC implements a fixed sleep/awake duration for sensor node and proposes a synchronization mechanism between nodes in a cluster. The main drawback of S-MAC is that it introduces high delay and lowers the throughput, so that it makes it less suitable for multimedia delivery. Other related works, T-MAC [18], X-MAC [19] and LC-MAC [20] have improved the performance of S-MAC with the introduction of adaptive schemes based on traffic loads. However, most of these previous works are not useful for video delivery due to the lack of a mechanism to support video-related quality of service (QoS) requirements.

In [21], Xie *et. al.* have proposed the Residual Energy Aware with Adjustable awake/sleep duty cycle (READC), an adaptive scheme to adjust the sensor device duty-cycle based on the distance from the sink node. For the sensor nodes that are close to the sink, the authors adopt a duty cycle to meet QoS requirements, whereas for the nodes that are far from the sink, a special duty cycle to reduce the energy consumption is employed. Another solution to adjust the duty-cycle based on the comparison between the energy consumption of a sensor node and of the entire packet delivery flow is proposed in [22]. A different approach on duty cycle adjustment is based on traffic condition of the network [23]. The author has proposed the Adaptive Wake-up Period (AWP) scheme to adjust the Wake-up/sleep time of the sensor nodes following network load conditions. In [24], Coutinho *et. al.* proposed a framework to evaluate the effects of sleep duration on the energy consumption of a duty-cycle for Underwater Sensor Networks (USNs). The authors argued that the fixed sleep interval duty-cycles do not affect the energy consumption but the management of sleep interval can extend the USNs lifetime.

In terms of battery-aware solutions, Kennedy *et. al.* in [25] have proposed BaSe-Amy, a scheme that monitors the mobile device's battery level, the remaining video stream duration and transmission packet loss. Based on these pieces of information, BaSe-Amy decides to decrease or not the current video quality level in order to achieve energy saving. Solutions for energy-efficient device-differentiated adaptive multimedia delivery solutions which employ inter-device cooperation, balance quality and cost for network selection or enable efficient cellular-WLAN offload were proposed in [26], [27] and [28], respectively. Another work applied the C-means clustering technique in order to estimate the State of Charge (SoC) for battery in electric vehicles [29]. Several surveys focus on energy optimisation for wireless adaptive video delivery [30], energy-aware mobile content delivery [31] and power efficient wireless video sensor networks [32].

This paper bridges the gap between battery power level awareness and adaptive multimedia delivery in a VSN context. Different from previous works, it proposes the UAMD solution which makes use of a utility function in its decision process of adjustment of node active/sleep time to save energy while performing QoS monitoring in order to support

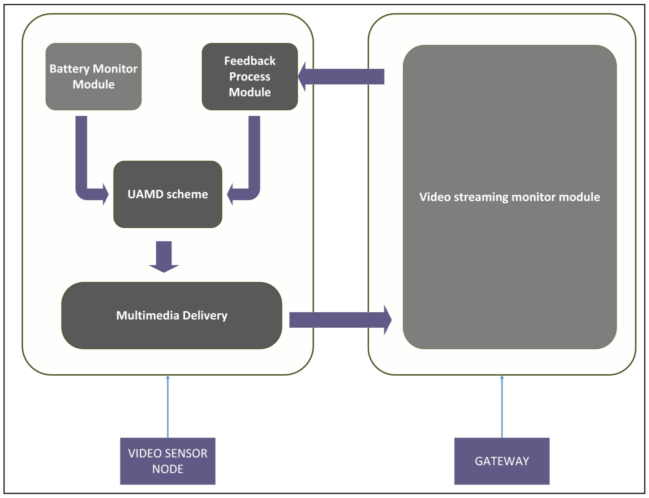

Fig. 2. UAMD-based system block-level diagram

maintaining good QoS levels.

III. The Uplink Adaptive Multimedia Delivery (UAMD) Scheme

A. Block-level Architecture

The block diagram of our proposed scheme is illustrated in Fig. 2. UAMD's main functional modules are described as follows in the context of its main two components: Gateway and video sensor nodes.

At the level of the video sensor nodes:

- Battery Monitor Module: periodically collects the information about the node's battery level
- Feedback Process Module: collects feedback from Gateway on the quality of video streaming.
- Uplink Adaptive Multimedia Delivery (UAMD): employs the proposed scheme which makes use of a utility function to make decisions regarding adjusting the wake-up/sleep time of radio transmission based on node remaining battery levels and video streaming throughput.
- Multimedia delivery: delivers the multimedia content via the wireless interface.

At the level of the Gateway:

- Multimedia streaming monitoring module: receives the multimedia stream, makes an estimation on the quality of the delivery and sends feedback to video sensor node.

B. Battery-throughput Utility Function

This paper uses the term duty-cycle from [16] and is mathematically defined based on node active and sleep time in equation (1):

$$\delta = \frac{T_A}{T_A + T_S} \tag{1}$$

In equation (1),

- T_A refers to the time duration the radio transmission of a video sensor node is in one of the Active states. These states are *Transmit (Tx)*, *Receive (Rx)* and *Idle (Idle)*.
- T_S refers to the time duration that the radio transmission of a video sensor node is in the *Sleep (S)* state. In this state other node components related to processing and sensing are still on.

The UAMD scheme aims to find an optimal value for the duty cycle following nodes' battery state and the video throughput. The following components are employed in the utility function:

1) **Remaining energy level (%)** - E: is defined as the ratio between remaining and the maximum energy value.
2) **Power depletion rate (Joules/s) -** P: is defined as the energy consumption per time unit of video sensor node. As it is the largest energy consumer in the node, in the UAMD scheme, the focus is on the node's radio transmission.

The power depletion rate for radio transmission part has four components, one in each of the four node states: Tx, Rx, Idle and Sleep denoted as follows: P_{Tx}, P_{Rx}, P_{Idle}, and P_S, respectively. The energy consumption per time unit (or power depletion rate) can be computed in relation to the value of the duty cycle as in equation (2):

$$\begin{aligned} P(\delta) =& \delta \times (P_{Tx} + P_{Rx} + P_{Idle}) + (1-\delta) \times P_S \\ =& \delta \times P_A + (1-\delta) \times P_S \end{aligned} \tag{2}$$

The utility function for energy efficiency can be written as in equation (3):

$$u_b(\delta) = \frac{E}{\delta \times P_A + (1-\delta) \times P_S} \tag{3}$$

Denote R as data rate at sender side, with duty cycle value δ, the utility function for estimated throughput can be written as in equation (4):

$$u_t(\delta) = R \times \delta \tag{4}$$

Let w_b and w_t be weighting factors for battery and throughput utility functions, respectively. By combining equation (3) and equation (4), the overall battery-throughput utility function results as shown in equation (5):

$$\begin{aligned} \triangle(\delta) =& 1 - \{w_b \times u_b(\delta) + w_t \times u_t(\delta)\} \\ =& 1 - \{w_b \times \frac{E}{\delta P_A + (1-\delta) P_S} + w_t \times R \times \delta\} \end{aligned} \tag{5}$$

By setting the values of the two weights, different overall utility function behaviour is obtained: *Quality-oriented*, *Energy-oriented* and *Balanced-oriented*, respectively.

C. UAMD Algorithm

UAMD operation is based on dividing the delivery transmission in discrete time intervals (denoted as adaptation cycles). In each such cycle information is gathered regarding the node battery depletion and delivered video throughput and based on the overall battery-throughput utility function, the optimal value for δ is determined based on equation (6):

$$\delta^* = \underset{\delta \in [0:1]}{\arg\max} \quad \triangle(\delta) \tag{6}$$

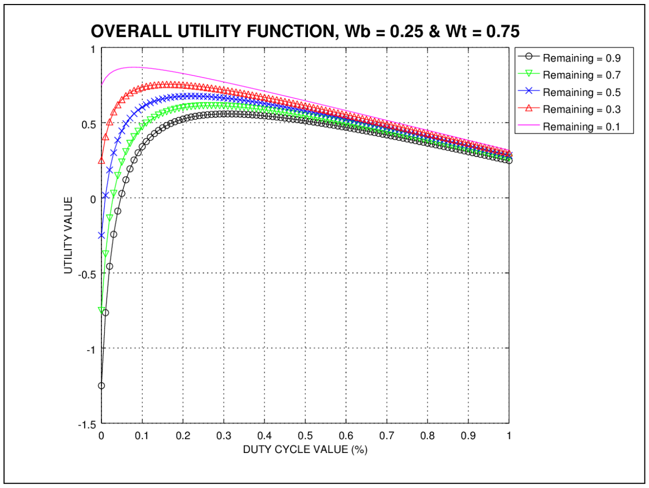

Fig. 3. Overall Utility Function in a quality-oriented case, where $w_t = 0.75$ & $w_b = 0.25$

Solving equation (6), the value for δ results as shown in equation (7):

$$\begin{aligned} &\frac{\partial\triangle}{\partial\delta} = 0 \\ \leftrightarrow &\frac{AD\delta^2 + 2P_S A\delta + BP_S - CD}{(D\delta + P_S)^2} = 0 \\ \leftrightarrow &\delta^* = \frac{-2P_S A + \sqrt{4P_S^2 A^2 - 4AD(BP_S - CD)}}{2AD} \end{aligned} \tag{7}$$

In equation (7):

$$\begin{aligned} A &= w_t R(P_A - P_S); \\ B &= w_t P_S R; \\ C &= w_b E; \\ D &= P_A - P_S; \end{aligned} \tag{8}$$

The actual algorithm for UAMD video sensor node duty cycle adaptation is described next, considering a regular adaptation cycle of τ seconds:

Algorithm 1 UAMD adaptive duty cycle adjustment

```
<Initialize value for w_t and w_b>
<Initialize data rate R>
<Read remaining energy (%) E>
for <each τ seconds> do
    <Estimate value of P_S>
    <Estimate value of P_A>
    <Read remaining energy E>
    A ← w_t R(P_A − P_S)
    B ← w_t R P_S
    C ← w_b E
    D ← (P_A − P_S)
    δ* ← (−2 P_S A + sqrt(4 P_S^2 A^2 − 4AD(B P_S − CD))) / (2AD)
```

TABLE I
SIMULATION SETUP

Parameter	Value
Simulation Length	20000 seconds
Number of Gateway (GW)	1
Number of Video sensor nodes	5
Cell layout	Single cell; Radius - 100 meters
WiFi Mode	IEEE 802.11n 2.4 GHz
Antenna Model	Isotropic Antenna Model
Initial Energy	10800 (Joules) 3 WattHours
T_A + T_S	1 second
Battery duration check	10s
Data rate (Mbps)	0.96
P_{Tx} (Watts)	1.14
P_S (Watts)	0.10
P_{Idle} (Watts)	0.82
P_{Rx} (Watts)	0.94

IV. SIMULATION-BASED TESTING

A. Simulation Settings

Network Simulator (NS-3) [33] is employed as the modeling and simulation tool for testing the proposed UAMD scheme. Network topology (as illustrated in figure1) consists of one Gateway (GW) and three video sensor nodes (VSN). Each of node falls into one of the following three categories: *Quality-oriented*, *Balanced-oriented*, and *Energy-oriented*. The parameters for the simulations are included in Table I.

We assume that the video sensor nodes use the H264/MPEG-4 AVC video compression for their content delivery to the Gateway. Different video quality levels are considered and their associated characteristics including bitrates, resolutions and frame rates are presented in Table II [13].

B. Test Cases

The proposed UAMD scheme is tested in 3 different test cases:

- Quality-oriented case: w_t = 0.75 and w_b = 0.25
- Energy-oriented case: w_t = 0.25 and w_b = 0.75
- Balance-oriented case: w_b = w_t = 0.5

The UAMD scheme is compared with two other previous works:

- Fix duty cycle (FDC): The duration that the video node is in sleep/awake state is fixed (like in S-MAC [16]).
- Adaptable Wake-up Period (AWP) [23]: The duty cycle is adjusted based on traffic conditions and does not take into account the battery level.

V. TEST RESULTS AND DISCUSSIONS

Figure 4 and Figure 5 present the results obtained for the throughput and remaining battery levels when considering the three different solutions: UAMD, FDC and AWP. In particular UAMD was employed with nodes set in *Quality-oriented*, *Balanced* and *Energy-oriented* modes, respectively. Throughput decreases when UAMD is employed, following battery life time decrease. It can be observed that among 5 test cases, Quality-oriented UAMD shows the best result in

TABLE II
ENCODING SETTINGS FOR THE MULTIMEDIA STREAMING

Quality Level	Video Codec	Overall Bitrate [Kbps]	Resolution[pixels]	Frame Rate[fps]
QL1	H.264/MPEG-4	1920	800× 448	30
QL2		960	512× 288	25
QL3		480	320× 176	20
QL4		240	320× 176	15
QL5		120	320× 176	10

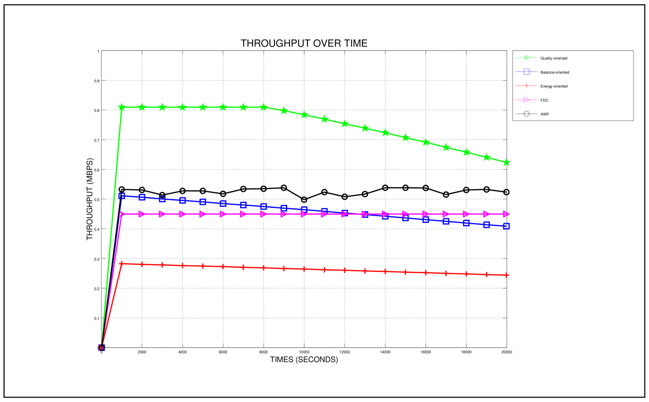

Fig. 4. Throughput

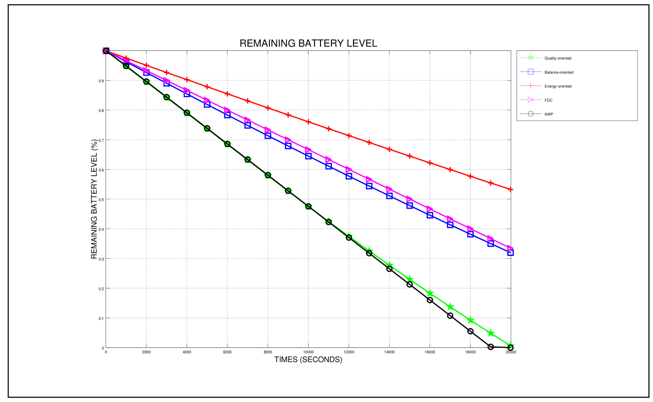

Fig. 5. Battery lifetime

terms of throughput at approximate 0.77 $Mbps$. Balanced-oriented UAMD, FDC and AWP cases have similar throughput values with 0.46 $Mbps$, 0.45 $Mbps$ and 0.5 $Mbps$, respectively. With average 0.26 $Mbps$, The Energy-oriented UAMD is only suitable for delivering the lowest video quality (see Table II).

Next energy efficiency is evaluated (see Table III) based on the remaining battery level (%) and power depletion rate (Joules/s). Due to the lowest duty cycle ($\delta = 0.27$ on average), the energy consumption of an Energy-oriented UAMD node is far lower than in other cases at 0.38 Joules/s and therefore the remaining energy level is more than 50%. In contrast, the batteries of AWP and Quality-oriented UAMD nodes are fully depleted at the end of the simulation. The Balance-oriented UAMD and FDC nodes present similar results in terms of their depletion rates (approximately 0.60 Joules/s) and they have nearly 40% remaining battery.

These simulation results are dependent on the duty cycle value choice. In the UAMD scheme, the duty cycle is mainly dependent on the remaining energy level and the weight values. When the battery level is decreasing, based on the objective of performance, the video sensor node decides to decrease its $Active$ state time at different values for different use cases: more agressive in the Energy-aware case and less agressive in the Quality-oriented case.

VI. Conclusions and Future Works

This paper proposes UAMD, a battery-aware adaptive multimedia delivery scheme for a video sensor network nodes. The scheme adjusts the operation of video sensor node's radio transmission part according to its remaining battery level and monitored throughput. UAMD was tested in a simulation environment with in three different test cases: Quality-oriented, Balance-oriented, and Energy-oriented. The simulation results showed how the UAMD scheme outperforms two other duty-cycle-based adjustment algorithms.

Future work will involve improvements of the performance of UAMD by enhancing the intelligence of the video sensor nodes. One possible way to do that is to collaborate with neighbour nodes in order to form a Machine-to-Machine (M2M) communications system or with other scalar sensor types (for example, motion detection sensors) and adapt the operation based on past experience. Additionally, we also consider to apply a Reinforcement Learning-based algorithm to extend the scheme based on the use of utility function described in this paper. Validation of the UAMD work in a real life physical hardware platform (e.g. Raspberry Pi) is also envisaged. This will enable to collect real data and make comparisons with the simulation results.

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TABLE III

SIMULATION RESULTS

	THROUGHPUT (Mbps)				
	Quality-oriented UAMD	**Balanced UAMD**	**Energy-oriented UAMD**	**FDC**	**AWP**
Mean	0.755	0.46	0.26	0.45	0.50
Variance	0.0045	0.0013	2×10^{-3}	3×10^{-3}	6×10^{-3}
	DEPLETION RATE (JOULES/S)				
	Quality-oriented UAMD	**Balanced UAMD**	**Energy-oriented UAMD**	**FDC**	**AWP**
Mean	0.77	0.57	0.38	0.62	1.04
Variance	0.06	6×10^{-3}	8×10^{-4}	0	3×10^{-4}
	DUTY CYCLE VALUE				
	Quality-oriented UAMD	**Balanced UAMD**	**Energy-oriented UAMD**	**FDC**	**AWP**
Mean	0.64	0.45	0.27	0.5	0.8
Variance	0.05	6×10^{-3}	7×10^{-4}	0	1×10^{-4}

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