# Enabling experimentation in mobile sensing scenarios through 4G networks: the NITOS approach

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***Abstract*—Wireless technologies have evolved rapidly over the past years, directly affecting our everyday living with the wide penetration of smart mobile devices. As such, the research community has placed major efforts in shaping and forming the future wireless technologies for enhanced end-user experience. Nevertheless, protocols and algorithms over wireless networks are better evaluated in real world scenarios, where simulations and complex theoretical models fail to characterize and emulate their behavior. Networking experimental facilities (testbeds) fill this gap by allowing experimental network measurements to serve as a basis for extracting valuable findings. In this paper, we present the extensions to the NITOS testbed for supporting experimentation in mobile sensing scenarios, by employing smartphones in vehicular environments, communicating using WiFi and 4G networks. We emphasize on the ease of configuration, execution and reproducibility of these experiments, leveraging the hardware and software tools provided by the NITOS testbed.**

## I. Introduction

Recent technological advances have brought enormous changes in mobile devices, becoming nowadays increasingly sophisticated, miniaturized and practical. Hence, smartphones, tablets and wearable devices have become part of our everyday life, being the main computing and communication mobile apparatus. A key feature of the aforementioned devices is the rich set of embedded sensors that enable the collection of meaningful data of the physical context around the user. Collecting data by distributed mobile users can give birth to innovative services that can be useful for the society as a whole, instead of just benefiting the individuals.

Collecting and analyzing a vast number of raw data in real-time and in large-scale can lead to the formation of emerging applications. Environmental monitoring is an example of such an application, attracting a lot of interest lately since it is directly connected to human health. To note that, environmental pollution is currently monitored by static measurement stations of high-cost. This limits the indications to a small-scale, failing to provide the spatial distribution of pollutants in urban environments.

On the other hand, mobile devices can achieve an unprecedented level of coverage in both space and time, given their ubiquity and the high density of population in urban areas. Moreover, the tremendous growth of wireless technologies offers high-speed Internet that can be utilized for massive data collection in real-time. Notably, mobile operators have updated their infrastructures to provide enhanced overall capacity, by employing 4th Generation (4G) mobile networking technologies. As such, WiMAX, LTE and LTE-A deployment has already been launched by most mobile network operators worldwide [1] [2], enabling upgraded inter-networking performance and end-user perceived Quality of Service (QoS). The LTE protocol design creates fertile ground for its future capacity improvement; from the peak downlink throughput of 300Mbps in Release 8, it is expected that maximum throughput will reach 1Gbps with the beyond Release 10 amendments. This growing network capacity can therefore be employed to meet the needs of traffic demanding applications, such as mobile sensing.

Despite the technological advances, limited resources exist worldwide which enable experimentation with open infrastructures in order to study and evaluate several facets of mobile sensing. To note that, most of published works by today are based solely on simulation results due to the innate difficulty in conducting experiments using real devices with wireless connectivity. Consequently, those works fail to provide reliable and credible results, as indicated in [3], [4] and [5]. Therefore, the requirement for research platforms that allow experimentation under real-world settings is further highlighted. To this aim, several wireless experimental facilities (testbeds) have been developed over the recent years. NITOS Future Internet (FI) facility [6] is one of the largest infrastructures continuously evolving through major extensions reflecting the latest technologies and trends in the FI ecosystem. The management of NITOS and the whole experiment lifecycle is performed via the cOntrol and Management Framework (OMF) [7] while the OMF Measurement Library (OML) [8] is in charge of the orchestration of generated data.

In this work we exploit the NITOS facility and we further expand its capabilities to support experimentation employing smartphones carried by volunteer users, equipped with environmental sensors, while utilizing WiMAX and WiFi wireless networks for backbone access.

The main contributions of this paper are: (i) we describe the extensions made to the OMF framework in order to deal with mobile phones and sensing; (ii) we describe the implementation of a device connected to users smartphones, used to acquire environmental data; (iii) we present indicative results from a proof-of-concept experiment that takes advantage of the NITOS extensions.

The rest of the paper is organized as follows. Related work is presented in Section II. Section III illustrates the overall architecture of NITOS facility with the extensions made. Section IV presents the individual components utilized along with their enhancements and configurations. Section V demonstrates the experiment realized and section VI concludes the paper and outlines potential directions.

## II. Related Work

Although modeling the wireless channel parameters (such as external distortion) has significantly improved over the past years, non-deterministic effects, present in real world settings, can deteriorate the overall performance of the under study algorithm/idea. Towards ameliorating this defect in the wireless simulation platforms, several testbeds have been developed to support experimentation with real networking equipment. A pioneering work on this field is [9], where the authors rely on the large-scale ORBIT testbed which features a WiMAX experimental network that acts as the backbone for mobile nodes mounted on vehicles. This work exploits OMF for the management of the experiments but it is not focused on sensing applications involving mobile users. Similar to this, authors in [10] are emulating a vehicular testbed for the application evaluation of Intelligent Transportation System services under a real network setup. Another testbed supporting mobile experimentation is in [11], where users can employ real moving robots equipped with wireless nodes to conduct an experiment. The experimenters are able to provide the desired path that mobile nodes should follow during the experiment, and their framework takes care of the potential collisions of the mobile nodes. However, this testbed is operating in an indoor field, utilizing only WiFi and ZigBee technologies. The same in [12] where robots carry wireless sensor devices instead of wireless nodes, also operating in an indoor environment.

Nonetheless, mobile sensing is still merely addressed when experimenting with real infrastructure. A noticeable work in this field has been done in [13], where the authors developed a city-scale wireless sensor network with both fixed and mobile nodes. The mobile nodes are commercial devices deployed on public transport buses and municipality vehicles to perform air quality measurements throughout the city. The backbone plane is realized over the old-fashioned GPRS standard and they lack to adopt a widely used experimental management framework such as OMF. Another example of a city-scale mobile sensing network is described in [14] where trams carry custom devices that sense air pollution. However, this is an application system aiming to provide the spatiotemporal distribution of air pollutants, without experimentation capabilities.

Towards filling this gap, in [15], [16] and [17] authors developed a city-scale mobile sensing infrastructure that relies on bicycles of volunteer users. In these works a custom-made device was employed, endowed to gather environmental measurements as well as the available WiFi networks in the under-study city. The sensing framework is available through the OMF platform, thus enabling user-friendly experimentation with the mobile components. However, in these works only WiFi and ZigBee technologies were used in order to enable communication with the mobile devices. Finally, in [18], authors equipped vehicles with wireless nodes in order to gather environmental data. Experimentation was conducted through OMF, yet the backbone network was based on the short-range WiFi technology.

Therefore, to the best of our knowledge, no integrated framework exists that successfully combines experimentation with real network resources and mobile sensing capabilities. To this aim, we enable mobile sensing capabilities on the NITOS testbed and build the appropriate software extensions to the state-of-the-art testbed management framework in order to support such efforts.

In the following sections we provide some information on the architecture of the testbed and the designed components towards enabling city-wide environmental measurements collection, using 4G network infrastructure.

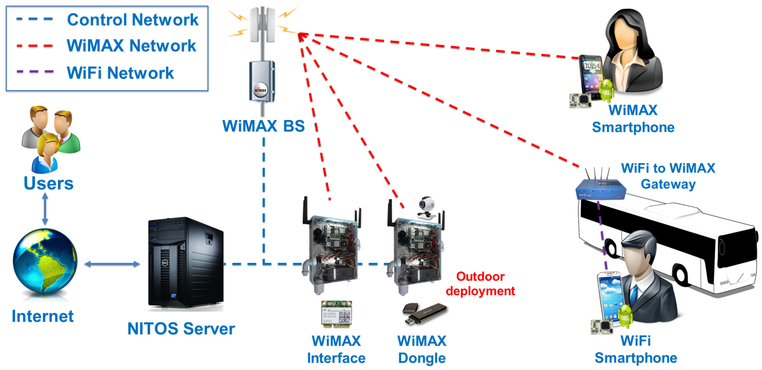
## III. NITOS Architecture

NITOS FI facility consists of three distinct testbeds which are located in different locations, each one with unique prevailing environment conditions. There is an indoor testbed located in an RF-isolated basement, an office testbed and an outdoor testbed prone to external RF interference. Overall, the testbed hosts equipment that enables researchers to perform their experiments in the domain of wireless communications, including technologies such as WiFi, WiMAX, LTE and Software Defined Radios (SDR). Moreover, the facility is complemented with OpenFlow equipment, a Wireless Sensor Network and a Cloud infrastructure which allows the conduction of complex experimental scenarios. NITOS is open and remotely accessible to any researcher who aims to deploy and experimentally evaluate networking protocols and applications under real world settings.

An architecture diagram of the NITOS facility can be seen in Figure 1a where the different resources of the testbed are depicted. An integral part of the testbed are the WiMAX base station and the custom-made wireless nodes, equipped with 802.11 a/b/g/n and cellular network interfaces (HSPA, WiMAX, LTE). All the different components (servers, nodes, base stations) are interconnected through a control plane Ethernet connection.

The OMF framework is a key component of NITOS, since it allows experimenters to automate their experiments instead of setting up everything manually by logging into each node to configure/control its operation. The concept is similar to network simulators where the user describes a topology along with the applications running during the simulation. The difference is that the topology consists of physical nodes on which OMF can execute any application that is available on the target system (like for example a traffic generator). Also, measurements are automatically collected with the help of the OML library. Configuration and control of node operation occurs through specific properties, which are part of "formal" resource descriptions, and can be done not only with the experiment setup but also during experiment runtime. The basic components of the OMF framework are the Experiment Controller (EC) and the Resource Controllers (RCs). The role of the EC is to orchestrate the execution of the experiments, written in the OMF Experiment Description Language (OEDL). The EC interprets OEDL and sends appropriate messages to the corresponding RCs. In turn, each RC is responsible for abstracting and controlling one or more underlying physical or logical resources. It basically converts the messages received from the EC into resource-specific commands, and relays the response back to the EC.

Even though NITOS features a diverse number of resources and experimentation capabilities, there is limited support regarding the mobile domain, which we tackle in this paper by presenting extensions implemented in NITOS. Towards enabling enhanced mobile experimentation, we introduced




(a) The NITOS wireless and vehicular testbed topology.

(b) Mobile sensing module.

Fig. 1: NITOS Architecture diagram and developed device for mobile sensing.

several extensions to the testbed in order to meet the following requirements: (i) support experimentation involving smartphones; (ii) enable environmental sensing using mobile users; (iii) provide wireless connectivity over a wide-area; and (iv) provide vehicular environment.

For the purpose of providing experimentation support for smartphones, we developed an OMF RC for Android enabling the experimenters to remotely control the smartphones through OMF. Additionally, we developed a hardware device featuring environmental sensors that can be attached on the mobile phones for enabling participatory sensing. We have also developed an Android application responsible for acquiring the measurements generated by the sensing device and store them through OML. For the purpose of providing wide-range connectivity we used the WiMAX setup and developed the necessary extensions in OMF for supporting its configuration through the framework. Finally, in order to mount wireless nodes on vehicles, we modified the NITOS wireless nodes to a lightweight version that can be powered through any vehicle's power supply.

## IV. NITOS Extensions

In this section we present the NITOS resources that allow the configuration of a complex experiment using Android smartphones in a vehicular environment over WiMAX and WiFi networks. Some of the existing testbed applications and frameworks were enhanced in order to meet our experiment requirements and some were introduced as new testbed extensions for supporting mobile experimentation. In the following subsections we describe our main software and hardware contributions.

### *A. WiMAX Infrastructure*

NITOS testbed is offering the Airspan Air4GS WL24G [19] meso-scale WiMAX base station as part of its experimental infrastructure. Users can take advantage of the base station deployment and free-of-charge evaluate protocols and algorithms under a real 4G environment. The WiMAX base station is configured in a standalone mode, meaning that is is operating as a simple access point, without the need to connect to an ASN-GW, as seen in Figure 1a. In order to support experimentation with WiFi enabled Android phones, the testbed is also equipped with WiMAX to WiFi gateways.

Users are able to reserve the WiMAX setup (WiMAX base station together with WiMAX-enabled wireless nodes) and configure it through OMF. Then, we describe the necessary extensions to the core OMF framework which facilitate access to these resources:

**WiMAX OMF Service:** An OMF service that enables the configuration of the WiMAX base station through a REST based API has been developed. More specifically, the service is in charge of translating HTTP commands through the offered API to the appropriate SNMP messages for configuring the base station parameters (such as the transmission power, modulation and coding scheme per client, etc.). Its implementation was based on the existing service provided at the GENI WiMAX testbed sites, developed by WINLAB [20] supporting commercial WiMAX base stations and on the respective implementation supporting LTE base stations [21]. Our additions lay on developing the respective driver for supporting the Airspan base station that is installed at the NITOS premises, which required extensive changes in the method that the settings are configured (like SNMP) and the different parameters exposed by each base station.

**OMF RC:** Towards controlling the WiMAX end-clients, we developed an OMF Resource Controller (RC) that translates OMF configuration messages to the appropriate functions for setting the nodes' WiMAX interfaces, the WiMAX to WiFi gateway or the Android smartphone. These messages are translated to the respective API that each device uses (eg. SNMP/HTTP for the gateway, setting an XML file for the Android phone etc.) in order to finally establish a connection over the WiMAX network.

**OMF EC:** In order to incorporate the aforementioned functionality in the testbed, a parameterized OMF Experiment Controller (EC) has been implemented, able to parse and create the appropriate RC configuration messages from the parameterized OEDL syntax.

Given these extensions, the experiment flow is the following: (i) The users login to the NITOS server where they can access these WiMAX control services; (ii) If they have a valid reservation of the WiMAX resources for that specific timeslot, access is granted to the services; (iii) They configure the WiMAX base station through HTTP commands, in order to create their desired experimentation environment; (iv) Once the base station is configured, they describe their experiment in OEDL and execute it using OMF, handling the WiMAX end-clients.

### B. Android Mobile Phones & Applications

In order to create an uncontrolled mobility environment, we provided smartphones to volunteer users from University of Thessaly as a means to create real random mobility patterns.

More precisely, an additional OMF RC was developed to allow remote control of Android phones through OMF. The customizable parameters include the configuration of the WiFi interface and the execution or termination of specific Android applications. The OMF RC runs as a Background Service so that user's interaction with the device isn't hampered and is either booted at start up or can be started/stopped manually through a simple User Interface. During its operation, it can serve multiple experiments sequentially without the need of any human intervention. Furthermore, resilience to disconnections during experimentation is being supported, so that an experiment doesn't stop abruptly due to lost messages from the EC.

The OMF RC Android application deals with the problem of configuring and controlling remotely a smartphone. However, the need of acquiring measurements from mobile phones is part of the measurement collection phase which is normally handled by the OML framework. For this purpose, we developed a Monitoring application for Android [22], capable of acquiring measurements from the smartphone's interfaces and sending them to an OML server to be stored. Besides its monitoring capabilities concerning the interfaces of the phone, it can be also instrumented to obtain measurements from external devices that are connected to the phone, a feature that we exploited in order to attach a hardware sensing device described in the following subsection. Another important feature of the application is its capability to temporarily store the acquired measurements in the phone's storage when Internet connectivity is disrupted. The application can be started either by the user manually or by the afore-described OMF RC, thus providing the flexibility to experimenters for remote control of the sensing application.

### C. Microcontroller Sensing Board

Despite the fact that the latest off-the-shelf smartphones embed a vast number of sensors to acquire raw data from the user's environment, they do not integrate any sensor specialized for environmental monitoring. To tackle this challenge, we developed a small-sized, low-cost embedded device that can be interfaced with external sensors and feed the collected measurements into Android platforms through a USB connection. Due to its low-profile it can be placed beneath the back cover of conventional smartphones, as illustrated in Figure 1b, while it can be powered by the smartphone's supply through the same USB connection.

The device features a 32-bit ARM Cortex-M4 microprocessor running up to 72MHz and operates at 3.3V. A few GPIO pins are exposed and can be interfaced with sensing modules. The developed module integrates a serial communication port to communicate with the host Android smartphone realized over the USB connection. The device implementation relies on the Teensy 3.0 [23] board which has advanced capabilities; through the Teensyduino loader we can flash Arduino [24] firmware on the device. The Arduino platform supports firmware development with a mild learning curve, while its established user base with a large number of publicly available libraries can be used to easily facilitate communication with external sensors. Our implementation currently integrates a temperature & humidity module, a light-intensity sensor and a CO2 concentration sensor, all placed on the smartphone's back cover. Notably, the device can be further extended to support additional sensing modules, broadening its scope of environmental monitoring. The raw data acquired by the physical sensors are subsequently forwarded to the host smartphone and received by the aforementioned Android application.

Nevertheless, an obvious disadvantage of our implementation is the requirement of a USB connection with the target smartphone that might interfere with the user's activity. We can easily overcome this obstacle by utilizing a wireless interface (such as Bluetooth) in order to connect the device wirelessly with the host Android, as we have demonstrated in our previous work [25].

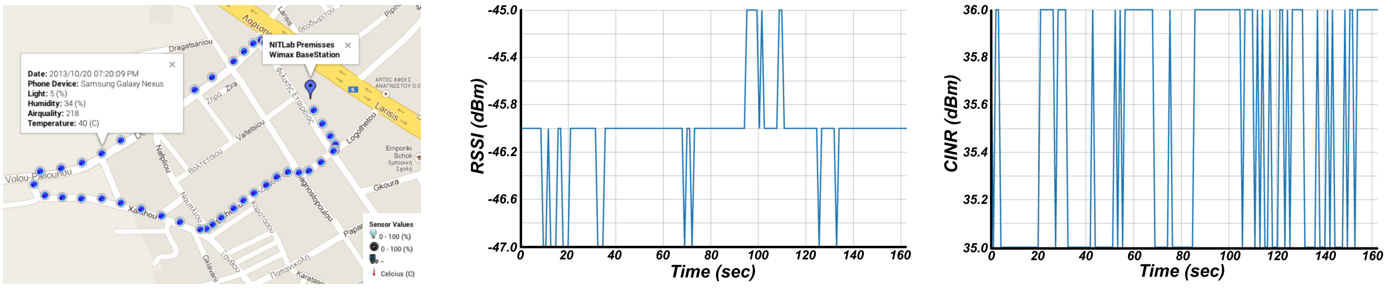
## V. Experimental Evaluation

An indicative experiment was carried out to showcase the capabilities of the NITOS testbed and how the different components can be combined together to compose sophisticated experimental scenarios. The following use case sets up a participatory sensing scenario where multiple users, who carry Android mobile phones, upload their measurements to a central database. In our target scenario, we mounted a NITOS lightweight node on a public transport bus, thus involving a vehicle as part of the experiment.

In more detail, the experiment utilizes the WiMAX technology as the backbone connection for the wireless node installed at the vehicle. The node acts as a WiFi to WiMAX bridge, thus enabling Internet connectivity for the bus passengers over the WiMAX link. The configuration of the WiMAX base station and the gateway node is performed via the OMF framework. Particular passengers carry Android phones, which collect environmental measurements and forward them to an OML server. The Android monitoring application is responsible for generating and forwarding measurements to the OML database, while the Android OMF RC deals with the configuration of the phone's functionalities.

During the scenario execution, the experimenter is able to monitor the acquired measurements on an interactive map, which is continuously updated as soon as a new measurement arrives at the OML server. The map offers detailed information per measurement, like for example the time and exact coordinates of each acquired set, as depicted in Figure 2a. Moreover, it is possible to monitor throughout the whole experiment the Received Signal Strength Indicator (RSSI) and Carrier to Interference plus Noise Ratio (CINR) values of the WiMAX link (Figures 2b and 2c), which are represented with the help of the OML graphical representation library. In case of the bus loses connectivity and the Android application loses connection with the OML server, the measurements are stored locally with their coordinates and timing tags and they are uploaded as soon as the bus gets into the coverage range of the WiMAX base station.

During the experiment execution, human intervention was none at all and intermittent connectivity was handled successfully by the provided tools of the testbed. Hence, the experimenter was able to monitor his/her experiment and focus on the interpretation of the results as he/she was not distracted by experiment configuration and execution. Thus, we showcased that mobile experimentation in large-scale can be successfully managed through the necessary extensions and tools, which are provided in the NITOS FI facility, encouraging that way




(a) Sensor values depiction on map.

(b) RSSI monitoring over the experiment lifetime.

(c) CINR variation over the WiMAX link.

Fig. 2: Experiment execution and obtained results.

researchers to employ experimentation over simulation for evaluating their work.

## VI. Conclusions and Future Work

In this paper we discussed about the need for experimental results obtained through experimentation in real world settings in sophisticated scenarios. We presented the NITOS testbed and emphasized on some of its key components that enable experimenters to conduct experiments involving Android smartphones with environmental sensors, vehicular networks that utilize WiMAX and WiFi communications and combine all these together to compose a participatory sensing scenario. The ease of configuration and experiment execution was handled by the OMF framework and the extensions that we made to it. The complementary library of OMF which is OML was used for the measurement collection and depiction which enabled the live monitoring of the whole procedure by the experimenter.

We envision to establish a large city scale testbed by incorporating the nodes of the NITOS testbed on the fleet of the transit buses and create a number of access points throughout the city that feature different communication technologies and are not limited to WiMAX or WiFi. These include technologies like LTE or even ZigBee. Our final goal is to be able to provide the necessary infrastructure for Future Internet experimentation in a large number of environments like vehicular and city-scale.

## VII. Acknowledgements

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