Challenges in the Life-cycle of Sensor Networks for Automation and Densification of Environment Monitoring in Rural Africa

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Abstract: The paper discusses challenges in the life-cycle of sensor network based environment monitoring stations deployed with the purpose to automate and densify the environment observation network in East Africa. The research involved is divided into two separate parts, the design and validation phase happening in the academic environment, and the subsequent manufacturing, deployment, operation, maintenance and recycling phases, while still being research objects, happening outside the academic environment.

Keywords: Wireless Sensor Networks, Environment Monitoring, Automatic Weather Stations, Low-power

1. Introduction

There is a widely accepted need for environment monitoring including a wide spectrum of parameters to facilitate forecasts of weather and climate change, farmers' decision-making in agriculture, monitoring of drinking water quality, pollution of air, water or land, all sorts of early warnings, environment impact assessment, etc. The stakeholders in environment information are everywhere, in all sectors of society.

Recent developments in sensor and sensor network technologies make massive monitoring feasible and affordable. There are, however, many challenges involved in different parts of the life-cycle of sensor systems with the purpose to automate and densify sensor networks for environment monitoring. We discuss these challenges based on our experience from earlier deployment of broadband and wireless sensor networks in rural Africa [1,2,3,4,5] and involvement in ongoing work [6,7,8,9,10]

One of the ongoing projects is WIMEA-ICT, a NORAD-funded project [6] aiming at capacity building at some East African Universities while improving the accuracy of and access to weather information by the communities in the East African region through suitable ICTs for increased productivity and safety. The project is expected to contribute to mainly three of the seventeen UN sustainable developments goals [11], namely: 2) Zero hunger; 6) Clean water and sanitation, and 13) Climate action.

The WIMEA-ICT project is organized in four research components (RC1-4): The design and deployment of an affordable and dependable weather station (RC3), Secure and integrated storage of the weather data (RC2), Analyses and forecasting based on the collected data (RC1), Dissemination of weather data adapted to end-user needs (RC4).

Among the deliverables from this project is the deployment of some 70 observation stations reporting synoptic weather and agricultural parameters in South Sudan, Tanzania and Uganda. The life cycle of these stations are in focus in this paper.

In the following sections, we discuss challenges in the different parts of the life-cycle. We start with a discussion about needs and requirements. We then discuss the design and validation phase, which will happen almost entirely in the academic environment. We then proceed to the subsequent manufacturing, deployment, operation, maintenance and recycling phases, which, while still being research objects, will happen outside the academic environment.
2. Needs and requirement analyses

Needs and requirements analyses are required on many levels, including end-users, service providers, manufacturers, regulators, operators, maintainers, infrastructure owners.

Some of the challenges involved in formulation of user needs are classic. Expert users need to keep up with the technical development to see what is possible and non-expert end-users are often limited in their visions by what they believe is possible. They need to have some sort of picture of what is realistic in order to be able to express themselves about how to use new possibilities to satisfy basic needs beyond wishful thinking. This process has to be an educational dialogue about the objectives, what could possibly be accomplished, what parameters should be monitored and why, how the collected data will be used for analyses and forecasting, and how results should be disseminated.

2.1 Needs and requirements of key stakeholders

The key stakeholders in the WIMEA-ICT project are the National Meteorological Services (NMS) of South Sudan, Tanzania and Uganda. The project has conducted national surveys in these countries in cooperation with their national meteorological agencies, SSMS in South Sudan, TMA in Tanzania and UNMA in Uganda, to assess the status and requirements of their weather station networks. These surveys show some of the key challenges.

1. Robust affordable communications between the weather stations and the data reception centers is an absolute necessity for sustainable operations.

2. Weather station designers and users have to cooperate to address vandalism of weather station equipment using all possible methods, including selecting components that are not attractive for other purposes, careful selection of the installation location to maximize security, and, if worse come to worse, detection and identification of vandals so that they can be brought to justice.

3. Weather station sensors require strict calibration protocols, so they can be standardized against already well tested sensors. This ensures that the readings of the different station models are a match within a specific region. Existing manual stations are usually the reference calibration stations.

4. The observation stations should be robust, requiring as little maintenance as possible throughout their lifetime with optimized power consumption.

5. When densifying the sparse weather station networks, site selection for new observation stations should be done with reference to various climatological zones of each country. This will not only increase the number of weather stations in the countries but also increase redundancy in climatological zones such that reliable data is still available even when some stations are temporarily down.

6. The criteria for site selection to achieve densification should also consider: i) the status of communication pathways e.g. network coverage at potential sites; ii) physical security at station sites to reduce the likelihood of vandalism; and iii) Land ownership policies at the station site to avoid misplacement, re-location and obstruction of the observation station at a later time.

7. The data collected has to be securely stored for operational forecasting models and research purpose.

2.2 Regulatory requirements

Besides the needs and requirements formulated by key stakeholders, there are more general regulatory requirements that need to be followed if the research leads to commercial products. Even if this will not happen in the WIMEA-ICT project as such, awareness of these requirements already in the design process will facilitate the industrial uptake of the results.

One possible starting point for understanding these requirements is the CE marking (Conformité Européenne), which is recognized worldwide although local rules in some countries might go a bit further. The CE marking refers to many different directives that have to be followed depending on the type of product. The main focus is on environment, health and safety. Going into details, it is not always trivial to determine exactly which standards a specific product has to conform to.

For electronic products like the weather stations that the WIMEA-ICT project are concerned with, a typical test suite would include the appropriate parts from the Radio and Telecommunication Terminal Equipment (R&TTE) directive including Safety, RF, EMC, EMF and Human exposure to electromagnetic fields, RoHS for manufacturing and WEEE (Waste Electrical and Electronic Equipment) for recycling and disposal.

EU directives target the EU market. In the WIMEA-ICT case, since the weather stations are to be installed in African countries, local rules and regulations apply. EU rules are, however, adopted by many countries to facilitate trade. For international trade, there are a number of international conventions under the auspices of the UN Environment Protection Programme (UNEP) controlling transboundary movements of hazardous substances, wastes and their disposal, e.g. the Basel Convention (www.basel.int).
In the USA, the FCC Declaration of Conformity is a similar directive for electronics components. Unfortunately they are a bit different aspects, which means that testing for conformity becomes more tedious and expensive.

3. Design and validation
We will now proceed to discuss issues related to the design and validation of automatic weather stations based on wireless sensor networks. Although the design process, including testing of prototypes, consists almost entirely of research and development activities that can be conducted in the academic environment, requirements from subsequent phases, including manufacturing, deployment, operation and maintenance, need to be considered. While still being objects for research, these latter phases of the life-cycle will happen outside the academic environment. We will start discussing methods and tools and then proceed to the technical design and validation.

3.1 Methods and tools
Our basic research method is iterative systems design. The iterations include findings in the evaluation of field tests as well as refinements in user requirements, advances in related research and new products on the market. The modular design facilitates incorporation of new results and products improving the performance of our final design. R&D is becoming globally distributed and WIMEA-ICT is a good example. The efficiency in such projects depend entirely on sophisticated environments supporting collaboration, such as Science gateways providing access to tools for discussion, design, storage and retrieval, etc. We would especially like to point at the tools being set up by the EU Sci-GaIA project [12], including the - Discourse Forum [13] where researchers can communicate via structured chatting in categories and topics. In the WIMEA-ICT project, there are currently 22 participants active in this chat discussing 29 topics recorded in a searchable archive. The number of contributions has the first year, on the average, been about 1 per day and the number of views about 10 per day.
- Open Access Repository [14] where completed documents can be made available and efficiently disseminated
- Online course framework [15] where courses are created as deliverables from the project, to educate stakeholders to understand the design of the weather stations, and how to manufacture, deploy, operate and maintain them.
- the Africa-Grid Science Gateway [16] set up by the EU e4Africa project, providing access to software tools, such as WRF, a widely used open source software tool for meteorological analysis and forecasting requiring substantial computing power, and also submit computing tasks for processing at some high performance computing centers, if authorized to do so. Access to shared data sets, such as the TRODAN data set of weather observations from Nigeria, is another service provided via the science gateway.

Other software tools used by WIMEA-ICT researchers include gEDA tools for electronic design and automation [17] that has been used to design power supply units for the sensor nodes, OpenSCAD for 3D-design [18] that has been used to design solar irradiation shields and Github [19] for storage of working documents, version control for software development and dissemination of hardware and software designs. Besides the tools explicitly mentioned here, there are tools like compilers, simulators, and many others available for the researchers.

A particular resource that will be set up to facilitate manufacturing of weather stations is an OpenLab MakerSpace offering equipment for small scale manufacturing, such as 3D-printing, milling of PCB-cards, etc.

3.2 System architecture
The challenges in the design phase of the WIMEA-ICT weather station include functional as well as non-functional requirements. Among the former, we have the functionality required to reliably, accurately and securely capture and transport data samples from sensors to a central repository. Among the latter we have properties like manufacturability, affordability, dependability, unattractiveness to vandals, etc.

Legacy equipment for environment monitoring consist of a centralized system with sensors connected to a data-logger. The data is often manually collected but increasingly the data logger is connected to Internet via fixed or wireless data services of some sort.

The model discussed in this paper replaces the centralized system with a distributed system consisting of local wireless sensor networks having a few sensor motes reporting readings from connected sensors to a sink mote connected to a gateway with buffer storage and uplinks to Internet.

This distributed model facilitates putting sensor nodes at appropriate locations within an observation station without wiring problems. According to WMO recommendations, wind should be measured 10m above ground, away from disturbing obstructions. An unobstructed location at 10m is also good for a pyranometer measuring of solar irradiation. Air temperature and humidity should be measured 2m above ground using a solar irradiation shield, preferably in a shadowed place but still without obstructions to air circulation. Soil temperature and
moisture should obviously be measured at the ground level. A rain gauge can be placed anywhere between ground and 2m in an unobstructed but still not too windy location. Sensors for atmospheric pressure can be placed at any of these locations. Per default, a WIMEA-ICT observation station has four nodes:
- 10m node measuring solar irradiation and wind parameters, direction and speed.
- 2m node measuring air temperature (T) and humidity (RH)
- Ground node measuring soil temperature, moisture and precipitation
- Sink node measuring atmospheric pressure and directly connected to the gateway at a location facilitating establishment of uplinks.

![The architecture of the WIMEA-ICT observation station](image)

The distributed model also facilitates having redundant nodes reporting the most essential parameters independently, some distance apart, to improve data quality and dependability.

The four nodes all need a mote to which the sensors are connected, a power supply and relevant enclosures with appropriate ratings to withstand challenging weather conditions. For example, in the 2m node, there is an irradiation shield required to protect the sensor from direct or indirect solar radiation, and an at least IP67 rated enclosure for the electronic parts, including the mote and power supply.

Accurate, power-lean and affordable sensors with reasonable power requirements are becoming increasingly available, especially for synoptic weather parameters. Some of them generate pulses to be counted, such as a tipping bucket rain gauge or an anemometer, Others provide an analog signal, like photo diodes generating a current translated into a voltage over a resistor to be recorded via an analog to digital converter (ADC). Yet other sensors are digital, pre-calibrated and accessible via open standard bus protocols, such as I2C, One-Wire or SPI, for example the SHT25 sensor for air temperature and humidity. Many sensors are to be considered as sensitive scientific instruments that need to be handled carefully to deliver high quality data. Robust packaging is essential.

### 3.3 Technical design challenges

The key technical challenges when designing wireless sensor networks for environment monitoring to be deployed in large numbers, include selection of components minimizing the power consumption, integration of power supply systems and dependability issues. The design of the first generation WIMEA-ICT prototype and an analysis of how requirements are met in more detail, is available in [7].

For embedded systems implementation we have been exploring TinyOS and Contiki. We selected the latter since we found it easier to learn and use for developers with a computer science background and found it to be an advanced platform with an appropriate tool chain for development of Internet of Things systems [20]. Among the available motes, we chose to work with the RS2 mote [21] based on the ATMega128RF component integrating an MCU, IEEE802.15.4 transceiver and an 8 channel 10bit ADC. At the time the 1st generation design was frozen, this mote supported Contiki 2.5. It now supports full Contiki version 3.0, which will be exploited in the 2nd generation prototype. There is recently also an ATMega256RF version available, which is more power-lean and provides more buffer storage.

On the protocol side we have chosen the IEEE802.15 standard on the link level [22], and use the RIME network
protocol [23] supporting periodical broadcasts from the motes, otherwise in deep sleep, to an always awake sink-node forwarding all reports via sensd, a lean restful protocol on the application level, to a gateway supporting several uplink alternatives. As gateway, a Linux-based embedded system, the Raspberry Pi version2, is used. It came out number one in a benchmarking of similar systems regarding performance and power consumption in January 2015.

Design of power-lean systems has reached a level where the next step is to include just as much functionality that you actually need and to let as many parts of the system as possible be switched off or go to deep sleep in stand by mode. To allow all parts of a system do that is called duty cycling and requires non-trivial synchronization so that parts of the system required to communicate to wake up at the same time. Synchronization can be accomplished in different ways but also requires extra power and adds complexity. It is not always evident that you save total power by duty-cycling all parts of a system.

The power supply system need to be autonomous in the sense that it should have a dependable storage that can be charged from locally available renewable power sources, such as solar and wind, and that can buffer enough power to sustain operation even when the sun is not available and there is no wind. Backup power sources and systems such as fuel cells [24] are emerging.

Traditional batteries based on chemical processes, such as the common and easily available lead-acid battery, suffer from drawbacks such as complex and time consuming charging, severe limitation of the number of charge-discharge cycles, risk of explosion at higher temperatures, etc. New components, such as ultra-capacitors and new Lithium-based chemical cells are emerging. An advantage with the capacitors is that they have almost no internal resistance, which makes the rate of charging limited only by the capacity of the power source. They also claim to take an almost infinite number of charge-discharge cycles. A disadvantage is that the voltage drops during discharging since the voltage of the capacitor is proportional to the charge. This is not really a problem when using TTL logic since the voltage levels during discharge, roughly 2.2-3.8V, match the ranges in which most components work [3,25,26,27]. There are also new Lithium-based chemical battery cell technologies to explore. One of the more promising is the LiFePO4 cell. It is more stable and easier to charge than other Lithium technologies that we have tested. It can also be connected in parallel with ultra-capacitors to combine the advantages of low internal resistance of the capacitor cell for fast charging and constant discharge voltage of the chemical cell during discharge.

**Figure 2. The 2nd generation Wimea-ICT 2m node prototype before and after assembly**

Regarding enclosures and installation structures, we have chosen a combination of standard components used in electrical and plumbing installations and 3D-printed components where tailor-made details are necessary. The 2m node shown in figure 2 has a few 3D-printed details, including the solar irradiation shield built up by a top, seven body segments and a double bottom design preventing indirect radiation reaching the sensor, and two holders for the sensor board and mote. Besides the 3D-printed details there is also a standard IP67-rated electrical connection box, a cable gland holding a 12mm PVC pipe leading to the sensor board inside the pagoda, the mote, a psu unit based on a printed circuit board manufactured using a low cost CNC-controlled mill, a solar panel and some cabling. The bill of material is below €300 and can probably be pushed down further.
3.4 Validation

Generally, validation includes formal verification, simulation and testing. In our case the formal part is limited to abstract reasoning, simulation in the hardware and software design tasks and testing of prototypes, including laboratory tests and field-tests. There are several challenges associated with field tests in African rural environments that are hard to model and thus require attention also after deployment. Besides protection against extreme weather exposure in terms of temperature, humidity, flooding, winds, UV radiation and severe EMI transients due to heavy lightning, you will have to consider damage caused by animals, from termites to elephants, and human vandalism.

The first generation prototype developed in the WIMEA-ICT project was deployed for field-testing in Bergen in March 2015 [6]. The measurements and other observations made verify the general concept and the choice of some of the sensors, but have led to discussions about improvement of some details. Examples of improvements considered in the design of the 2nd generation prototype to be deployed during the first half of 2016, include:
- A more power-lean gateway/sink-node combination. Experiments are under way along several tracks, including duty cycling of components while keeping extra useful functionality, on one side, and minimizing functionality using fewer and less complex components, on the other side.
- Development of variants of the power supply to test hybrid batteries combining ultra-capacitors with other cell types.
- Improved solar irradiation shield for the 2m-node. A benchmarking experiment comparing different commercial and own-made alternatives is under way.
- Benchmarking of rain gauges and development of an own-made 3D-printed rain gauge

Our conclusion from this work is that there are good enough solutions, including power-lean designs and sufficient power supply, for our autonomous local wireless sensor networks. The remaining challenge in that part is to improve the dependability an attend to details regarding sensors and enclosures.

The main remaining issue is the power consumption of the gateway and we are now looking into alternative gateway components, possible downgrading the functionality of the gateway in favor of lower power consumption. This requires more research. The Raspberry Pi 2B used in the 1st generation prototype, came out best in a benchmarking study a year ago. A KTH MSc student team just completed a comprehensive similar study a year later [28]. This work outlines methods for comparison of low-power power gateways for wireless sensor networks and also compares the current market offerings using these methods, including Raspberry Pi, Banana-pi, Beagle bone black and a power lean travel gateway, all running different flavors of Linux and using a 3G modem and Ethernet as uplinks. The team especially looked into the availability of sleep states allowing duty-cycling. In this study, the Beagle Bone Black came out first reducing the power in our previously used Raspberry Pi2 gateway with a factor 3 due to power cycling. We are, however, still searching for even more power-lean solutions.

4. Manufacturing, deployment, operation and maintenance

In this section we will discuss the manufacturing, deployment, operation and maintenance of the weather stations. The task of manufacturing 70 observation stations to be deployed in three East-African countries can not be described as a mass production but rather as the implementation of a large prototype series. It is anyway sizable enough to require an approach beyond what is normally possible in an academic environment. It is substantial enough to require investigation of available local supply chains and innovative approaches to stimulate complementing entrepreneurial efforts required, both regarding manufacturing and subsequent quality control, deployment, operation and maintenance of the observation networks.

Since it is an ambition of the WIMEA-ICT project to build local capacity along the whole value chains of weather observation, analysis, forecasting and dissemination, we have been discussing approaches stimulating local entrepreneurs to get involved in innovative business models complementing traditional models for operation of observation stations where the NMA or other responsible authority takes care of everything. An approach that we are currently exploring involves issuing a call for proposals targeting local stakeholders in a weather station to submit a plan for how they could become custodians, adopting a weather station and manage the manufacturing, deployment, operation, maintenance and recycling of “their” weather station. Proposers would be contacted to discuss what benefits they would appreciate, in return for guaranteeing continuity in weather data delivery and providing security measures preventing vandalism. Examples of such benefits could be piggy-backing on the gateway uplink to get local Internet access, receive tailored localized forecast services based on the collected data etc. We are currently in the process of formulating guidelines for proposers responding to such a call.

Support that can be offered from the academic partners beyond know-how and advice, include 70 weather stations
kits and associated student teams (BSc, MSc and/or PhD-level) and their teachers/supervisors taking on manufacturing and deployment projects for academic credit in the Technology Transfer Alliance (TTA) framework [29] based on the Challenge Driven Education model [30].

For manufacturing, traditional models will be compared with innovative models involving local entrepreneurs, e.g. by stimulating local makerspaces providing 3D-printers and cnc-controlled tools, that local entrepreneurs can share. We have been stimulated in this work by the maker space movement and projects like the UCAR MMA weather station project [31]. One outcome of this is the testing of 3D-printing of a radiation shield for weather stations [32]. There is currently a discussion about the possibility to support the establishment of service providers providing 3D-printing for Science, Education and Sustainable Development.

Operation of the deployed weather stations to be essentially automatic. Some sort of local supervision is necessary, to provide information that is hard to catch automatically, intervention if problems occur, e.g. sending broken components to a maintenance shop for repair and/or replace it with a new one.

Key challenges in the research on business models relevant for the approach we are exploring includes minimizing costs for the different parts, manufacturing, deployment, operation and maintenance, and finding and evaluating value propositions to local stakeholders in an observation station. These challenges involves both technical and business aspects in wider senses.

Relevant value chains of environment monitoring stations and networks will be analyzed in order to understand the relations between stakeholders. This analysis will be used to design experiments with new business models providing added value for the local stakeholder communities. Stakeholder segments will be identified and analyzed to understand their problems and expectations to capture and deliver value that can solve community relevant problems and meet expectations. A combination of a Business Model Canvas [36] and lean startup approach will be used to simplify iterative testing of business models until the captured and delivered value not only addresses the expectation of customers but also creates a sustainable business model facilitating the societal impact of the overall proposal.

A business model canvas consist of nine building blocks: 1) value proposition, 2) key activities, 3) key partnerships, 4) key resources, 5) relationships with the customers, 6) customers, 7) channels, 8) revenue stream and 9) cost structures.

Other ideas and concepts that can be useful in this part of the project include: Coase theorem [33] describes the economic efficiency of an economic allocation or outcome in the presence of externalizations. It states that if trade in an externality is possible and the transaction cost sufficiently low, bargaining will lead to an efficient outcome regardless of the initial deal. Joy’s law [34] is more into using virtual resources via the internet allowing people to share a purpose and have established roles, responsibilities, and modes of communications. According to von Hippel [35], users may innovate for own use, to personalize a product or to create a new product not to be found on the market. Lead-users and lead-companies go a step further: What they think and create is likely to attract more people in the process and tend to become breakthrough innovation, mainly since they plan, follow and adapt to the market trends. A well-known example is the LEGO Producer-User Ecosystem [37] revealing three types of interactions: 1) reduced risk for entrepreneurial lead users and the producer firm, 2) the extension of the design space of the producer firm, 3) the creation of buzz within the user community.

New tools and technologies, like those discussed in section 3.1 facilitate new communication techniques that allow users/developers/companies to share data and information at low cost. The approach is used in all parts of the WIMEA-ICT project and will be extended to new stakeholders joining the project, which will lead to democratization of innovation in environment monitoring networks. Bottom line is: We will test and explore how users and open innovation can help us to come up with innovative products and services and create sustainable business models and integrate them with technical and application development.

5. **Out-phasing and Recycling**
In Europe, there is a framework for waste management and recycling based on the the EU directives on Restrictions on Hazardous Substances (RoHS) and management of Waste Electrical and Electronic Equipment (WEEE). These directives have an impact on the process of putting advanced electronic equipment on the market. Essentially all manufacturers have to have an agreement with an approved waste management company and pay a fee proportional to the type and number of sold products. Many of the waste management companies are members of a European organization, www.weee-forum.org, facilitating trade within Europe. Although Norway, Iceland, Switzerland and Turkey are not EU member states, they have similar legislation.
We intend to include a detailed instruction about how to dispose of the different components in a weather station when it has to be phased out and sent for recycling. It should be noted that our design is compact and lightweight. It will have a low environment impact.

6. Conclusions and future work
The WIMEA-ICT project is unique in the sense that it covers research, development, innovation and entrepreneurship required for product development, manufacturing, deployment and an organization of operation and maintenance. It is work in progress. The current status is that we have a 1st generation prototype that has been field tested since March 2015. We also have a 2nd generation prototype design that will be assembled in three copies to be deployed in Dar es Salaam, Kampala and Juba in January 2016 to be benchmarked with official stations. The bill of material for these prototypes is relatively low and can be reduced even further in a larger series. We are exploring models for manufacturing and deployment of some 70 stations and get them evaluated in field tests during 2017 and produce some PhD theses based on this work in 2018.

7. References
[8] iGrid, the project, recently started work on a low voltage direct current (LVDC) Nano-grid concept allowing pooling of investments in equipment for harvesting renewable energy sources, such as solar and wind, in local communities. Website pending.


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