A Novel Automatic Utility Data Collection System using IEEE 802.15.4-Compliant Wireless Mesh Networks

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Abstract

In this paper, we propose a novel Automatic Meter Reading (AMR) system using the IEEE 802.15.4-compliant wireless networks. The mesh network based automatic utility data collection system (AUDCS) provides a cost-efficient solution by exploring the self-organization, self-healing capabilities of the mesh networks and utilizing the state-of-art semiconductor chips and the radio transceivers compliant with IEEE 802.15.4 standard. An IEEE 802.15.4 network may operate in either the star topology or the peer-to-peer topology. The peer-to-peer mode is chosen for the AUDCS system, as it is more flexible and robust than the centralized implementation based on the star topology. In the AUDCS system, each node has the capability of two-way communications and may relay or forward the data for the neighboring nodes within the transmit range, hence eliminating the need of installing dedicated communication nodes to collect data. In addition, mesh networking provides the self-healing function by automatically re-routing via other neighboring nodes. The application data characteristics are exploited in the data gathering and dissemination to achieve better energy efficiency. Experimental results of the prototype test-bed will be presented and discussed.

Introduction

Automatic Meter Reading (AMR) is an electronics system that provides functionalities of remote meter reading of usage rate of electricity, gas, water and generates billing to charge customers according to supplied amounts for energy suppliers. Utility service providers are increasingly interested in taking the advantages of AMR [1-4]. The majority of the current AMR is implemented by collecting data walk-by or drive-by, which limits the additional services to be added. With the rapid advancement in semiconductor and communication technology, it is possible and feasible to have a metering network to gather data remotely and efficiently. Most recently, smart meter reading using Zigbee Technology has drawn much attention [5-7]. Smart metering via an advanced metering infrastructure (AMI) has been a hot trend in the utility industry because of the promises of AMI technologies in enhanced customer service and greater energy efficiencies [6]. This not only benefits the utility company, it also allows the customer to monitor their daily energy usage and to optimize their energy usage.

In the AMR systems the collected data can be transmitted through power line carrier (PLC), the existing wired Internet infrastructure, and RF wireless communications [2, 3]. The PLC communication system uses a built-in power modem that receives and transmits data over the power lines. The carrier can communicate voice and data by superimposing an analog signal over the standard 50 or 60 Hz alternating current (AC). The PLC method is good for low-density scenarios, such as at rural areas. The utility company may also uses the existing Internet network to communicate to the meter, by either making use of the consumer's personal computer modem or integrating a modem to the metering system. The utility company will dial the modem to start transferring data. The shortcoming of this method is that the existing Internet service has to be available.

In comparison with the PLC and wired Internet, wireless communications have the advantages of cable free, easy, flexible installation and maintenance. One commonly used method is to use the existing cellular network. For example, GSM (Global System for Mobile communications) systems support Short Message Service (SMS) [2, 8] for data transmission from the meters. The meters are either built with an SMS network interface or connected to a local area network, which uses a communication gateway to access the cellular network, as shown in Figure 1. This method requires the availability of the digital cellular SMS service. The SMS interface module is also relatively expensive. Another restriction is that you have to subscribe the SMS service from the wireless company, which adds extra cost and may prevent the system from real-time monitoring. Alternatively, we propose a wireless mesh network based AMR system that is more cost-efficient and able to collect real-time data.

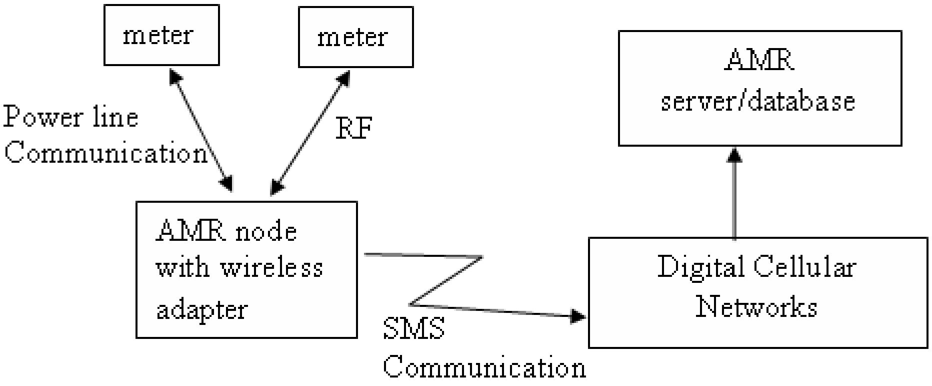

Figure 1. AMR system using cellular networks

Automatic utility data collection system using mesh networks

In this paper, we propose an automatic real-time utility data collection system using wireless mesh networks (AUDCS-mesh). The proposed system utilizes the two-way communication between AMR nodes to forward the readings back to a collection center or AMR server in a mesh network. Due to the fact that the meters at residential area are not far away from each other, each AMR node is able to relay or forward the data for its neighboring nodes to the direction of the collection center via short-range wireless communication. Data will eventually reach the collection center. The system will not be limited by the service availability of the cellular networks. The conceptual system design is illustrated in Figure 2.

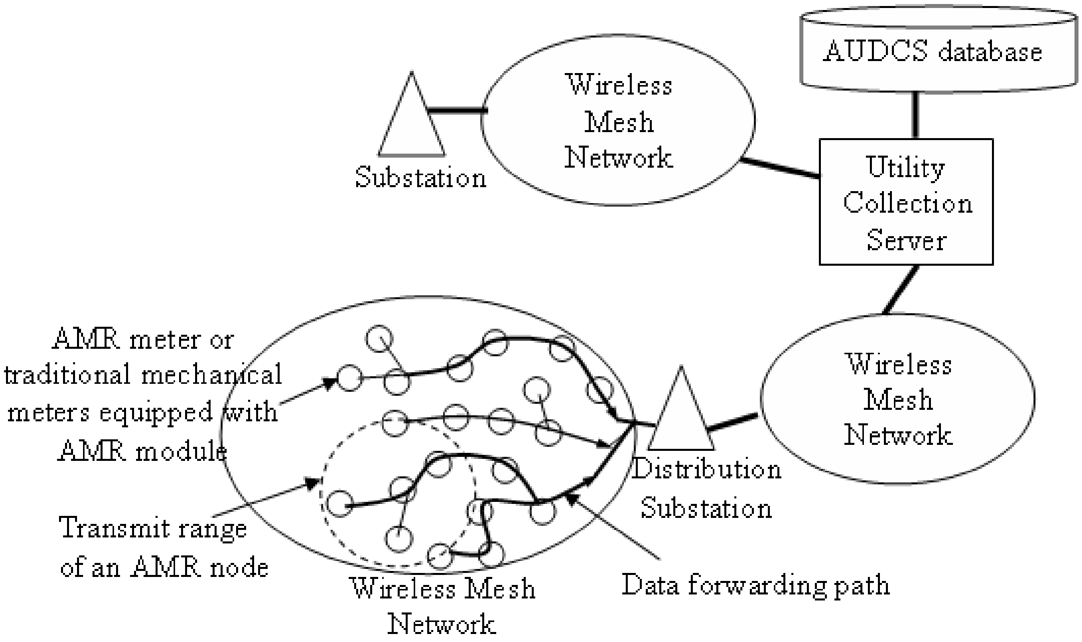

Figure 2. System architecture of the AUDCS mesh network

The ad-hoc communication mode will be utilized in the self-organizing AUDCS mesh networks. Unlike the other centralized implementation, the mesh network implementation is more flexible and robust [9, 10]. In this system, each node has the capability of two-way communications and can forward the data for the neighboring nodes within the transmit range. It eliminates the installation of dedicated communication nodes to collect data. The self-organization feature means AMR nodes will become connected and start to collect data without human intervention once they are deployed. Each node selects appropriate relay neighbors based on specified criteria.

In addition, mesh networking also provides the self-healing function by automatically re-routing via other neighboring node. For the centralized approach, once a specific communication node fails, such as the AMR node equipped with wireless adapter, all the nodes belonging to this cluster will not be able to transmit meter readings back to the collection center. Figure 3 illustrated the self-healing capability of mesh networks. In Figure 3-(a), the data of end node 1 are transmitted back to the collection center via the route 1-2-3-4-5; when some node fails (here assuming node 3, as shown in Figure 3-(b)), then the communication links associated with node 3 cannot be used any more, and the data from node 1 will be automatically rerouted back to the collection center via another path 1-6-7-8-5.

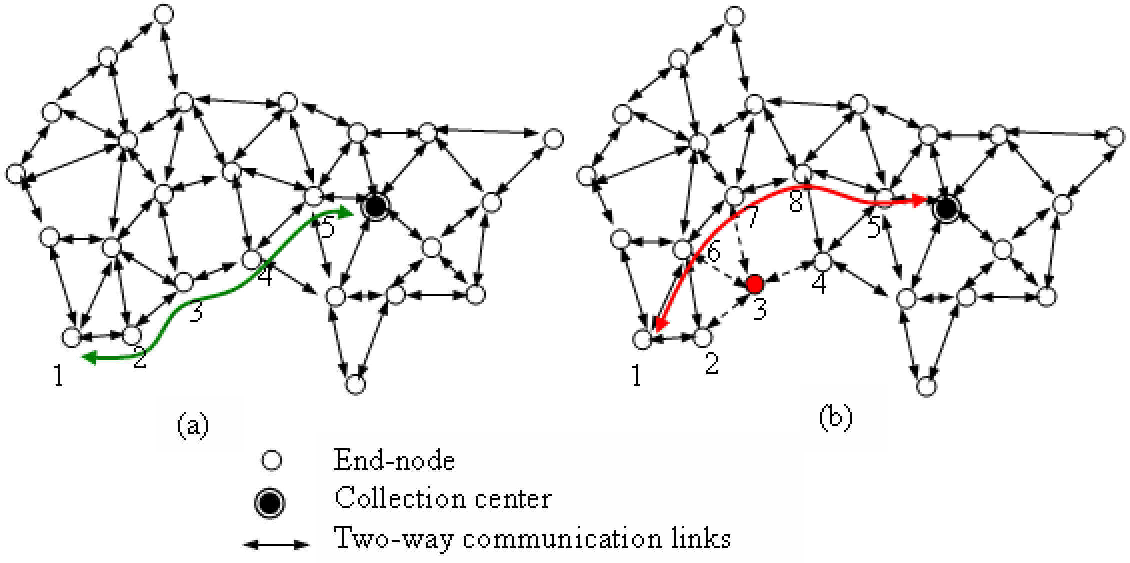

Figure 3. Self-organized and self-healing mesh networks

An initial system with five prototype nodes has been tested in the laboratory. The AMR module prototype adopts the IEEE 802.15.4 compliant transceivers and ZigBee stacks. Before we continue to explain the implemented system, we will have a brief introduction of IEEE 802.15.4 standard and ZigBee protocol stacks.

IEEE 802.15.4 standard and ZigBee

IEEE 802.15.4 standard defines the protocol and interconnection of devices via radio communication in a personal area network (PAN) [11]. It operates in the ISM (Industrial, Science and Medical) radio bands, at 868 MHz in Europe, 915 MHz in the USA and 2.4 GHz worldwide. The purpose is to provide a standard for ultra-low complexity, ultra-low cost, ultra-low power consumption and low data rate wireless connectivity among inexpensive devices [11]. The standard uses carrier sense multiple access with a collision avoidance medium access mechanism and supports star as well as peer-to-peer topologies. The media access is contention-based and it is possible to allocate time slots by PAN coordinator to devices with time critical data. The maximum raw data rate is 250 kilo-bits per second (kbps), which can satisfy various industry control and automation needs for wireless communications. The data rate may be scalable down to the needs of sensors to 20kbps with extended transmission range.

While IEEE 802.15.4 standard specifies the physical layer and media access control protocols, the upper layers protocols are not covered. ZigBee Alliance [12] is an organization of industrial companies that promote IEEE 802.15.4 standard based technologies. It publishes specification set of high level protocols based on the IEEE 802.15.4 standard (2003). ZigBee technology may be used in various applications in industrial controls, embedded sensors, medical devices, smoke and intruder alarms, building and home automation and others. The network is designed to use very small amounts of power, so that individual devices might run for one year or more with a single alkaline battery. They may use a mesh or star topology that allows low power consumption over the sensor network. Based on these features provided by IEEE 802.15.4/ZigBee, the ZigBee technology is very suitable for our application.

Hardware design and implementation

In order to implement the mesh network, the existing electromechanical meters or the mechanical gas/water meters have to be modified or provide related data for AMR. The traditional meters may be attached with a retrofit module that is capable to convert meter readings to digital signals and transmit the data back to collection centers. The main components are illustrated in Figure 4. A disk-type electrometrical meter includes a mechanical counter and a gear assembly and the number of the disk revolution per KWh is fixed for a meter. To get the reading from the dial-meter, we can count the revolution of the disk with the help of a sensor. Possible solutions are using Hall-effect sensors/switches, or opto-electronic sensors to generate a pulse for each disk cycle. The pulse is further counted and converted to digital signals by the microcontroller. A microprocessor is needed to process the data and a radio module for wireless communications.

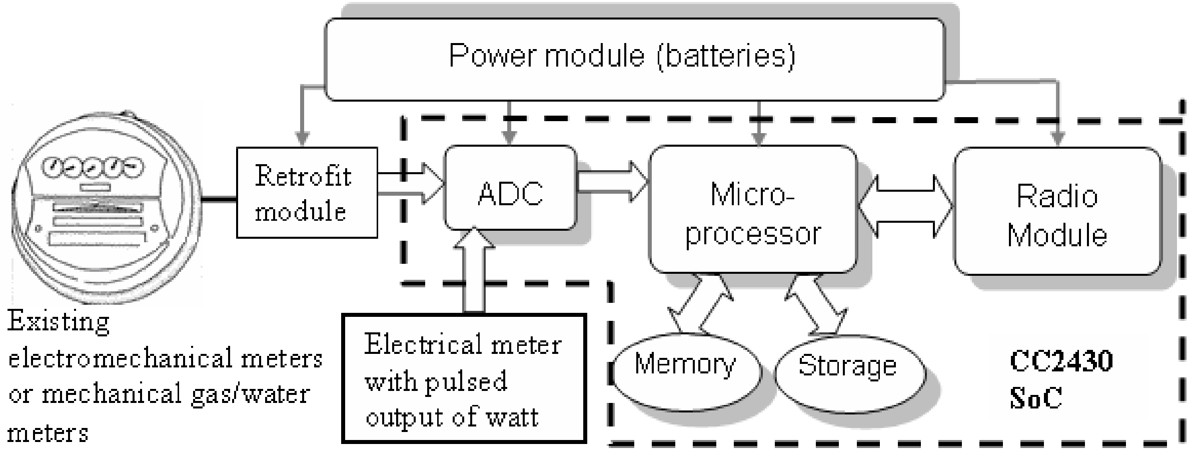

Figure 4. AMR end node architecture

The widely used diaphragm gas meter and the nutating disc water meter can also utilize the same mechanism to obtain the readings. As we can see from figure 4, several meters located at the same location may be connected to the one AMR module so that cost may be further reduced. In order to achieve our design objectives, up-to-date low-cost, ultra-low power consumption ICs and the IEEE 802.15.4-compliant radio transceivers will be considered.

In our prototype design, we adopt the IEEE 802.15.4 standard compliant transceiver CC2430 from Texas Instruments [13]. CC2430 provided a system-on-chip (SoC) solution for 2.4GHz IEEE802.15.4/Zigbee. It combines the excellent performance of the leading CC2420 RF transceiver with an industry-standard enhanced 8051 microcontroller (MCU), with 128 KB flash memory and 8 KB RAM. Both the embedded 8051 MCU and the radio components have very low power consumption, as shown in Table 1. The CC2430 also includes digital RSSI/LQI (Receive Signal Strength Indicator/Link Quality Indication) support and 12-bit ADC (Analog-to-Digital Converter) with up to eight inputs and configurable resolution. Two

Table 1 Power consumption of CC2430EM reference design with V_{DD} = 3.0V and 25^{o}C[13]

Operation mode	Typical current consumption	Condition
MCU Active, 16 MHz, low MCU activity	4.3 mA	Digital regulator on. 16 MHz clock running. No radio, crystals, or peripherals active. Low MCU activity: no flash access (i.e. only cache hit), no RAM access
MCU Active, 32 MHz, medium MCU activity	10.5 mA	32 MHz clock running. No radio or peripherals active. Medium MCU activity: normal flash access, RAM access
MCU Active and receive Mode	26.7 mA	MCU running at full speed (32MHz), 32MHz clock running, radio in receive mode, -50 dBm input power. No peripherals active. Low MCU activity.
MCU Active and transmit Mode, 0dBm	26.9 mA	MCU running at full speed (32MHz), 32MHz clock running, and radio in transmit mode, 0dBm output power. No peripherals active. Low MCU activity.
Power mode 1 .	190 µA	Digital regulator on, 16 MHz oscillator and 32 MHz crystal oscillator off. 32.768 kHz oscillator, Power on Reset and sleep timer active. RAM retention
Power mode 2	0.5 µA	Digital regulator off, 16 MHz oscillator and 32 MHz crystal oscillator off. 32.768 kHz oscillator, Power on Reset and sleep timer active. RAM retention
Power mode 3	0.3 µA	No clocks. RAM retention. Power on Reset active.

powerful USARTs with support for several serial protocols. Combined with the Zigbee protocol stack (Z-Stack) from TI, the CC2430 is one of the most competitive ZigBee solutions. The cost of the chip is around 5 dollars each. For larger volume, the cost may be even lower. It enables the AMR node with Zigbee wireless communication to be built with very low total bill-of-material costs.

Several 2430EM boards are used to develop the system, as shown in figure 5 [13]. On the left, EM is shown on the SmartRF04 Development Board. This board is used for programming EM and serving as an emulator to present EM's features directly, such as range testing, RF measurements and prototype development. EM is shown on Battery-board in the left picture. Battery board is used to power the EM with use of two AA batteries. The battery board is in the size of 1.5 inches by 1.5 inches.

Figure 5 CC2430EM and battery board

Communication protocol design and implementation

In order to put the mesh networks into operation for real-time data collection, appropriate communication protocols have to be designed and implemented. Many energy-efficient data gathering and dissemination approaches have been proposed in literature for wireless sensor networks (for example in [14-16]). The basic concepts of the self-healing automatic routing selection are described as follows: each node detects pilot signals from its neighboring nodes and determine which communication link to use for data transmission. When a node fails, its neighbors will remove it from relay list and select another neighbor node for communication based on certain criteria, such as signal strength, distance from the collection center, and the available energy, etc. Different algorithm may be implemented to determine the optimal path for data collection.

The data gathering/collection approach may be carried out on a cluster-based, tree constructive based or chain-based mesh network. The selection of appropriate network organization depends on the physical location of AMR nodes and the data features. In addition, distributed data compression and aggregation method may be implemented to improve the efficiency of data gathering. The scalability and fault-tolerance of the protocols are also important issues need to be addressed.

Power consumption estimation of the AMR node

Along with the energy-efficient network protocol design, it is possible for the individual devices to run for several years with a pair of AA battery. In the following we assume that the meter will be read every 5-second by the microcontroller and every 2 minutes the collected readings will be sent back to the collector. Assume it takes 200 ms for each meter reading and 200 ms for other computation. Consider each meter reading is represented using

2 Bytes, and the data packet header is 15 Bytes, then the time needed to transmit those data every 2 minutes is

Ttx = (15 bytes header + (2 bytes * # of readings))/data rate
= (15+2*2*60/5)*8bits/250kbps = 2.016 ms

Assume the average transmission for forwarding other nodes' data is three time of the transmission time for itself and in average each node spend the similar time for receiving data Trx = 3*Ttx = 4.032 ms. So the overall average current consumption (using the data in table 1 above) in the 2 minutes is

(400 ms*10.5mA + 2.016ms*26.9mA*3 + 2.016ms*26.7mA*3)/2minutes = 0.038mA

Assume a NiMN AA battery has the capacity of 4800mAHour, then the lifetime for the each individual device is around 4800mAHour/0038A ≈ 526 days. This estimation is based on the assumption that the utility meter is read every 5 seconds.

AMR node prototype

Each prototype of the implemented AMR nodes includes a Multitek kilowatt hour meter, a battery board with CC2430, and several loads. The coordinator node is connected to a PC via serial port to display and store the collected meter readings. The Multitek kilowatt hour meter has pulsed analogue output of instantaneous watts. The analog signal is converted to digital signal by the ADC module in CC2430 using differential analog inputs for further processing. A sample small mesh network with 5 nodes has been set up to test the system.

The software is developed using IAR Embedded Workbench EW8051 based on TI's Z-stack. The routing protocol implementation is summarized as follows. Each node has ID, Address, Distance (number of hops to coordinator) and neighbor list. The neighbor list consists of neighbor's ID, neighbor's Address and Distance, and optional signal strength. Each node broadcast its ID, address and Distance periodically so every node updates their neighbor list accordingly. When a node wants to send data, it will directly communicate with center if its distance is 1. Otherwise, it will choose a neighbor with the smallest distance.

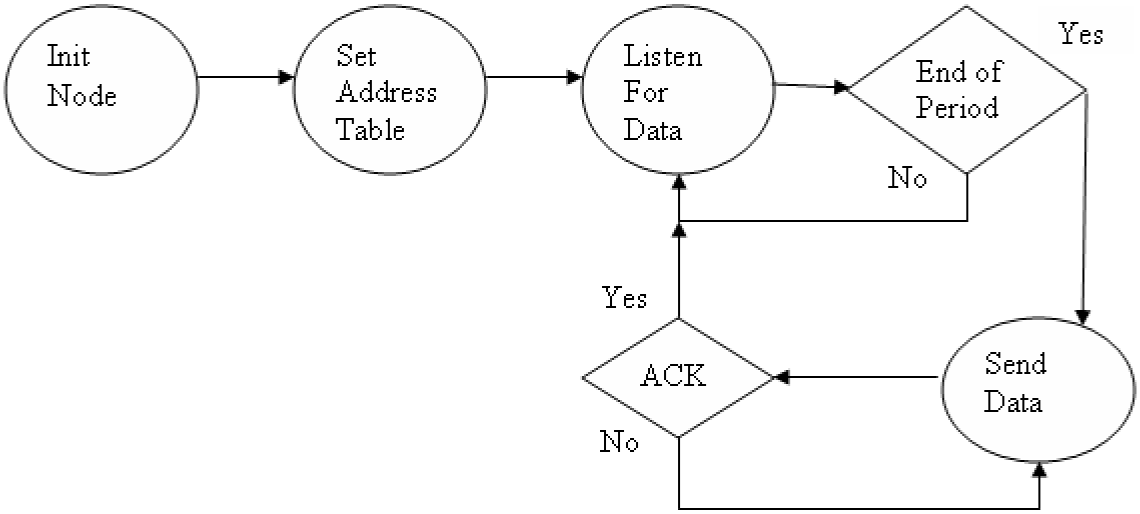

Figure 6 Simplified node state transitions

The node state transition diagram is shown in figure 6. At first, each node initializes itself to be ready for communication. Initialization includes frequency setting, RF preparation and address assignment. After initialization, nodes start to communicate each other and broadcast their addresses. During broadcast each node sets its address table and routing table.

For the application of utility data monitoring, nodes may send the readings periodically. So a node waits and listens to the medium during a period before starting to send. Although, theoretically, a period can be couple of second, in practice period ranges 5-15 minutes are reasonable. When period ends, node changes its state to transmission. In this state, data read from meter via sensors and ADC are prepared to send. An acknowledgment packet must be received after each transmission to make sure that transmission is made without any problem. Node retransmits until ACK is received.

Conclusions and future work

In this paper we proposed an Automatic Utility Data Collection System using IEEE 802.15.4-Compliant Wireless Mesh Networks. We have discussed the hardware design and software implementation aspects of a five-node system. We will work on a larger network with more nodes for extensive mesh network performance evaluation and comparison with other systems, and explore more advanced data aggregation algorithms. Security issue is also a big challenge for mesh networks and needs to be addressed. While the AES security coprocessor is included in CC2430, it has not been utilized and implemented in current prototype and will be investigated in the future.

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Biography

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