Smart Metering for Domestic Water Flow – Challenges and Resolutions

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ABSTRACT

In this paper, a smart metering system for domestic water flow meters is presented. The system comprises front-end readers that are attached to the legacy mechanical flow meters, and a cloud-based back-end system for data collection, monitoring and control. The paper focuses on the difficulties and challenges associated with the front-end segment, where tough requirements are imposed by utility companies. Careful firmware-hardware co-design is presented, with a main focus on the energy constraint. The processor selection and the architecture of the embedded firmware which achieves a system lifetime of 5 years yet allows daily communication is also demonstrated. Finally, the roadmap for mass production and deployment is considered.

Categories and Subject Descriptors

D.3.3 [Performance]: Power Consumption.

General Terms

Algorithms, Measurement, Documentation, Performance, Design, Economics, Reliability, Experimentation, Theory, Verification.

Keywords

Smart Metering, Automatic Meter Reading, Target Detection, Battery profile.

1. INTRODUCTION

Egypt has a population of about 85 million, and receives an annual Nile water share of 55.5 billion cubic meters [1]. Around 85 percent of that water is used in agriculture, but a lot simply leaks away. According to [2] Egypt loses two billion cubic meters of water to evaporation, and three billion cubic meters to grass growing on the banks of the Nile and on river islands. Around 40 percent of the remaining water - used domestically and in industry (2.3 billion cubic meters) - is lost to leaking pipes and drains, while 2.5 billion cubic meters are used to generate electricity.

The domestic water sector in Egypt faces many challenges. Among the approximate number of flow meters deployed, which is approximately 20 million, more than 50 % of it either provide inaccurate readings or are completely defective. This results in calculating bills according to coarse estimation, which leads to inconsistent bills and delayed payments. Furthermore, pipe leaks, tampering and un-authorized joints add to the gap between production cost and revenues. A study is presented in [3] which gives an estimate the Non-Revenue Water to be 34%. Egypt invests 3 billion Egyptian pounds yearly in the sector of water and waste matter, so the sector losses from Non-revenue water exceed 1 billion pounds (2.7 Million pound per day!)

In this paper, we present and Automatic Meter Reading system for mechanical water flow meters used in domestic and industrial sectors. The system consists of a reader that is attached to the meter and is connected to a backend server through the cloud. Readers are battery-powered and are connected to the cloud through built-in GPRS modems. The backend system collects data from all meters and applies different data analysis needed for billing, tamper detection, leak detection, usage profile, and other utility-related parameters. Interoperability between system elements is achieved through Hardware-Firmware-Software co-design process.

The rest of the paper is organized as follows. Section 2 presents background on AMR systems, and similar work on water metering in specific. The architecture of the system, including hardware and firmware segments, is demonstrated in section 3. Special focus on the energy management task is discussed in details. Section 4 describes the backend part of the system, and introduces the concept of mediation layer and device abstraction. Finally, the conclusion and future activities for the industrialization phase of this system is presented.

2. BACKGROUND

Automatic meter reading (AMR) is a technology which automatically gathers data from energy, gas, and water metering devices and transfers it to the master station in order to analyze it for multi purposes. Data are read remotely, without the need to physically access the meter. The advantages include reducing peak demand for energy, supporting the time-of-use concept for billing, enabling customers to make informed decisions, and reducing the cost and increasing the accuracy of meter reading. AMR technologies may include handheld, mobile and network technologies based on telephony platforms (wired and wireless), radio frequency (RF), or power-line transmission.

AMR for Water meters can also be used at the water source, well, or throughout a water system to determine flow through a particular portion of the system. The domestic water consumption is measured through mechanical flow meters which are generally located outdoors or within a man-hole. AMR for such meters is challenging as it implies attaching reading device (reader) to the meter. The reader should work properly under temperature, dust, rain and direct sunlight conditions, and should be completely autonomous. Generally, IP68 casing is required to ensure tolerability to such harsh conditions.

The Global Smart Water Network can be categorized by technology into two segments:

- Smart Water Meters
- Monitoring and Control Systems.

Key Vendors for smart water meters include: Arad Group, Badger Meter Inc., Elster Group, Itron Inc., Neptune Technology Group Inc., Sensus USA Inc.

Relying on turn-key solutions for smart water metering has its advantages of fast roll-out and develop on past experience of the service provider. However, this approach has many drawbacks. Besides the high initial and operational costs associated with the turn-key solutions, those systems are designed for specific types of meters that should be equipped with special components to enable compatible reader interface [4]. The different types and vendors of meters installed in Egypt several years ago calls for more tailored solutions that could easily fit on various types of existing meters. Furthermore, the low-revenue small flow meters (1/2 inches and 3/4 inches) represent the majority of existing meters. Therefore, for any AMR system to be used under these conditions, it should be presented at ultra-low cost.

Another important evolution of the AMR that is expected to spread in the near future is the concept of Machine-To-Machine (M2M) operator [5]. The concept of M2M Operator is that the smart metering, like any other communications technology, could be introduced to utility companies as a “service”. In this regard, the utility companies could ask the M2M operator for meter reading among many other services including: metering, billing, alerts, profiling, etc. This paradigm enables Telecom operators to invest in M2M business much more than availing the connection. In the meantime, utilities will hand-over all the technical related issues of the AMR to the operator, and will just pay per-service or per-meter.

For the reasons above, we at Orange Labs worked towards design and development of a complete water-flow AMR system with this view in mind. The front-end reader presented in this paper is totally designed in the lab and its cost ranges from 30 to 45 USD, which is less than half of its counterparts in the market. Further cost reductions and reduced-cost versions is planned after the first trial. Furthermore, the smart metering platform presented here is designed relying on Orange proprietary platform called (Intelligent Application Enabler) which is a mediation layer between devices layer and application layer. This architecture enables the back-end to be compatible with different meter types, including Gas and Electricity. The work presented in this paper is considered the first step towards introducing the concept of M2M Operator in Egypt.

3. SYSTEM ARCHITECTURE

This section describes the architecture of the AMR system for water flow. From the design view point, the system comprises three components:

- Reader Hardware
- Reader Firmware
- Backend Platform

Fig. 1 illustrates the architecture of the water AMR system.

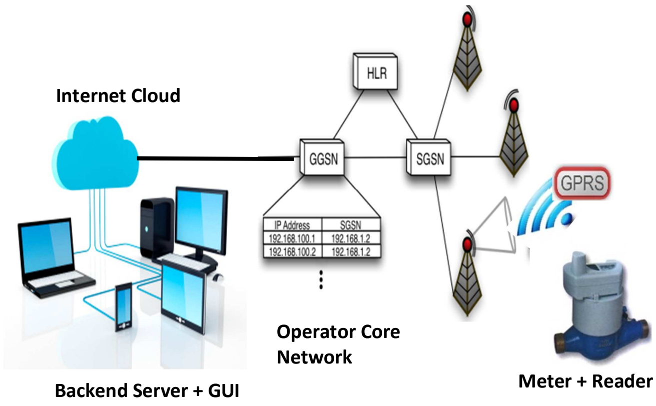


Figure 1. Block Diagram of water flow AMR system.

The main requirements of the utility companies for an AMR system could be briefed in the following points:

1- Reading accuracy : 10 liters.
2- Reading time step : 15 minutes
3- Minimum reading rate : Once daily (96 readings).
4- Power source : Battery only.
5- Minimum lifetime : 5 years.
6- Tamper detection.
7- Reverse-flow detection.

The architecture of each module, and the design approaches to meet the above specifications is presented in the following sections.

3.1 Hardware Architecture

The reader module attached to the flow meter contains four main components: Sensing, processing, communication and battery. The sensing part is responsible for detecting a rotating target integrated in the meter. The target is a small sheet of metal attached to a rotary wheel that is mechanically attached to the turbine by a set of gears. The rate of revolution is directly proportional to the water flow rate. Furthermore, the direction of the target rotation indicates a forward/reverse flow. The detection of the target is done by magnetic coupling, which uses the idea of eddy current losses in the target.

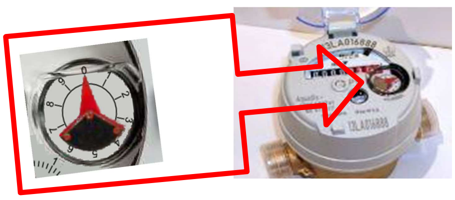


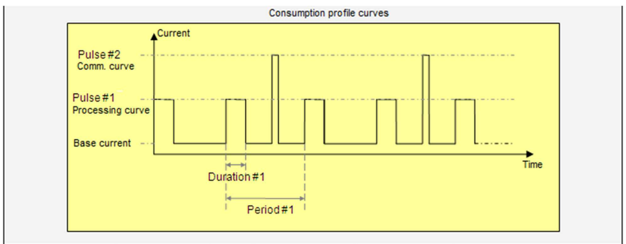
Figure 2. Target at water flow meter.

The processing section is responsible for reading the status of the sensing circuit and detects the existence and rate of target rotation. The processor keeps track of the target rotation and accumulates overall consumption during a predefined duration.

The unit also keeps track of the tamper sensor and records any trial to detach the reader.

In order for the processor to accurately track target revolution and in the same time preserve battery, the processor takes only snapshots of the target position at a specified sampling rate. In between those snapshots, the processor forces itself into the sleep mode where the power consumption is at minimum. The sampling rate is specified according to the maximum rate of target revolution, which is equivalent to the maximum water flow tolerated by the meter. The processor sampling rate is such that each revolution is sampled at least three times, so the target motion and direction is detected. Of course this rate differs from one meter to another, and it is a direct function of the maximum flow rate supported by the meter (designate by Qmax), which is the maximum allowed water flow in m3 per minute.

The battery section represents the power source for the whole system. The selection of the type and capacity of the battery is a key in meeting the utility requirements. The 5-years lifetime requirement needs very low self-discharge battery, which excludes rechargeable batteries from the selection list. Also the battery should be able to supply high-current pulses needed by the GPRS modem during the communication with the cloud server. Those pulses could be as high as 2-Amperes during the data exchange session occurring at least once daily. On the mechanical side, the battery should fit easily in the reader compartment, and should be of reasonable weight to avoid mechanical stress on the meter. The temperature range of the battery should be selected to cover hostile outdoor environment, with a wide operating temperature range. Fig. 3 indicates the current profile drawn from the battery. Upon specifying the amplitude and duration for each pulse, the amount of energy consumed from the battery per day is calculated, and hence the total capacity for a given lifetime could be reached.



	Current	Duration	Period	Notes
Base current	35 µA			
Pulse #1 Best case Processing	15 µA	24 h	24 h	24h/day in lowest processing consumption
Pulse #2 Best case Comm.	200 mA	20 s	24 h	Once per day for best communication session
Pulse #1 Worst case Processing	125 µA	24 h	24 h	24h/day in highest processing consumption
Pulse #2 Worst case Comm.	200 mA	80 s	24 h	Four times per day for worst communication session

Figure 3. Battery discharge profile.

The communication segment of the reader consists of a GPRS modem which is used to send water consumption data and receives commands and setting from the back-end. Each modem has a unique serial number that is used for authentication and provisioning of the meter at the back-end. To save battery and meet the system lifetime, the modem is switched-on once daily to communicate with the back-end server and just after the session ends, it is switched-off. Fig. 4 illustrates the block diagram of the reader, indicating the main blocks discussed.

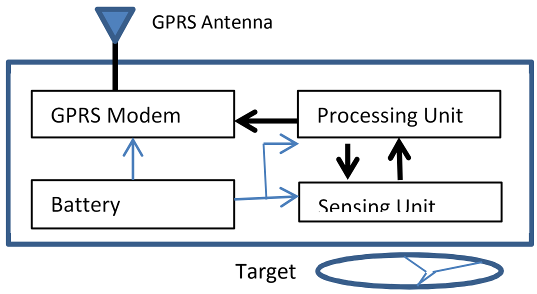
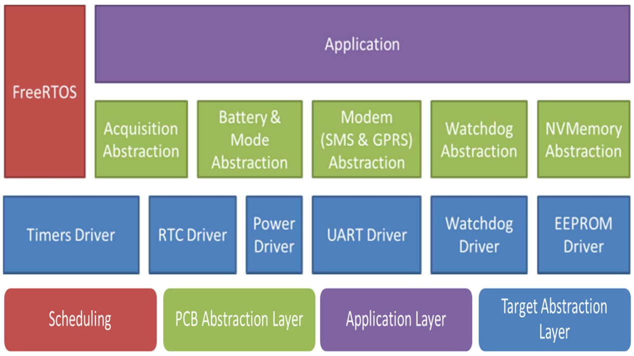


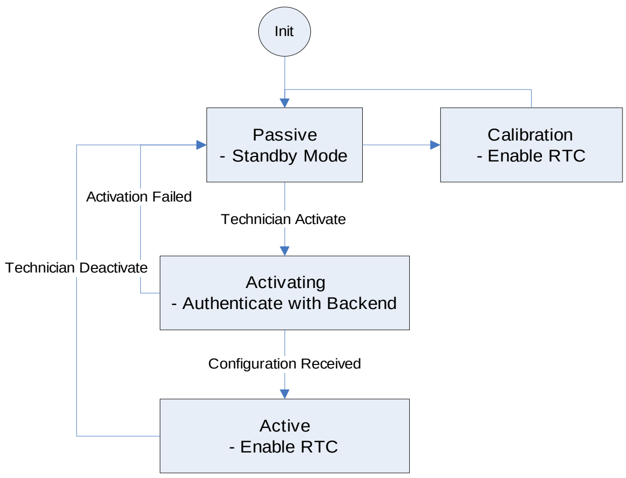
Figure 4. Block diagram of reader hardware units.

3.2 Software Architecture

A classical approach is elected for grouping firmware modules in layers that abstract the layer on top from the underlying hardware. The lowest layer is the target abstraction layer. It contains the modules that drive the uC peripherals used by the system. The layer on top of that is the board abstraction layer. It contains the modules that drive the different PCB circuit modules. The top most layer is the application layer containing all the system logic without any hardware dependency. The static architecture of the firmware, together with the device state machine are illustrated in Fig's. 5a, 5b.



(a)



(b)

Figure 5. (a) Firmware static architecture of the reader and (b) reader state machine.

3.3 Acquisition Polling Rate

As shown in section 3.1, the acquisition polling rate is one of the main contributors to the system's power consumption. The minimum acceptable rate needs to be carefully calculated to ensure no flow pulses are missed.

If only two sensing elements are used for acquisition they need to be placed in such a way that guarantees an overlap in detection to enable the possibility of flow direction identification. In that case a simple algorithm similar to that of quadrature decoding can be used to count pulses and their direction. The four generated states must all be acquired to guarantee system integrity. Also there is a lot of added complexity on the placement of the sensing elements. In the case where three sensing elements are placed equidistantly the time it takes to enter and exit the target detection state of each sensing element depends on the size of the target. The other main factor deciding the polling rate is the maximum needle speed. This latter factor is a function of the Qmax as well as the amount of flow that one revolution of the needle represents K.

The fastest needle we are required to support represents a K of 0.01m3 and is on a meter with a Qmax of 100m3/h.

$$Target\ angular\ velocity = \frac{100}{(3600 * 0.01)} = 2.778\ revs/sec$$

The target size is close to one fourth of the revolution but we shall use one fifth to add a safety factor.

$$Polling\ Rate = Target\ angular\ velocity * 5 = 13.889\ sps$$

An additional power conservation technique is using an adaptive polling rate. If the water flow stops for some time the system could go into a lower power mode by sampling at a slower rate. Then boost the polling rate up to support maximum flow as soon as any state change is detected. This technique makes use of the fact that the change in water flow speed cannot be instantaneous. During the gradual speed up it will be easy to detect the state change at the lower sampling rate and then change the rate to allow full system readiness.

3.4 Operating Modes

The main strategy for power saving is to have both the Microcontroller and the GPRS Modem in their lowest possible power modes for as long as possible with respect to the times when they are running. There are two main functionalities required by the system: Meter Reading Acquisition and GPRS Modem Communication.

$$Functioanlity\ Duty\ Cycle = \frac{Active\ Time}{Period}$$

The modem communication periodicity is constrained by the industry norm of automated water meter reading. It is expected to happen once daily. This is excellent given that the session from network negotiation until HTTP response reception can be completed in less than 30 seconds. So we can keep the modem in the Shut Down power mode for the whole day except for the 30 seconds in the active mode. The consumption of shut-down as well as active power modes is indicated in Table 1.

$$Communication\ Duty\ Cycle = \frac{30}{24 \times 60 \times 60} \times 100\% = 0.035\ \%$$

Table 1. Modem Power Modes

Power Mode	Consumption	Usage
Active	30mA with 2A Bursts	-Modem Communication
Shut Down	35uA	-Waiting for Modem Communication

The acquisition periodicity is the inverse of the polling rate calculated earlier. Assuming a 16 sample per second rate the periodicity becomes 0.0625 seconds. For constraints related to the sensing technique used one sample requires 2.5 milliseconds to be acquired.

$$Acquisition\ Duty\ Cycle = \frac{0.0025}{0.0625} \times 100\% = 4\%$$

The flowchart of the acquisition section of the firmware is depicted in Fig. 6.

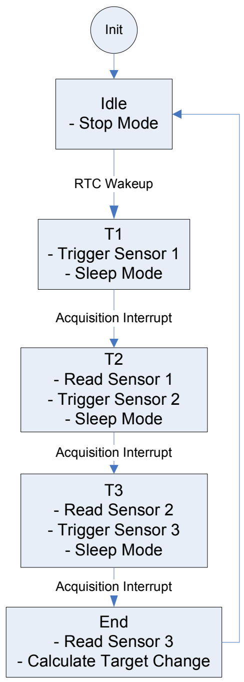


Figure 6. Flowchart of the Acquisition Section.

Identifying that the acquisition sample is mostly consumed waiting for the sensor to respond after activation, we can reduce the duty cycle even further. The controller can sleep between sensor trigger times to only be interrupted by the acquisition-complete interrupt. This should drive the overall duty cycle well below 1%. Table 2 shows the consumption of the microcontroller operated at different modes.

After applying the above mentioned optimizations, the break-down of the energy consumption from the battery is illustrated in Table 3.

Table 2. Microcontroller Power Modes

Power Mode	Consumption	Usage
Active @ 4MHz	500uA	-Modem Communication -Triggering Acquisition -Applying Acquisition Algorithm
Sleep	50uA	-Waiting for Acquisition Completion
Stop	3.5uA	-Waiting for next Acquisition cycle
Standby	1.5uA	-Waiting for Activation

Table 3. System Energy Breakdown

Functionality	Consumption (Ah/year, %)	Conditions
Communication Energy (Best Case)	0.41, 48%	One session per day – Best-case processing.
Communication Energy (Worst Case)	1.64, 79%	Four sessions / day - Best-case processing.
Processing (Best Case)	0.44, 52%	One Communication session per day
Processing (Worst Case)	1.4, 77%	One Communication session per day

3.5 Microcontroller Architectural Advantages

3.5.1 Direct Memory Access

Modern microcontrollers allow peripherals to have direct access to the RAM. When used right, this feature could greatly reduce code execution time and thus save power by letting the hardware do all the heavy lifting while other code can execute in parallel. In our case we communicate with the GPRS modem via UART peripheral. We build the string required to be sent to the modem and initiate transmission by pointing the UART to the beginning of our Tx buffer in memory and indicating the size. The HW does all the serial character by character transmission by iterating through our buffer while our instructions manage the sensing circuitry.

3.5.2 Internal Oscillators

We use two of the three internal oscillators made available by our microcontroller. A lower speed oscillator is used to clock our RTC and a higher speed oscillator is used as a system clock. The higher speed oscillator is factory calibrated and we use it to calibrate the lower speed oscillator during system startup. Using internal oscillator cuts device cost and decreases consumption but comes at some accuracy and drift risks. We also use the timestamp acquired from our backend system during communication time to correct for any drift on our RTC caused by the lower speed internal oscillator.

3.5.3 Comparator Peripheral

Having a comparator to use inside our microcontroller with configurable threshold reduced the complexity and cost of our PCB design by eliminating a component from the circuit. In addition it allowed for easier supply management from the battery as no additional biasing voltage would be required.

3.5.4 Independent Peripheral and Port Clocking

We rely heavily on putting our microcontroller in low power level states for reduced consumption. During the active state we are also very cautious by only enabling those peripherals and ports required by the current activity. The modular static architecture combined with the Cortex-M's feature of independent clock gating of each port made our job easier. For each module we created a resume and suspend routine that follow the following pseudo code.

Function Suspend_X:

- Configure all pins in Analog Input mode (Schmidt trigger OFF)

- Disable the used peripherals

- Disable the clocks going to the used peripherals

Function Resume_X:

- **Enable the clocks going to the used peripherals**
- **Configure the pins required by this module**
- **Start the required peripherals**

3.5.5 Development Tools

An energy efficient microcontroller by ST was chosen for our device, built around ARM's Cortex M-3 core. It brought the right balance between low power consumption and powerful 32-bit processing. Not to be tied to any proprietary development tools we elected to work with an open source toolchain. GNU's gcc was used as a cross compiler in addition to gdb for debugging. An eclipse based IDE was also selected for the same reasons.

4. IAE AND BACKEND PLATFORMS

The previous sections discussed the water AMR system from the frontend (meter) side. The data collected by all the readers attached to meters are sent through the GPRS modem to the application server for data analysis as previously mentioned. The backend system that is implemented in this system contains two main modules: The Intelligent Application Enabler (IAE) mediation layer, and the Application layer. In the coming sections we will present functions associated with both modules.

4.1 IAE Platform

The IAE is a generic platform developed by Orange [6] and allows M2M operator to create and manage end-to-end M2M services on behalf of its customers. The main functionalities of IAE could be briefed as follows:

- It is a mediation platform between devices and customer IT environment which enables data collection, message and device management services.
- It provides "network operations" capabilities such as messages exchanges supervision and devices network supervision.
- Based on this platform, M2M operator can provide or integrate complete M2M solutions addressing customer specific challenges.

- It allows the customer to ensure communication between their devices and their business applications.

The M2M operator can then deliver a purpose-built M2M end-to-end service beyond connectivity, encompassing terminal devices, network, and back-end applications. The high-level diagram of IAE and its location within the cloud connected application server is shown in Fig. 7.

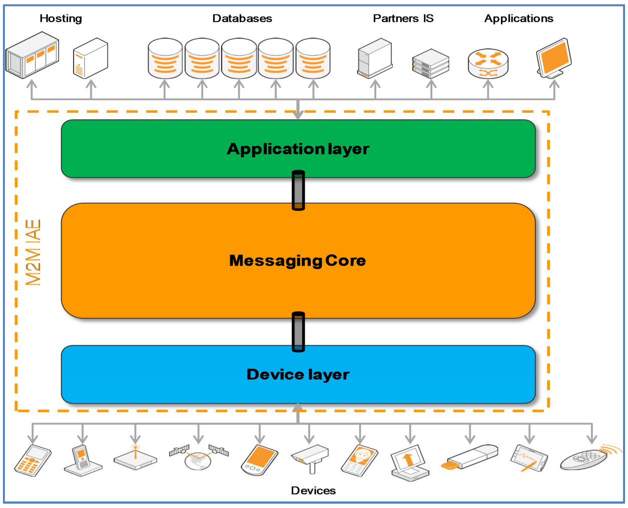


Figure 7. IAE platform architecture.

4.2 Smart Metering Application

The Smart Metering Application interface is a Java-developed application that interacts with the IAE layer and extracts meter information using standardized API's. The IAE abstraction layer makes the Application compatible with many types of devices and meters. The utility requirements are the main factor that defines the main functions and GUI for the designer. A typical page of the application layer is shown in Fig. 8 and is called "Meter Page". It illustrates the meter serial number, type and periodic value of the water consumption. Of course the application could be tailored according to specific utility needs, while keeping the device interface and the IAE intact.

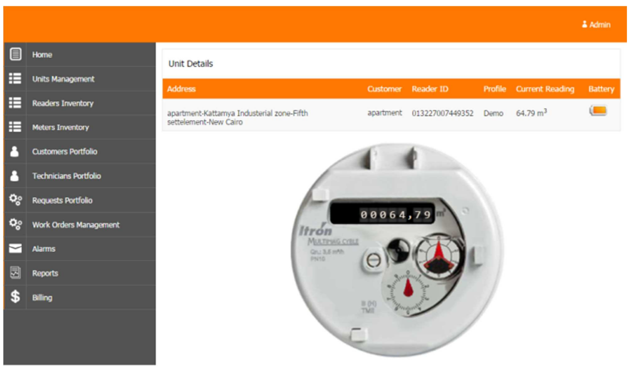


Figure 8. GUI snapshot of the smart metering solution.

5. CONCLUSION

An AMR system for measuring domestic water consumption is demonstrated. The system includes a reader that is attached to the water flow meters and a cloud-connected server hosting the back-end system. The reader main challenge is in energy conservation, under the battery operation and imposed lifetime. A careful hardware-firmware co-design process has been followed to meet the lifetime criterion.

The back-end system containing IAE mediation layer plus the application is also presented. The IAE enables the developers a device abstraction layer through predefined API's by which, the final application is device-independent.

The presented system architecture is an early effort to introduce the concept of M2M operator in Egypt, through availing meter reading as a service to the utilities. Orange Labs in Cairo is currently testing a first version of this system in a private utility company, and initial results are encouraging. A first test pilot for 50 meters is planned before the end of 2014.

6. REFERENCES

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