Cognitive Wireless Sensor Networks Framework for Green Communications Design

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Abstract— **Cognitive Wireless Sensor Networks is an emerging technology with great potential to avoid traditional wireless problems such as reliability, interferences and spectrum scarcity. Because of the Wireless Sensor Network fast growth and the use of batteries, current rate of power consumption per unit of data cannot be sustained. Therefore, one of the major challenges face today is low power consumption in Wireless Sensor Networks.Cognitive Wireless Sensor Networks framework is a key issue in green communications because of many protocols, strategies and optimization algorithms could be tested. In this paper a framework composed of a network simulator with cognitive capabilities and low power Cognitive Wireless Sensor Networks real devices with a feedback relation is presented. The benefits of the proposed framework are demonstrated with three different scenarios and simple cognitive green communications strategies. Results show how new concepts have been integrated in the framework with good results and as simple cognitive radio strategies can reduce large amount of power.**

Keywords-cognitive; framework; low power design; wireless sensor networks

I. INTRODUCTION

Wireless network power consumption has not been an important research issue because it has been insignificant in comparison with wired network consumption. Over the recent years, wireless and mobile communications have increasingly become popular with consumer. According to [1], global mobile data traffic will increase 26-fold between 2010 and 2015 (in 2010 global mobile data traffic grew 2.6-fold). Mobile data traffic will grow at a compound annual growth rate of 92 percent from 2010 to 2015, reaching 6.3 exabytes per month by 2015. Taking into account this prediction, the current rate of power consumption per unit of data cannot be sustained.

In regards to wireless networks, one of the fastest growing sectors in recent years was undoubtedly Wireless Sensor Networks (WSN). According to the report [2], WSN market will grow rapidly from $0.45 billion in 2011 to $2 billion in 2021. WSN are increasingly introduced into our daily lives. Potential fields of applications are from home control to military scenarios or critical information infrastructure protection. In this kind of scenarios, lifetime of the nodes typically ranges from 2 to 5 years, making power consumption a dramatic requirement to establish. Thus, reducing energy consumption is one of the most important challenges to face when designing WSN.

Recently, to increase lifetime (as well as other very important problems like spectrum scarcity, interferences or reliable connections), most WSN rely on the new cognitive paradigm. Cognitive Network is an intelligent wireless communication system that is aware of its surrounding environment, and with the possibility to adapt its internal parameters to achieve reliable and efficient communications (in terms of power consumption too) [3]. This solution benefits from “free” environmental energy according to the “green” philosophy, which is to reduce the carbon footprint and to improve reliability of power supply automations.

In order to enable design and development of new green protocols and power reduction techniques for Cognitive Wireless Sensor Networks (CWSN) and evaluate their performance, simulation and emulation environments are necessary. The challenge in simulators is to determine if these simulations provide us a good enough correspondence with real deployments. In this paper, a complete simulation and emulation framework for CWSN using regular standards is presented. The simulator is based on the Castalia simulator including all the cognitive modules. The simulations are fed with real CWSN devices to provide a more realistic approach.

The organization of this paper is as follows. In Section 2, works in CWSN simulator and emulator frameworks are reviewed. In Section 3, new CWSN framework is described. In Section 4, a proof of concept is shown. Finally, the conclusions are drawn in Section 5.

II. RELATED WORK

Because of the novel research field, there are not many specific frameworks for green communications design over CWSN. It is natural that most of works are based on WSN simulators.

There are several WSN simulators used by researchers to develop their works. For example, NS-2 [4] is one of the most well-known simulators. Most of the WSN research society uses this simulator, although the latest release was in 2008. NS-3 will be its substitute, but it is still in the early stages. OMNET++ [5] is another framework very well-known among researchers. It proposes a modular library which could be used to develop network simulators. Only by composing different modules, the developer can create its own simulator or scenario.

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Several other simulators have been developed for WSN. TOSSIM based on the TinyOS operative system, COOJA, OPNET, GloMoSim, JSim, NetSIm, QualNet, etc. are more WSN simulators without cognitive features.

In [6], Vijay, et al. show different approaches to CWSN, like architectures or techniques. Inside the techniques section, an implementation of cognitive solutions over OPNET simulator is mentioned [7]. They implement a comparison between standard ZigBee protocol and a new one with a CR mode, which can detect incumbent users. However cognitive features are basic.

In SEnsor Network for Dynamic and cOgnitive Radio Access (SENDORA) FP7 project simulator platforms have been developed. In [8], the SENDORA system level simulator is described. The simulator is based on the network simulator NS2, enhanced with the Miracle extension, which provides the support of multi-layer, multistack architecture, and a more realistic propagation model to simulate different network protocols over the same physical channel. The Miracle modules are:

- Sengine: manages the sensing information coming from the Sensing module. Optionally it manages the cooperative sensing communications.
- WSNNet: takes care of routing issues. It fills the packet field related to the next hop for the communication.
- WSNMAC: implements the S-TDMA based access scheme. Sensors are synchronized to a timeframe.
- WSNPhy: manages the transmission power. Sensors use the minimum transmission power that allows them to receive and decode correctly all the packets with a given probability.
- Sensing: implements the sensing process and all sensing algorithms.
- Channels: simulates the transmission over a channel and enables the sensing process.

Others, even more important aspects, such as collaborative spectrum sensing, information sharing or output data obtaining are not yet implemented in any CWSN simulator.

A lot of work on CWSN simulation should be done in order to get the next step in the development cycle: the implementation. Only few works could be found on CWSN implementation. An example of implementation is [9]. The AUTOMAN system is used as a platform to create a monitoring application. The system controls power consumption and voltage fluctuation in a WSN. This is one of the first real systems that use cognitive capabilities to improve some network parameters.

After the simulation stage, researchers usually use a test-bed, before the real implementation. There are multiple test-beds for specific developments. Two are the most important test-beds nowadays: TWIST [10] and VT-CORNET [11] because of their general purpose features and their quality.

The TKN Wireless Indoor Sensor Network Test-bed (TWIST) is a multiplatform, hierarchical test-bed architecture developed at the Technische Universität Berlin. The self-configuration capability, the use of hardware with standardized interfaces and open source software make the TWIST architecture scalable, affordable, and easily replicable. The TWIST instance at the TKN office building is one of the largest remotely accessible test-beds with 204 SUT (system under test) sockets, currently populated with 102 eyesIFX and 102 Tmote Sky nodes. The nodes are deployed in a 3D grid spanning 3 floors of an office building at the TUB campus, resulting in more than 1500 m^2 of instrumented office space.

The Virginia Tech COgnitive Radio NEtwork Testbed (VT-CORNET) is a collection of Cognitive Radio nodes deployed throughout a building at the Virginia Tech main campus. The test-bed consists of a total of 48 Software-Defined Radio nodes. Test-bed is implemented with a combination of a highly flexible RF front end, and an openly available Cognitive Radio Open Source System framework.

Research on CWSN simulators is emerging, but it is in a primary state. The simulation with a high number of nodes is necessary in WSN scenarios. It is very expensive to build a lot of real devices to test a concrete low power strategy. The integration of real data devices and a high number of nodes is only possible using a feedback relation. Currently, there is not a CWSN simulator with standard protocols and real devices feedback that uses cognitive characteristics for intelligent energy management in order to test new policies, to assess collaboration schemes or to validate different optimization mechanisms. SENDORA, the only simulator with cognitive capabilities does not use real device data for the power model. Therefore, an implementation of a new completely cognitive module over a WSN simulator, specifically Castalia Simulator [12], based on OMNET++ framework and a new CWSN device with three different radio standard interfaces is proposed.

III. CWSN FRAMEWORK

Most common network simulators have tested energy models, but these are theoretical models covering general cases. So, it is necessary to introduce real measured data by a cognitive radio prototype developed to make these simulations become more realistic. Thus, it is also possible to find differences in commercial solutions using the same technology.

Moreover, the deployment of a network of real devices is very difficult and expensive, especially a network with large number of devices. This is the great advantage of the introduction of simulators. By adding data taken from functional prototypes to simulation results, the accuracy of simulations is better.

Thus, the combination of both elements results in a complete and useful framework to validate optimization mechanisms for energy consumption.

As seen in Section 1, cognitive characteristics are applicable to intelligent energy management. Thus, it is important to provide a CWSN Framework to test new policies, to assess collaboration schemes and to validate different optimization mechanisms.

CWSN framework is composed of two fundamental elements: a network simulator and low power cognitive radio real devices.

A. CWSN Simulator

The CWSN simulator described in this section is based on the Castalia simulator. This base simulator has been chosen because it is focused on WSN, is based on OMNET++, which has a modular and simple implementation, and its physical layer and radio models are most realistic. For a good intelligent energy management mechanism simulation, the new simulator has to provide spectrum sensing capabilities, multiple frequencies, channels and modulations, Virtual Control Channel (VCC) to share cognitive information, primary and secondary users, an optimizer, and results and data graphical representation.

Although Castalia simulator physical layer is one of the best ones compared with other simulators, a sensing block is critical for simulating cognitive networks. Castalia simulator supports most common modulations and is also prepared to include new ones. Moreover, some typical radios for WSN are included, such as CC1010 or CC2430. Interference is another important aspect of the sensing module. Detected noise in the spectrum is very important for the behaviour of the network. For this reason, the interference model should be very precise.

It is mandatory to implement real different wireless radios in each node allowing changes in all the interesting parameters: modulation, transmission power, consumption, etc. Each wireless interface is associated with a power consumption model. The consumptions model are described in a file where reception modes, transmission power levels, delay transition between different power mode matrix, power transition matrix, and different sleep levels power are defined. Researchers can easily add new features (sleep mode, transmission parameter).

Cognitive networks can be distinguished from others due to the adaptation of their parameters according to information gathered about the environment. It is very important that the information could be shared between nodes. A Virtual Control Channel (VCC) has been implemented for that purpose. The low power protocol-based mechanisms need all the network information for a correct optimization.

Normally, WSN simulators make differences in the nodes only when the technology implements it. For example, coordinators and end nodes on ZigBee protocol. In a CWSN simulator, a new difference between nodes should be implemented: primary users (PU) and secondary users (SU).

Finally, when the simulator executes an application or scenario, the developer needs a simple way to extract the results. For that requirement, changes in the resource manager module are necessary.

Once the requirements have been explained, the CWSN simulator will be described on detail.

Castalia structure has been modified in order to provide the simulator with Cognitive power manager support. Fig. 1 and Fig. 2 show the new simulator structure.

Fig. 1 shows the Castalia node internals. There are several radio interfaces, one resource manager and one CR module. The communication between nodes is through Virtual Control Channel (VCC). Application uses sensor manager as physical interface.

In Fig. 2, the CRModule internals are showed. There are four main components: repository, optimizer, policy, and executor. Access is the VCC interface.

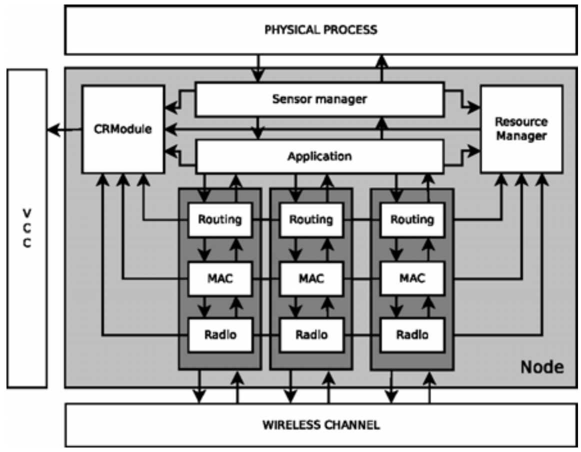

Figure 1. Castalia node internals adapted to cognitive radio

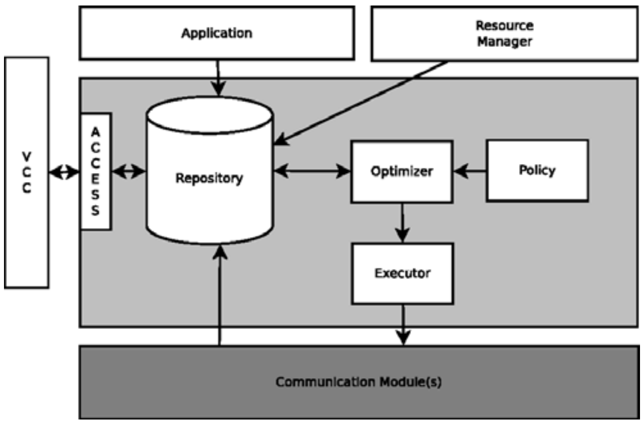

Figure 2. Castalia cognitive radio module (CRModule) internals

Radio of the communication modules provides new API methods for changing the active channel. This change enables developers perform spectrum scans and hops among channels.

These changes transform Castalia into a simulator capable of running cognitive experiments for green management design. The simulator is equipped with a new module which includes all these cognitive features, the CRModule. This module structure is composed of the following elements [13]:

- Repository: Which retrieves information about the local and/or remote nodes: information learned, decisions made or current state. The kind of information stored depends on the context and the requirements of the system. Some of the modules which feed the repository with information are: communication modules, applications, the resource manager and the optimizer.
- Access: This module allows a local repository access to the repository of remote nodes. At the same time, it exports a subset of the local repository to remote nodes.
- Policy: Enforces the requirements for the global system depending on several factors, not only power consumption, but interferences or noise, quality of service, etc.
- Optimizer: It processes the repository information bearing in mind the requirements imposed by the policy module. Decisions regarding the behaviour of the local node are the results of these processes. They are stored in the repository and evaluated by the executor.
- Executor: This module performs the decisions made by the optimizer.

Since all the elements are developed as Castalia modules, they communicate and access each other via the OMNET++ message system. Besides, it provides the Virtual Control Channel (VCC), a new method for sharing cognitive information among the CR modules of the nodes. CR modules can access to exported information of remote repositories through this channel. It allows CR modules to be aware of their surroundings and, even, the whole network.

Power model can be fed from real device measures. This framework uses real devices implementations to measure different power characteristics that are included in the power model. That feedback provides better accuracy and the simulation is closer to a real scenario. There are other features that are interesting, but very difficult to integrate in the simulator like fading or blocking. We are planning to continue integrating real features in the simulator to improve the accuracy**.**

B. CWSN devices

A test-bed platform to develop cognitive radio communications for WSN and to obtain power model data has been implemented (Fig. 3).

CWSN device is looking for optimizing communications in real time according to different application needs. Therefore, the device design has to consider power consumption, data rate, reliability, and security in order to be useful for a large number of applications.

For our goal, power consumption is a very important challenge. It is necessary to control the consumption of each separate component, and to implement shared strategies that try to reduce the overall consumption of the network.

Interference with other wireless devices or noise problems has to be avoided, which implies that nodes have to change their frequency and modulation as fast as possible. For this reason the prototype has three different network interfaces. The reduction of interference can be an important factor to reduce the consumption of the network.

CWSN need to connect to different kinds of standard commercial devices or internet gateways. Consequently a much extended-use wireless solution as an interface has to be implemented.

This prototype has to be capable of collecting data about the state of the network and of sharing the information with other nodes. In addition, each node will be able to change protocol parameters, the entire protocol and wireless interfaces in real time. Thus, it is mandatory to coordinate all the network devices.

Figure 3. Cognitive Wireless Sensor Network Device prototype

The control function is made by a Microchip PIC32MX795F512H, which is a 32-bit flash microcontroller. This is a high performance processor with low consumption and low cost. In addition, Microchip provides a lot of

CWSN platform has three radio interfaces:

- A WiFi Microchip device which can handle data rates of 2Mbps and uses a band operation between 2.412 GHz - 2.484 GHz. WiFi is based on the IEEE 802.11 standards.
- MiWi interface, a Microchip protocol which can handle data rates about 250kbps and uses a band operation between 2.405-2.48 GHz. This is a proprietary wireless protocol designed by Microchip Technology that uses small, low-power digital radios based on the IEEE 802.15.4 standard for WPAN.
- Last interface is based on Texas Instruments CC1010. It can handle data rate of 76.8kbps and uses a band operation around 868 Mhz. This interface provides a new communications band in an ISM frequency.

Software has to discover other nodes, sense the radio-electric environment, exchange configuration information, establish communication channels, and switch on or off the radio interfaces and sleep or wake up the node. The network manages data routes optimizing consumption, data rate, reliability and security.

Three wireless interfaces have been used in this device, with different standards and protocols. The integration of a new interface or device in the consumption model of the simulator is very easy. The real device measures and fill the file are only necessary

IV. DEMOSTRATIVE USE OF THE FRAMEWORK

In this section, the results of simulations related to green communications design are presented. The goal is not the algorithm or mechanism itself. The goal is to check that several new policies, collaboration schemes or optimization mechanisms can be implemented in this framework.

The reduction of power consumption is a task that involves the overall design across all layers of the communication protocol. Focusing layer by layer, several strategies for optimizing the consumption can be listed for each level, but due to cognitive characteristics, address the problem of consumption holistically has more advantages.

The opportunities to optimize energy consumption can be divided in three blocks: that get through the sensing of the spectrum, those related to the capability to change transmission parameters and those that depend on the ability to share knowledge of the network. Each scenario uses a strategy of a different block.

First scenario is related to the capability to change transmission parameters. It is composed by five nodes with 802.11 and 802.15.4 radio interfaces. Four nodes are sending data to the central node. In this scenario nodes simulate two different applications. The first one is a multimedia application where both bit rate and packet size are high. The transmission rate needs a WiFi interface while WPAN has not the capacity for multimedia applications. However, in a WSN, general applications have only sensing functions (temperature, light, etc.) where the bit rate and the amount of information are very low. In this case, the low-power optimization strategy consists on using the interface with less power consumption for a specific data rate. When the data rate is high only 802.11 is possible, but for a specific data rate 802.15.4, is better because of its less power consumption. This algorithm could be dynamically changed according to other constraints as battery life, distance between nodes or quality of service. Real data is used in the power model from a MRF24J40MA-based device for 802.15.4 protocol and MRF24WB based device for WiFi transmissions. In the simulation the power measures over the CWSN device are included (Wi-Fi transmission 74.8 mW and WPAN transmission 3.6 mW). As shown in Fig. 4, when the data rate is high 802.11 is used for transmission, but when data rate decreases 802.15.4, is better because of its less power consumption. The second part of this figure (zoomed in Fig. 5) shows the consumption with WiFi and WPAN common sensing application with the same packet size and the same interval between messages.

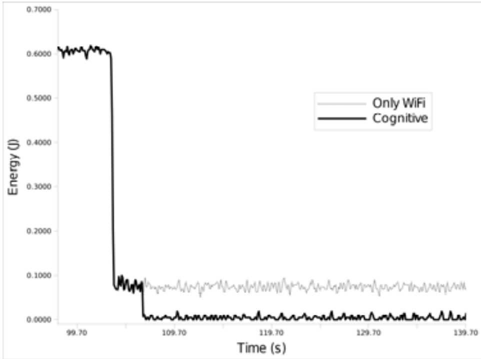

Figure 4. Power consumption for the Cognitive algorithm and WiFi

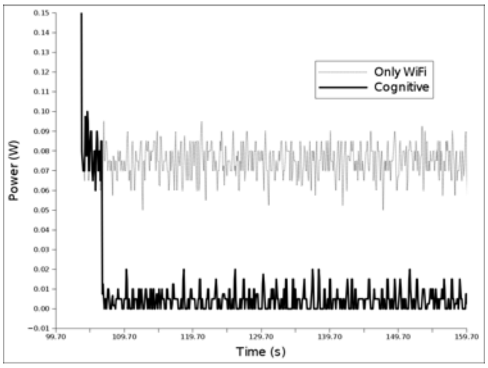

Figure 5. Detail of power consumption for the Cognitive algorithm and WiFi

Using a low power protocol system saves the 94% of energy (Fig. 4). Only in the commutation period, where the nodes need to communicate the interface change, the consumption is similar to WiFi. After that, the energy saving is considerable. The second scenario simulates an application whose nodes send packets with the maximum payload allowed by the simulator (1000 bytes with 802.11 and 100 bytes with our implementation of the WPAN protocol). The application starts sending a package every 10ms and the time is increased until the bit rate reached by 802.11 is supported by the WPAN protocol (reached at time 600). Fig. 6 shows how the consumption of WPAN in the first period of the simulation time is greater than WiFi because WPAN needs more transmissions for the same data. It means that 802.15.4 does not reduce the consumption of every application with a low bit rate but a cognitive module choosing the right protocol in every time can achieve that goal.

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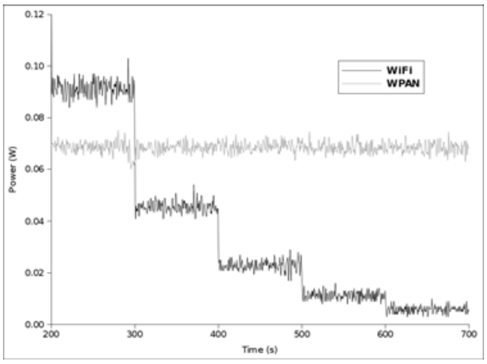

Figure 6. Power consumption for the Cognitive algorithm and WiFi (Scenario 2)

The third scenario shows optimization through the sensing of the spectrum. It consists of two nodes with 802.15.4 radio interfaces. One of them (the receiver node) moves through space and the other (transmitter node) is fixed (Fig. 7). Within the path of movement experienced by the mobile node, sometimes node B will be closer to the node A than others. In a common network design, the node A will transmit information with a power fixed. That makes that certain packets will lost (by distance between nodes) and others were transmitted with more power than necessary. Adding cognitive capabilities to this scenario, the network could be aware of the minimum power necessary to ensure the reception of packets while minimizing energy consumption. For this simulation, a power model real data from a MRF24J40MA-based device for 802.15.4 protocol has been used.

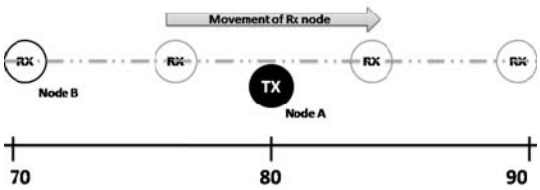

Figure 7. Mobile node scenario

In Fig. 8, power consumption of transmission node (node A in Fig. 7) is shown. Dotted line represents the consumption of node A in a network without cognitive capabilities and the solid line shows the consumption of the same node when the low power consumption algorithm is added. Hanging power transmission in relation to distance between nodes can reduce power consumption. Using this simple algorithm implies a reduction of up to 60% in some sections.

Increasing the complexity of algorithms or dealing with the problem of consumption in a holistic way (combining several techniques), it will be possible to obtain higher reductions.

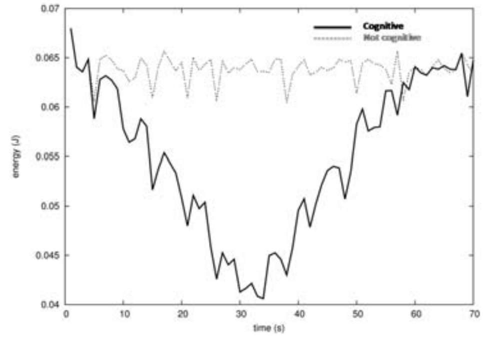

Figure 8. Power consumption for the Cognitive algorithm and 802.15.4 (Scenario 3)

V. Conclusion And Future Work

WSN power consumption became an important problem to face because of the use of batteries and their fast growth. The new cognitive paradigm has appeared to cope with very important network problems like spectrum scarcity, interference or reliable connections. Cognitive network features open up new interesting research challenges. Cognitive capabilities have to be applied to green communication design in WSN.

At this moment, it is important to provide a CWSN Framework to test new policies, to assess collaboration schemes and to validate different optimization mechanisms. In this article CWSN framework is presented. The framework is composed of a network simulator and low power CWSN real device. A new cognitive module has been developed over Castalia simulator and different real interfaces and power models have been integrated. CWSN platform has been build using a microcontroller and three different radio interfaces (IEEE 802.11, IEEE 802.15.4, and CC1010-based interface in 868 MHz band) because it is necessary to face different situations. This framework uses real devices implementations to measure different power characteristics that are included in the power model. This feedback achieves simulation results closer to a real scenario than regular simulator ones.

The benefits of the proposed CWSN framework have been demonstrated by implementing three scenarios. Very simple low power optimization strategies have been implemented using this framework. Results show how new concepts have been integrated in the simulator with good results and how a simple cognitive radio strategy can reduce large amount of power.

In conclusion, this framework represents a good opportunity for the development of new green wireless communications strategies for the new paradigm of CWSN.

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