# ESP32 based Edge Devices to Bridge Smart Devices to MQTT Broker for Healthcare Purposes in the COVID Scenario

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Abstract: The aim of this paper is twofold. First, it demonstrates a low cost implementation of a BLE/MQTT gateway to support monitoring and control of the patient health conditions from distance by means of the commonly used health devices. A variant of the CPS model is used to execute the monitoring and control tasks effectively. Secondly, it points out that such a gateway together with conventional BLE sensors on body temperature and oxygen in the blood and possible other BLE edge devices allow us to implement a pervasive warning system on COVID status and some general forecast on COVID diffusion. MQTT edge devices are also outlined for measuring the relevant health parameters at distance without the help of the above gateway, but in a way that the sensed data may interoperate with the ones taken by the conventional BLE devices.

## 1 INTRODUCTION

Many IoT platforms are available on the market to support the internet connectivity of sensors and actuators with the aim of developing ubiquitous monitoring and control of systems and processes belonging to several domains, e.g., healthcare, mobile information services and domestic appliances.

Such platforms generally implement control services using the communication and basic services of the Cyber Physical System (CPS) model as firstly proposed in (Gill, 2006). In our approach we used a variant of such model (Faro, 2020) consisting of a simplified CPS model to manage common needs in home automation and healthcare, called CPSc, where c stands for common. Also, our approach is based on a technology independent communication protocol, i.e., MQTT (Stanford-Clark, 2013), to improve sensors and actuators interoperability.

Aim of this paper is twofold. First, it demonstrates a low cost implementation of a BLE/MQTT gateway to support monitoring and control of the patient health conditions from distance by means of the commonly used health devices mainly provided with Bluetooth Low Energy (BLE) interface, thus further developing and finalizing the general themes introduced in (Faro, 2020). Gateways to allow devices provided with Radio Frequency (RF) or Long Term Evolution (LTE) channels to send/receive MQTT messages are for further work. Secondly, the paper illustrates how the use of the proposed gateway together with the use of conventional BLE sensors on body temperature and oxygen in the blood or other novel edge devices allow us to implement a useful and pervasive warning system on the current COVID status. How to derive from the collected data a general forecast on COVID spreading is also outlined in the paper.

Sect.2 extends the model of CPSc so that it may be used not only to manage basic home automation and healthcare needs but also mobility needs to help patient assistance. This model is useful to understand how the functions of the proposed monitoring and control system don't depend on the manufacturers and how such functions may be extended for the coordination of the overall control system by using proper customer processes.

Sect.3 explains the software structure of the overall architecture and in particular of the MQTT

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gateway that allows us to send through internet the data taken by BLE sensors to distant devices or remote centers without using smart phones. Sect.3 discusses also how implementing the visualization of the measured data and simple control services using the software Domoticz (Domoticz, 2015) to carry out timely interventions and health studies. Edge sensors that don't need external MQTT gateways are also proposed to implement distributed intelligent systems that increase the control capability of the edge nodes and reduce the network load.

Sect.4 discusses in details how exploiting the systems proposed in sect.3 for pervasively measuring in real time and at distance the body temperature and oxygen in the blood featuring the COVID status. The same approach is suggested to collect vital parameters relevant for other risky pathology. Sect.4 illustrates also: a) how using the devices available on the market and the advanced devices envisaged in the paper to collect the needed data, and b) how deriving from the measured data suitable warning information and a general forecast of the COVID diffusion.

The use of the suggested methods at a large scale is for future studies since this involves the agreement with other companies and Public Administration.

## 2 PERVASIVE AND UBIQUITOUS CYBER PHYSICAL SYSTEMS

CPS is a layered structure similar to the Internet of Things (IoT), that presents a meaningful coordination between physical and computational elements as shown in fig.1.

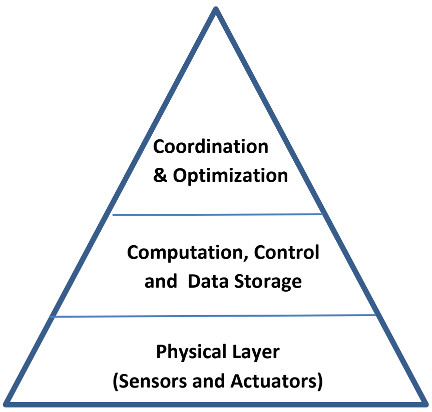


Figure 1: General structure of a Cyber Physical System.

A detailed functional architecture of CPSc to deal with patient assistance from remote to meet common healthcare needs is drawn in fig.2.

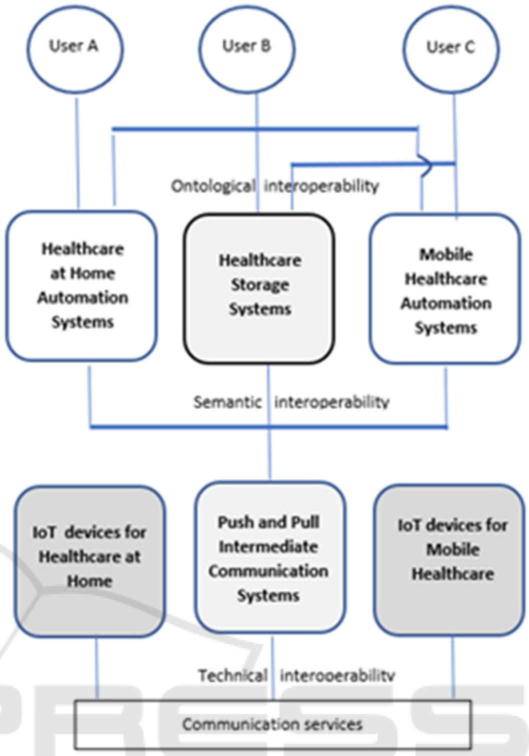


Figure 2: From the general CPS model to CPSc: a layered functional model to meet common healthcare needs.



The model of CPSc allows us to point out in details the main elements of the adopted CPS architecture:

- the sensors and actuators used to collect health data and to control the processes of a given field should take into account the data collected on another field. Generally the sensed data are sent by a push method to a control center that on its turn will follow the same push model for real time controlling the supervised application.
- the control services should store the collected data into internal files or into some data storage. The main aim of the control services is the one of finding suitable online recovery interventions possibly taking into account data from multiple fields.
- the customer processes should optimize the activities of the control services and hopefully should be able to find how to prevent dangerous situations and to manage possible anomalies of the supervised systems.

Fig.2 points out three types of users:

- user A able to manage only patients residing at home. Typically, user A may be the patient, a family member or the family doctor.
- User B able to supervise patients that are either at home or in mobility. This user may access the health data storage to carry out diagnosis and forecast. Typically, user B may be a doctor at hospital or at a clinical lab.
- User C able to manage walking or driving patients as well as to carry out diagnosis and forecast. User C may be the patient, a family member, the family doctor or the first aid staff.

The main feature of such model with respect to the IoT systems is that the systems involved in the cyber space should be able: to communicate, to carry out computation and to interoperate between them.

Although our approach aims to meet common health needs mainly using the IoT devices available on the market, we should note that this aim is not straightforward, since the available monitoring and control devices at level L1 for healthcare purposes are usually not able to exchange data directly between them, often they work as stand-alone devices. Only recently we may find BLE devices able to send the collected data to processes at level L2 where the data are stored and processed by a proper control system.

However, to process data coming from different sensors and to send commands to different actuators we need that such data are received and sent according to a suitable format (i.e., according to an agreed data semantics at control layer) and through a proper communication protocol.

For this reason, in our implementation the data are coded following the JSON format and are exchanged through an MQTT broker that is connected to the edge devices by the MQTT secured protocol, i.e., a version of MQTT that makes use of TLS (Transport Layer Security) encryption at the transport layer to enhance data security. Although other data communication protocols could be used for this purpose we chosen MQTT, or its secured version, for its simplicity and energy efficiency (Faro, 2020).

Also, to meet real time requirements it is suitable that the MQTT broker will be directly linked to the home automation system. Thus, we chosen Domoticz. that it is easily linkable to the MQTT broker even if other home automation systems can be used, such as SmartThings© or Home Assistant©.

The data received by Domoticz may be stored into internal files or into simple database such as Node-Red©. Also, such data could be stored on a large data storage (e.g., MySQL©) for further analysis.

In Domoticz the data sensed by a sensor on the field are processed as if they were collected by a virtual sensor associated to the real one. After processing such data, Domoticz will send the commands to the proper virtual actuator that on its turn will send these commands through the MQTT protocol as JSON messages to the real actuator.

In the proposed model, the customer processes should manage different control system following a shared format that allows the users to coordinate and optimize the different control systems using the terms of an agreed user ontology. This last aspect is outside the scope of the paper. The interested reader may find in (Costanzo, 2016) how customer processes could interoperate according to an user ontology.

Fig.3 summarizes the software architecture that implements the functional structure of CPSc. Besides the modules at level L2 and L3 discussed before, this software architecture allows us to point out at level L1 the key component to obtain a pervasive monitoring and control of the targeted applications, i.e., the BLE/MQTT gateway. By this BLE/MQTT gateway many BLE sensors or actuators not provided natively with MQTT communication may exchange messages with the automated control system through the MQTT broker. By using this gateway we may include in the monitoring and control system quite all the BLE devices commonly available on the market. Due to the relevance of this gateway in the CPSc architecture, it will be described into details in sect.3.

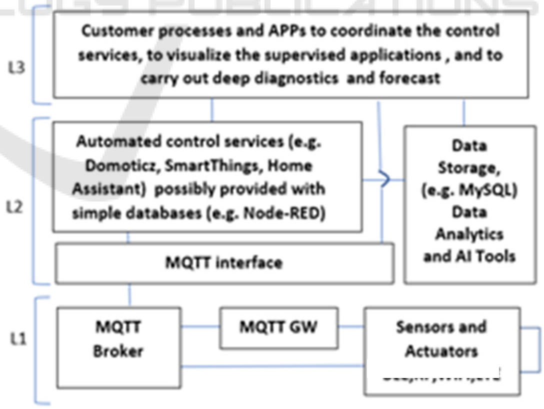


Figure 3: From the layered functional model to the layered software architecture for implementing CPSc.

Fig.3 points out that some systems may enter directly into the MQTT broker, i.e.: a) the user processes at level L3 to faster the visualization of the sensed data and for managing the edge devices, and b) the edge devices at level L1 with proper MQTT functionalities.

Since the use of edge devices provided with a proper MQTT gateway simplifies the overall architecture, in sect.3 we illustrate how implementing DIY sensors provided with MQTT functionalities.

A solution partially similar to ours is given by the recent project called Open MQTT gateway even if this project (see http://docs.openmqttgateway.com/) envisages autonomous Arduino based gateways that need the knowledge of the format of the frames containing the data sensed by the edge devices. This is not needed in our approach neither by the devices provided with an MQTT gateway shown in sect.3, neither if one adopts the method illustrated in sect.4.

Finally, fig.3 points out at level L1, edge devices able to interoperate between them without the help of an external control service (see the line connecting the sensor/actuator box with itself). This allows us to point out the recent trend to move intelligence towards the edge devices for improving real time control and reducing the network load.

# 3 MQTT GATEWAYS FOR M_CONNECTED HEALTHCARE

To build a BLE /MQTT gateway useful for mobile connected (M-Connected) healthcare, we can use several types of chipsets. In our implementation we chosen the Arduino© chipset since it has good performance and low cost. In particular, we chosen the ESP32 nodemcu chip (see fig.4left) since it allows us to use in the same chip two antennas: a BLE antenna to capture the data sent by BLE sensors on the field and a WiFi antenna to send the sensed data to internet through a WiFi channel. In the paper this gateway is denoted by $GW_{BW}$.

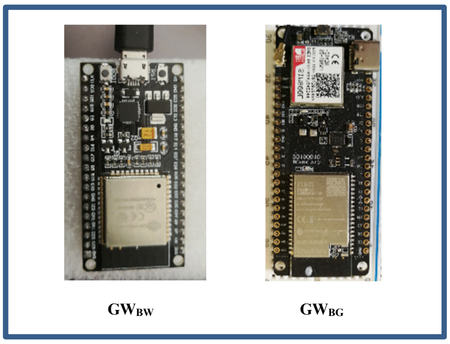


Figure 4: ESP32 chips for implementing a BLE-WiFi gateway on the left and a BLE/3G-4G gateway on the right.

Another interesting version of the MQTT gateway is the one denoted as $GW_{BG}$ (see fig.4right) that includes the BLE, WiFi and 3G/4G communication functions to allow the sensors to send data to the data center even when the subject is walking or driving using 3G/4G channels.

In the software of the gateway based on both the above ESP32 chips, the BLE data are converted to MQTT messages by a Lua script that is uploaded to the ESP32 by means of the Arduino IDE. Such Lua script combines three main sub-scripts:

- in $GW_{BW}$ the first script scans the available WiFi networks to connect the gateway to the one prefixed by the user. It is inspired by the WiFi scan script reported on the Arduino IDE. Analogously in $GW_{BG}$ the script connects the device to the 3G/4G network as illustrated in https://randomnerdtutorials.com/esp32sim800l-publish-data-tocloud/
- the second script scans the BLE sensors to connect the gateway to the one prefixed by the user, and to extract the relevant BLE data. The BLE scan is inspired by the script reported on the examples of the Arduino IDE. The capture of the data in the BLE frames depends on the format adopted by the sensor. If it is not known, then it is needed to investigate the format of the frames, e.g., by using a BLE sniffer.
- the third converts the BLE data to MQTT messages, and send them to the MQTT broker through WiFi or 3G/4G connections.

The main advantages of using such gateways are that they are easily portable either when the user is at home or when he is engaged in mobile tasks. Also, both these gateways may send the data to any control center, not necessarily the one of the manufacturers, where the data could be processed all together thus allowing the virtual devices to interoperate between them.

In this way the control center could take into account all the relevant parameters sensed by the available sensors and, after processing the received data, it could send: effective commands to the actuators installed on the field and warning messages to the user processes to manage risky events.

Finally, let us note that these gateways are autonomous micro-systems that are not implemented on the smart phone, thus satisfying the privacy constraints claimed by the users. i.e., by using such gateways we avoid to use the smart phones as gateways but we use them only as visualization devices so solving the problem advanced in (Zachariah, 2015) where the authors claimed that

"Internet of Things has a Gateway Problem". Indeed, the available gateways on the market are often software APPs implemented on the smart phones able to collect data sensed on the field and conceived to send such data through internet to a proprietary control system where the data are stored and deeply processed to discover dangerous events.

By the proposed gateway we may include in our non-proprietary framework:

- all the devices that are able to transmit health data to the smart phone but not to a remote data center, e.g. the wrist device that measure blood pressure and heart beat per minute produced by iHealth© , and the stress locator Bluetooth oximeter or the emotional sensor from skin responses of Happy-Electronics©.
- the devices managed by proprietary monitoring and control center such as the smart bands of Huawei or Xiaomi to measure many vital parameters, except the body temperature, and the BLE thermometer of Kinsa.

The proposed approach may be used also for the networking of the items known as iBeacons, i.e., low cost devices able to send BLE frames mainly for informing about the indoor position (Dalkılıç, 2017) but that are also used for sensing the parameters featuring human health and production processes.

Therefore, in the paper we propose the use of $GW_{BW}$ and $GW_{BG}$ to allow BLE sensors to send the collected data to any monitoring and control center in the network chosen by the user.

To achieve the maximum of pervasiveness we should take into account the IR devices not provided with BLE communication facilities so that it is possible also in this case to inform immediately the control personnel or the same subject on the values of the relevant parameters. However, since this needs some hardware modifications of such sensors, it is for further study.

Moreover, as said in the sect.2, the proposed gateway is not needed for managing the sensing and actuating edge devices provided with proper MQTT communication functions. However, such sensors should be designed carefully since they are acceptable in our approach only if they send data to the control center chosen by the user according to an agreed format (Faro, 2020), e.g., the JSON format, to allow the measured data to be managed together with the data sensed by all the BLE devices connected to the center through the MQTT gateway.

Moreover, using edge devices provided with MQTT functions generally increases the costs but improves the time performance. Therefore, their use in practice should be evaluated by a cost-benefit analysis considering that the advantage of using them is not only the one of achieving better time performance but also the possibility of pre-processing the data collected for an immediate control. These pre-computed data can be sent by these computational edge devices to the data center chosen by the user where they can be further processed together with the ones coming from the low cost IoT devices.

Fig.5 shows some possible platforms to manage the data collected by the sensors, i.e.:

- an MQTT APP resident on a smart phone to visualize the data and to receive alerts,
- a Raspberry PI platform powered by Domoticz and MQTT broker to monitor and control the health data and related home appliances or mobile systems. In particular, on this platform we may install a simple home automation center able to alert the users or family members in case of risky events without needing the use of remote centers installed at the family doctor or at the hospital.
- instead of Raspberry PI, one may use the NVIDIA Jetson Nano or the NVIDIA Xavier boards (Sparsh, 2019), where one may implement not only conventional control procedures based on threshold control but also advanced programs taking advantage from the AI tools available on such board, e.g. TensorFlow (Shukla, 2018) to develop deep control of remote applications as envisaged by the adopted CPSc model.

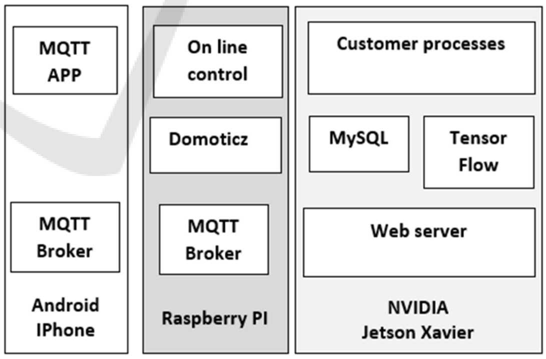


Figure 5: Functions, software modules and hardware platforms to implement CPSc: data storage, visualization and automated control services.

Fig.6 shows three main stacks to implement the sensing tasks described in the paper:

- The sensors provided with TensorFlow Lite (Tang, 2018), denoted in the paper as TFL, able to classify on line the health data patterns featuring the user health status. They are also able to send the sensed data to the MQTT broker and to receive the updating of the weights of the TFL model from TF resident on the server. Typically such an edge node could be an NVIDIA Jetson Nano (Cass, 2020).

- The sensors provided with MQTT communication functionalities that don't need of the BLE/MQTT gateway proposed in the paper. The collected data are sent through the MQTT broker to Domoticz that will carry out the due control on line. Typically such nodes could be Sonoff© devices provided with an operating system named Tasmota offering MQTT facilities (Tasmota, 2016).
- The commonly used sensors provided with BLE communication facilities that need the BLE/MQTT gateway to send (receive) data (commands) through the MQTT broker to (from) Domoticz.

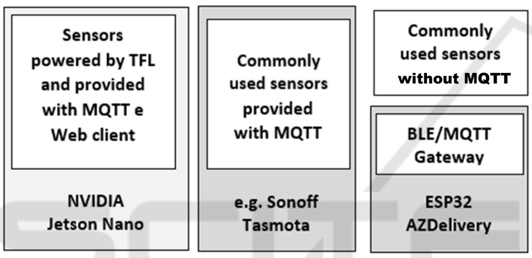


Figure 6: Functions, software modules and hardware platforms to implement CPSc: sensors and actuators stacks.

Let us note that although the MQTT edge devices are very effective to implement distributed intelligent control systems to meet real time constraints and to reduce the network load, they are still not largely diffused not only because of their relatively high cost, as said before, but also because the manufacturers aim at developing monitoring and control systems in which it is needed to use mainly their devices.

Thus, waiting for the availability of MQTT edge devices at a reasonable cost, it is useful to follow the approach proposed in the paper aiming at developing MQTT gateways, as illustrated in sect.4, to give rise to effective online health control system. This will extend the MQTT sensors, currently used for implement home automation processes (see module in the center in fig.6) to perform healthcare tasks.

Fig.7 shows how the ESP32 provided with WiFi functions can be used to develop an MQTT sensor. In particular, it shows two sensing devices to measure the body temperature: a wearable device based on MAX30205 on the right and an IR device based on MLX 90614 on the left. The software to be installed on the ESP32 to manage the sensed data coming from these sensors according to the MQTT protocol may be easily found on the Web.

Since the above DIY approach may require to use more than one electronic piece by a soldered circuit, it is not suitable for mass production. It may be suitably adopted for developing prototypical or dedicated systems consisting of a limited amount of MQTT edge devices especially when these devices consist of few parts, e.g., only of ESP32 and the sensor.

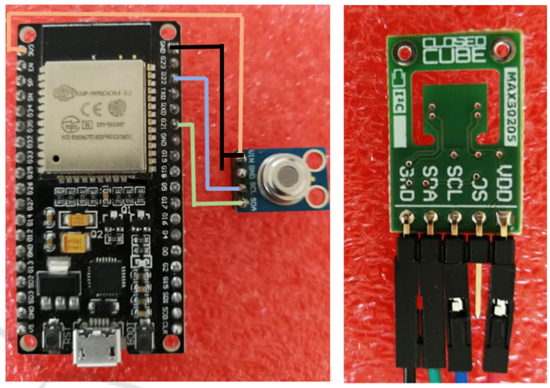


Figure 7: WiFi body temperature sensor on the left based on the IR sensor MLX 90614ESF BAA. This sensor should be connected through the interface I2C, i.e., (from up to down) VIN-3V3, GND-GND, SCL-G22, SDA-G21. The sensor MAX30205 on the right should be interconnected to ESP32 using the same rules.



## 4 MONITORING IN SEARCH OF COVID: ALERT & FORECAST

Although several parameters may be useful to trace COVID, we take particular attention on how to measure online the main relevant parameters, i.e., body temperature and the oxygen in the blood.

In the following we discuss how to do it by using the mentioned sensing devices to give an idea on how these devices may be used in our framework and the reliability of their measurements.

In particular, in this section we take into account three smart bands, i.e. the Honor Band 5i by Huawei (H5i), the one known as W11 and a low cost band belonging to T01 type. Such wearable devices are able to measure several relevant vital parameters, among which the oxygen in the blood, whereas only T01 is able to measure also the body temperature.

In our tests we taken into account also three types of thermometers that may complement the basic measurement apparatus needed for COVID, i.e., the portable forehead thermometer by Kinsa, a similar IR low cost device known as IR laser gun, and the wearable thermometer known as Smart Baby (SB) that can be used for children and adults.

Due to the increasing diffusion of iBeacons, a low cost iBeacon for measuring the body temperature is considered too.

All the obtained results were compared with the ones taken by certified medical devices. Also the use of the mentioned DIY devices will be taken into account.

Fig.8 illustrates how we may send the health data sensed by W11 (see fig.8a) to an MQTT broker using a portable MQTT gateway $GW_{BW}$ discussed in previous section.

Let us note that this task is not straightforward because to know the health data to send to the MQTT broker it is necessary to decode the BLE frames sent from W11 to the APP resident on the smart phone.

This is relatively easy if the format of the BLE frames is given by the manufacturers, otherwise this should be obtained by using a BLE sniffer, e.g., the Hollong sniffer and/or some APPs such as Light Blue and BLE Analyzer. In fig.8 we illustrate the main steps to be followed to discover the blood pressure measurement in the BLE frame of W11, i.e.,

- first we inspected using the BLE sniffer the frames sent by W11 to its APP during the blood pressure measurement phase (see fig.8b),
- after inspecting such BLE frames we understood that the hexadecimal digits of the frame related to the blood pressure, are the ones pointed out in fig.9, i.e.: Systolic blood pressure = 71 HX =113 mmHg, and Diastolic blood pressure = 4b HX = 75 mmHg.
- only at this point, the software loaded in the gateway (fig.8c) is able to send the relevant data to the MQTT broker where the data are read by the MQTT clients resident on remote mobile and on the Domoticz platform.
- this allows the blood pressure data to be visualized on the MQTT client resident on the mobile (fig.8d) and by the virtual Domoticz device identified by idx=37 (fig.8e).

The same procedure used to send the data collected by W11 on the blood pressure to the MQTT broker was followed successfully to decode the BLE frames containing health data measured not only by W11 but also by the smart bands H5i and T01.

Since the above data don't deal with body temperature except for T01, we tested also the above method to send to the MQTT broker the body temperature measured by the main BLE thermometers available on the market, e.g., Kinsa, Smart Baby, iBeacons and the IR laser guns.


Figure 8: Visualization of the blood pressure taken by W11 on several user devices. Let us note that the blood pressures shown on such devices refer to different proof sessions.

```
0000  99 53 65 50 1a 1b 17 00 04 00 1b 0d 00 90 71 4b
0010  64 00 01 00 00 00 00 00 00 00 00 00 00 00 00 00
0020  00 63 8b e1
```

Figure 9: BLE frames sent by W11 during the blood pressure measurement phase.

Although the proposed approach worked successfully for all the mentioned devices, it is not possible to say that it may be used for all the BLE sensors. Indeed, as said above, this result might be achieved if the manufacturers will make available the format of the BLE frames sent by their devices to the APP installed on the smart phone, otherwise the possibility of sending data from a BLE device to the MQTT broker should be verified experimentally case by case. However, in the paper we have demonstrated that our approach was successful at least for a set of devices able to measure the main health parameters relevant for COVID and to counteract other epidemic pathologies, such as the seasonal influences.

To have a first evaluation of the precision of the measurements mostly relevant for COVID, we compared the measurements of the blood oxygen saturation levels (in percentage) of a given user at a certain time with the one taken by a certified medical oximeter (MO) for the same person at the same time.

The results reported in tab.1 indicate that each tested oximeter, except T01, shows a satisfactory precision. Then several devices can be used with confidence to monitor and control at distance the oxygen in the blood using the proposed approach.

Table 1: Blood oxygen saturation levels (in percentage) measured by wrist bands compared with the one taken by a certified medical device, i.e., MO.

| | |
|---|---|
| H5i | 98 |
| W11 | 97 |
| T01 | 95 |
| MO | 98 |

An analogous test was done to verify the precision of the body temperature taken by Kinsa, Smart Baby (SB), T01, iBeacons and the DIY devices illustrated in the previous section, i.e., the IR contactless sensor $MLX_{96104BAA}$, and the contact sensor $MAX_{30205}$.

The results shown in Tab.2 deal with the temperatures of different parts of the body taken for the same user at the same time. Also in this case we found that all the IR and wrist thermometers available on the market and the ones built by using relevant body temperature sensors show a satisfactory precision, except T01.

Table 2: Body temperatures in °C taken by different thermometers for the same person at the same time.

| | Finger | Wrist | Hand | Forehead |
|---|---|---|---|---|
| IR Kinsa (cert.) | | | 36,5 | 34,6 |
| IR $MLX_{96104BAA}$ | | | 36,2 | 35 |
| IR LC | | | 36,4 | 35,4 |
| Smart Baby (cert.) | | 35,2 | | |
| T01 | | 36,5 | | |
| iBeacons | | 35,4 | | |
| $MAX_{30205}$ | | 35,1 | | |

Then, there are many devices that can be used with confidence for monitoring and controlling at distance and online the body temperature according to the proposed framework. Let us note that in our approach the body temperature and oxygen in the blood can be easily monitored also during the therapy followed by the user at home or at hospital, e.g., fig.10 shows a simple Blockly program that can be used by Domoticz to send warning messages to the doctors when the patients are in the risky range.


Figure 10: Blockly program to send an alert when the body temperature is higher than 37,5 °C.

A discussion on how the proposed approach may be used to exchange messages between the devices belonging to two different networks is given in sect.4.1 to demonstrate how the patient control may be carried out at distance from hospitals satisfying the privacy requirements. In sect.4.2 we propose a simple classification scheme of the available health measurement devices to clarify the types of devices that from our point of view are: a) few useful, b) of limited importance, c) upgradable by using our MQTT gateways and d) coherent with our requisites. How our approach may be used not only to implement an alert system but also to forecast the COVID outbreaks and similar events is illustrated in sect.4.3.

## 4.1 Interconnecting Domoticz Systems

A meaningful advantage of using Domoticz is not only the one to be linkable directly to MQTT or the one to allows us an easy implementation of an effective warning system, e.g., by means of Blockly commands, but also the one that it may be interconnected to another Domoticz system resident on a network managed by another administrator.

Indeed, the device interconnection proposed in the paper by using Domoticz may be obtained only if we know the addressing scheme to implement data exchange between sensors and actuators through the MQTT broker. This may be achieved by knowing: a) the MQTT names and the LAN addresses of the relevant devices, and b) the LAN address and the global address of the MQTT broker.

This means that by Domoticz it is possible to alert users by email and SMS or to send commands to actuators that are located on any LAN of the network managed by the same broker, i.e., belonging to the same administrative system. On the contrary, it is not easy to interconnect devices belonging to different administrative systems since this would require the knowledge of the addressing scheme of the devices of a network managed by a different administrator.

To overcome this problem we propose to adopt a naming scheme rather than an addressing scheme. This may be obtained in several ways, in the following we illustrate how interconnecting the Domoticz systems of the two networks through the web service named IFTTT (Xianghang, 2017).

Indeed, IFTTT makes possible that a device or system may execute commands expressed in the format "*IF This* (event) *Then That* (action)" where the event is detected by a device/system of a network A, whereas the action could be carried out by a device/system resident on the same network A or on a different network B.

Fig.11 shows how devices belonging to different networks can cooperate following the IFTTT procedure reported in www.domoticz.com/wiki/IFTTT_integration_with_Domoticz. In particular it points out how a Blockly command executed on a Domoticz system located at a retirement home A may be used for triggering an action of a device managed by a Domoticz system located at hospital B when the data sensed by some sensors at a retirement home are in the risky range:

*IF* body temperature of people X at A > 37,5
*&* oxygen saturation of people X at A < 90
*THEN* doorbell_D1 at B = ON

where the body temperature is taken by sensor T1 and the oxygen in the blood is detected by sensor O1.

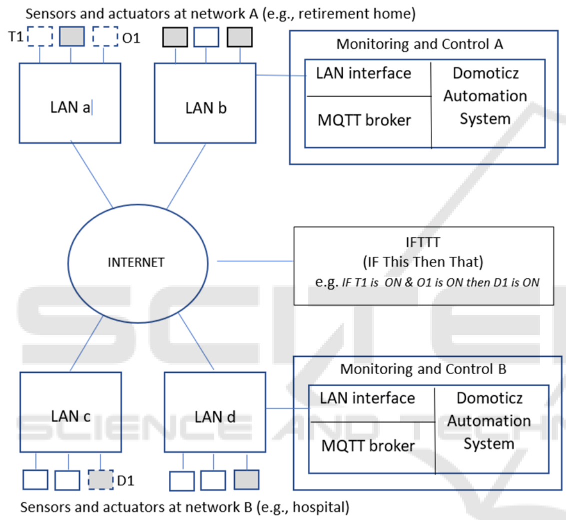


Figure 11: By interconnecting two Domoticz systems by IFTTT, events detected by sensors located in network A (i.e., T1 and O1) activate actions to be carried out by a device resident in network B (i.e. D1).

Let us note that the IFTTT approach is generally not suitable to manage a private network for flexibility and security reasons, whereas it is suitable to trigger specific actions in a network managed by a Domoticz system after the occurrence of a given event in the network managed by another Domoticz system since this is obtained by a naming scheme transparent to IFTTT.

This allows a hospital to make available on the global network only the devices that are really needed by remote patients, and vice-versa it allows patients to make available to a remote hospital only the home devices that are useful to monitor/control their pathology from distance.

## 4.2 Comparing Our Monitoring/Control Approach with Respect to Others

Previous sections let to emerge by examples and small case studies that the main point of our approach for an effective monitoring and control of COVID outbreaks is that the measurements of the relevant parameters, e.g., body temperature and oxygen in the blood, should be collected through MQTT protocol in real time into servers at disposal of the sanitary system not only when such parameters are beside the threshold but also when they are in the normal range for statistics studies.

Also, these measurements should be: a) sent by the edge devices to the servers without using smart phones mainly for privacy reasons, and b) taken by contact devices if they are used by only one person, whereas contactless technologies should be used to monitor several people, e.g. at a store or school entrance.

To better elucidate our point of view about the main features of an effective monitoring and control system for detecting possible COVID outbreaks we use in this section the following two dimensions scheme for classifying the available edge devices:

a) how data are collected by the sensors
   1. contact devices
   2. contactless devices

b) how the data are stored for further processing
   1. no data storage
   2. data storage on
      i. Scan Disk (SD)
      ii. smart phones
      iii. proprietary systems
      iv. user servers (*)

(*) The dimension b.2.iv includes servers installed on the user PCs and the one at family doctor or at hospitals authorized by the users.

This classification scheme allows us to point out that with respect to our point of view:

- the devices that belong to b.1.i or to b.2.i, independently on if they are contact or contactless, are of limited importance since they don't support online control from distance and generally don't contribute to build statistics for COVID forecast as envisaged in sect.4.3. In other words, their use is meant only for controlling that people entering into a public service are in the normal condition under the only responsibility of the operator taking the measurement.

- the devices that belong to a.1.ii or a.2.ii are acceptable only if they are for personal use and don't to send data to distant servers through smart phones since using smart phones as gateways should be avoided at least to meet privacy conditions.
- the devices that belong to a.1.iii or b.2.iii are not acceptable since sensible data should not be stored on the servers of the service providers.
- the devices that belong to a.1.iv or b.2.iv are the ones that best meet our approach at condition that the ones belonging to a.1.iv are for personal use.

These considerations clarify why we claim that our MQTT gateway installed on a portable IoT devices may improve the devices available on the market, often provided with BLE interface, by allowing them to send the sensed data to user servers.

In particular, the proposed gateway could be used to allow the following devices to provide the envisaged online control service even if they were not conceived natively for this purpose:

- the BLE smart/wrist bands and iBeacons used to measure relevant health parameters by an APP on a smart phone, and
- the BLE contactless control systems, e.g. the IR body temperature laser guns that take the body temperature for controlling people at the entrance of a public service.

Also, from the above scheme it is easy to understand why we encourage solutions that meet natively the requirements a.1.iv and a.2.iv, i.e., solutions in which the gateway is implemented in the sensor/actuator itself as the DIY projects in fig.7.

Finally, we note that recently there are on the market IR cameras for fever screening belonging to b.2.i that may partially fit our approach, i.e., the IP binocular cameras provided with thermal array sensors. Indeed, in such cameras the thermal and optical data can be visualized by any device connected to Internet (see fig.12) but they are usually stored on a local SD. Thus, an MQTT client should be installed on such cameras so that the data will be available online on the servers indicated by the users for the relevant processing.

However, the lack of such feature is partially overcome in this case by the fact that when these cameras detect undesired events, they are able to activate some relevant actions such as opening/closing the entrance door of a store and alerting distant control people.

Fig.12 deals with such a thermal IP camera able to control the facial temperature of a people at a certain distance from it (about 200 cm). Other IP cameras provided with simpler IR sensors are able to trigger actions depending not only on the facial temperature but also on the people identity even if they need that people passes closer to the camera (about 50 cm). In both the mentioned cameras, the data stored on SD can be used later for statistical processing.

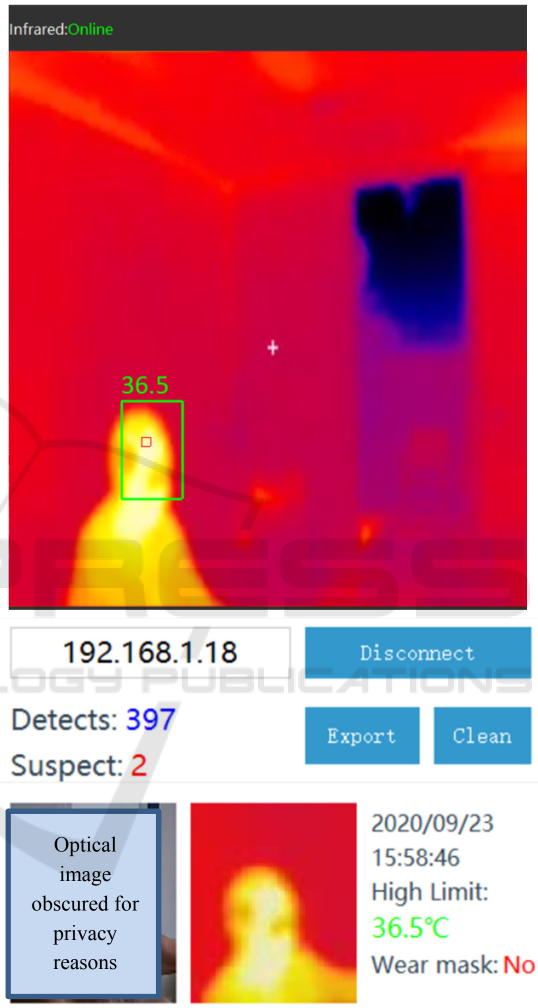


Figure 12: The optical and infrared images taken by IP cameras provided with an array thermal sensor for fever screening, such as the camera TI005© by LSVision, are available to any PC on Internet. Many walking people can be controlled contemporaneously. People with fever or without mask are signalled to the control personnel and are not allowed to enter into the controlled service.

## 4.3 Timely Discovering the Incipience of a COVID Outbreak

The users could authorize Domoticz to send the collected data to hospitals or clinical laboratories for a deep control of the health situation. The number of people affected by suspicious pathologies related to COVID could be reported in a map to point out unusual levels of community spread of illness over the past several weeks as proposed on the site Health Weather powered by Kinsa.

Another approach may be the one of sending the data on the body temperature and on the oxygen in the blood to a control center even if they are not outside the normal thresholds, but also when they are quite normal but different from the ones typically owned by the user.

A procedure to timely discover anomalies indicative of the incipience of a COVID outbreak may be implemented on a control center at the hospital or at a clinical laboratory using a classification approach similar to the one proposed in (Faro, 2009), i.e.:

- measure daily the health parameters $h_i$ relevant for COVID (such as body temperature, oxygen in the blood, heart beat per minute, diastolic and systolic pressure, breathing per minute). Let say N the number of health variables taken into account, and let us assume that the subject is every day in three main contexts: resting at home, working (at home, in the office , etc.), and commuting.
- represent the daily health status as a point in a N-dimensions space whose components are $\mathbf{p}_{m,k}[h_1]$ …. $\mathbf{p}_{m,k}[h_N]$, where m from 1 to 3 denotes the context and k from 1 to 30 is the day number in the last thirty days, e.g., 1 is the current day and 7 refers to seven days ago.
- built the similarity array S whose generic element s(d, k) represents the similarity $\mathbf{s}(\mathbf{p}_{m,d}, \mathbf{p}_{m,k})$ of the health status at day d with health status at day k for a given context m according to the metrics proposed in in (Faro, 2009).
- pass each row of the array S to a SOM neural net (Kohonen, 2013) having N input neurons and three output neurons to allow us to classify the daily status in three main classes, i.e. normal, abnormal and suspicious.
- alert the user if his current health status is risky since he is passing from normal to abnormal status and communicate to a control center every suspicious daily health status and how much it is distant from the abnormal one.

In this way, a control center may alert the users and compute two maps to study the COVID diffusion at macroscopic level, besides the public map dealing with the people affected by COVID. The suggested maps should be: I) the map proposed by Kinsa, and ii) the map showing the emerging anomalies at micro-community level as proposed in this paper. Both these maps could be indicative of the incipient COVID.

Currently, we are evaluating if a better classification could be obtained using the autoencoding neural network available in TensorFlow instead of SOM. By this choice we plan also to implement an online control of the suspected events at the user side. Indeed, after the learning phase needed to compute the weights of the neural autoencoder at the server side, we may use the autoencoder TensorFlow Lite (TFL) installed on the edge nodes, e.g., the NVIDIA Jetson Nano, to discover timely anomalies during the testing phase carried out on the edge nodes. Such nodes should send the sensed data also to the main control center, e.g., the one installed on the NVIDIA Jetson Xavier, to be used to update the weights of the mentioned autoencoder.

This would avoid to signal emerging anomalies when the health data of an user differ from the ones of the other users. Indeed, anomalies will be signalled only when the health data of an user differ from the ones usually featuring the same user in other days but in the same context.

## 5 CONCLUSIONS

The paper aims at contributing to the development of a pervasive health monitoring and control system not only for COVID but also for risky pathology of social relevance. In particular the paper has demonstrated how all the IoT sensors and actuators provided with BLE communication facilities may be included in a distributed intelligent system to discover timely if a people is affected by COVID or to identify, by means of suitable AI methods, the infections areas so that they may be suitably controlled. The methodology proposed and the technologies suggested could be adapted to control other epidemic events.

Like other proposed ICT tools to counteract COVID, the proposed approach should be implemented in a pervasive way to effectively reach the prefixed aims. However, unlike many other proposals, the monitoring and control outlined in the paper remains anonymous and does not involve critical personal systems such as smart phones without decreasing the effectiveness of the results at least to discover the incipience of COVID in small communities or city districts. Of course timely diagnostics at micro-community or personal level can be carried out only with the consensus of the interested people.

Future works deal with:

- a systematic comparison of the proposed approach with the existing ones by using more than the two dimensions chosen in the paper,
- the development of a contactless sensor for measuring the oxygen in the blood by taking into account relevant methods presented in the literature, e.g., (Liu, 215) and (Negishi, 2020),
- the implementation of a data protocol for interconnecting devices of different networks not only by means of IFTTT at Domoticz level, but also through platforms, e.g., Beebotte (Beebotte, 2017), that are able to interconnect different MQTT brokers,
- the development of deep learning tools based on the ones described in the paper to obtain a timely diagnosis of COVID and a reliable forecast for the epidemy diffusion.

# ACKNOWLEDGEMENTS

The methodology and the outlined technologies, especially the DIY ones, are currently under test in a project called I-HOSP to assist patients affected by risky pathology at distance, supported by EC regional funds in the action 1.1.5 aiming at promoting innovative projects dealing with key themes of the socio-economic development such as industry 4.0 and mobile-connected healthcare. Although the COVID monitoring is not in the main project aims, the proposed approach is also under test in another project of the same action called SELCA dealing with advanced clinical LIMSs (Laboratory Information Management Systems).

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