We Must Move – We Will Move: On Mobile Phones as Sensing Platforms

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***Abstract*—Even after more than a decade of research in the field, wireless sensor networks have not yet crossed the chasm: they are still in the early adoption phase and large scale deployments are missing. Sensor network research has long focussed on developing (mostly incremental) improvements on platforms to be, e.g., more simple and/or energy efficient. In this process, the self-imposed limitations led to mainly static deployments of small scale sensor networks. As a result, wireless sensor networks are not yet the commodity envisioned by many researchers in the field of environmental monitoring or pervasive computing. This trend has also impeded research into directions such as mobile sensor networks, which in contrast require platforms with increased complexity. We argue that mobile sensing platforms are well suited for a wide variety of tasks, and they are readily available in the form of mobile phones. We discuss the strengths and limitations of mobile phones against contemporary dedicated sensing platforms and highlight pros and cons in light of realistic application scenarios.**

I. Introduction

For more than a decade, researchers have been betting on the imminent deployment of large scale sensor networks and have designed and developed a plethora of solutions to operate these networks. Amongst others, the vision of Berkeley researchers that envisioned “Smart Dust” [1] has been influencing the WSN research agenda towards a “race to the bottom”, i.e., constantly decreasing size and energy consumption through increasing hardware integration. At the same time, research has investigated an abundance of protocols for more efficient, e.g., medium access control or duty cycling of sensor platforms.

However, this development has not yet led to a widespread deployment of sensor platforms outside highly specialized niche applications; in brief, WSNs are still not a commodity. One can even observe a converse effect: the constant push towards ever more efficient and lightweight sensing platforms has hindered innovation in terms of functionalities and capabilities. Deployments are mostly static and small scale to allow for maintenance of the sensors, retail prices of off-the-shelf sensing platforms have stagnated, and novel platform designs merely enter the market.

Recently, a radically different sensing approach has been proposed: mobile and participatory sensing [2], [3]. Instead of deploying dedicated sensing platforms, mobile phones (smartphones) fulfill the sensing role. In contrast to contemporary sensor platforms, mobile phones have been constantly improving in performance with respect to CPU and memory resources, and communication capabilities. Most notably, the sensors integrated in mobile phones are getting more and more sophisticated.

We argue that mobile sensing platforms are well suited for a wide variety of sensing tasks. We introduce two representative scenarios for sensor networks in Section II and discuss the strengths and limitations of mobile phones as well as of dedicated sensor platforms in Section III. We find that multiple factors are in favor of mobile sensing platforms, yet some limitations and constraints have to be acknowledged and require further research. In Section IV, we discuss our findings and conclude this paper.

II. Sensing Scenarios

Among the wide range of applications, we select two representative scenarios for WSN deployments: personal health monitoring and environmental monitoring. In both scenarios, we compare the utilization of both wireless sensor networks and mobile phones as sensing platforms. We provide examples for deployments for both scenarios and compare the possibilities offered by both kinds of networks.

A. Personal Health Monitoring

Wireless sensors networks, and more particularly, *body area sensor networks* (BASNs), are commonly used in healthcare scenarios. Usually, the monitored person wears specialized sensors on her body, which measure physiological parameters, such as blood pressure and body temperature [4], or the body acceleration. The BASN can be completed by static sensors, collecting information about the environment of the monitored person (subject), such as temperature, light, motion, and dust levels (see [5]), and deployed in rooms frequented by the subjects. Both worn and external sensors can be tasked to monitor daily activities, detect movements and track location, detect critical events such as falls of the subjects, or derive their medical status [6]. Concrete applications include assisted living for elderly citizens or home care of recently hospitalized people, who require constant monitoring, but not necessarily in hospitals. The remote monitoring allows these persons to stay in a familiar environment while being kept under observation.

These deployments, however, raise some practical issues. Typically, the wearable sensors are resource-constrained devices, which are specially designed to be non-invasive, and thus small in size. The resulting limits in processing capabilities require the introduction of base stations to gather the sensor readings and perform complex event processing. As a result the coverage of the base stations has to be planned, or else provides a virtual barrier for the monitored subject. Moreover, the energy budget of the sensors has to accommodate for constant transmission of critical parameters to the nearest base station. Finally, the monitored people are more likely to reject such additional devices.

In comparison, mobile phones have become everyday objects, which are generally familiar to the subjects carrying them. By using the embedded sensors or interfaced sensors (e.g., wearable accelerometers or air pollution sensors), the mobile phones can also be used to monitor physiological state and health issues, without limiting the mobility of the monitored people. One sample application that capitalizes on mobility is *MobAsthma* [7], which monitors the asthma condition of the subjects and their exposure to pollution. A peak flow meter and a pollution sensor are interfaced to the mobile phone via a Bluetooth connection, and measure the volume of air inhaled and expired along with the surrounding airborne particle concentration. These measurements, coupled with the patients' location, are made available to allergists to investigate the relationships between asthma attacks and exposure to air pollution.

Another example, *DietSense* [8], assists people, who want to lose weight by documenting their dietary choices through images and sound samples. The mobile phones are worn on necklaces and automatically take images of the dishes in front of the users. The images document the food selection and allow for an estimation of the food weight and waste on the plates. Moreover, the mobile phones capture the context during the meals by recording time of day, location, and sound samples to infer potential relationships between the user behavior and his context. The captured data are uploaded to a personal repository and are accessible by doctors and nutritionists.

B. Environmental Monitoring

In addition to personal health monitoring, both wireless sensor networks and mobile phones can be tasked to monitor the environment. For examples, sensor nodes can be deployed in indoor or outdoor scenarios to monitor the temperature, brightness, and humidity and measure the ambient conditions. Such deployments remain, however, static and ensure only a limited coverage that can only be determined in advance. Unpredictable events may therefore not be recorded by these sensors.

In contrast, mobile phones are carried by the users and hence, offer an unprecedented coverage. This enhanced coverage is particularly of interest to monitor air and noise pollution. For air quality monitoring, the mobile phones are interfaced with external pollution sensors to measure the concentration of e.g., carbon monoxide and ozone in the air [7]. The measurements are timestamped and geotagged before being uploaded to a server aggregating the readings and making them available to the public. Similarly, the mobile phones capture sound samples via the embedded microphone to evaluate the surrounding noise level and detect noise pollution,which can, e.g., affect human health and behavior [9].

TABLE I
OVERVIEW OF THE INTEGRATED SENSORS

	TelosB	Sun SPOT	iPhone 4	Nexus S
Gyroscope			x	x
Accelerometer		x	x	x
Digital compass			x	x
Proximity/IR sensor	x	x	x	x
Light sensor	x	x	x	x
Camera			2x	2x
Microphone			2x	2x
Humidity sensor	x			
Temperature sensor	x	x		

III. Adoption Assets: A Trilogy of Factors

In this section, we analyze and discuss the key factors in favor of an adoption of mobile phones as sensing platforms.

A. Technical Factor

We compare commonly used sensor nodes, TelosB [10] and Sun SPOT [11], to current mobile phones, iPhone 4 [12] and Nexus S [13], based on their technological features and their dissemination[1].

1) Embedded Sensors: Table I lists the sensors integrated in each platform and shows that the off-the-shelf mobile phones present a larger number of embedded sensors than the dedicated sensing platforms. Except for the proximity sensor, the light sensors, and the accelerometers, the sensor modalities of the sensor nodes and the mobile phones do not overlap. While the sensor nodes capture primitive data types, the mobile phones collect complex data types, such as sound samples or pictures, able to provide rich information about their environment. Even if mobile phones are originally not equipped with sensors required by a particular application, such as pollution sensors, these sensors can be easily interfaced via Bluetooth. In comparison, extending the sensing capabilities of the dedicated sensor nodes requires additional efforts and may be limited or even impossible due to the scarce resources of the sensor nodes. Furthermore, both mobile phones include positioning systems (e.g., assisted GPS, digital compass, Wi-Fi, and cellular triangulation), which enable automatic annotation of the sensor readings with the location of their capture without the need for external positioning systems.

2) Processing, Storage, and Energy Resources: The mobile phones are resourceful in terms of processing and storage. They are equipped with powerful processors and a substantial amount of memory, as shown in Figure 1 and 2. These resources allow for complex processing on device, which extends the range of possible sensing applications. Note that the Sun SPOT can be considered as an exception, since it

[1]While no actual deployment numbers where available for the dedicated sensor nodes, the growth in smartphone sales has been impressive; in Q2/2011 more than 20 million iPhones have been sold according to Apple Inc.

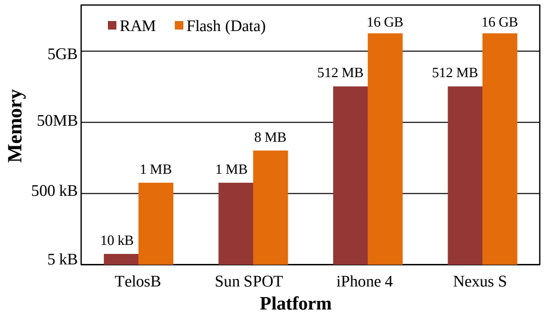

Fig. 1. Comparison of available memory (logarithmic scale)

Fig. 2. Comparison of available resources in function of the battery lifetime

has been mainly conceived as a research platform with CPU and memory being substantially more powerful than in other sensor nodes. However, the computing resources come at the cost of energy consumption. Typical standby lifetimes of mobile phones are up to 300 hours for the iPhone 4 and up to 428 hours for the Nexus S in 3G networks, according to the manufacturers. In comparison, the battery of sensor nodes in an energy-aware deployment can last up to years. Nevertheless, mobile phones are functional objects, whose primary function is to provide telephony or Internet services and not to sense. The users are already used to frequently recharge them and perform updates to benefit from their primary functionalities, thus catering for the provision of energy and basic maintenance without further efforts. In any case, constantly active sensing applications on mobile phones should be designed in an energy efficient fashion to minimize the effects on battery life.

3) Wireless Technologies: Table II illustrates the variety of the wireless technologies integrated in the surveyed sensing platforms. Both mobile phones support at least three communication standards that are widely deployed, while the sensor nodes only support the IEEE 802.15.4 standard, specially tailored for their scarce resources. Even if solutions to connect sensor nodes to the Internet have been proposed, e.g., in [14], they still demand efforts for the developers to be integrated in the considered deployment. Additionally, the Bluetooth standard enables to easily extend the set of sensors by interfacing external sensors.

4) Operating Systems and Programming Languages: Both the Nexus S, which runs the Android operating system, and the Sun SPOT are based on the Java programming language extended by specific libraries. In comparison, the TelosB and the iPhone are programmed using variants of the C programming language, NesC and Objective-C, respectively. Operating

TABLE II
SUPPORTED WIRELESS TECHNOLOGIES

	TelosB	Sun SPOT	iPhone 4	Nexus S
GSM/CDMA			x	x
IEEE 802.11			x	x
Bluetooth			x	x
NFC				x
IEEE 802.15.4	x	x		

systems for TelosB platform include the TinyOS and Contiki operating systems, while the iPhone runs the iOS operating system. Mobile phones offer thus a similar diversity in terms of programming languages compared to sensor nodes. Depending on personal preferences or requirements of the applications, the developers can therefore select Java-based or C-based programmable devices. Note that the developer community, in particular for mobile phone applications, is constantly increasing and advanced integrated development environments cater to the developers needs. As a result, the marketplaces of iOS and Android have been seeing unparalleled growth[2], while applications for sensor nodes are still mostly available in the academic domain.

B. Human Factor

The technical factor is usually considered as a key criterion in the development of a new sensing applications, while the human factor is often relegated to a second rank. This is however a determinant factor for the acceptance of the application and thus, its overall performance. Indeed, monitored people might turn off the sensing platform, either unconsciously by forgetting to charge the battery, or consciously, if, e.g., they feel their privacy intruded. In this section, we thus examine how both dedicated sensor nodes and mobile phones impact on the human factor and discuss their consequences on the application performance.

1) Acceptance and Unobtrusiveness: With over 5 billion mobile phone subscriptions worldwide [15], mobile phones are part of our daily life and have been accepted by the population at large. This level of acceptance provides for an unprecedented coverage and mobility. The mobile phones are commonly carried by their users while, e.g., commuting, and, hence, naturally follow the flow of the population. In comparison to static sensor nodes, this allows for additional coverage and monitoring of unplanned events. Besides, it opens the doors for novel application scenarios, where the sensing process is not only focused on a unique person or her environment, but on relationships between multiple people, and also their relationships with their environment. People are used to handle them, charge their batteries, and their utilization does not demand additional comprehension efforts. On the other side, the TelosBs and the Sun SPOTs are specialized devices dedicated to a unique task, namely sensing. The large public may not be familiar with them, as they are primarily

[2] According to the Apple quarterly report in Q2/2011, there are more than 425,000 apps in the iOS App Store, which served more than 15 billion downloads since its opening in July 2008.

deployed in research projects or small scale applications, such as building and factory automation.

2) Interactivity, Involvement and Visibility: The possibilities offered by dedicated sensor nodes for the users to interact with are typically insufficient. They mainly consist of, e.g., LEDs, switches, or analog inputs, whose usability is inappropriate for non-expert users. Elaborated sensor nodes can be extended by additional displays to increase their usability. They however require additional design and development efforts for the application developers and only support unidirectional information flow, mainly from the sensor node to the users. On the contrary, mobile phones support off-the-shelf bidirectional interactions between both the sensors and the users. They offer multiple usable modalities to interact with, such as touch screens, keyboards, or vocal recognition. Users can therefore easily control and get feedbacks from the sensing applications. Such interaction possibilities allows for involving the users in the sensing loop. Without even considering active participation of the users in the sensing process (which may rapidly become burdensome for the users), the participants can be encouraged to participate and contribute to sensing campaigns by introducing reward programs. Besides, the online marketplaces for apps and their exponentially growing market offer an unprecedented visibility for sensing application. Using these services, the application developers can easily come into contact with millions of people and democratize sensing applications.

C. Economical Factor

Considering the retail prices, TelosB and Sun SPOT appear to be cheaper than the mobile phones. At the time of writing, in the German market, their current prices oscillate around 200 EUR for the TelosBs and 300 EUR for the Sun SPOTs (i.e., a kit of one base station and two SPOTs), while the Nexus S and the iPhone 4 cost around 500 EUR and 600 EUR (without any telephony/Internet subscription), respectively. However, the deployment of sensor nodes typically requires a specific investment due to the specialization of the platforms. In contrast, the mobile phones can be configured to perform additional tasks: sensing applications can exploit the already deployed mobile phones for their campaign, thus virtually reducing the deployment costs to zero.

IV. Discussion and Conclusions

In this paper, we have compared both dedicated sensor platforms and mobile phones, according to three factors: the technical factor, the human factor, and the economical factor. In summary, we have shown that mobile phones feature a larger number of embedded sensors, support more wireless standards, excel in computing resources and have a more active developing community, the combination of which makes them ready for mobile sensing application support. The technological features come at the price of the higher energy consumption, which represents one of the most important weaknesses of the mobile phones. Despite their interesting capabilities, they require frequent charges of their batteries, limiting their autonomy and preventing long-term deployments in hazardous or difficulty accessible zones. The analysis of the recent mobile phones on the market shows a trend to embed as much technologies as possible, without regards to energy consumption. Yet, even if this trend continues, the human centered design of mobile phones is expected to ensure that the charging cycle is appropriate and not shorter than once in 24 hours. The role of mobile phone application developers is to conceive energy-aware applications, algorithms or protocols, avoiding an exhaustion of the batteries within few hours. Furthermore, the mobile phones are already deployed, accepted by a large public, and offer interaction possibilities, which remain impossible with dedicated sensor nodes. In conclusion, mobile phones represent interesting sensing platforms, which open new perspectives for sensing applications. Their adoption is however still in its infancy and requires further research. We believe that a closer link to the wireless sensor network community will prove key to the success of mobile sensing platforms.

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