POLITECNICO DI TORINO
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SwarmBike: an IoT Sensing Platform for Air Pollution

(Summary)

Relatore
prof. Fulvio Corno

Candidato
Carmelo Migliore

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In recent times, the world has seen the rising of the so called **Internet of Things**. Many common objects, from wristbands to cars, from household appliances to ambient sensors, can be now connected to the cyberspace. The contemporary enormous success of smartphones has lead to the idea that sensor data collected by the users can be exploited in various ways, opening new scenarios especially for environmental monitoring. Crowd sensing scenarios, where "smart citizens" collect precious information at a relatively low cost, may become a key enabler for **smart city** services, exploiting new ICT technologies in order to increase efficiency and improve the overall quality urban areas.

This thesis work, made in collaboration with the TIM SWARM Joint Open Lab, aims at leveraging on people who moves around the city to collect air quality data, while also offering new services related to more sustainable ways of moving. The objective of this work, in particular, is to design and prototype SwarmBike, an IoT platform for **air pollution sensing**, based on a monitoring device which can be purchased by users and mounted on their **bicycles**. The main idea is to exploit bikes as mobile sensor nodes which can gather data from the environment. This way air pollution can be sensed either while cycling, enabling the estimation of the quality of the air breathed by the cyclist, or when the bike is parked, permitting to collect better statistical air quality data in a certain zone of the city. Given the fact that a high amount of users is needed for the system to work properly, it cannot rely only on volunteers. Therefore, it was decided to add other secondary features to the device, in order to make it more appealing to users. The secondary features have been selected based on the results of a survey conducted among some cyclists. The results showed that the most wanted feature was an **anti-theft system**, with the possibility to remotely visualize the position of the bike on a map and to receive notifications on a smartphone in case of a theft attempt. To implement those features, the SwarmBike device has to meet some requirements:

- Its weight and its size must be acceptable for being carried on a bike
- It must run on battery and an acceptable battery life must be achieved
- It must have a GPS module and a cellular modem for connecting to the Internet
- It must have an accelerometer to detect motion
- It must be easily managed and configured through a smartphone app

A deep analysis of all the main air pollutants was performed to decide which one to track and which sensors to use. The analysis was mainly focused on the pollutants present in urban environments: gaseous pollutants and particulate matter (PM). Different sensor technologies needed to detect and measure the level of those pollutants were evaluated. Particulate matter sensors are mainly based on optical principles (light scattering), while low-cost gas sensors can be grouped in two main types: semiconductor sensors and electrochemical sensors. Particulate matter sensors can have a not negligible power consumption, consequently they were not considered suitable for a battery operated device like SwarmBike. Semi-conductor gas sensors can also have a high power consumption, given the fact that they need a heater to work properly. Furthermore, semi-conductor sensors have a poor reading accuracy. It was thus decided to employ **electrochemical sensors** to detect gaseous pollutants: those sensors, whose principle is based on redox reactions, have a very low power consumption and provide a good accuracy. They also are already calibrated at the factory. The only additional requirement for this type of sensor is an electronic circuit called "potentiostat", which is needed for the chemical reactions to happen correctly and for the conversion of the output current in a voltage that can be read by a microcontroller. Low cost electrochemical gas sensors are a relatively new technology, therefore the choice of the pollutant to monitor has been influenced by the availability of those sensors on the market. The easiest low cost electrochemical sensors to purchase were **Carbon Monoxide** (CO) ones, therefore it was decided to monitor that particular gaseous pollutant.

As can be seen in figure 1, the overall architecture of the SwarmBike system consists of three major components:

- The device itself, mounted on a bike
- The smartphone application
- The cloud backend

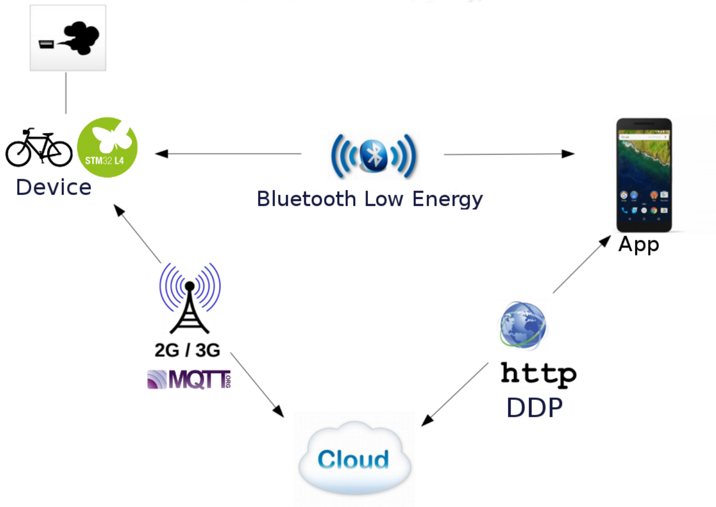

Figure 1: Architecture of the SwarmBike system

The device is the component which has to be mounted on the bike. It can communicate with the mobile app using Bluetooth Low Energy (BLE) and with the cloud through a cellular connection and the MQTT protocol. For prototyping the device, it was decided to use a **STM32L4 Nucleo** board. Nucleo boards are low-cost developing platforms produced by STMicroelectronics. Specifically, STM32L4 boards have the particularity to be both high-performance and ultra low-power, therefore they fit perfectly with the requirements of SwarmBike. The chosen CO electrochemical sensor was a Nemoto NAP-505, while a Texas Instruments LMP91002 has been used as potentiostat. It was necessary to design and realize a custom PCB to integrate the sensor and the potentiostat, because the LMP91002 comes only in a small WSON package. The device has also been equipped with a GPS/GPRS module, a BLE expansion shield and an environmental sensors shield (which included an accelerometer, temperature, humidity and pressure sensors).

The device has **two working modes**: normal mode and anti-theft mode. In normal mode, enabled during bike rides, it periodically acquires air pollution data and sends them to the cloud. In anti-theft mode, enabled when the bike is parked, it continues to acquire and send pollution data (at a lower rate) but more importantly it uses the accelerometer to detect motion. In fact, if motion is detected an alert is sent to the server which in turn sends a push notification to the mobile app, in order to warn the user of a theft attempt. For the implementation of the **firmware** of the device, it was decided to exploit **ARM mbed OS**, an open source IoT operating system provided by ARM, which makes it easier to develop embedded applications. All the software which drives the device has been written using the **C and C++** programming languages. It is worthwhile to mention that it was necessary to develop some collateral software for the first prototype of the device. The additional developed software has been publicly released under the Apache license and includes the porting of the Eclipse Paho MQTT client, the drivers for the GSM/GPRS module and for the potentiostat, and the adaptation of the lower layers of mbed to the chosen Nucleo board.

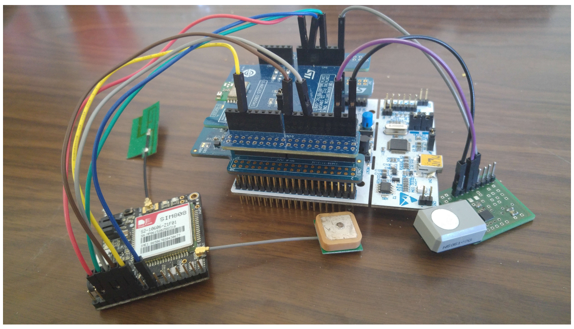

Figure 2: The prototype of the SwarmBike device: on the left the GPS/GPRS module, on the right the custom PCB with the CO sensor and the potentiostat, at the center the STM32 Nucleo board with the expansion shields

The **smartphone application** is the component used to manage and configure the SwarmBike device. It permits to set authentication information on the device (e.g. username and password for the MQTT connection), it shows instant sensors values and it permits to enable and disable the anti-theft mode. It communicates with the device using a BLE connection. The mobile application is also responsible for showing in real-time the remote position of the device on a map in case of theft or loss. The application has been developed for **Android** and it is compatible with the 5.0 "Lollipop" version or newer.

For the **cloud backend**, it was decided to adapt some technologies and applications already used by TIM. An IoT platform, SiteWhere, has been used to collect and store all the data received from the devices. Those data can be accessed and analyzed using a set of REST APIs. An application developed using the Meteor.js framework, on the other hand, has been used to manage all the other server-side features. This application in fact, when the anti-theft is enabled on the device, receives its position and builds a map, which can be visualized on the mobile app or through a web browser. In case of a theft attempt, it also receives an alert from the device and in turn it sends a push notification to the smartphone app exploiting Google Cloud Messaging.

The **results** obtained by this thesis work demonstrate that monitoring air quality by using bicycles as probes is a perfectly achievable objective. SwarmBike is a valid prototype which could be improved and extended in order to be used in real life scenarios. The battery life of the device, measured using a 10000 mAh powerbank, reached almost 45 hours of continuous work, which is an acceptable result for a prototype (considering a usage of 8 hours per day, the device would permit 5 days without a recharge). The weight, including the 10000 mAh powerbank, is 650 grams, and the size of a first cardboard case is 20.5 x 12.5 x 9 cm. Device's battery consumption, weight and size could be significantly reduced by adopting a custom PCB design, however the first prototype of the device is acceptable and can be easily mounted inside a bike's basket and used to test the system.

Regarding the Carbon Monoxide acquired data, given the fact that the sensor does not need calibration, it was possible to estimate the gas concentration straightaway. The gathered data were perfectly plausible and compatible with the expected carbon monoxide concentration in a city like Turin, ranging on average from 1 to 10 ppm (see figure 3 for an example). Unfortunately, it was not possible to cross-validate the acquired data with high accuracy sensors, because such a professional instrumentation was not available at TIM. To remedy this flaw, an experimentation will be done in the next months in collaboration with ARPA Piemonte to permit a stricter validation of the gathered pollution data. SwarmBike has also been selected by TIM for an experimentation in quartiere Campidoglio, in the context of the "Torino Living Lab" project, an initiative launched by the Torino city council.

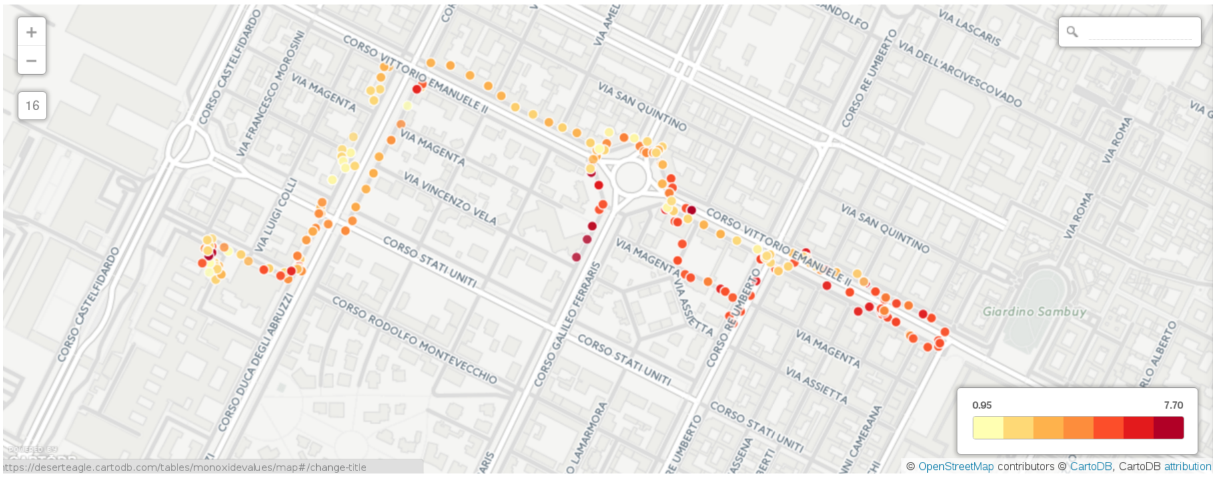

Figure 3: Values are in parts per million