On-line Remote EKG as a Web Service

Augusto Ciuffoletti*
e.mail: augusto.ciuffoletti@unipi.it

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Abstract

A 3-leads, non-diagnostic EKG has a role in emergency rescue and homecare. In this paper we introduce the design and a prototype of a service, provided to a doctor and a patient, for the on-line remote visualization of patient's 3-leads EKG. The architecture is based on the HTTP protocol, using commercial off-the-shelf devices to implement the sensor on patient's side, a browser on a laptop Personal Computer (PC) on the doctor's side as viewer, and a cloud container to connect the two using Websockets. A prototype is built to evaluate signal latency, power consumption of the patient side device, and the quality of the rendering. After some experiments, latency is measured below 1*sec*, and power consumption is estimated in the 2A*3.3V range; visualization is comparable to commercial, non-diagnostic products. The prototype patient device is portable, and can be operated using rechargeable battery packs. Its cost is below 100$, and all the required equipment is commercially available. The architecture is ready for *on field* evaluation, and we indicate how to improve power consumption while reducing cost.
Keywords: Non-diagnostic ekg; Websocket; Cloud PaaS; EKG acquisition; Arduino; Raspberry Pi

1 Introduction

There are cases where heartbeat monitoring would improve doctor's assistance, but the patient and the physician are not in the same room. What we need in that case is to transmit the electrocardiogram (EKG) from patient's heart to doctor's display: this is an *on-line remote EKG*. The number of use cases for remote EKG is long and includes assistance in rural areas, emergency rescue, automated processing and alert, long term recording etc. In most cases a diagnostic 12-leads measurement is inappropriate, since it requires time and a specific training to be prepared, while a 3-leads, non-diagnostic EKG is fitting. Two stories illustrate its possible utilization.

One is that of an ambulance with paramedical personnel rescuing a injured person after a car accident. It is likely that the location is covered by a ground or satellite broadband provider, and that an Access Point (AP) is available, e.g. by tethering a smartphone. With an on-line remote EKG service the 3-leads trace is delivered to the medical staff in the hospital, that defines the emergency level.

A different homecare story is that of a cardiac patient that is periodically contacted by the family doctor to check general conditions. In that case the physicist uses a remote EKG service to receive the trace without leaving its desk during a phone call, possibly interacting with the patient about electrodes position or body posture.

This paper addresses the long distance delivery of a non-diagnostic EKG, using cloud facilities integrated with personal devices.

*Dept. of Computer Science, Universitá di Pisa L.go B. Pontecorvo - 56122 Pisa ORCID:0000-0002-9734-2044

2 Background and previous works

The electrical functionality of the heart is a fundamental diagnostic information for the medical staff. Its recording dates back to the end of the 19th century. From that time, research addressed first the amplification of the signal, whose amplitude is in the μV range, and next the design of filters that remove unwanted components (like powerline *hum*, or signals from other muscular activity). The current state of the art on EKG filtering is in [11].

Computers come into play in connection with filters, and today they extract the fundamental features of the EKG signal. In [10] the authors introduce an approach and evaluate the computing resources needed, with a survey of other research results in the field. A recent survey is also in [14].

With the advent of the Web, storage and transport of EKG data emerge as a practical perspective. In [13] the author investigates its use for human identification, and incidentally creates a database of EKGs, that later became a precious resource for many. The availability of historical data is relevant for medical research, daily health-care use, and educational purposes.

The primary concern with the transport and storage of an EKG is about its confidential nature. In [18] the authors survey a number of cryptographic systems that can be used to secure the transport and the storage of biosensor data. The paper assumes the presence of a number of distinct sensing devices aggregated in a Medical Sensor Network (MSN).

The ubiquitous presence of wireless networks justifies the realization of portable (or even *wearable*[2]) EKG devices that forward the trace to a nearby PC or tablet. When many such devices are aggregated in a network, we speak of a Body (or Personal) Data Network (BAN). In 2001, [12] introduces the basic principles and concepts, and, ten years later, a survey in [3] lists nine BAN projects, 5 of which include EKG. Detailed designs of BAN devices are found, for instance, in ([19]), [17], [7]. However they are appropriate for local area networks, confined in a room or a building.

The availability of cloud servers allows overcoming such limits. In [21] the authors propose a cloud-based infrastructure: the physician and the patient are clients of a Web server that processes the EKG, evaluates its quality, and provides parameter extraction and visualization. The server is in the Amazon Web Services (AWS) cloud, while the client uses personal devices that interact with the server using Secure Hypertext Transfer Protocol (HTTPS).

To facilitate the diffusion of the remote EKG service, we need to address the cost of the hardware devices, which also meets the needs of developing countries and of rural areas, as in [20] and [8].

In this paper we show how a cloud infrastructure can be used to relay the EKG from the patient's device to the doctor's laptop: in a nutshell, we actualize the ideas in [21], but with the target of [12]. This result is obtained using low cost devices and established protocols and infrastructures, without overlooking security aspects.

3 An open service for remote EKG

The design guidelines authorize several alternatives, and we propose the architecture outlined in figure 1.

The right box represents the devices on patient's side. We observe the analog stage with the operational amplifier and the filters, the processor that encodes the analog signal on a serial line, a Hypertext Transfer Protocol (HTTP) user agent that further processes the signal and manages the Websocket. This stage is connected to the Internet with a wireless link, and reaches the cloud server.

The devices on doctor's premises are in the left box: a wireless AP, and the smart device (a PC or smartphone) with a HTTP client that manages the Websocket, and displays the EKG in a convenient way.

From the security perspective, we highlight that only the routers inside the APs need to expose a public Internet Protocol (IP) address, therefore both patient's and doctor's devices can

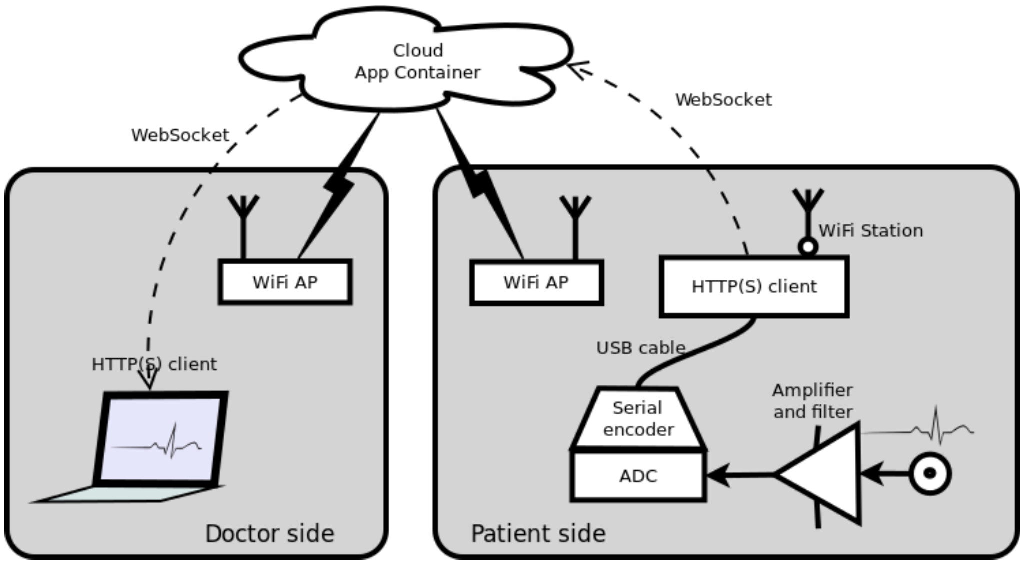

Figure 1: Remote EKG service infrastructure layout

be protected by a Network Address Translation (NAT) and other security techniques implemented on the router, according with common practice.

The cloud server needs a limited computational capacity, and it may exist just for the time needed by the physicist to examine the EKG: it is the ideal candidate for a microservice instance [15]. A Platform as a Service (PaaS) provider can create a new instance of a microservice in a few seconds, make it accessible in the Internet with a unique Uniform Resource Locator (URL), and destroy it after use.

The cloud provider is responsible for the security of the server, whose URL is known only to the partners. However, server life span is so limited that the potential intruder has little time to identify and attack it, especially if communication is encrypted, for instance with Transport Level Security (TLS).

The adoption of HTTP as the transport protocol is a cornerstone, since cloud services, that are reachable only using this protocol, provide a flexible, reliable and secure infrastructure for EKG transmission. Although real time aspects of the remote EKG are incompatible with the HTTP request/response mechanism, the *WebSockets* [9] have been recently introduced to allow unsolicited communication between client and server. WebSockets have a behavior similar to Transport Control Protocol (TCP) channels, but are encapsulated in a HTTP session.

In our architecture, the PaaS server acts as a relay point: two separate WebSockets are created to this end, one with the patient, another with the doctor, and the data are trasparently transferred from the former to the latter. This configuration turns out to be easily scalable, with costs that at the prototype stage can be null, and with excellent security features.

In addition, with HTTP the doctor uses the browser of his laptop to view the EKG, without the need to install new software. The architecture is therefore agnostic of the operating system installed on doctor's premises.

To have similar benefits also on patient's side, we introduce the following principles, that, in this paper, are synthesized in the Open Source, Low Cost, COTS (OpLoC) acronym:

- **Open Source**: components and protocols are exhaustively documented and freely reproducible;
- **Low Cost**: the less expensive option is always preferable. In particular, if a functionality is already available, it is not re-implemented;

```
void Timer2OveflowISR( ) {
  int i;
  unsigned long int t;
  if ( full [b] ) {
    Serial.println (fail);
    return;
  }
  for (int Channel = 0 ; Channel < 6 ; Channel++) {
    Data [ Channel ] [ b ] = analogRead (Channel );
  }
  full[b]= true;
  b=b1;
}
```

Table 1: The function triggered every 4*msecs* on the MCU

- **Commercial Devices**: devices must be available on retail (aka Commercial Off-the-shelf (COTS)).

Put together, the three principles ensure that an implementation is easily reproducible, and makes a solid ground for further investigation. In addition, low cost ensures that its applicability is not selective by scale and wealth.

4 A prototype for a remote EKG service

This section describes a concrete implementation of the above abstract design. In figure 3 we see the device on patient's side, while in figure 4 we see the display in the browser. Together with the OpLoC hardware components, the prototype contains also three ad-hoc software products, whose code is publicly available on the Bitbucket and GitHub platforms:

- the analog-to-serial encoder in the Micro-Controller Unit (MCU) [6]
- the HTTP patient-side User Agent (UA) [4]
- the doctor's page and the Websocket manager in the cloud container [5]

The sensor: amplifier and filter

The prototype uses the popular *Olimex EMG-EKG* sensor board [1]: its size is $6 \times 8 \times 3cm$, and the cost is around 30$. It is usually sold with EKG pads.

The board integrates a 3rd order filter at 40Hz and two high-pass filters to remove high frequencies and baseline drift.

A single board acquires a non-diagnostic 3-lead EKG through a 3-pole jack. The design of the board allows to stack up to 6 boards for a diagnostic 12-lead EKG, but our prototype uses just one of them.

The MCU: Analog Digital Converter (ADC) and serial encoder

The MCU is a popular Arduino Uno board, whose cost is around 10$. The connection with the Arduino-compliant Olimex board described above is obtained by *stacking* the two boards: the result is mechanically stable and sufficiently compact. The analog output of the sensor board is converted into a 10-bits integer by the ADC embedded in the MCU.

To have an accurate timing, needed for filtering and analysis purposes, a hardware interrupt triggers data fetch with a frequency of 250Hz [16]. The code snippet for the interrupt handler is in table 1: note that it is prepared to collect six analog data for a standard 12-lead EKG, but only one is used in the prototype. The main loop waits for the buffer to be readable, and encodes a space-separated line:

```
<h>:<m>:<s>.<msec> <v1> <v2> <v3> <v4> <v5> <v6>\n
```

The first field is a $1 msec$ resolution timestamp, and the other six fields, of which only one is used in the prototype, are integers in the interval $[0 - 1023]$ that correspond to a sample. The encoding does not introduce any rounding or information loss, and its redundancy is functional to data integrity. The timestamp is not as accurate as the sampling period: it is used only for rendering.

To avoid interference between data fetch and encoding, a two positions buffer is introduced, with access regulated by a semaphore.

It is worth saying that Olimex provides a different driver ([1]), but its accuracy is not sufficient for the task.

MCU to Single Board Computer (SBC) interface

The two units communicate using their Universal Asynchronous Receiver-Transmitter (UART)s, with a baudrate of 115200. Since the maximum length of a line is 44 8-bit characters, and 250 lines are produced each second, the MCU outputs 11000 bytes per second. Since one stop bit per byte is added, this requires a baudrate of 99000, which is consistent with UARTs one.

Patient side user-agent

Since the sensor unit has tight timing requirements and limited capabilities, it is more appropriate to decouple the HTTP UA on a distinct platform. The Raspberry Pi 3 used in the prototype is a SBC that uses production-level libraries to implement the patient-side user agent. Its cost is about 25$.

The UA is written in Python, and opens a Websocket connection with a container hosted in the Heroku cloud whose URL is:

```
http://<container fqdn>/in/<id>
```

where `<id>` is a unique id for the device. When the Websocket is opened, the UA starts sending EKG samples encoded as JavaScript Object Notation (JSON) objects with two fields: the timestamp, and one value.

4.1 The server

The server is a container in the Heroku cloud: for the sake of simplicity, the prototype envisions one single container hosting several concurrent EKGs instead of a short lived micro-service for each of them.

The server is implemented using the *Python/Flask* micro-framework and the `gunicorn` Web Server Gateway Interface (WSGI) HTTP server. It provides three families of application routes:

- `/` which returns a presentation page,
- `/in/<id>` used by a patient's UA to open a Websocket, as explained above,
- `/<id>` used by doctor's UA to open a Websocket and receive the EKG,
- `/out/<id>` used as endpoint for doctor's Websocket

The server waits for a patient's UA request on the `/in/<id>` route, upgrades the session to a Websocket and prepares to receive a request from doctor's side with the same `<id>`: until then, all received data are lost. If doctor's request arrives first, the server returns a negative reply.

When the server receives doctor's request on an `/<id>` path matching patient's UA, it delivers a page containing the JavaScript code to open the WebSocket on `/out/<id>` and displays the EKG.

Since each patient UA has a different identifier, a single server may host several EKG at the same time, each of which is received by only one doctor UA.

The security mechanisms announced in the 3 are not fully implemented: namely, in the prototype the server is persistent and communications use plain HTTP. The implementation of such features appears to be quite straightforward, and it is a matter for the improvement of the product.

The display UA

The UA on doctor's side is a web browser running on a laptop. The doctor opens the HTTP session using a URL with the Fully Qualified Domain Name (FQDN) of the server and the `/<id>` route. If the corresponding patient is already connected, the response contains a resource composed of the familiar EKG canvas and of a JavaScript application that opens a WebSocket on the `/in/<id>` route. From it the EKG is received and the Chart.js library is used to display it.

The JavaScript application filters out the $50Hz$ powerline noise with a moving average of five values and finds R peaks to compute heartbeat frequency. This demonstrates the possibility of additional filtering and feature extraction on doctor's side, and provides a readable result.

5 Results and future work

A relevant parameter is the latency between the production of the signal and its visualization: it has been measured as lower than one second. Autonomy with battery operation has an impact on practical usability as well: using a $2200mAh$ rechargeable power bank an autonomy of 72 minutes has been measured, and the prototype operates with the 3.3V power supply provided by the Raspberry.

The Raspberry Pi 3 over-kills its task, and it is a candidate for replacement with a more focused OpLoC device. Being in charge of implementing the patient's WebSocket, it uses 50% of the space, 90% of the power (nearly 1500 mA), and 30% of the cost.

The interface on doctor's side (see figure 4) should be extended with a switch to select filtering, feature extraction and evaluation tools, and the possibility to save, and replay, the trace. A Smartphone interface is close to reach, but the limited size of the display makes the EKG significantly less readable.

6 Discussion

An open-source on-line remote EKG architecture has been introduced. This kind of service is already offered in return for a payment, as part of health-care packages, and it is usually based on proprietary hardware/software resources. In contrast, this paper aims at an architecture based on open source resources, with an attitude that we summarize in the OpLoC acronym: hardware, software, and communication protocols are affordable open source products. A few of them have been designed for the purpose (namely, the client/server software and the serial protocol), but the rule is to use COTS resources. One of the resources is in the cloud, the web-server that transfers the EKG from the patient to the physician: no exception, it is a *plain* open-source web server. To demonstrate that the architecture is feasible and to evaluate its performance, we implemented a prototype that is exhaustively described and reproducible. The OpLoC principles foster a wider diffusion of a useful device on a more competitive basis, and make it applicable to disadvantaged or marginal regions.

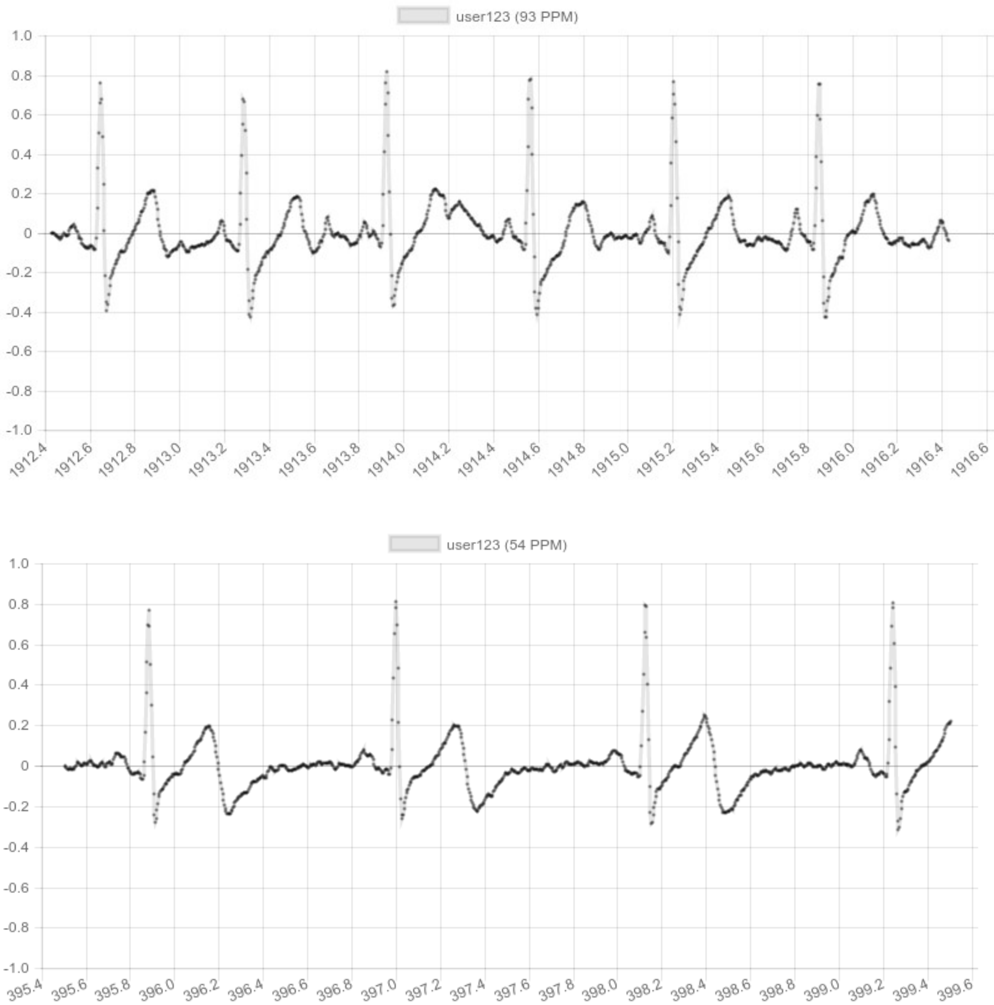

Figure 2: Two EKGs: one after exercise, using elastic bands on left and right wrists and right ankle, another at rest, using adhesive electrodes on chest. They have been captured as screenshots form doctor's browser using the prototype described in the paper.

7 Abbreviations

OpLoC Open Source, Low Cost, COTS

COTS Commercial Off-the-shelf

EKG electrocardiogram

UA User Agent

FQDN Fully Qualified Domain Name

HTTP Hypertext Transfer Protocol

HTTPS Secure Hypertext Transfer Protocol

URL Uniform Resource Locator

JSON JavaScript Object Notation

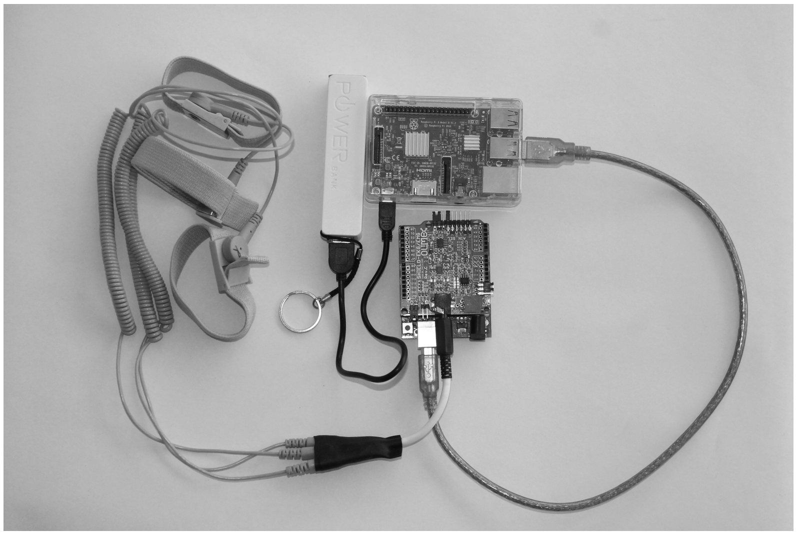

Figure 3: The patient-side prototype device, with three elastic bands, the $2200mAh$ battery, the Arduino/Olimex EKG boards and the Raspberry Pi 3

WSGI Web Server Gateway Interface

MCU Micro-Controller Unit

SBC Single Board Computer

PaaS Platform as a Service

AP Access Point

BAN Body (or Personal) Data Network

MSN Medical Sensor Network

PC Personal Computer

AWS Amazon Web Services

NAT Network Address Translation

TLS Transport Level Security

ADC Analog Digital Converter

UART Universal Asynchronous Receiver-Transmitter

IP Internet Protocol

TCP Transport Control Protocol

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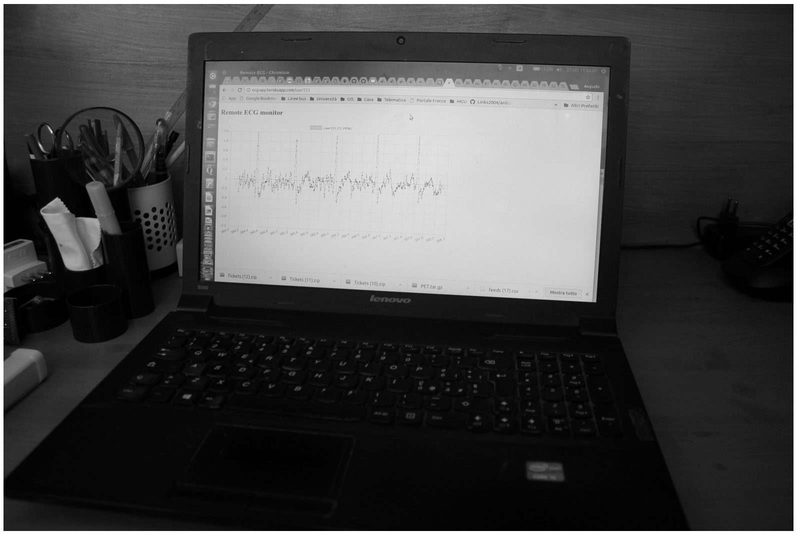

Figure 4: The remote EKG display on doctor's side

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