Smart water grid: a review and a suggestion for water quality monitoring

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ABSTRACT

Water is a valuable resource and an elixir of life. It is intimately linked to living standards around the world. Reducing water stress and conserving the resource is vital. It is the need of the hour to ameliorate conventional water resources systems to monitor water quantity and quality parameters continuously in real-time. Smart solutions play an important role in monitoring system parameters and making on-site measurements. This paper focuses on Smart Water Grid, an ingenious way to monitor and preserve the quantity and quality parameters in real-time by deploying remote sensors in the water distribution system. It presents a review of various sensors deployed, networking protocols used and cloud platforms employed in monitoring the water distribution system. The suitable networking protocols for the water distribution systems are suggested by analyzing various smart solutions. It also proposes an architecture for an IoT-based system to monitor residual chlorine concentration in the water distribution system. Smart Water Grid using Wireless Sensor Networks and the Internet of Things enables the monitoring of on-site conditions and generates alerts during abnormal conditions. It can enhance timely decision-making which will help in managing valuable water resources more efficiently.

Key words: internet of things (IoT), smart water grid (SWG), water distribution system (WDS), water quality, wireless sensor networks (WSN)

HIGHLIGHTS

• Conventional methods of water sampling are time- and labour-consuming. Information and communication technology plays a significant role in monitoring WDS.
• SWG is useful for monitoring on-site water quantity and quality parameters continuously.
• Various sensors, networking protocols and cloud platforms used in monitoring WDS are reviewed, and a new methodology for monitoring residual chlorine concentration using IoT is suggested.

GRAPHICAL ABSTRACT

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INTRODUCTION

Life does not exist without water. Nowadays, water is used not only for survival consumption; it is also used as a resource of luxury and comfort. As a result, water scarcity increases. National Intelligence Council (2012) reported that by the year 2025, most countries will become water-stressed. Apart from the scarce availability in terms of quantity, water quality has also become a concern in recent decades.

Disease and Risk Report (2012) of the World Health Organization (WHO) highlighted that diarrhea is the root cause of the deaths of approximately 1.5 million people every year. Slackness in the implementation of pollution control laws often results in a discharge of untreated effluents from domestic and industrial emissions into water bodies (Edokpayi et al. 2017). It is important to have clean and potable water to avoid countless diseases and to create a healthy living environment.

The Water Distribution System (WDS) is the main mode of water supply for urban communities. A reliable water supply in terms of quantity and quality is significant in this urbanized world. Conventional methods to measure water quality parameters are time-consuming and do not offer real-time detection of water quality (Ahmed et al. 2020). It is necessary to monitor the on-site conditions of WDS. Information and communication technology play a significant role in monitoring and managing the WDS in real time (Gautam et al. 2020). To overcome the defects of the conventional analysis and to monitor the WDS in real-time, the Smart Water Grid (SWG) is developed. The SWG is structured to monitor and control the water consumption, leaks and water quality changes in a WDS. Smart water quality monitoring is a cost-effective and efficient system in monitoring water quality parameters (Pasika & Gandla 2020).

This paper presents a review of earlier literature related to the implementation of smart technologies in WDS. The review focuses on the application and developments of Wireless Sensor Networks (WSN) and the Internet of Things (IoT) in monitoring water quantity and quality parameters in WDS. The review summarizes the focus of the studies, sensors deployed and networking protocols used for WSN. In addition to this, the cloud platforms that are used are also reviewed for IoT. The main focus here is given to networking protocols since the suitability and performance of the smart monitoring system in terms of power consumption, data transmission range and data transmission rate are influenced by it. As an outcome, a new methodology to monitor the quality of water in the WDS in a smart way using the Internet of Things (IoT) is also suggested in this paper.

CONVENTIONAL WATER QUALITY SAMPLING AND ITS SHORTCOMINGS

The conventional water quality measurement method requires sample collection from the source, conveyance, preservation and lab analysis. This method is time- and labour-consuming and the accuracy of the results is doubtful compared with on-site measurements. It is associated with two significant issues. (i) Most water bodies change quality parameters often with time and space. (ii) During transportation and preservation the samples can react with the new environment, which can alter the physical, chemical and biological characteristics. The biochemical alterations by the microorganisms can modify the concentrations of dissolved oxygen, carbon dioxide and organic compounds; subsequently they may alter the pH, chemical solubility and several other parameters (Horne & Goldman 1994). Thus, there is a need for reliable practices to represent the on-site conditions of water quality.

REAL-TIME WATER QUALITY MONITORING AND ITS IMPORTANCE

Monitoring the water quality is one of the important steps performed in developing and managing water resources. It is essential to go for advanced solutions to overcome the problems associated with the conventional water quality monitoring. One such solution is continuous real-time monitoring. It can provide a better insight into water quality issues and the factors affecting quality. Also, it reduces the time, cost and workforce associated with the conventional analysis. The real-time monitoring of water is required to make decisions regarding safe water supply, water treatment, regulatory problems, recreational purposes and public safety (Hirsch 2014).

Natural disasters, water terrorism and other such emergencies can affect the health of water resources (Gleick 2006). The pH, turbidity, dissolved oxygen, residual chlorine, Total Dissolved Solids (TDS) and microbial contamination are the key parameters to be monitored. Most water resources systems have now established several methods to collect continuous and real-time data about the supply and water quality. Smart water management solutions are gaining importance with the rapid development in communication technologies, primarily Wireless Sensor Networks (WSN) and IoT.
WSN is a technology used in IoT, it contains a large number of sensors but they cannot directly send the information to the internet. If it is required to send data to the internet, then a router device or sink node is necessary. In an IoT system, the internet is an inherent component. Sensors can directly send information to the internet and store them in the cloud where storage, analytics and live visualization can be done. An IoT system involves hardware, software, networking protocols and cloud technologies to gather, store and analyze the data to make better decisions.

SMART WATER GRID
An integrated set of products, solutions and systems that enable the WDS to remotely and continuously monitor, diagnose and optimize all aspects of WDS is known as Smart Water Grid (Savic 2015). It helps in prioritizing and managing maintenance issues. SWG uses WSN and IoT with different electronic communication devices and routing protocols to deliver real-time data continuously from several locations. The collected data is useful in optimizing the WDS performance. It also provides meaningful information to the end-users. Thus, SWG brings a considerable improvement by presenting the real-time data up front and makes the authorities analyze the data and take necessary actions in a short time. It is not only useful for significantly improving the age-old WDS but also for solving global water stress (Joshi 2020).

OPTIMAL SENSOR PLACEMENT
Sensor placement plays an important role in an SWG. The widely used objective functions for optimal sensor placements are to minimize the time of detection, minimize the impact, the size of the population exposed and the extent of the damage (Ostfeld et al. 2008; Adedoja et al. 2019). Optimal sensor placement helps in better diagnosis of WDS (Nejjari et al. 2015). To improve the system efficacy and lower the cost, appropriate optimization algorithms must be used (Krause et al. 2008).

Wu et al. (2007) attempted to identify suitable monitoring locations to detect contaminant intrusion within the WDS. The authors highlighted three possible monitoring points: (i) at the outlet of the treatment plant; (ii) vulnerable areas like the end region of branched pipes and corroded regions; and (iii) representative monitoring points (locations that exactly reflect the water quality as much as possible in the WDS). The Water Age Index (WAI) was used as a surrogate measure to identify the representative monitoring points.

Yazdekhasti et al. (2020) assessed the Life-Cycle Cost (LCC) and energy utilization of sensors deployed to monitor and detect leaks in WDS. The Leak Detection Index (LDI) was used to assess the cost and energy consumption sensitivity to data sampling rate, data transmission rate and sensor spacing. It was discovered that power utilization and LCC are profoundly sensitive to the sensor spacing; the larger the node distance, the more modest is the utilization and vice-versa. When the sensor spacing is less, more sensing nodes are required to sense which will increase the initial investment and power consumption (Halgamuge et al. 2009). This will escalate the operation and maintenance cost to a higher level. When the sensors are spaced at a very large distance, the accuracy of data will decrease. Thus, it is necessary to optimize the sensor placement to maximize the performance and to minimize the overall cost and power consumption.

REVIEW ON WIRELESS SENSOR NETWORKS
The architecture of a typical WSN is shown in Figure 1. The sensors scattered in a field (source nodes) sense, collect and route the information to the sink node. The sink node forwards the sensory data to the end-user or client via the internet using networking or communication technologies. A WSN covers many spatially distributed, battery-operated, embedded devices that are networked to collect, process and transfer the sensory data to the users.

Several technologies like Radio Frequency Identification (RFID), Global System for Mobile communication (GSM), General Packet Radio Service (GPRS), Zigbee, Long-Range wide-area network (LoRa), Bluetooth, Low Power Wireless Personal Area Networks (LoWPAN) and Wi-Fi systems using 2G, 3G and 4G networks have been used to transfer the sensory data in
A summary of earlier studies on WDS using WSN is presented in Table 1. The summary includes the focus of the study, sensors used, networking protocols employed and the key inferences.

<table>
<thead>
<tr>
<th>Authors &amp; year</th>
<th>Focus of the study</th>
<th>Sensors</th>
<th>Networking protocol</th>
<th>Remarks/Key points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stoianov et al. (2007)</td>
<td>Detect and locate the leaks and bursts</td>
<td>Pressure and pH sensors</td>
<td>Bluetooth and GPRS</td>
<td>Duty cycling of sensor nodes was adopted for power saving.</td>
</tr>
<tr>
<td>Christodoulou et al. (2010)</td>
<td>Detect and localize the leaks</td>
<td>Pressure, flow, humidity, acoustic, soil moisture and noise sensors</td>
<td>GPRS</td>
<td>Duty cycling was adopted for power saving. Stargate communication gateway was used to control the duty cycling of sensors. A decision support system was used for detecting and localizing leaks in WDS.</td>
</tr>
<tr>
<td>Whittle et al. (2010)</td>
<td>Hydraulic parameters (flow rate and pressure), water quality and acoustic parameters</td>
<td>Pressure, flow, pH and acoustic sensors</td>
<td>Wi-Fi</td>
<td>Wi-Fi is suitable for short-range communication. Decision support tools and software were used for simulation and optimization of water demand zones. Acoustic parameters are used for leak detection.</td>
</tr>
<tr>
<td>Ediriweera &amp; Marshall (2010)</td>
<td>Hydraulic parameters</td>
<td>Pressure and flow sensors</td>
<td>GPRS and GSM</td>
<td>GPRS and GSM are suitable for high-rate data transmission. Notifications and alert messages were sent to the consumers during anomalous events.</td>
</tr>
<tr>
<td>Alkandari et al. (2012)</td>
<td>Water quality parameters</td>
<td>pH, dissolved oxygen and temperature sensors</td>
<td>Zigbee+802.11 Ethernet radio</td>
<td>Zigbee is a low-cost and low power consumption protocol. Long-range data transmission can be achieved by coupling Zigbee with Ethernet.</td>
</tr>
<tr>
<td>Offiong et al. (2014)<em>, Lambrou et al. (2014)</em>, Cloete et al. (2016)<em>, Priya et al. (2017)</em></td>
<td>Water quality parameters</td>
<td>pH, dissolved oxygen, temperature, turbidity, electrical conductivity and oxidation reduction potential sensors</td>
<td>Zigbee</td>
<td>Zigbee is suitable for short-range communication.</td>
</tr>
<tr>
<td>Almazyad et al. (2014)</td>
<td>Detect and localize leaks</td>
<td>RFID tags</td>
<td>RFID</td>
<td>Power conservation was achieved by duty cycling.</td>
</tr>
<tr>
<td>Kruger et al. (2015)</td>
<td>Water consumption</td>
<td>Flow meters</td>
<td>6LoWPAN+Wi-Fi</td>
<td>Low power consumption, low cost, resolves co-existence problems occurring between network layers.</td>
</tr>
<tr>
<td>Public Utilities Board Singapore (2016)</td>
<td>Monitor the flow, quality and leak</td>
<td>Flow meters, pressure, pH, turbidity and temperature sensors</td>
<td>Radio frequency, 2G, 3G, Wi-Fi</td>
<td>Low cost, low power consumption and high data transmission. Alert messages were sent to the consumers in case of abnormalities.</td>
</tr>
</tbody>
</table>

*All the four studies focused on same water quality parameters and used the same networking protocol (Zigbee).

WDS. A summary of earlier studies on WDS using WSN is presented in Table 1. The summary includes the focus of the study, sensors used, networking protocols employed and the key inferences.

**REVIEW ON THE IOT**

IoT is a remarkable progression in the area of internet technology. It is a prominent research topic in the fields of engineering, science and technology due to its vast application as well as for its amalgamation of various communications and embedded technology in its architecture. An IoT network connects physical devices that share and retrieve electronic information. It
includes a wide variety of smart devices, ranging from tracking information from the human body to the production of large industrial machines (Kenton 2020).

The objective of implementing IoT is to obtain real-time useful information on the ground with minimal human intervention. IoT extends its solutions to various application domains such as home automation, agriculture, infrastructure, transportation, space, and healthcare industries, water systems and military works. Thereby, it gradually transforms them into smart systems. Here, the term ‘smart’ refers to the automation and remote operation of devices that can be accessed from anywhere with mobile phones or computers using an internet connection. The architecture of a typical IoT is shown in Figure 2. It consists of sensors that communicate to the cloud through gateway devices. A gateway acts as a bridge between sensors and cloud platforms. It can communicate with sensors/devices over different networking protocols and then the data is sent to the cloud. Once the data enters the cloud, analysis and processing take place. Finally, it can be sent to the intended user/client.

Sensors which are deployed in the physical devices are connected to an IoT platform: (i) to collect the data; (ii) to process and analyze the data; and (iii) to support the specific application services. These IoT platforms can precisely extract useful information. The information can be used to detect patterns and problems, generate alerts and make recommendations (Clark 2016). The most common four-level IoT architecture includes: (i) Perception Layer; (ii) Network Layer; (iii) Support Layer; and (iv) Application Layer as shown in Figure 3.

Burhan et al. (2018) described the architecture of IoT elaborately. (i) The ground layer is the perception or discernment layer. It is the actual physical layer and has a heterogeneous category of sensors for detecting actual conditions of the environment. For sustainable energy management, the perception layer can be coupled with solar panels, and piezoelectric, electromagnetic and thermoelectric harvesting techniques (Radhakrishnan & Wu 2018). (ii) The network layer is a transport layer, which transports the acquired data from source nodes to sink nodes using wireless communications. The network layer uses communication and networking technologies such as Wi-Fi, Bluetooth, LoRa, Zigbee, etc. for data transmission. (iii) The support layer is a data processing layer that stores, analyses and processes massive quantities of data (big data) received from the transport layer. Cloud computing is primarily used to manage the data in a centralized manner. (iv) The application layer
is the topmost layer and it describes all IoT-related applications. It is the connection between end-to-end IoT devices. This application layer is the service layer that is answerable for conveying application-specific services to the clients.

A summary of earlier studies on WDS using IoT is presented in Table 2. The details on the focus of the study, various sensors deployed, networking protocols along with IoT cloud platform used and key inferences are included in the summary.

**PROPOSED IOT ARCHITECTURE FOR RESIDUAL CHLORINE MONITORING**

The use of WSN and IoT in monitoring water quantity and quality parameters in WDS is reviewed in this paper. It is observed that a few parameters need more attention. One such key parameter that has to be monitored in real-time in WDS is residual chlorine concentration. The core reason behind which the residual chlorine parameter is not taken for real-time monitoring is the requirement of a high initial investment. Residual chlorine, also called free chlorine, is the minimal quantity of chlorine retained in water after it is applied for a certain period or contact time (Safe Water System, CDC 2014). The residual chlorine constitutes an important safeguard for water against microbial contamination during transportation from treatment plants to consumer points. It is correlated with the absence of microbes and is a gauge for the potability of the water (Safe Water System, CDC 2014).

A few studies have been carried out in continuous monitoring of residual chlorine concentration using amperometric, spectrophotometric, colorimetric and potentiometric sensors in a controlled environment (Banna et al. 2014; Yaroshenko et al. 2020). These sensors are useful in real-time monitoring of the residual chlorine in water but cannot be incorporated in IoT technology. Perelman & Ostfeld (2013) proposed the use of mobile sensors to monitor residual chlorine concentration to prevent contamination events and to increase system security in WDS. It was reported that inclusion of fixed sensors in addition to the mobile sensors was necessary for accurate results. Zidan et al. (2018) developed a prototype to monitor and control chlorine at the desired level in a water treatment plant in a controlled lab environment. An ultrasonic level sensor and residual chlorine sensor in conjunction with an Arduino controller measured the tank water level, tank chlorine level and chlorine concentration in the measuring station. The dosing pump was controlled based on the chlorine concentration in the measuring station. The sensed data received by the gateway devices were transmitted to the cloud using Wi-Fi technology. MongoDB, a web-based cloud application, was used to analyze and process the chlorine data and to alert users directly in the case of variations in chlorine concentrations, system errors and abnormal water quality conditions. However, real-time monitoring of residual chlorine over a large-scale WDS is yet to be explored.

In this paper, an IoT-based monitoring of residual chlorine in WDS is proposed and the architecture is shown in Figure 4. For measuring residual chlorine, flow-through-type chlorine sensors are preferred where the sensors can directly be immersed in water. They can measure the residual chlorine in a range of 0 to 20 mg/L, the pressure range is up to 1 bar and the resolution can be 0.01 mg/L with an accuracy of ±2%. This type of sensor can be directly connected to microcontrollers and can be easily deployed in any WDS.

Remote monitoring of residual chlorine in WDS demands low data rate and long-range data communication. Thus, LoRa technology can be an ideal networking technology to monitor the residual chlorine in WDS stretching over several kilometres. The cloud platform has to be decided depending upon the client services provided by the service providers. The profit of monitoring residual chlorine in WDS using IoT outweighs its cost by providing benefits like public health and acting as an early warning system. The day and night continuous monitoring of residual chlorine in the system is possible and it can be viewed as graphical charts and tables using application services.

**IMPRESSION**

From the detailed review, it is observed that the WSN and IoT narrowed the use of long-distance wiring and human expertise. The life-cycle cost of a sensor depends on the optimal placement of the sensor. The larger the sensors spacing, the less is the power consumption. Closer spacing of sensors increases the power consumption and thereby increases the operation cost besides the capital cost. Optimal sensor placement is a key factor in deploying WSN and IoT technology; it helps in stimulating the performance of WDS.

Communication technologies like Wi-Fi, Zigbee and LoRa have been mostly preferred in real-time monitoring. Wi-Fi technology is preferred in water quality monitoring due to its low cost, high speed, wide coverage area, common standards and easy interfacing between hardware and software components. However, it has a few drawbacks, such as high power consumption, low coverage area and the requirement of a central access point. It is noted that the Zigbee protocol has been.
Table 2 | Summary of earlier studies on smart monitoring of WDS using IoT

<table>
<thead>
<tr>
<th>Authors &amp; year</th>
<th>Focus of the study</th>
<th>Sensors</th>
<th>Networking protocol</th>
<th>Cloud platform</th>
<th>Remarks/Key points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verma et al. (2015)</td>
<td>Monitoring the tank water level and the volume of water available for supply</td>
<td>Ultrasonic water level sensor</td>
<td>Sub-GigaHertz radio network+Google App Engine</td>
<td></td>
<td>Duty cycling was adopted for power saving. The cloud platform provides an online data visualization in graphical patterns and performs data analytics.</td>
</tr>
<tr>
<td>Anjana et al. (2015)</td>
<td>Monitoring the water supply and water quality and controlling wastage by deploying smart water metering system</td>
<td>Flow meters, pH and oxidation reduction potential sensors</td>
<td>6LoWPAN+MySQL data+Visual Studio Express 2013</td>
<td></td>
<td>Daily and monthly water consumption was monitored. Tracks and monitors the water quality parameters. In the case of variations in the supply, SMS alerts were sent to the consumers. Automatic leak detection helped to localize the leaks and control the flow. The system was used to identify overconsumption and wastage.</td>
</tr>
<tr>
<td>Shahanas &amp; Sivakumar (2016)(^a), Geetha &amp; Gouthami (2017)(^a)</td>
<td>Monitoring the tank water level and water quality parameters</td>
<td>Ultrasonic water level, pH, conductivity, turbidity and temperature sensors</td>
<td>Wi-Fi+Ubidots</td>
<td></td>
<td>Low cost and low power consumption. Suitable for short-range communication. Consumer alert messages were sent in the case of any contamination events in the WDS. Daily and weekly average water consumption was monitored. The data was used to identify the consumption rate and for demand forecasting.</td>
</tr>
<tr>
<td>Shirode et al. (2018)(^a), Nikhil et al. (2018)(^a)</td>
<td></td>
<td></td>
<td>Wi-Fi+Thingspeak</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Devasena et al. (2019)(^a), Gautam et al. (2020)(^a)</td>
<td></td>
<td></td>
<td>Wi-Fi+cloud platform not mentioned</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuentes &amp; Mauricio (2020)(^a)</td>
<td></td>
<td></td>
<td>Wi-Fi+IBM cloudant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saravanan et al. (2018)(^a)</td>
<td>Monitoring the hydraulic and water quality parameters</td>
<td>Flow and temperature sensors</td>
<td>GPRS, GSM, SCADA system+cloud platform not mentioned</td>
<td></td>
<td>Live data streaming and analysis heading to better decisions. Alerts were given in the case of abnormalities in supply.</td>
</tr>
<tr>
<td>Srihari (2018)(^b)</td>
<td>Control water crisis</td>
<td>Flow and pH sensors; water control valve</td>
<td>Ethernet+MQTT protocol+cloud platform not mentioned</td>
<td></td>
<td>IoT-based WDS ensure equity in water distribution. Alert notifications were sent to the consumers in the case of abnormal events in the system and supply.</td>
</tr>
<tr>
<td>Das &amp; Jain (2017)(^b), Rajurkar et al. (2017)(^b)</td>
<td>Monitoring the rate of flow and water consumption, controlling wastage</td>
<td>Flow sensor</td>
<td>Zigbee+Thingspeak</td>
<td></td>
<td>Zigbee is suitable for short-range communication. Consumption data was sensed for all seasons and used to forecast the water demand. Current and average water consumption were measured. Alert messages were sent to the consumers in the case of overconsumption.</td>
</tr>
<tr>
<td>Alves et al. (2019)(^b)</td>
<td></td>
<td></td>
<td>Zigbee+Firebase Android Studio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chinnusamy et al. (2018)(^a)</td>
<td>Monitoring the tank water level, rate of flow and water quality parameters</td>
<td>Ultrasonic water level, flow, pH, dissolved oxygen, turbidity</td>
<td>LoRa+Graffna</td>
<td></td>
<td>LoRa is suitable for long-range data communication. It is a low power consumption protocol. Control (Continued.)</td>
</tr>
</tbody>
</table>
Zigbee is preferred for real-time monitoring of WDS which demands low data rates and short-range communication. LoRa technology is also preferred for its low cost, low power, wide-coverage, long-range communication, and security. LoRa enables long-range communication links extended to several kilometres with high sensitivity and computing anti-interference. Thus, it is suggested that this LoRa communication is a better option for remote monitoring of WDS that runs several kilometres and covers a wide area.

CONCLUSION

In this paper, earlier studies on monitoring, diagnosing and controlling the water distribution system remotely and continuously using Wireless Sensor Networks and the Internet of Things were reviewed. The use of WSN and IoT is a low-cost solution, reduces human intervention and also generates greater benefits for society. In future, integration of information and communication technologies for water resources monitoring and management will be inevitable. It is noted that power savings and performance enhancement can be achieved by optimally placing the sensors.

It is concluded that the Zigbee communication protocol can be used for short-range monitoring and LoRa for long-range monitoring. It is proposed that this LoRa communication is suitable for remote monitoring of residual chlorine concentration in WDS. The WSN and IoT-based Smart Water Grid assists in making evidence-based decisions on managing water quantity and quality. SWG is a promising solution with the ability to provide extended benefits to utilities and users through remotely
and continuously monitoring and managing the system using data-driven insights. Smart Water Grid can provide the water authorities with propitious solutions in managing precious resources more effectively and economically.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

**REFERENCES**


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