VECIMS 2003 - International Symposium on
Virtual Environments, Human-Computer Interfaces, and Measurement Systems
Lugano, Switzerland, 27-29 July 2003

Intelligent, Low-power and Low-cost Measurement System for Energy Consumption

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Abstract* – In the area of utility measurement systems, there is increasing awareness to the importance of using intelligent and secure meter readers. The aim is not simply that of reducing operational costs; aspects such as availability of real-time determination of consumption (mainly in the case of energy meters, but potentially also for water consumption etc.) are relevant not only for actions such as real-time billing but also in view of an increasing environmental awareness leading to "preferential" billing in particular times of the day or of the week and requiring availability of fine-grained statistics. All these actions in turn involve the requirement of data integrity; when utilities other than power providers are considered, the device should be battery-powered (and very long battery life must be granted), so that low-power design becomes a further requirement while being permanently either in active or in standby mode; moreover, not being connected to the power network means that wireless connections for transmitting and receiving information must be taken into account. Finally, these devices should be made available to the general public and thus be low-cost ones. This paper describes how all the above constraints have been analysed in the design of a wireless meter reading system.

I. INTRODUCTION

Traditional measurement systems for electricity, gas and water consumption usually do not allow management flexibility (e.g. multi-billing models) and they require a human data reader. In addition, network connections between meters and data collection points are basically non-existent; it is thus impossible to implement a flexible management policy, remotely controlled, based on data evaluation and on consumption statistics. As utility requirements for measuring energy consumption increase, so does the importance of intelligent measurement system. Utility providers are more and more interested in cutting operational costs by replacing human readers with intelligent devices collecting measurement information. Even more relevant, they want to improve their billing models by determining real-time energy consumption and acting in consequence (similar considerations hold, e.g. for water consumption). In the present paper we will describe a research project (see [1] and [2]) carried out at the Advanced Learning and Research Institute (ALaRI: http://www.alari.ch) of the University of Lugano (http://www.unisi.ch)[1]. The project development lifecycle started from the *Inception Phase* where we collected the system requirements information during meetings organized with the representatives of those companies interested in this project. All the collected information were reported in an Operational Concept Description document which was reviewed by the project team and the companies representatives. The document included also a short description of current systems available in the market: the so called State of the Art (see Section 2). The Operational Concept Description document was a good starting point to begin the *Elaboration Phase*, which consisted of writing the Hardware and Software Requirements Analysis and Design document including the UML formalization of the system (see Section 6). Once the elaboration phase was performed we started the *Construction Phase* from a simulation point of view. This paper will present the *state of the art* in Section 2, while Section 3 discusses the *problem description* in terms of objective, constraints and operational scenario. In Section 4 is described the *system configuration flexibility* in order to support changes in the utility policy. Section 5 describes the *low-power and low-cost analysis* with few details on battery requirements. The *project approach* is briefly discussed in Section 6 in particular about the UML choice for the system-level specification. The paper ends with *future evaluation and perspectives* presented in Section 7. Section 8 is dedicated to the *references*.

II. STATE OF THE ART

A. Background

As markets deregulate, Intelligent Meter Reader (IMR) solutions become increasingly attractive, and even systems with one energy, gas or water meter, where the meter is traditionally read on site only once per month, can be profitable for commercial and small industrial customers. Using the analysis of consumption data, any unnecessary consumption can be identified and eliminated faster than before. The time from the reading operation to the generation of the invoice by the energy supply company is reduced and

[1] The project constitutes the Master project of a small students group sponsored by some of ALaRI's industrial partners, namely ABB, ST Microelectronics TXT-e-solutions and AIL; the authors are indebted to Mr. Bruno Sabbattini (ABB), Mr. Jeff Owen (ST Microelectronics), Mr. Flavio Fusetti (TXT-e-solutions) and Mr. Marco Bigatto (AIL) also for stimulating useful discussions and criticism.

simplified, which in turn reduces administrative costs. Furthermore IMR system offers an innovative path to transparent details of costs and hence to effective cost savings for all stakeholders.

B. Description of changes

The IMR is a special case of field service representing such a vast opportunity that it warrants its own category, in fact, this application is well established and it has its own trade group, the *Automatic Meter Reading Association (AMRA)* [3]. The vast fleets of vehicles and personnel now engaged in reading utility meters at homes, offices and factories can be replaced entirely by telemetry-equipped meters that read and send meters data automatically. Many utilities are already using telemetry for this purpose, and many more will adopt it as deregulation takes hold state by state and utilities are forced to face new competition. Many wireless service providers, including a number of private wireless networks, have aggressively pursued this market opportunity. GSM has some advantage comparing to the other networks, primarily its digital foundation and public network cost-effectiveness, apply particularly well in an application such as wireless IMR. Wireless IMR is an interesting opportunity for another reason as well: many large industrial and commercial utility customers and their service providers are starting to explore real-time pricing, energy sellbacks and other flexible options. Altera Corporation (www.altera.com) announced in April 2003 that Altera's Cyclone™ FPGA devices and Nios® processor are an enabling technology for wireless IMR's. **Real-time pricing**, for example, can reward users for shifting demand to off-peak times. The catch is that all of these potential service features require real-time data collection and control, and that's where telemetry comes into play. By reading a meter remotely every 15 minutes instead of on site once a month, for instance, a utility can work with customers to shift loads and manage prices. *New York's KeySpan Energy* [4] is a great example of the potential for wireless IMR and process control. By applying wireless telemetry to switch meter collection from a schedule-based system to a demand-based system, the city could nearly triple its average profit per meter, not including wireless equipment and service costs. Another key advantage of a wireless solution is adding **theft monitoring** through the wireless link; as soon as someone tries to vandalize a meter, the system notifies the police. This reduces both theft costs and the considerable costs of sending service crews out to repair vandalized meters. Responding to the cost and complexity of both landlines and private communication networks, the utility began installing GSM-based monitoring and control points throughout its gas and electricity network. In addition to attaching GSM modules to its electricity meters, KeySpan uses GSM telemetry to monitor gas pipes and substations. The company is also exploring ways to use telemetry to **dispatch repair crews** and control both gas and electricity distribution systems.

III. PROBLEM DESCRIPTION

Wireless IMR is a reading system to help utility providers to get consumer consumption data regarding gas, electricity and water via wireless technology.

A. Objective

The objective of this project was to design a device able to perform real-time determination of energy consumption (that is, where, when and to what extent energy is consumed), using wireless technology in a low-power and low-cost environment. As described in Figure 1, meter readers should be very close to meters[2]. Usually meters are located in home basements where GSM signal is not available. The Meter Reader is the low-power device which aims to solve this problem by reading, in a regular basis, data measured by meters and sending them (e.g. once a day) to a Data Collector (DC) through a wireless Bluetooth connection. The DC, located where the GSM signal is available, collects data and store them in the local memory. Then the DC sends these data to the utility provider via GSM. As well as that the utility (or service) provider should be able to read at any time the data stored in the DC and, in real-time, the meter data.

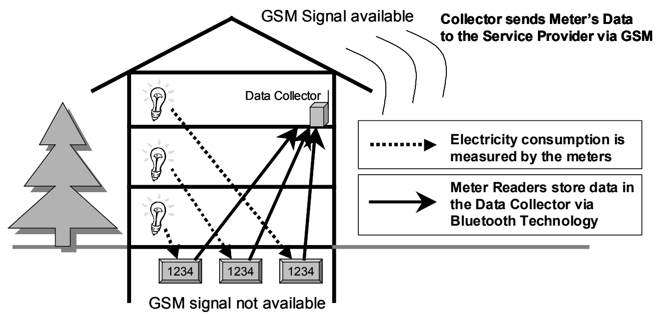

Fig. 1. Problem description

B. The project constraints

The constraints of the project are basically the following:

- security requirements on the wireless data transmission to be ensured;
- very low cost;
- very low power consumption;
- modularity and scalability in order to be ready for alternatives and/or future technologies: e.g. GPRS and UMTS;
- data format for the transmission;
- measuring point identification;
- measuring point status;

[2] In this paper the meter reader is the embedded system we are analysing, whereas meters are traditional devices dedicated to energy consumption measurement.

- the time base: there is only one time base for the whole system (standard time DCF 77). A quarter of an hour is the smallest measuring period. Longer measuring time are multiple of a quarter of an hour.
- data storage: analysis of the integration with existing systems at the utility side.
- In this paper we will focus on low-power and low-cost analysis as described in Section V.

C. The operational scenario

The Wireless Intelligent Meter Reading features: in this section we would like to explain the Wireless IMR features. Figure 2 provides a summary of the overall system, where the Wireless IMR is inserted, and of its operation.

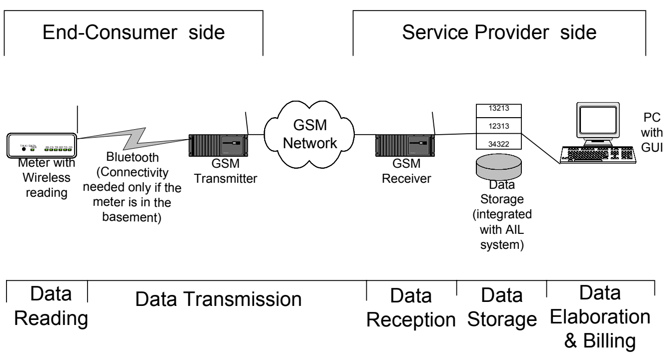

Fig. 2. High-level system description of Wireless IMR

In order to better describe the WIMR features, as shown in Figure 2, we divided the system in two sub-systems corresponding to the End-Consumer and the Service Provider side. Features at the End-Consumer side: The **data reading** operation can be performed in two different ways depending on the meter type: electronic or mechanical (traditional) meter. In the *first case* where, at the End-Consumer side, is installed an electronic meter, it is sufficient to introduce suitable sensors in order to make the system able to read meter values. In the *second case* (mechanical/traditional meter) the meter reading and radiation can be done using an *Eye Detection Method*: the image of the meter digits is transferred by simple mirror and lens technique to a CMOS image sensor. Both solutions are possible. The data will be transmitted using **standard data formats** provided by AMRA [3], which is an international, nonprofit association addressing problems of standardization, justification and deployment practices in the application and advancement of enhanced customer-service and resource-management technologies. AMRA offers membership services and educational forums that focus on AMR issues affecting electric, gas and water utility-service companies worldwide. See also [5] and [6]. The **data transmission structure** does not directly connect the meter to the GSM network, for a number of different reasons. Usually, meters are located in basements, so that the GSM signal reception is very weak or even not present at all. To avoid this problem we considered a transmission architecture using a wireless local area network that brings the data to the GSM transceiver located a few meters away from the basement in a position where there is an acceptable or full GSM signal reception. Using **Bluetooth** could be a good solution to the problem, since it is a low-power and low-cost technology. **Bluetooth** is one of the technologies which can be used for **transmitting data** from a given meter location point to the GSM transmitter. Bluetooth devices are **high-quality, low-cost and low-power devices**: usually the chip-set cost is quite lower than 10 US$ and each unit is self-powered. The **transmission of the metering data** to the Service Provider side can be performed **using GSM technology**. The fragmented nature of the telemetry and telecom markets has given rise to a wide variety of technology alternatives, from low-power radio to landlines. A recurring theme in these markets, however, is that where GSM has been available, it has been widely and successfully employed. The metering data from the Bluetooth unit can be transmitted to the GSM base station. Features at the Service-Provider side: The **reception of the metering data** is done through the GSM network. One or many stations located at the provider side can be used for receiving this data and monitoring the load. The data received will be **stored in a database,** developed ad-hoc for each Service Provider or **integrated** with existing utility system. The **data reading** at the utility side is performed from a software interface developed ad-hoc that displays the collected data. In case the utility has already a system in place, this functionality is granted by the integration with the existing system.

IV. SYSTEM CONFIGURATION FLEXIBILITY

The meter reader device is designed in order to grant a good flexibility level to support utility requirements. It often happens that utility providers change, during their lifetime, the billing policy, which usually has an important impact to the measurement system configuration. In fact billing models change even between utilities so that the measurement system should be flexible enough. In our Wireless IMR we have foreseen a bi-directional Bluetooth connection allowing changes in the Meter Reader software configuration. Configuration changes allowed are first of all related to the meter reading frequency. The utility should be able to decide which is the time window needed for their billing model. In this way, each utility is able to customize the meter reading frequency in order to avoid problems when global pricing politics change the way to bill energy consumption. Low-power constraints, on one side, and the foreseeable use of semi-permanent memories (e.g. Flash Memories) requiring more power for writing than for reading, on the other side, outline a *reconfiguration practice* that should be limited both in frequency and in relevance (e.g., concerning updates of tables, or at most substitution of small library segments). At the sensor side two main points are:

- updating the timer data specifying when to start again the Bluetooth connection (new data sent to the data collector),
- the capability to upload new versions of Optical Character Recognition (OCR) software.

Both require extra capabilities if the Bluetooth connection must be kept active for retrieving software updates. We also have to take into account extra requirements due to the choice of the encryption techniques. We carefully analyzed this issue and we devised a secure channel with start point inside the sensor hardware and end point inside the company server. Moving the encryption inside the DC would not be a feasible solution mainly because of the possibility of attacking the Bluetooth channel. The two possible solutions that will be evaluated by the utility are digital signature with a private key flashed in the micro-controller on the sensor side or symmetric key encryption with a copy of the private key in the company server. Each solution has a different impact, not so much in hardware/software requirements (encryption here does not need to be fast), as in power consumption. Simulations will be carried out during the codesign phase to ensure that both schemas can be applied. Data collector (DC) should be the target of in-depth analysis regarding reconfigurability issues: basically it should receive the encrypted data from meter readers and store them in a little database, preparing and sending later one or more messages (SMS) with all readings that have to be sent to the central station. This situation could be simply afforded by a static hardware resource with pre-defined software. In our approach we foresee a fully customizable hardware and software platform whose capabilities can be extended up to let it become a central station for domotic appliances. We think in fact that it could become also an interface for reading temperatures, for creating alarm systems (anti-theft monitoring of the house), and in general to let the energy company have a competitive advantage against other companies for the deployment of new home services. Due to relevant changes that could be required in the hardware during the appliance lifetime, we think that one possible solution consists of FPGAs with embedded micro-controllers and extra devices that companies are planning to insert them during next years. We are going to exploit modular hardware modules that can be added or removed on-site. Reconfiguration can be achieved either statically at Compile Time (thus customizing the system to individual requirements) or dynamically at Run Time by means of SMS. Currently there are different approaches in exploiting the advantages of reconfigurability. The main of them are the following (See [9]):

- “The Swiss Army knife” approach
- “Lego” method.
- “The team” methodology
- “The ant colony” approach
- “The immune system” method

Our case matches to ”The Swiss Army knife” paradigm in the electronic devices connected to the sensors. The basic idea is to choose one of a set of prepared configurations. In this way we are able to get maximal degree of freedom in order to use sensors from different suppliers (or eventually to update them). The operator will decide which one from predefined blocks to use in any concrete case. We think about universal solution which is possible to apply in different countries. The controller will be housed on the utility’s premises and the decision of system reconfiguration will be taken after changing the billing policy as example. A very important point is that deciding about reconfiguration must be very easy and very reliable. In order to reconfigure a system we considered four control mechanisms categorisable as (See [9]):

- Central, external intelligent controller
- Central, internal intelligent controller
- Distributed, intelligent
- Distributed, unintelligent

We decided to use the “central, external intelligent controller” mechanism to be located in utility company. It is possible to combine this kind of controller with other ones, such as “distributed intelligent” or “distributed unintelligent”. The “distributed intelligent” controller could be implemented inside the DC and take care of both: theft monitoring and also end-consumer device reconfigurability. A further feature could be the ability to detect FPGA’s problems (faults) in the embedded system and switch to a spare block (see [10]) by sending a message to the service provider. At the sensor side, in order to design low–power devices, we could use distributed unintelligent approach. In fact, low-power consumption, is possible to be achieved with lower degrees of intelligence.

V. LOW-POWER AND LOW-COST ANALYSIS

Radio devices normally present power consumptions from few tens of milliamps. Under such conditions autonomy of more than one month is impossible even using heavy-duty Lithium batteries. In order to reduce power consumption, the Bluetooth transmitter operates in “sampled” mode: it is periodically switched off, in standby and activated. The duty cycle of this operation directly determines the residual mean consumption. Reductions of the power consumption of 99 to 99.99% are commonplace, so that the device autonomy can be of several years. Because the transmitters at the utility meter are switched off most of the time, there is a risk of missing messages and therefore walking up the course of a communication. In order to minimize this risk, the Bluetooth transceiver of the data concentrator transmits a prelude frame containing the address of the enquired meter before the transmission can be established. The transmission time will be longer for the Bluetooth transceiver for the data concentrator (DC), but this device is not under strict power consumption constraints like the radio transmitter on the meter. In a first phase (see Figure 3) the meter reader (MR) detects the prelude message containing the corresponding address coming from the DC. The MR powers up to operation mode and sends his address to the DC. Now MR and DC are synchronized, the useful frame can be sent by the MR. The MR power-up-time is a function of the listening time necessary to detect the prelude with the corresponding address but it also has to integrate the MR start-up time.

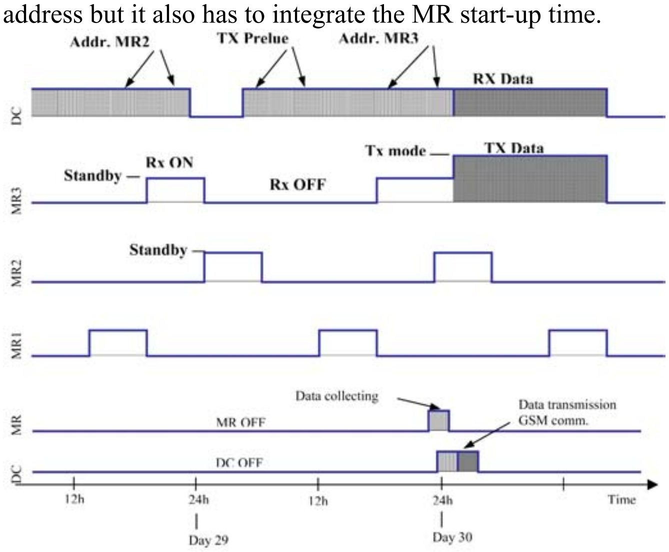

Fig. 3. WMR System behaviour: starting communication for message exchange

A Real-Time Clock in the MR keeps track of the date, time and the scheduling. The time in the MR has to be synchronized with the time in the DC. In order to enable the asynchronous mode of collecting and sending data, the MR has to be regularly in standby mode (with frequency of 1 day) even when the DC doesn't require the communication. The time schedule, the recording and reading time of the data are stored in the small on chip memory of the RTC device.

A. Battery requirements

The progress has been moderate. A battery holds relatively little power, is bulky, heavy, and has a short life span. Battery power is also very expensive. Small devices like MR are powered with a non-rechargeable battery. Among the common power sources, energy from non-rechargeable batteries is the most expensive. Table I below reflects the cost per kWh using non-rechargeable batteries. Non-rechargeable batteries have a high internal cell resistance, which limits their use to light loads with low discharge currents.

Table I. Cost per kWh using non-rechargeable batteries

	AAA Cell	AA Cell	C Cell	D Cell	9 Volt
Capacity (alkaline)	1100mAh	2500mAh	7100mAh	14,300mAh	600mAh
Energy (single cell)	1.4Wh	3Wh	9Wh	18Wh	4.2Wh
Cost per Cell (US$)	$1.25	$1.00	$1.60	$1.60	$3.10
Cost per KWh (US$)	$890	$330	$180	$90	$730

In order to select the right battery, it is important to know the behavioural factors of the different battery types and the environment conditions. General battery requirements for the MR are:

- High Temperature range (storage, operation)
- Low self discharge
- Low cost
- Low memory effect

Table II. Advantages and disadvantages of few battery types

Type	Advantages	Disadvantages
Zinc-carbon (LeClanche) ***"standard"***	Least expensive. Widely available.	Lowest energy density. Sloping discharge curve. Poor high-current performance. Internal resistance increases as discharged. Poor low-temperature performance.
Zinc-carbon (zinc-chloride)	Less expensive than alkaline. Better than LeClanche at high current and low temp.	Low energy density. Sloping discharge curve.
Alkaline manganese ***"alcaline"***	Moderate cost. Better than zinc chloride at high current and low temp. Maintains low internal resistance as discharged. Moderate energy density. Widely available.	Sloping discharge curve.
Lithium oxyhalide ***"lithium"*** and **Manganese Dioxide**	High energy density. Highest energy density per unit weight. Flat discharge curve. Excellent at high and low temp (-40 …+80 C). Extraordinary shelf life. Light weight. High cell voltage (3.0V).	Expensive.

VI. PROJECT APPROACH

A. UML

The Unified Modeling Language (UML, see [7] and [8]) is a language for specifying, visualizing, constructing, and documenting the artifacts of software systems, as well as for business modeling and other non-software systems. The UML represents a collection of best engineering practices that have proven successful in the modeling of large and complex systems; it is interesting to envision its extension for specification and modeling of hardware-software systems as well, since the first design phases, i.e. before hardware-software partitioning has been effected. In this project UML has been used in the design of a wireless meter reading system consisting of hardware and software components. In recent years, the Unified Modeling Language, UML, has been introduced and is now widely used, basically for requirements specification in the design of complex software systems. UML does not guarantee project success but it does improve many things. For example, it significantly lowers the perpetual cost of training and retooling when changing between projects or organizations. It provides the opportunity for new integration between tools, processes, and domains. But most importantly, it enables developers to focus on delivering business value and provides them a paradigm to accomplish this. UML is a modeling language rather than a methodology. It is largely process-independent, in fact is not tied to any particular development life cycle. However, to get the most benefit from the UML, one should consider a process that is:

- Use Case driven
- Architecture-centric
- Iterative and incremental

This use case driven, architecture centric and iterative/incremetal process can be broken into the traditional Software Development Life Cycle phases, (inception, elaboration, construction and transition) which can be applied very well in the development process of this project [11]. It was decided to use UML because it meets the following high-level requirements specification:

- It is technology independent;
- It is Hardware/Software partitioning independent;
- It allows specification of both functional and non-functional requirements and constraints;

The advantage of using UML is that it makes the whole designed system highly modular, so that we could structure the whole WMR system as the interconnection of a number of different blocks consisting of Hardware and Software components.

VII. FUTURE EVALUATION AND PERSPECTIVES

In the Information Society Technology, customers ask for faster, cheaper and low-power consuming solutions. “Anytime and anywhere access to the Internet” is no more a nice to have but a must, which pushes the wireless standard and industry growth in the pervasive computing area.

A. Field service applications

Industries and agencies that employ field service crews for monitoring, replenishment or repair represent some of the biggest opportunities for the telemetry market. We can break the applications into 3 categories. ***Systems that need to be refilled:*** The humble vending machine could benefit greatly from wireless telemetry. The current refilling process, which is based on fixed schedules and not on measured demand, now suffers from three major inefficiencies. Telemetry-equipped machines can place orders when needed, with the right mix of products, to optimize sales and minimize replenishment costs. ***Systems that need to be emptied:*** Conversely, machines that need to be emptied at unpredictable intervals, such as parking meters and token collection points on mass transit systems, could enjoy the same benefits. In both cases, expensive fleets of vehicles and drivers are employed to service individual transaction points, which individually account for very little revenue but collectively account for very high costs. ***Systems that need to be serviced or repaired:*** The opportunities in this category range from office machines to railroad crossing barriers to elevators. One of the newest applications in this area is tying telemetry transmitters to the uninterruptible power supplies (UPS) connected to critical computing or telecommunications systems. Since the UPS can keep the system running for only a matter of minutes in most cases, the transmitter can alert technicians to shut the system down gracefully or switch to backup power or backup networks.

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