An Energy-Efficient Protocol Based on Semi-Random Deployment Algorithm in Wireless Sensors Networks

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Abstract

The merger between embedded systems and wireless communications has given birth to a new technology called wireless sensor networks. The main purpose of these types of networks is to be able to monitor the area in which the sensors are deployed, in order to collect information and make decisions. The decisions made by the end user thus depend on the quantity and quality of information received at the base station. Therefore, the sensors must be able to collect as much information as possible in the area of interest (AoI), resulting in maximum coverage of this area. Due to the low capacities of sensors, coverage and data collection algorithms need to be energy efficient to ensure a fairly long network lifetime. In this paper we focus on maximizing network lifetime while collecting and sending a big quantity of data to the base station. Our solution is executed in two stages; the first of which is to cover the network as much as possible using static nodes and mobile nodes, and the second presents the process of collecting and processing data to the base station. Compared to many other algorithms in the literature, our solution is better in terms of coverage percentage of the AoI, data received by the base station and in terms of energy consumption.

Keywords: Area Coverage; Energy Consumption; Sensors Deployment Problem; Wireless Sensor Network

1 Introduction

In recent years, the need to observe and control physical phenomena such as temperature, pressure or brightness is essential for many industrial and scientific applications. As a result, many technical and technological advancements in the fields of microelectronics, Micro-mechanical and wireless communication technologies have made it possible to create small communicating objects equipped with a measurement unit, a computing unit, a memory unit and a radio unit for communicating [16]. The massive deployment of these devices in a given area, allows to establish a network whose nodes are sensors: it is a wireless sensors network. With their various advantages, this technology has established itself as a key player in today's communication network architectures [17]. A wireless Sensor Network (WSN), which is a targeted wireless network, consists of a significant number of miniaturized electronic devices, called sensors, distributed over a specified area in order to sense the environment and communicate the accumulated information from the monitored field to other networks (*e.g.*, the internet) [8]. These networks have been extensively used for monitoring of various physical or environmental conditions. These networks are typically deployed in hard-to-reach areas for humans, and once deployed, sensors must work unattended. A WSN has several application perspectives and each application has its own constraints. However, in all areas, the role of a sensor network is almost always the same: the sensors must monitor certain phenomena and send information to a base station, which in turn relays them to an end user via internet [15].

A network of sensors suffers from several technical weak points such as communication range, monitoring range, low battery, and network deployment circumstance problems such as the difficulty of building a sensor network in volcanoes, mountains, or in the oceans [4]. Sensor deployment can either be deterministic or random. In deterministic deployment, coverage can be maximized as a result of optimal placement of sensor nodes. Random deployments are preferred when the region information is not known apriori [1].

In such systems, maximum coverage of the AoI and full connectivity between the deployed nodes are two important factors in sending as much good quality information as possible to the end user through the base station for better decision-making. This can be illustrated when resolving problems like detecting and tracking of intruders in restricted areas or monitoring volcanic zones. Such applications require full area coverage. Furthermore, the most critical zones should be covered by more than one sensor node.

Various works have been done in the literature in order to solve this type of problems after deployment of sensor nodes. Some of them consider random deployment, others consider a deterministic deployment while others consider both. In this paper, we propose a method to cover as much as possible the AoI after semi-random deployment, using both static and mobile sensors while ensuring full connectivity between the deployed nodes. This method is followed by an algorithm of scheduling node activity that minimizes the energy consumption of the nodes while collecting and sending data to the base station [21]. Despite the encouraging results presented in this paper, what is left is to include a security mechanism to secure the information exchanged by the nodes of the network [14].

The remainder of this paper is organized as follow: In Section 2 we present the various works dealing with the deployment, coverage and connectivity problems; in Section 3, we describe our contribution, then in Section 4 we present differences between our protocol and some other protocols existing in literature. Section 5 deals with some experimental results. A conclusion with open problems ends the paper.

2 Related Works

In the literature, the coverage problem is separated in three types of coverage: Area coverage, barrier coverage and point coverage. Works presented in [10] have been done in order to introduce basic concepts related to coverage and connectivity.

2.1 Area Coverage and Connectivity

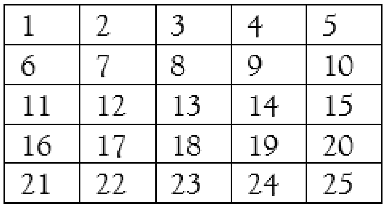
The goal in the area coverage problem is to cover the whole area. Therefore, in some cases, the number of sensors is not sufficient; the goal of area coverage becomes maximizing the coverage rate. Works intended to resolve area coverage and connectivity problem are massively done. Recently, [9] proposed a solution which guarantees maximum coverage of the AoI and connectivity between sensors. A schedule algorithm is also proposed in that paper in order to minimize energy consumption of both static and mobile nodes, and both normal nodes and CH. The clustering protocol used and the strategy of feeding empty clusters are not optimal and therefore, sensors exchange too much messages during the first stage of the algorithm. In [19], authors propose a Distributed Scheduling Medium Access Control (DSMAC) algorithm for optimizing the network lifetime of sensor nodes. The geographic distribution of sensor nodes takes into account coverage and network connectivity constraints. Furthermore, DSMAC algorithm allows a full coverage of the monitoring area; but the process of sending data to the base station is not scheduled. In [4] authors achieve both random and deterministic deployment in order to cover as much as possible the area of interest. After deployment, they propose a random node activity scheduling which relies on a random number P_i that helps to determine the next node to be activated to monitor information in a cluster. Thus a node whose residual energy is finished can be chosen to be activated and, since this node is the one that has to select the next node to be activated in a cluster using P_i, this cluster can be paralyzed and sensors in this cluster won't be able to collect information anymore. Connectivity between sensors of this cluster and sensors of the other clusters is therefore impossible. [2] proceeds to a random deployment of static nodes and thereafter, proceeds to deployment of some mobile nodes that are used to repair the coverage holes after initial deployment of the static nodes. This solution ensures a good coverage ratio but not connectivity between sensors. [11] proposed an algorithm that guarantees full coverage and multiple connectivity [10] after regular sensors deployment. But this solution assumes that the AoI is regular. In [8], a deployment approach based on flower pollination algorithm (FPCOA) was proposed. This approach can find the optimal placement topology in terms one QoS metric and ensures simple connectivity between sensors but it did not incorporate other QoS metrics like energy consumption

2.2 Barrier Coverage and Connectivity

Wireless sensors networks are not only designed to sense events occurring in the deployment area; they can also be used to detect intruders that attempt to penetrate in this area. So, the goal of barrier coverage is to guarantee that every intruder crossing the barrier of sensor will be detected. Few works are present in the literature for barrier coverage and connectivity. Nevertheless, we can cite the solutions of [20] and [13]. [20] provides partial coverage after a centralized and probabilistic deployment. The connectivity in this case is intermittent; Meaning that, some of the deployed sensors can not communicate with the base station. [13] made The assumption that $R \geq r$ where R is the communication radius and r is the sensing radius in order to ensure full coverage and permanent connectivity after a distributed and deterministic deployment.

2.3 Point Coverage and Connectivity

It is often unnecessary to monitor the whole area in many applications; thus monitoring some specific points is sufficient. Each of these points (called point of interest (PoI)) should therefore be covered by at least one sensor node. [6] assume that PoI are static and guarantee temporary coverage and intermittent connectivity with random deployment and distributed algorithm. [5] resolved a similar problem differently, and consider that PoI are not static. [7] considers the problem of full coverage with permanent connectivity. In fact, the authors ensure full



1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25

Figure 1: Subdivision of AoI in sub-areas

coverage of the PoI using forced based deployment algorithm. These solutions do not propose a node scheduling activity to minimize the energy consumption of the sensors.

Each of the works presented in this section addresses the problem of coverage and connectivity in different ways. However, depending on the constraints related to the deployment environment or the types of sensors, the proposed protocols rarely take into account the energy consumption of the sensors and their activity during the lifetime of the network. The solution proposed in this paper ensures full maximum coverage of the AoI, connectivity between sensors and minimizes energy consumption of the sensors. It also guarantees that the roles of the different CHs can be exchanged because of the use of ICP [12]. Finally the scheduling algorithm allows to collect any event occurring in the AoI and send it to the base station.

3 Our Contribution

3.1 Assumptions and Notations

3.1.1 Assumptions

In this work, it was assumed that:

- The area of interest is a square of side C;
- The area of interest must be divided geographically by N_z sub-areas of dimension L×L and diagonal D as shown in Figure 1;
- Using [12], the number of CHs can be estimated;
- All the sensor have the same sensing range and the same communication radius and are able to know in which sub-area it has been deployed.

3.1.2 Notations

In the rest of this work, we will use some notations that we define in this section:

- T_i: Awakening time of a normal node;
- T_s: Time used by a normal node to send data to its CH and receive an acknowledgment;
- T_c: Time used by a normal node to collect data in its cluster;
- T_{ne}: Next awakening time of a normal node;
- N_c: Number of sensors of a cluster;
- T_{sSB}: Time after which a CH should send data to the base station;
- R_c: Communication radius of a sensor;
- R_s: Sensing radius of a sensor;
- n_{zc}: Number of sub-areas covered by a CH;
- n_{znc}: Number of non covered sub-areas;
- N_z: Total number of sub-areas;
- S: The set of sub-areas;
- S_{CH}: The set of sub-areas covered by a CH.

3.2 Mathematics Models

We represent the WSN by a graph G = (V;E), where V represents all nodes of the network and E represents the set of edges giving all possible communications.

3.2.1 Coverage Model

Let A represent the AoI and q a point located in A. The area covered by a sensor S_i∈V is defined as the total area located within R_s [17]. Analytically, the area covered by a sensor S_i∈V is given by Equation (1):

$$C(S_i) = \{q \in A / d(S_i; q) \leq R_s\} \tag{1}$$

So, the area covered by a set of sensors S = {S_1, S_2, ..., S_k} is analytically defined by Equation (2):

$$C(S) = \bigcup C(S_k), k = \{1, ..., |S|\} \tag{2}$$

3.2.2 Connectivity Model

Let us consider S_i and S_j two sensors nodes deployed in the AoI. S_i and S_j are directly connected (one-hop connectivity) if and only if d(S_i;S_j)≤R_c. According to [18], a WSN is considered to be connected if there is at least one path between the sink and each node in the considered area.

3.2.3 Lifetime Model

Let M = {S_1, S_2, ..., S_n} be the set of nodes of a wireless sensor network; S_i ∈ M a given node with lifetime T_i. In [17], network lifetime is defined by the duration within which the network is deployed and the first node loses all its residual energy. So, if T_n is the network lifetime, it is computed as follows (equation (3)):

$$T_n = minT_i \tag{3}$$

3.3 First Stage: Area Coverage Procedure

The first stage of our solution consists in covering as much as possible the AoI in order to collect a maximum number of information. To achieve this, we proceed as follows:

- First deploy deterministically the different CHs in the AoI such as d(CH_i,CH_j)$\leq 2R_c$ and such as each CH is placed at the center of its sub-area;
- Static nodes are then randomly deployed in the AoI. The idea here is to allow each sensor to belong to the cluster of a CH;
- Application of ICP [12] to initiate clustering. In ICP, acknowledgments are deleted in order to reduce energy consumption during the clustering process. But in our case, acknowledgments will be allowed in order to permit to each sensor to send an acknowledgment to its CH. So, the clustering process becomes:
  - Each CH broadcasts its id to neighbors sensors;
  - If a sensor receives one message from one CH, it becomes a cluster member (CM) of this CH; but if it receives many messages from many CH, it becomes a gateway (GW) node for all the clusters of these CH;
  - Sensors can then send an acknowledgment to the CH containing its id, its role (CM or GW) and the identifier of the sub-area in which it is located;
  - When a CH receives an acknowledgment, it increments the variable n_{zc};
  - After reception of all acknowledgments, each CH then broadcasts the ordered list of its cluster's members to all its cluster's members with parameters T_i, T_s, T_c and N_c. Thus, each sensor will be able to know its CH and all its neighbors in a cluster.

Theorem 1. *Let S_{CH} be the set of sub-areas covered by a CH. The number of non covered sub-areas n_{znc} can be computed by $n_{znc} = N_z$ - $\mathbf{C}(\bigcup(S_{CH}))$ where* ***C*** *is the function to determine the cardinal (number of elements) of a set.*

Proof. Since N_z is the total number of sub-areas, n_{znc} can be obtained by a substraction between N_z and the total number of sub-areas covered by the different CHs. Since two CHs can cover the same sub-areas, the function **C** such a way that it removes duplicates entries. Finally, the application of the function C($\bigcup(S_{CH})$) makes it possible to obtain the exact number **n** of sub-areas covered by the different CHs; and therefore, doing N_z-n yields the number of uncovered sub-areas. □

At the end of the previous steps, each static sensor knows in which cluster it belongs. if n_{znc} is equal to zero, the AoI is fully covered. Else, the challenge is to find a way to cover non covered sub-areas using mobile nodes. To do this, we proceed as follows:

- First we determine the identifiers of all non covered sub-areas using formula: S $\setminus \bigcup(S_{CH})$);
- Secondly, we deploy mobile nodes in these sub-areas.

The algorithm of this stage is given by algorithm 1.

Algorithm 1 AoI coverage

```
Begin
Deterministic deployment of CHs.
Random deployment of static nodes.
Each CH broadcasts its id.
if sensor receives only one message then
    Become a cluster member of the CH.
end if
if sensor receives many messages then
    Become a gateway node.
end if
Sensors can then send an acknowledgment to the CH containing its id, its role (CM or GW) and the identifier of its sub-area.
Each CH broadcasts a list of its cluster's members with the parameters $T_i$, $T_s$ and $T_c$ to its cluster's members.
Computation of $n_{znc}$.
if $n_{znc} == 0$ then
    End of the coverage process.
end if
if $n_{znc} \neq 0$ then
    determine the identifiers of all non covered sub-areas.
    deploy mobile nodes in non covered sub-areas.
end if
End
```

3.4 Second Stage: Node Scheduling Algorithm and Sending Data to the Base Station

In this section, we describe how the nodes will be scheduled in order to collect and send data to the base station. Since normal nodes and CH are scheduled differently, we thus propose two algorithms that will permit us to manage both CH and normal nodes simultaneously.

3.4.1 Normal Nodes Scheduling Algorithm and Sending Data to the CH

Each node has in its memory the ordered list of its neighbors; so it knows when it should wake up and begin collecting or sending data. According to our notations, a normal node remains awake during T_i. We therefore pose $T_i = T_s + T_c$. So, a normal node executes these instructions when it is awakened:

1) It starts by computing the next time after which it should be awaken with the formula: T_{ne}=(N_c-1)T_i;

2) If this node has data collected previously in its memory, it sends it to its CH and waits for an acknowledgment during the time T_s;

3) It remains awake during the time T_c waiting for an event to occur in the AoI;

4) The sensor falls asleep after T_i.

The pseudo-code of our description above is given by the algorithm 2.

Algorithm 2 Normal nodes scheduling algorithm and sending data to the CH

```
Begin
Computation of $T_{ne}$.
if node has data in its memory then
    Sending data to the CH during $T_s$.
    Stay awake during $T_c$.
    Fall asleep after $T_i$.
end if
if node has no data in its memory then
    Sending data to the base CH during $T_i$.
    Fall asleep after $T_i$.
end if
End
```

3.4.2 CH Scheduling Algorithm and Sending Data to the Base Station

Our solution recommends that every T_{sSB}, a CH must send data to the base station. T_{sSB} is computed with the formula: $T_{sSB} = N_c$*T_s; which means that, after one round of diffusion of its cluster members, it starts sending data to the base station. Before sending these data, the CH starts by executing the second part of the DSMAC algorithm [17] which will permit them to synchronize sensors belonging to the path relying the CH and the base station by sending beacon frames. This will permit us to know all the nodes that will remain awake during the transmission of data to the base station. The CH can then initiate the transmission. Algorithm 3 describes the pseudo-code of this solution.

4 Comparative Study Of Our Protocol With Some Others Existing Protocols

In Table 1, we make a comparative study between our protocol and some others.

Algorithm 3 CH scheduling algorithm and sending data to the base station

```
Begin
i=1.
while i $\leq N_c$ do
    Waking up every $T_i$ and stay awake during $T_s$.
    Receive data from a normal node and send an acknowledgment to this node.
    T = $T_s$*i.
    if T == $T_{sSB}$ then
        Determining the nodes in charge of forwarding data to the BS.
        Sending data to the BS.
        i=1.
    end if
    if T $\neq T_{sSB}$ then
        i=i+1.
    end if
end while
End
```

5 Performance Evaluation

In this section we evaluate the performance of our approach and compare it to other approaches. The simulation conditions are shown in the Table 2.

The following curves are the result of at least 100 experiments. In our implementation, the MAC layer is managed in such a way that a node can only receive one message at a time.

5.1 Coverage Ratio

In Figure 2, we make a comparison between our protocol and several others in terms of coverage ratio. In fact, the comparison is made between our protocol and FPCOA [8], SRDP [4] and A2CDC [9].

Because of the semi-random and semi-deterministic deployment, our protocol has the best coverage ratio compared to FPCOA and A2CDC. Since SRDP uses a deployment strategy similar to ours, our algorithm used to feed empty clusters allows us to obtain a better coverage ratio.

5.2 Number of Transmissions During Clustering Stage

The major improvement highlighted in this paper concerns the partitioning protocol and therefore the coverage algorithm. Indeed, it was a question of increasing the coverage ratio while minimizing the energy consumption spent by the sensors during the clustering and coverage phase. This was done by reducing the number of transmissions and messages exchanged during the clustering phase. Figure 3 illustrates graphically what we are explaining.

Table 1: Comparison between our protocol and some others

Protocols	**Deployment strategy**	**Node scheduling algorithm**	**Clustering algorithm**
FCOA [8]	Random	No	No
SRDP [4]	Semi random and semi deterministic (square based)	Random selection of the next activated node	Yes
DSMAC [19]	Deterministic (square based)	Deterministic selection of the next activated node	No
A2CDC [9]	Random	Deterministic selection of the next activated node	Wadaa et al. [22] and Bomgni et al. [3]
Our protocol	Semi random and semi deterministic (square based)	Deterministic selection of the next activated node	ICP [12]

Table 2: Conditions of the simulations

Configurations	Value
Communication and sensing radius	8 m
Area of interest (AoI)	100m×100m
Initial sensor's energy	1000 J
Deploy sensor nodes number	Up to 200

5.3 Network's Lifetime

We compared the efficiency of our protocol with three other protocols named Flower Pollination Coverage Optimization approach (FPCOA) [8], Semi-Random Deployment Protocol (SRDP) [4], DSMAC [19] and A2CDC [9] in terms of energy consumption. The results are shown in Figure 4.

Our protocol is clearly better than the one of SRDP, FPCOA, DSMAC and A2CDC in terms of energy consumption. Since FPCOA doesn't use a clustering scheme to maintain connectivity and reduce energy's consumption of the sensors while exchanging messages, it consumes more energy. The SRDP protocol certainly uses a clustering algorithm, but the latter is not really efficient. In fact, clusters are formed by exchanging *hello* messages between CH and its members. Furthermore, this protocol guarantees connectivity and data harvest by randomly activating a sensor which will collect data in the cluster each time. The fact that the active sensor is determined randomly after a computation of a random parameter P consumes more energy at each time that a sensor has to be activated. Finally, the clustering protocol used in A2CDC is more expensive in terms of energy consumption than the one used in our protocol; Which results in very low power consumption from the beginning of our protocol, due to the very small number of messages exchanged during the clustering phase.

5.4 Average Packets Received By The Sink

Figure 5 illustrates that our protocol outperforms DSMAC, SRDP, FPCOA and A2CDC according to the num-

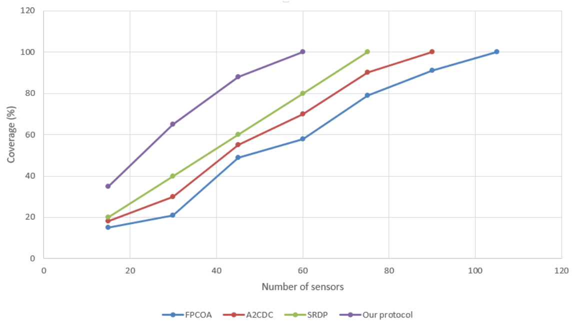


Figure 2: Coverage ratio

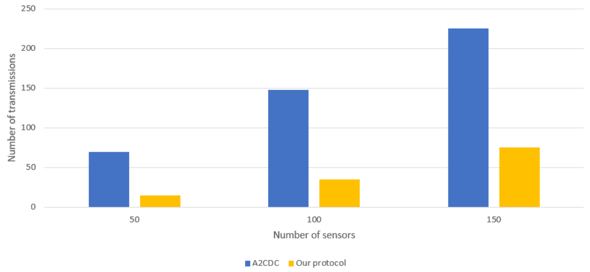


Figure 3: Transmission amount

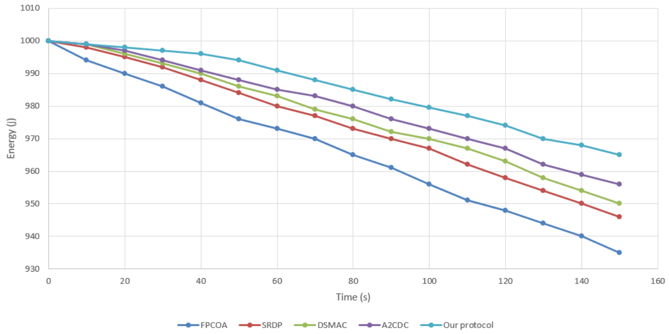


Figure 4: Network's lifetime

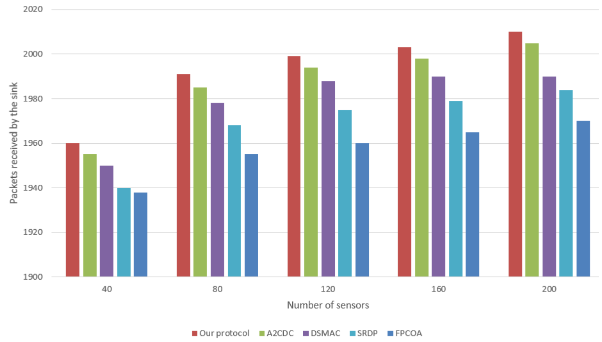


Figure 5: Average packets received by the sink

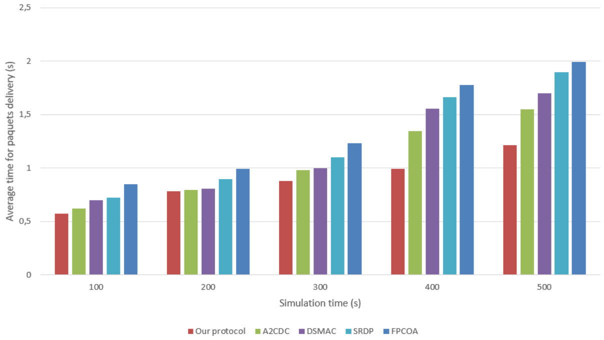


Figure 6: End to end delay

ber of packets received by the Sink. The main reason is due to the fact that our protocol avoids collisions because of the implementation of the CSMA/CA protocol and is based on DSMAC algorithm which mitigates the number of collisions. Our protocol is better than A2CDC only because of the type of deployment. In fact, deterministic deployment ensures more connectivity than random deployment.

5.5 End-to-End Delay

End-to-End delay refers to the time taken for a packet to be transmitted across a network from source to destination. Figure 6 shows that our protocol outperforms DSMAC, SRDP, FPCOA and A2CDC, due to better connectivity between the sensors and better sensors positions within the network.

6 Conclusion

In this paper, we propose an **energy-efficient protocol based on semi-random deployment algorithm ensuring better quality of service and connectivity in wireless sensors networks**, a protocol that aims to optimize coverage and network connectivity while minimizing the energy consumption of sensors during information exchange. To solve the problem, our protocol takes place in two phases: we firstly present our approach to guarantee full coverage of the AoI based on both deterministic and random deployment of sensors, and secondly, we use an algorithm similar to the one presented in [9] to schedule normal nodes and CHs during the phase of collecting data in the monitored area and the phase of sending data to the base station. The proposed approach has been compared with several other approaches in the literature in term of energy consumption, total number of transmissions and average number of packets received by the BS. Experiments show that our solution is better than the other approaches, guarantees connectivity, reduces the number of transmissions and messages and avoids collision of messages.

The results presented in this paper are really encouraging, but several open problems remain. In future work, we plan to introduce a security protocol to ensure the integrity of the data circulating in the network.

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