Wireless Sensor Networks in the Context of Developing Countries

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***Abstract*— Wireless sensor networks are a network of small sensing devices which collaborate with each other to gather, process and communicate over wireless channel information about some physical phenomena. These self-organising, highly robust and energy efficient networks can be excellent sentinels for monitoring underground mining, wildlife and various physical infrastructures such as bridges, pipelines, and buildings. This paper introduces wireless sensor networks, identifies specific application domains and investigates their scope and usefulness in the context of developing countries.**

I. Introduction

Developing countries have a multifaceted challenge in utilising and maintaining resources most dear to them. While the causes of inefficient utilisation of resources are complex and their remedies may not be straightforward, we motivate the use of smart micro-electronic sentinels to deal with those problems which require duly reporting of properties of a certain physical phenomena. The smart sentinels go by the name wireless sensor networks and interface the physical world with computers, thereby creating a profound flexibility for awareness and remote controlling. They are characterised by their little demand for attention from human operators, their capability of self-management; operation in adverse places and near the occurrence of the actual phenomena; great accommodation of node mobility or failure; and effective node cooperation in order to carry out a distributed sensing task.

The relative simplicity, smallness in size and affordable cost of wireless sensor nodes permit heavy deployment in places or objects in which a sensing task is carried out. Such characteristics make wireless sensor networks (1) robust to adverse situation and/or node failure; (2) capable of sensing at a considerably higher sensing granularity; (3) capable of functioning without the need for a human agent to manage the network in general or individual nodes in particular; and (4) to communicate a sensing event at long distances in a reliable and energy efficient way. In this paper, we introduce wireless sensor networks, discuss their building blocks, and identify several application domains in the context of developing countries.

The rest of this paper is organised as follows: in section II, we give a detail account of wireless sensor networks; in section III, we motivate those applications which are relevant to developing countries; in section IV, we provide concluding remarks.

II. Wireless Sensor Networks: What they are

Wireless sensor networks are established by a collection of small sensing devices. In many practical applications, a good portion of the sensed data is accumulated at a control centre, usually called a *base station*. The sensor nodes pre-process raw data and collaborate with each other on a meta-data basis to reduce the amount of data effectively transmitted to the base station which acts mainly as a gateway to the Internet, to a local area network (LAN), or to a stand-alone computing device. The destination computer eventually analyses the data and extracts meaningful information as a result of which an action can be carried out. This action can be carried out automatically by an actuator or manually by a human agent.

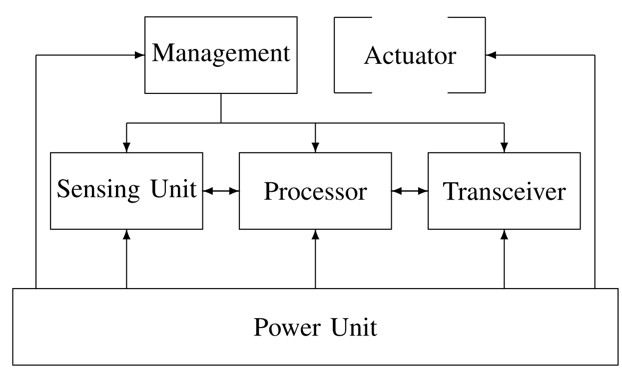

Fig. 1. Basic architecture of a sensor module.

A. Sensing and Processing

A wireless sensor node integrates one or more sensors, a processor, a communication unit, a power supply and management unit and, if need be, a security and an actuation unit [1]. Depending on the sensing task for which the network is deployed, there can be multiple sensors integrated within a single node. The sensors can be either active or passive. Active sensors release some sort of signal to detect a physical phenomenon. Examples of active sensors include seismic geophones, infrared dipoles, and radar. Passive sensors, however, transform a physical phenomenon into electrical energy. Most available sensors are passive sensors. Examples of what can be recorded by passive sensors include temperature, humidity, light, vibration, microphone, mechanical stress or tension, blood pressure, blood flow, oxygen, heart rate, respiratory rate, chemical (soil makeup), and smock. An onboard analogue-to-digital converter (ADC) transforms the analogue output of the sensors into its digital equivalent which is handled by the processing unit. Usually up to 70 kilo samples per second and up to 12 bit resolution is achieved by most commercial sensor nodes. For reasons of power conservation, some of the common signal processing functions may be offloaded into a low-power application specific integrated circuit board (ASIC).

B. Communication

In wireless sensor networks, communication is made over a wireless channel. This eliminates or at least significantly reduces the need for an established communication infrastructure, expensive setup and maintenance costs. Moreover, frosty landscapes which hitherto proved to be extremely costly and trying for wired communication can easily be populated by wireless sensor network for a reliable sensing task.

Having said this, there are certain challenges which call for further research. Firstly, because wireless sensors are deployed in a relatively large field and involve several nodes, the potential for interference is considerable. As a result, the communication range between nodes should be limited to a short distance. Secondly, in most situations, a wireless sensor network is haphazardly deployed, and the sensing task may be for a limited time only. Hence, the radio channel should be unlicensed. More importantly, compared to sensing or task, communication tasks a node significant power. Given the limited available power supplied by non-renewable batteries, this determines the network's lifetime. Subsequently, a careful planning has to be made regarding communication. An additional and practical challenge as far as communication is concerned is that it may not be feasible to maintain a line-of-sight link and in the case of mobile nodes, the channel may no longer be modelled as a time invariant model. This implies that a high degree of cooperation is required among the nodes whenever a dead-end is encountered or the multipath scattering of the link is significantly high.

C. Deployment

Because of their self-organising characteristics and robustness, wireless sensor networks can be deployed in less benign environments and inaccessible places as well as in places where employing humans is costly. Although back-end communication infrastructures are needed to interface wireless sensor networks with the Internet or a local area network, they can also function in the absence of any communication infrastructures. This makes them particularly attractive for developing countries where the presence of stable communication infrastructures as a prerequisite for deploying computing systems may not be feasible.

D. Power Management

A typical constraint for wireless sensor networks is power. Most wireless sensor nodes operate with non-renewable batteries. Given the potential inaccessibility of the deployment setting, it may not be possible to change batteries or to recharge them. In many scenarios, wireless sensor nodes may not be reused once they exhaust their energy. This makes it imperative to optimise the network life time by introducing power efficient policies to wireless sensor nodes in particular and the network in general. When fully active, a sensor node requires from 1 to 50 mW [2]. A power management policy can be applied to different components of a sensor node at different circumstances in order to minimise these requirements. Usually, the radio component consumes considerable power and therefore is set into a sleeping mode when there is no data to either receive or send. Knowledge of the application domain also enables to set other components into a periodical sleeping mode when there is no interesting event to capture. In general, power is managed by driving the following policies:

- Sleep (memory standby, interrupts active, clocks active, CPU off);
- Sleep (memory retained, interrupts active, clocks active, CPU off); and,
- Sleep (memory retained, interrupts active, clocks off, CPU off).

Due to a deliberate node redundancy, the lifetime of a wireless sensor network can be optimised by making most of the sensor nodes sleep while a selected few act as sentinels to awake the others when an interesting event is emerging. Depending on the urgency of capturing an event, any one of the above policies can be applied to minimise power consumption.

III. Application Domains in Developing Countries

The unique features of wirelessly operated sensor devices propelled researchers to identify potential applications for these relatively novel networks. Today, sensor networks hold the promise of improving processes and conditions in many areas as well as leading to entirely unforeseen opportunities. This applies also to developing countries, nonetheless the applicability of wireless sensor networks must be reassessed considering prevailing challenges and actual needs that are typical for those regions.

In general, the most severe difficulties when applying Information and Communications Technology (ICT) in developing countries are low capital formation and a lack of reliable power supply. Low budgets of public authorities put hard constraints on what can be purchased and is thus inevitably reflected in both quality and quantity of the employed devices. Additionally, the used ICT systems should be operable for a reasonable period of time without steady power supply where necessary. In view of these challenges, wireless sensor devices turn out to be well-suited for some application areas in less developed countries. Firstly, they are relatively cheap with a unit price of less than 100 USD. Secondly, a sensor module is usually energised through a battery, and, although not yet available, sensor modules could use solar or geothermal power. At the same time, both sensor hardware and protocols are constantly improving thereby further reducing total power consumption. By this means, a sensor network can operate untethered – independent of any external communication infrastructure or electricity network.

Only a subset of the proposed applications are of interest to developing countries. Costs and effort required for deploying and maintaining a sensor network, probably substituting other technology in place that people are familiar with, have to be justified. There must be a non-negligible benefit for all participants involved. This could be, for example, that less personnel is required to operate a system (system provider saves money), the accuracy of some information retrieval service is considerably improved (system user gets more meaningful data), or a function can be realised that would not be possible using existing technology (system manufacturer captures new market). A wireless sensor network can only be helpful if there is a substantial need. Applications such as smart aeration and lighting control in apartments, extensive traffic monitoring in large urban areas, or supply-chain monitoring in state-of-the-art production plants do not qualify because they lack a broad need in developing countries and are therefore of lower priority.

We believe that sensor networks are relevant to developing countries in the following application areas, which are listed in descending order with regard to their importance:

- Environmental Observation and Forecasting
- Disaster Prevention
- Agricultural Management
- Structure Health Monitoring
- Habitat Monitoring

Concrete applications that can be assigned to the first three application areas more or less directly affect the people's living conditions. An earthquake or volcano eruption warning system and monitoring of hazardous zones on a production plant can increase safety and prevent devastating incidents. Similarly, the ability to retrieve soil moisture in real time enables efficient irrigation and agricultural planning which is especially important in semi-arid regions of developing countries. As a side effect, researchers can gain a better understanding of certain phenomena since the sensor network provides multifaceted and more accurate data with shorter delays compared to traditional approaches. The same holds for habitat monitoring, where wildlife can be studied without unnecessary human intrusion in remote areas. As for structure health monitoring, safety, environmental, and commercial aspects come into play. Fast detection of a leaking oil pipeline can certainly reduce environmental damages and thus reduce negative impacts on the health of people and animals. At the same time, remote controlling of railroads and pipelines enhance effectiveness and help to reduce expenses.

After giving a brief overview of the relevant application areas, we discuss each of them in more detail in the subsequent chapters. We present concrete sensor network applications, partly supported by experiences from field studies, and show how these applications can be valuable for developing countries.

A. Environmental Observation and Forecasting

In the area of environmental observation and forecasting we find a plurality of applications that, on the one hand, aim at establishing an early warning system to protect the population, and on the other hand, provide researchers with the means to study certain phenomena. This is because instrumenting natural places, such as national parks, volcanos, riverbanks, rift zones, and woods with numerous networked sensor nodes can enable long-term data collection at scales and resolutions that are difficult to obtain otherwise [3]. The intimate connection with its immediate physical environment allows each sensor node to provide localised measurements and detailed information that is hard to obtain through traditional technology.

These features make the following applications feasible and beneficial in the context of developing countries:

- Volcanic Studies and Eruption Warning System
- Meteorological Observation
- Fire Detection
- Earthquake Studies and Warning System
- Water Quality Monitoring
- Flood, Cyclone and Tsunami Warning System

Dependent on the geographic region, one or several of these applications are conceivable. A good warning system can effectively help to mitigate the damages caused by natural disasters [4]. Hence, the development of wireless sensor networks to assist meteorologists, geologists, and volcanologists has a great deal of importance in many less developed parts of the world.

As a proof of concept, a wireless sensor network consisting of three nodes was deployed on Volcán Tungurahua in central Ecuador in 2004 [5]. The sensors were equipped with microphones and collected continuous data from the erupting volcano. In 2005, a larger and more capable network was deployed on Volcán Reventador in northern Ecuador. An array of 16 nodes equipped with seismoacoustic sensors was deployed over 3 km. The system routed the collected data through a multihop network and over a long-distance radio link to an observatory, where a laptop logged the collected data. The responsible researchers state that in contrast with existing volcanic data acquisition equipment, the sensor modules are smaller, lighter, and consume less power. Moreover, the resulting spatial distribution greatly facilitates scientific studies of wave propagation phenomena and volcanic source mechanisms.

In [4], the authors outline a system aided with sensor networks for flood controlling and warning in Bangladesh. They argue that any country that is under the threat of flood requires a flood monitoring, controlling, and warning system. The first activity is the deployment of the sensing devices in the riverbanks, whereas the placements of the sensors are influenced by the flow path of the river, past records of water flow and future prediction of the route of the river. Additional infrastructure of local base stations and a central monitoring system must be set up as well. In operation, the central monitoring system analyses the processed data and could issue a flood warning where the responsible authorities are, for example, informed via Short Message Service (SMS) to their mobile phones.

Two ongoing deployments of wireless sensor networks related to groundwater quality monitoring are presented in [6]. The first one is a system to understand the prevalence of arsenic in Bangladesh groundwater, the second one is a system to monitor nitrate propagation through soils and groundwater in California. In both deployments, so-called *pylons* are used. These apparatus consist of an enclosure housing the small wireless devices which connect to groups of sensors embedded at multiple depths in the soil through long wires. The devices wirelessly transmit samples back to a PDA-like device acting as a base station. As for Bangladesh, three pylons equipped with suites of sensors (soil moisture, temperature, carbonate, calcium, nitrate, chloride, oxidation-reduction potential, ammonium, and pH), deployed in different depths (1, 1.5, and 2 meters below ground), collected data for a period of 10 days. Even with this short deployment, the sensor network captured some interesting phenomena.

This review pointed out that there is a lot of effort made to transform environmental observation and forecasting applications of sensor networks from paper into real-world projects. First field experiments raise the hopes for future undertakings to come. It is yet to setup a system that proofs its reliability in the long run, from which developing countries could particularly benefit

B. Disaster Prevention

In addition to the warning systems discussed in the previous section, we propose sensor networks for hazardous workspaces like underground mining, steelworks, and refineries. Most of these places entail a high risk by nature which is amplified by poorly engineered constructions in developing countries.

Wireless sensor networks can be deployed in underground mining for surveillance of deteriorating grounds, toxic gases, and unstable grounds. In refineries sensors can be used to track workers which can facilitate to alert an operator if someone accidentally enters a temporary hazard zone or to guide firefighters to the people in danger. These applications can help to increase workplace safety and thus save many people's life.

C. Agricultural Management

To this day, it remains uncertain whether the resources and technologies available in developing countries will be sufficient to satisfy a growing population's demands for food and other agricultural commodities [7]. Especially in the semi-arid tropics millions of people suffer from hunger because precipitation is scarce and unpredictable. In order to map out a farming strategy that uses the available resources most effectively, information on the temporal and spatial variability of environmental parameters, their impact on soil, crop, pests, diseases, and other components of farming is needed [8]–[10].

Fig. 2. Oil Pipeline

In [7], the authors present their experiences with the on-going design of a decision support system for resource-poor farmers, which uses the wireless sensor network technology for the improvement of farming strategies in the face of highly variable conditions. The field study is carried out in rural Karnataka (India) and focuses on water conservation measures and the prediction of crop water requirements for deficit irrigation. Sensors are placed in comparable fields, where different water conservation measures are used. In this way, comparative readings of soil moisture can be obtained. Those can then be used to assess the efficiency of different water conservation measures, such as building bunds and planting trees to trap water in the shallow layers of the soil, or using mulch and gypsum to reduce evaporation. Additionally, using the recent trend of soil moisture values recorded by sensors and the knowledge of these points, the farmer can predict the behaviour of his crop and use simple water management techniques.

As this application shows, wireless sensor networks can be successfully employed to support resource-poor farmers in developing countries. Scarce precipitation and a high demand for food forces them to increase their crop employing better farming strategies. Here, the reliable and detailed information gathered by the sensor network about soil moisture and other environmental parameters proved to be the source of these achievements.

D. Structure Health Monitoring

The widely accepted goals of a structure health monitoring system include detecting damage, localising damage, estimating the extent of the damage and predicting the residual life of the structure [11]. The latest approach in this field, the wireless sensor network based approach, is promising because it has many advantages: low deployment and maintenance cost, deployment flexibility, large physical coverage, high spacial resolution, etc.

In many developing countries we find old and derelict infrastructure. Bridges and railroads, perhaps built by a former colonial power, are still in use and are at the same time extremely vital points of the transportation infrastructure. Historical buildings such as churches, castles, and monasteries are in bad repair but these objects of cultural value are obliged to be preserved for future generations. Here, seismic and pressure sensors can be deployed to detect and localise stress fractures. A precise knowledge of stress fractures can be applied for predictive maintenance and for issuing timely warnings to users.

Also, the supply network consisting of pipelines conveying water, oil, and gas are to be considered for structure health monitoring. They require a reliable sensing system since they transport risky and expensive materials over long distances without human attendance. In case of potential leakages or breakdowns due to thunderstorms, floods, encroachment, misuse, etc., problem areas should be immediately discovered and arrested. Wireless sensor networks can be deployed to pipelines on-demand. For example, in very hot areas the rise of a pipe's temperature above a certain threshold can be monitored by temporarily mounting sensor modules on the outer surface. Permanent deployments are relevant for controlling and managing the pipeline from remote. Adjusting the flow and checking the chemical composition are two possible operations.

E. Habitat Monitoring

Habitat monitoring represents a class of sensor network applications with enormous potential benefits for scientific communities and society as a whole [3]. The huge extent of the areas to be covered and the impact of human presence in monitoring plants make the deployment of sensors modules an interesting option. Of special concern are the disturbance effects of even well-intended researchers frequently trampling into the animal's habitat. This can lead to distorted results by changing behavioural patterns or distributions or even reduce sensitive populations by increasing stress factors.

In [3], the authors present their experiences with a deployed network of 32 nodes on Great Duck Island, Main. The goal was to monitor the behaviour of storm petrel. To this end the sensors were placed for example inside burrows, grouped into sensor patches, and transmit sensor readings to a gateway, which is in turn responsible for forwarding the data from the sensor patch to a remote base station through a local transmit network. The base station then provides data logging and replicates the data every 15 minutes to a database in Berkeley, California, over a satellite link.

Habitat monitoring is an important mean to better study the behaviour of animals with regard to breeding, movement, foraging, etc. In this way potential relations to typical challenges of developing countries like deforestration, monocropping, and new human settlement as well as the global warming problem could be identified. Wireless sensor networks can help to advance in this research area whereby also the whole society can profit by preserving rare species in biological reserves.

IV. CONCLUSIONS

In this paper, we presented wireless sensor networks as an emerging technology that has the potential of aiding developing countries to carefully utilise scarce resources, to protect and maintain infrastructures, and to prevent undesirable occurrences. Subsequent to an overview of anatomy and benefits of these networks, we proposed a series of application areas where sensor networks could be most helpful.

We pointed out that because of their sensing accuracy, robustness, low degree of human interaction, and operability in harsh environments, wireless sensor networks should be considered for monitoring applications (environment, infrastructures, habitats), agricultural management, and disaster prevention. Even though the blueprints for practical implementations are yet to be developed, we expect essential progress from the research community in the near future. Joint projects that bring politicians, researchers, manufacturers, and most important people on the ground together, must be set up to realize the proposed applications. Only with collaborative effort the new technology at hand can be leveraged in a sustainable manner.

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