Automated Meter Reading based on IEEE 802.15.4

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Abstract—This paper presents an AMR (Automated Meter Reading) system based on IEEE 802.15.4. It uses low-power routers and end-devices, which are in the SLEEP mode most of the time, so that the wireless network can operate for more than 10 years using low-cost batteries. This paper presents the main features of the proposed network protocol, and a hardware implementation in the 868 MHz ISM band. A pilot has been also deployed in the Cartuja Island in Seville to assess system performances.

Keywords— AMR, Automatic Meter Reading, water meters, wireless networks, autonomous nodes, low power, communication protocols.

I. INTRODUCTION

With the improvement in the quality of live and the advances in communication technologies, there is an increasing demand of smart metering, both, in residential and non-residential areas. Among others, customers demand billing based on real (non-estimated) consumption, real-time information, interaction with the utility, access to adaptive fares based on time and zone, etc. As a consequence, AMR (Automated Meter Reading) systems have received a lot of attention in different markets, like electricity, gas, water and heat [1].

AMR systems usually require a large investment in acquisition, installation and conditioning of, both, the meters, and the communication network. Even though the terminals have a low cost, the huge number of terminals (up to millions for large cities), make the total cost of the system too high for a wide acceptance.

The high economical effort required for the deployment of AMR systems makes convenient to work towards a common use of the communication infrastructure, and some steps are being done in this direction [2]. However, in many countries the companies in charge of electricity, water and gas infrastructure are different, which makes difficult to achieve the integration of their metering systems.

In the case of gas and water the problem is aggravated, as there is not a power source available to supply the meter readers and the communication devices. Then, autonomous, battery-operated circuitry has to be designed with a long operating lifetime of, typically, 10 years.

For these low power systems the metering rate is of importance. On the one side, a short period is required for advanced services like early detection of leakage, water or gas misuse or fraud, and to enable policies oriented towards a rational and sustainable consumption. On the other hand, a high rate of metering increases the power consumption and diminishes the lifetime of battery-operated devices.

In the case of water, these new services are of a high importance, especially in countries with a deficit in hydric resources, like the south of Europe, the southwest of the USA and the Middle East. In the case of AMR of water meters, the challenge is the design of low-cost terminals providing a high metering rate (e.g., with an hourly basis) and autonomous operation with a lifetime longer than 10 years. This system has to be able to read any type of water meter, either mechanical or digital. Its operation has also to be very cheap, avoiding the intensive use of expensive communication networks. Then, the readings of a large number of water meters have to be concentrated before accessing the IP network via GPRS/GSM or some other equivalent network.

This paper presents a new AMR system for water meters based on IEEE 802.15.4. The synchronization and data transmission is based on the beaconing procedure defined in the standard. The proposed network uses a tree topology with router terminals in different hierarchical levels.

Section II presents the proposed communication protocol. Section III discusses the hardware design of nodes (end-devices, routers and coordinator). Section IV shows some experimental results about RF coverage and power consumption. A pilot has been deployed in the city of Seville with 1,000 water meters, which is detailed in Section V. Finally, some conclusions are drawn in Section VI.

II. WIRELESS NETWORK AND COMMUNICATION PROTOCOL

Some AMR systems which can be applied to water meters have been recently reported. Some of them directly connect the meters to the central station using SMS with a GSM modem [3]-[4], while others are based on IEEE 802.15.4 with ZigBee in the upper layers [5]-[6]. Some market solutions have also recently appeared. Good summaries of wireless AMR system protocols can be found in [7]-[8].

However, SMS and ZigBee based solutions hardly can maintain a high metering rate without an external supply, and
the market solutions based on proprietary protocols do not achieve true low cost.

In this paper a new network protocol based on IEEE 802.15.4 is proposed along with some innovative techniques to lower cost and reduce power consumption.

In the proposed system, to reduce the cost per meter, every end-device is able to read a battery of up to 50 meters connected by the standard bus UNE 82326 for electronic meters and by a standard serial bus for mechanical meters, including reed and inductive reading. Specific low-cost autonomous interfaces have been designed for every meter type.

### A. Network Topology

The proposed network uses a hierarchical structure with a tree topology (Fig. 1). At the top, a coordinator node manages the network. It has a direct connection with level-1 routers, which, in turn, communicate with level-2 routers, and so on. At the bottom, routers concentrate the data coming from end-devices. Routers can be connected to end-devices in any level of the hierarchy, except the coordinator itself. Even though only four levels of the hierarchy (coordinator, level-1 and level-2 routers, and end device) have been considered in our implementation, the proposed protocol can be extended to a higher number of hierarchical levels, if necessary.

![Figure 1. Network topology](image)

The coordinator node concentrates the data from the whole network and sends them to the central station by means of a gateway with IP interfaces (Ethernet and GPRS/GSM). A network can contain up to 256 routers (regardless the gateway with IP interfaces (Ethernet and GPRS/GSM). A network and sends them to the central station by means of a communication link bandwidth. The time between beacons is divided into slots, which can be occupied by superframes (Fig. 3). These are arranged so that a fixed number of them are assigned to the coordinator, another set of slots are assigned to level-1 routers, and so on.

The superframe of a router contains a fixed number of slots, which are dynamically assigned to its end-devices depending on their communication needs (Fig. 4). To manage this dynamic assignment there are some reserved bits in every superframe, which are used to signal the communication needs of the router node and of its end devices.

This information is taken into account for the slot assignment in next superframe. Note that, in any case, every end-device and router has a minimum number of slots periodically reserved to send a “keep alive” signal in order to guarantee the consistency of the network. This dynamic assignment also guarantees a near-optimal use of the communication link bandwidth.

<table>
<thead>
<tr>
<th>BIT no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>1-level Router</td>
<td>2-level Router</td>
<td>End-device</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

![Figure 2. Network addressing](image)

The hierarchical structure allows easy addressing of every node in the network (Fig. 2), which facilitates routing algorithms.

### B. Network design

The proposed network uses the beacon scheme of IEEE 802.15.4 for synchronization and data transmission. The time between beacons is divided into slots, which can be occupied by superframes (Fig. 3). These are arranged so that a fixed number of them are assigned to the coordinator, another set of slots are assigned to level-1 routers, and so on.

The superframe of a router contains a fixed number of slots, which are dynamically assigned to its end-devices depending on their communication needs (Fig. 4). To manage this dynamic assignment there are some reserved bits in every superframe, which are used to signal the communication needs of the router node and of its end devices.

This information is taken into account for the slot assignment in next superframe. Note that, in any case, every end-device and router has a minimum number of slots periodically reserved to send a “keep alive” signal in order to guarantee the consistency of the network. This dynamic assignment also guarantees a near-optimal use of the communication link bandwidth.

![Figure 3. Structure of Superframes (an example)](image)
Just in the beginning of a superframe there is a slot reserved for alarms. In this way, critical situations can be rapidly signaled bypassing the conventional way of reserving regular slots in the next superframe. As this special slot is not pre-assigned, a contention can occur when several nodes try to use it. Then, this mechanism of alarm generation has to be reserved to very exceptional cases.

Some mechanisms have been implemented to guarantee a certain number of attempts of re-connection after a failure. Simple procedures have also been implemented to allow new end-devices or routers to enter or leave the network, which are not described here for the sake of space.

The security mechanism of IEEE 802.15.4 has been implemented in the lower levels of the protocol.

Every single network parameter (time inter beacons, number of hierarchical levels, number of nodes in every level of hierarchy, number of superframes, number of slots per superframe, etc.) is defined by the user in configuration time, previous to the network creation.

C. Synchronization

The requirements of autonomy forces both, routers and end-devices, to remain in ultra-low power SLEEP mode most of their operation time. Precise synchronization is required to guarantee that the nodes awake just when they are required to communicate.

An adaptive clock synchronization scheme has been implemented, which automatically corrects any clock deviation with respect to the coordinator clock, which is taken as the network reference. This mechanism uses the beacon timing to adjust the internal clocks.

D. Message Type

Two types of messages (Data and Network Management messages) are distinguished. Data Messages can use large or short addresses, according to the IEEE 802.15.4 protocol. Network Management type messages manage association and re-association requests and other kind of messages required for network formation and management.

Note that the communication is bidirectional, so that the coordinator can send data or commands to routers and end devices, if required.

E. Installation Mode

When the network starts up, for the first time, a specific installation mode has been considered to speed up the network formation process. This installation mode is managed from the coordinator, and, in this mode, the coordinator and every router in the network is maintained awaken. Note that the installation mode cannot take a long time to avoid excessive discharge of batteries.

In installation mode every end-device sends a broadcast message with information about its characteristics and waits for an answer from coordinator and routers. Once this information has been collected, the end-device selects its router according to a set of parameters, which have been discussed above, and issues an association request. If the association is not successful, the end-device selects the next candidate and the process is repeated until the network has been set up.

F. Over-The-Air software Update (OTAU)

A new mode for on-the-air software update has been included. Presently it requires the nodes of the network to remain active until the update finishes, although a new version where the update is done without interrupting normal network operation is being developed.

These procedures are not described here for the sake of space.

III. HARDWARE DESIGN

Every single node (coordinator, router or end-device) uses the same communication hardware (Figures 5 and 7a). The transceiver AT86RF212 and the microprocessor ATXMEGA256A3, both from ATME, are used to build the communication module. ATME also provides an IEEE 802.15.4 stack for this arrangement.

To increase receiver sensitivity, a LNA is placed at the reception input of the transceiver. In addition, the transceiver has a poor linearity for high power output, which prevents the node from being used in the maximum power output level in the 868 MHz band. To overcome this problem a linear amplifier has been placed at the transceiver output. To minimize the number of components and to reduce total cost, the same device has been selected to act as LNA and power

6002
amplifier, and a set of RF switches select the proper signal path in reception and transmission.

![Figure 5. Block diagram of the communication block](image)

The communication hardware is completed with some circuitry to manage power consumption, a PCB antenna, external memory and a real time clock, which also acts as a watch-dog. The PCB antenna is optional and it is usually reserved to end-devices (Fig. 7b) where the unitary cost is a key factor due to the large number of end-devices in the network.

End-devices have attached a small PCB with the meter reader. There are presently two different boards. The first one drives the UNE 82326 bus for electronic water meters. The second one drives a standard serial bus. Specific readers for mechanical meter, reed relay and inductive reading have been developed which are connected to the end-device using the extended serial bus. These readers are low-cost and autonomous. Up to 50 meters can be connected in both, the UNE 82326 and the serial bus.

Figure 7c shows the coordinator node attached to an ARTILA M508T board which acts as a gateway providing connectivity to the IP network, either by cable (Ethernet or fiber) or wireless (GPRS/GSM)

![Figure 7. Hardware design; a) Communication module, b) End-device including meter reader and battery, and c) Coordinator node inserted in the gateway](image)

The gateway stores the data coming from the readers in internal non-volatile memory, which is remotely accessed by means of an embedded data base server. Old data are stored in a SD card for a certain period of time, and finally removed to avoid memory overrun.

IV. EXPERIMENTAL RESULTS

The RF block has been exhaustively tested in 868 and 915 MHz bands. The designed module meets the specifications for interferences, and the transmission masks specified by the IEEE 802.15.4 standard in the maximum output power level.

![Figure 6. Coverage tests (Cartuja Island, Seville)](image)

Coverage tests have been also carried out using the designed module with and without power amplifier. Figure 6 shows the layout of the test points of one of the coverage tests carried out in the facilities of the School of Engineering, University of Seville, located in the Cartuja 93 Technological Park in Seville. This zone is located in the middle of the right side of the aerial photograph shown in Fig. 10. The transmitter node is located in position labeled “0” at two distances from the ground: 2 and 4 meters. The receiver node is moved from one location to another inside a water register made of concrete, as it is the normal location for end-devices.
As expected, the RSSI improves when the power amplifier is ON. In every case the received signal was strong enough for a proper signal demodulation.

These results correspond to the European ISM band with 868.3 MHz carrier frequency, 600 kHz signal bandwidth and 20 kbps BPSK modulation. Other coverage tests have been done in open space, where line of sight links with more than 600 m have been proven to be stable with the power amplifier on. Similar tests have also been carried out in the 915 MHz band, and for other modulation schemes supported by the transceiver with excellent results.

Concerning power consumption, Table I shows a summary of the power consumed by every type of node in extreme conditions.

V. A PILOT DEPLOYMENT

To test the performances of the AMR system, a network has been deployed with 4 level-1 routers, 8 level-2 routers, and 160 end-devices, with a total of 450 water meters (electronic type connected by bus UNE 82326) and other 550 simulated water meters, to attain a total number of 1,000 meters. Most of the end terminals have only a few of water meters, but some end-devices were connected to a maximum of 50 meters. Fig. 9 shows some of the water meter banks used in the experiment.

![Figure 9. Some of the water meters banks used in the pilot](image)

Fig. 8 shows the test results in terms of the RSSI (Received Signal Strength Indicator). Note that, in some locations, especially those labeled 19 and 20, the signal has to travel through several buildings made of concrete.

![Figure 8. Coverage tests. RSSI is in dBm for different configurations of the transmitter node (PCB/Dipole Antenna, with/without power Amplifier). The Receiver is inside a register made of concrete with a PCB antenna and its LNA is activated.](image)

Table 1. Node consumption including electronic meter reading using bus UNE 82326.

<table>
<thead>
<tr>
<th></th>
<th>End Device</th>
<th>Level-2 Router</th>
<th>Level-1 Router &amp; Coordin.</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDD (V)</td>
<td>3.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission (mA)</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reception (mA)</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep (µA)</td>
<td>13</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Max consumption</td>
<td>160</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(reading 40 meters)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery type for 10</td>
<td>17 Ah</td>
<td>17 Ah</td>
<td>34 Ah</td>
</tr>
<tr>
<td>years autonomy</td>
<td>(for 50</td>
<td>(3000 meters)</td>
<td>(3000 meters)</td>
</tr>
<tr>
<td>meters, hourly</td>
<td>reading)</td>
<td></td>
<td></td>
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</table>

As expected, the RSSI improves when the power amplifier is ON. In every case the received signal was strong enough for a proper signal demodulation.

The pilot covers a wide area in the Cartuja93 Technological Park in Seville (Fig. 10). The largest distance between elements is between the coordinator and one of the level-1 routers located more than 500 m far away. Some of the links go through several buildings. The green marks labeled “End Device” represent a bank of end-devices.

This pilot was started in March 2012, and a negligible rate of communication failures has been reported up to now. All of them were properly fixed by the automatic mechanisms of reconnection, which are part of the protocol.

VI. CONCLUSIONS

A new AMR system has been presented for the reading of meters without a power source, as it is the case for water and gas. A protocol has been defined based on the IEEE 802.15.4 standard.

A tree topology has been chosen with variable number of routing levels. In our implementation two levels of routers has been chosen. Due to hardware limitations, every network is limited to a maximum of 512 end devices and a maximum of 4096 remote meters, every end-device being able to read up to 50 meters connected to a bus.
The hardware implementation for the 868 MHz and the 915 MHz bands have been done, achieving the maximum power level considered in the standard with a high linearity thanks to a linear power amplifier which can be also used as LNA in reception. Power consumption is very low which guarantees autonomous operation of end-devices and routers with low-cost batteries. A demonstration pilot has been deployed in the Cartuja Island in Seville with 160 end devices and 1,000 meters.

Compared to other AMR systems published in the literature, including market products, the proposed AMR system exhibits the following performances:

- A large number or meters per network (up to 4096)
- A large autonomy of every single node (end-devices and routers) without maintenance (10 years typically)
- Automatic adaptation to local environment, as the network itself selects the best configuration in the installation mode.
- High metering rate and guaranteed latency thanks to a synchronization process based on beaconing.
- Bidirectional networks which are able to read meters and to send commands to end-devices and routers.
- Reliable and effective network management

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