Wireless Automatic Water-meter Reading System

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Abstract – Wireless automatic meter reading (AMR) system based on a fixed radio network brings many advantages when compared to other meter reading techniques. After an introduction to the state of the art of AMR systems in general, and particularly of water meter reading system, a wireless automatic water-meter reading system founded on ZigBee technology is presented. Set forth in the text are main characteristics of this low cost and low power system. The benefits of imlementing ZigBee protocol as the solution for the imposed requirements are rather thoroughly discussed, mainly in the aspect of network configuration as the basis for robust data transmission, wide area signal coverage and lowering devices' power consumption.

I. Introduction

There are three key elements in an automatic meter reading (AMR) system: consumption measurement, meter reading and data transmission, and data processing and billing [1]. An AMR system has to be cost-effective. That means reducing the costs of implementation, maintenance, while providing robust and reliable performance. On top of that, the relationship between the customer and the supplier must be considered.

Primary technologies associated with AMR systems are: inductive meter reading, walk-by meter reading, fixed wire network and fixed radio network (wireless sensor network). Researches have shown that, on cost grounds alone, the fixed radio network reading cost per meter is significantly lower than with other technologies. Fixed radio technology is especially suited for densely populated areas [1].

Wireless sensor networks bring advantages in the form of lowering the cost of sensor installation. Lowering the cost is achieved by avoiding the need for cabling, materials and testing which all raise the costs of labour. Secondly, 'the last meter connectivity problem' – cable connectors getting loose, lost, misconnected or broken - is no longer an issue [2].

When it comes to water consumption management, there are certain issues that need to be considered: infrastructure and architecture costs, the costs of moving from manual (or other) meter reading technology to wireless AMR, the ability that AMR provides to reduce meter reading costs, better demand management and leakage detection. The environmental issues also have to be taken into appreciation. Water scarcity due to lack of natural spring water, advancing pollution etc. is one of the major environmental issues. The water consumption has to be controlled on global and local basis. In Croatia, currently, the most of consumers living in buildings pay water bills irrespective of the consumption. Water consumption is registered, in most cases, by a single meter per whole building. The building's consumption bill is shared among occupants. Often is the case that someone consumes water very irrationally and the others 'pay his bill'. A pilot project showed greatly lowered consumption when water meters were installed in every apartment, so every consumer paid the charge only for his own consumption.

Wireless automatic meter reading system presented in this text - comprised of water-meters with ZigBee radio on one side and database management system on the other side - takes into account all of the previously mentioned issues. Therewithal, certain specific demands and constraints have to be taken into consideration to provide an effective solution both for the consumer and the supplier, including long battery lifetime, signal range, packet latency, ease of installation and maintenance. The benefits of using ZigBee technology in development of the wireless automatic water-meter reading system set forth in further text concern the very same issues: battery lifetime is extended using well defined beacon timings, wider range is gained with the appropriate network topology, the network parameters are adequately preset to avoid greater depths and high packet latency, and last but not least, the ease of installation and maintenance is achieved by avoiding cabling and by applying algorithms for quick error spotting and debugging.

II. ZigBee technology

ZigBee technology is a low data rate, low power consumption, low cost, wireless networking protocol targeted towards automation and remote control applications [3]. It operates on a total of 27 channels across the three frequency bands specified: 1 channel in the 868MHz band (Europe), 10 channels in the 915MHz band (North and South America), and 16 channels in the 2.4GHz band (used worldwide). The data rate is 250kbps at 2.4GHz, 40kbps at 915MHz and 20kbps at 868MHz [2]. The ZigBee stack architecture is made up of a set of block called layers, based on the Open Systems Interconnecting (OSI) seven-layer model. The ZigBee network layer (NWK) supports star, tree and mesh topologies [4]. The tree topology is used as the most appropriate in development of the wireless automatic water-meter reading system, taking into consideration all the requirements set before it, including long battery lifetime, time synchronization, latency and range.

III. ZigBee technology as the basis of wireless AMR system

Main part of the wireless AMR system (Fig. 1) is ZigBee network, comprised of water-meter units with radio and the coordinator. All devices are full functional devices (FFD) and they operate at 2.4GHz. Each node acts as a router, forming all together the tree network. The network is beacon-enabled. The coordinator is the originator of beacon packets. Other routers synchronize with those beacons. Most of the time the devices spend in sleep mode (LPM). After a certain time interval elapses, a router wakes up and tries to synchronize with its parent's beacon. While a device is in the active mode of operation, it sends a readout if requested by the coordinator. Active mode duration can be adjusted to gain a certain duty cycle, so that battery lifetime could reach as much as ten years.
The coordinator serves also as a data collector. The coordinator receives readout requests from the user through GSM module. The list of tasks is kept within the coordinator. The data collected from the WMUs is saved in EEPROM and sent forward to database unit when requested.

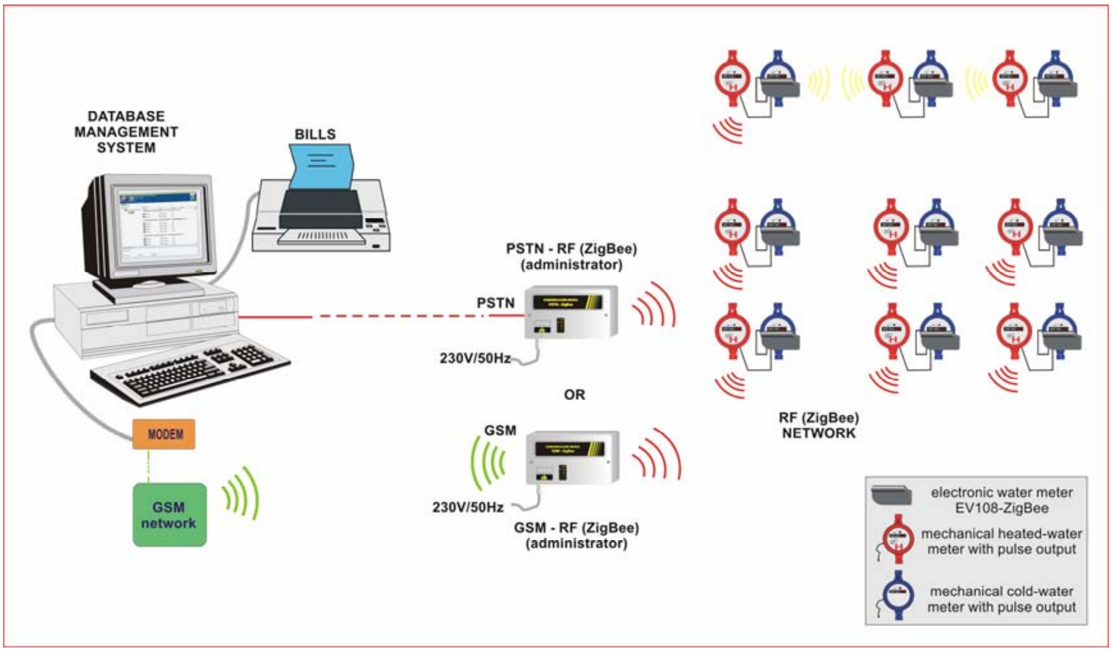

Fig.1. Wireless automatic water-meter reading system

A. Water Metering Unit (WMU)

The basic unit of the whole system is water-metering unit with ZigBee radio. It consists of the mechanical sensor with pulse output, the MCU and 2.4GHz transceiver, as depicted in Fig. 2. The MCU is Texas Instruments MSP430F1611 and the transceiver is Chipcon CC2420. The water flow is detected with a mechanical water meter connected to an active sensor. The detection principle is the change of induction, which enables the unit to function also in flooded pits. Because of the specially designed sensing part of the meter, no magnetic tampering is possible and the meter can safely operate in harsh environments. The output pulses from the sensor are registered in the MCU and the total consumption is periodically saved in the EEPROM. Typically, there are two mechanical meters connected to one MCU: one for cold and one for heated water. That, however, depends only on the watering infrastructure in a building. Another important feature of the WMU is the battery voltage level monitoring. If the battery voltage falls below a certain value, special status packet is sent to the coordinator. Beside that, voltage level is the part of every WMU's readout.

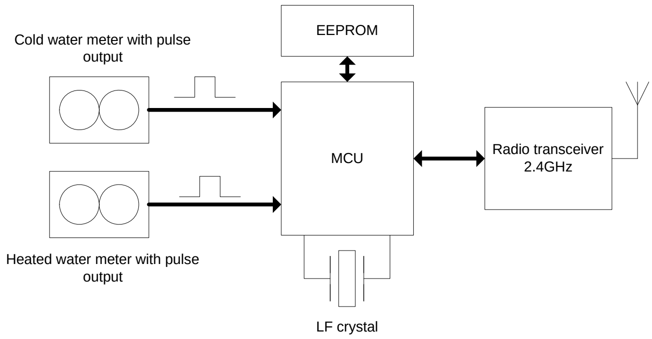

Fig.2. Schematic diagram of WMU

B. Data collector

Data collector unit (Fig. 3) consists of the MCU (TI MSP430F1612) with external EEPROM and ZigBee transceiver CC2420 comprising the coordinator, and GSM module.
The coordinator is the only device in the network that is always 'on' (mains powered). It is responsible for network initialisation, time synchronization of all devices in the network, and for parsing and sending readout requests to the WMUs and sending readouts back to the GSM module. It also keeps and updates the routing table, where each entry contains individual node's specific data. The coordinator receives requests from the user through GSM module and keeps the track of received readouts afterwards.

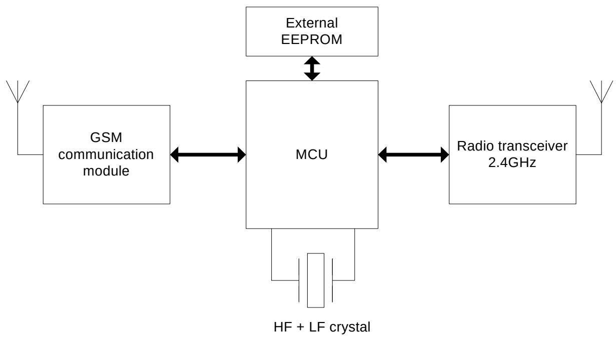

Fig.3. Schematic of data collector

C. Network configuration

The system is comprised of a coordinator and ‘children’ nodes acting as routers, forming altogether the tree ZigBee network. The coordinator is responsible for network formation. It starts sending beacon packets and associates new devices to the network. Network topology is set by defining certain network configuration parameters: the maximum depth of the network (the distance in number of hops between the coordinator and the most far away node), the maximum number of children nodes per router (a router is allowed to associate to the network) and the maximum number of children routers per router (ZigBee router routes messages to its children nodes, in contrast to ZigBee end device which can only communicate with its parent). All devices are full function devices, so currently active configuration can change if needed in the case a node malfunctions. The exact structure of the system network cannot be pre-determined due to variable dependencies such as location of devices on the spot and radio propagation during network formation. The redundancy in values of the formerly mentioned parameters has to be such that on-the-spot problems could efficiently become bridged over during system installation.

The network formation process also provides a routing algorithm called ‘tree routing’. The ‘Cskip’ address allocation algorithm provides address ranges that allow any device to quickly identify whether a particular network address belongs to a descendant of that device (and through which of its children), or elsewhere in the device tree [5]. As a result, any device could make simple routing decisions based on passing a packet up or down the device tree. The most significant benefit with tree routing is its simplicity and its limited use of resources: simplicity in making a route decisions (by looking at the destination address) and the lack of the need for memory resources to store routing information. According to ZigBee protocol all communication after joining the network is made on a short 16-bit network address, instead of the extended 64-bit MAC (medium access) layer address. In order to extend battery life, short 16-bit addresses are used to shorten the packet sizes and hence the time a device is actively communicating. The extended 64-bit address is used during the association message exchange when a newly associated device gets assigned a short 16-bit network address.
Another advantage of the tree network is wide area of signal coverage. If network parameters are adequately preset, signal path can be extended to reach the far-most device (with the greatest depth). Although that means increasing the number of hops, the packet latency is not an issue here, because the devices’ readouts are not expected to perform in real time, yet on the monthly basis.
While considering packet routing and transmission robustness, the mesh topology comes in first place. However, to establish a proper mesh network, the devices should always be alert and expecting a packet. That brings forth the power consumption issue. Should a device always be in active mode with its radio receiver active, this would lead to significantly increased power consumption and the need for mains powered device. However, because of the safety reasons in the first place and also to avoid cabling and repeated battery replacement, the WMUs not only have to be battery powered, but also have to guarantee the battery lifetime extended to a few years term. Beacon enabled network gives the devices the opportunity to spend the most of the time in a low power mode. A device wakes from low power for a short while and tracks the synchronization beacon and eventual request from its parent. It re-sends then a beacon, so its children could also synchronize. If a device receives a data or command packet from its parent, it decides upon the route based on the simple tree routing algorithm: if a packet is destined for its child node, the device routes the packet to the child; if a packet is destined for itself, it processes it; if a packet is destined neither to itself, neither to any of its child nodes, the packet is then disregarded by the device. On the other side, if a packet comes from one of its child nodes (and is not destined for itself), the device sends the packet to its parent. In that way the tree network with the use of tree routing algorithm and beacon synchronization make the devices able to accomplish low power implementation demands.

D. Low power consumption

All devices except the network coordinator are battery powered. To extend battery lifetime the devices spend the most of the time in sleep mode. In sleep mode the transceiver is off and the MCU is in LPM3 (low power mode 3). In LPM3 the CPU is off, main clock is disabled and LF auxiliary clock stays enabled, so the MCU consumes up to max. 5 μA [6]. Active mode duration is significantly shorter than of sleep mode, so duty cycle of about 900ppm is achieved. The use of beacons with the longest beacon interval (BI = 251.65824s) and short active mode time (250ms) leads to very low power consumption, although during the active mode the consumption increases significantly due to transceiver receive and transmit circuits' activity (Tx~17.4mA, Rx~19.7mA) [7]. Active mode time is comprised of transceiver warm up time, the beacon uncertainty time and the time a node takes to route the beacon and requests to (or from) its child nodes. Since all types of batteries exhibit a recovery effect, in which their lifetimes may be extended if current is drawn from them in bursts, rather than an equivalent average current, the goal is to shorten the bursts [8]. The optimisation of the active mode duration should extend battery life to at least 10 years.

E. Time base accuracy

Network synchronization is gained with beacons (Fig. 4). Superframe specification field of a beacon frame carries crucial timing information used for synchronization [9].
Beacon interval is usually set once, during network configuration. However, it can be changed if requested. If a device loses synchronization, it will try to re-associate with its parent. If that doesn't work out, the device will try to synchronize to one of its neighbour device's beacon. The coordinator updates the routing table each time a device is associated or disassociated to the network.

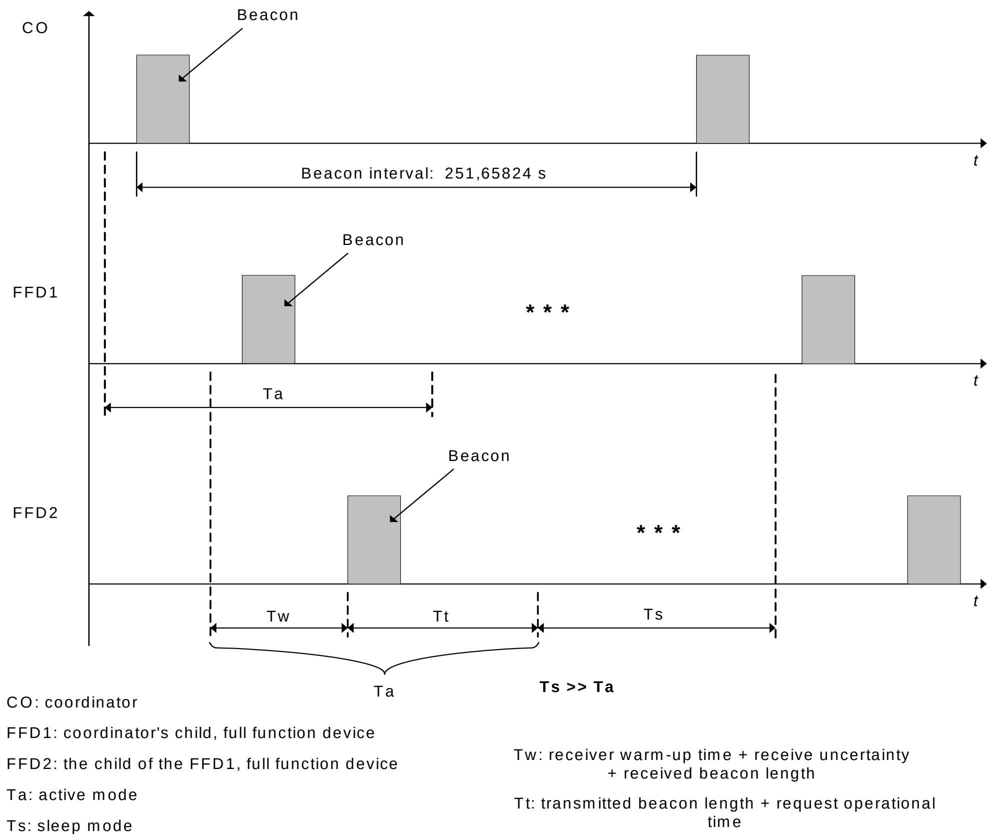

Fig.4. Beacon synchronization

The use of beacons imposes a reliable time base issue. To receive a scheduled transmission, the receiver must be 'on' at the appointed time. However, the receiver's time base is of finite accuracy. The resulting time uncertainty forces the receiver to turn on early enough, in order to avoid missing the desired transmission. Extending active mode duration, yet, leads to higher power consumption. To compensate timing uncertainty the learning algorithm is employed [8]. Algorithm tracks the apparent time offset at the receiver, then starts the receiver warm up certain time earlier to provide some margin for error.

Temperature instability of a time base might also cause large timing errors. The HF and LF oscillator circuits have to be suitably designed to prevent time base instability. To mitigate time base error, frequency calibration is performed using special software algorithm.

F. Range

For the 2.4GHz band, the receiver must exhibit the sensitivity of –85dBm and for a transmitter rated at 0 dBm, calculations show a maximum theoretical free space range of approximately 220 meters [2]. In real environments is the range somewhat decreased, especially in an indoor application. The range increases if a transmitter's output power is higher. The upper output power limits are designated by the local regulatory agencies.

The network topology proposed in this system provides short-range compensation by appropriate management of the network parameters: the depth, the number of routers and the number of children per node. In that way, all nodes can be reached, although through higher number of hops. The latency is greater when the packet is routed through more hop devices, but it doesn't essentially impair system performance.

IV. Conclusion

As presented in this paper, the ZigBee technology can improve an automatic meter reading system due to its unique features. Low cost, low data rate and low power consumption are the characteristics, which correspond to the requirements imposed on the design of a water meter reading system. The wireless automatic water-meter reading system presented here uses ZigBee networking to avoid difficulties and problems inherent to other meter reading techniques [1]. No cabling and no (not so frequent) manual readouts lower the reading costs and suit both, the supplier - better consumption and leakage control, readings are done from the office, and the consumer - lower bills and better control over his own consumption. For the implementer there are a few aspects that have to be carefully considered when developing such system including printed circuit board layout, time base circuitry and battery power source, to gain an effective and reliable application. Whilst in other kind of application e.g. wireless watt-hour meter reading system [3], or [10] the mains powered devices allow greater flexibility when determining the topology and overall functioning, in the wireless water-meter reading system there are constraints that need to be carefully considered. ZigBee technology, however, enables bypassing these constraints, providing the system with low power battery operational devices, with the best suited, yet simple, network topology and with the reliable and secure data transmission channels. In the text presented AMR system ensures longer battery life in the way that higher power consuming mode of operation lasts as short as possible, but long enough for a device to carry out all required packet exchanging. Most of the time a device spends in low power mode (LPM). The ratio of low power mode (~250ms) and high power mode (251,65824s) gives the duty cycle of about 990ppm. When taking into account LPM consumption of ~ 6μA, ~20mA in active mode and a battery of 2400mAh capacity, the battery life could be extended even up to 10 years.

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