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Sensor network infrastructure for AMI in smart grid

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Abstract

Utility companies incur financial loss due to transmission losses as well as non technical losses like power theft and billing irregularities. Smart meters with the required functionalities along with an intelligent grid form an Automated Meter Reading (AMR) infrastructure which can improve the distribution efficiency. AMR infrastructure can be expanded by allowing for bi-directional communication between the grid components to form an Advanced Metering Infrastructure (AMI). This helps for the smooth interaction between grid components to load and off-load the distributed energy sources while supporting an efficient Demand Side Management of power. Communication technologies play a vital role in the implementation of smart grid and Wireless Sensor Networks are gaining attraction in this field. Routing protocols with high reliability, low latency and that can co-exist with the established protocols are the need of the hour. Routing Protocol for Low Power Lossy Networks (RPL) fit into this space well. An attempt to build an automated infrastructure using RPL for collecting the metering information, which at a later stage can be easily upgraded to an AMI setup by simply adding the supporting end devices for a much more intelligent smart grid, is carried out in this paper

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Keywords: AMR;Demand side Management(DSM);RPL

1. Introduction

Demand for electrical energy is increasing at a rate which the power generating companies are not able to keep up with in the production side. In developing countries like India, the huge imbalance in the demand and supply has forced the distribution companies to rely on load shedding so as to have a control on the supply side. This creates a lot of inconvenience for domestic users and huge financial losses for industries. With the existing centralized

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generation and distribution model, most of the grids have reached their optimum size, and scaling up of these grids can lead to frequent grid failures. Efficient management of the available resources is the need of the hour. In order to have a better control and higher utilization, Power companies are looking forward towards decentralized generation and distribution of power which requires a reliable bi-directional communication between various grid components. Under these circumstances suitable technologies has a larger role to play by incorporating intelligence to every grid component as well as to the overall grid infrastructure. Implementation of appropriate Demand Side Management(DSM) techniques with the help of these intelligent devices will provide a better experience for the end users. SMART GRID perfectly fits into this space by providing a grid infrastructure with an improved efficiency and reliability, along with smooth integration of renewable and alternate energy sources through automated control and communication technologies.

An important area of improvement in DSM is the active role of the customers, who can control their energy usage more efficiently in response to the variable energy supply conditions/prices. Consumers can be charged at variable rates based on the Time Of Usage (TOU) with higher rates for the peak period and lower rates for the non-peak period. This can lure the customers to plan their usage for their own benefit as well as reducing the load during the peak period. This requires mechanisms to capture the energy usage of the customer at a more frequent interval, probably on an hourly basis rather than the current mechanism of bimonthly or monthly readings. By upgrading the existing grid with features for the above functionalities, we can establish a smart grid. This requires a large scale deployment of capable sensing and control mechanism along with a dedicated two way communication infrastructure to effectively control the smooth operations of the grid. Wireless Sensor Networks consists of low power sensor nodes with limited computational capability that are capable of meeting the requirement of pervasive communication and control capabilities at low cost. This is one of the most sought after technologies for smart grid. Although the components of the grid are immobile, the quality of links between any two pairs of components is not constant and is vulnerable to fading effects and signal interference making them a lossy network. With low power individual nodes and the unpredictable nature of the links, WSN can be classified as a low power and lossy network. Appropriate routing protocols with high reliability along with low latency need to be designed and RPL fits well for such kind of application. RPL is an internet routing protocol specifically designed for wireless sensor networks and standardized by the IET.

1.1. Smart Grid

When the legacy power transmission infrastructure is augmented with a communication infrastructure and smart components, it becomes a smart grid. This communication infrastructure makes it easy for the exchange of control and state information of the participating components in the grid. According to Erol-Kantarci & Mouftah(2011)[5], The main objectives of the smart grid are as follows:

- Allowing two way flow of information and electricity
- Being future proof with scalable architecture
- Instigate efficient Customer Energy Management
- Being Self Healing and Environment friendly

Smart grid enabling network management strategies provide effective grid integration of Distributed Renewable Energy Resources(DER) along with a proper Demand Side Management(DSM) of power usage by providing real time data from/to the control centers as well as the smart control unit at the customer premises

1.2. Demand Side Management(DSM)

Demand Side Management are mechanisms used to control the energy consumption at the customer side of the meter with the objective to effectively use the available energy without installing new generation and transmission infrastructure as mentioned by Rad et al(2010)[9], DSM programs include conservation and energy efficiency programs, fuel substitution programs, demand response programs and load management programs. Load management programs usually aim at reducing consumption and/or shifting of consumption from peak to non peak hours. Reduction in consumption can be achieved by encouraging energy aware consumption patterns. Shifting consumption pattern can be attained by making the customers to use high-power house hold appliances to off-peak hours to reduce the Peak to Average Ratio (PAR) in load demand. One method of load management is called as Direct Load Control(DLC), where based on the agreement between the utility company and the customer, the utility company will remotely control the operations of the certain high-power devices of the household. However in this method, users privacy can be a major concern and a barrier in implementing DLC. Another approach for DLC is to have a smart pricing mechanism where users are encouraged to individually and voluntarily manage their loads. Methods that can be followed for implementing this approach include Critical Peak Pricing (CPP), Time Of Use Pricing (TOU) and Real Time Pricing (RTP) as discussed in Rad et al (2010)[09]. Pedram Samadi et al(2010)[11] has studied on a infrastructure of a single energy source shared among many subscribes to arrive at an real time pricing mechanism for the smart grid. A Utility maximization algorithm implemented in a distributed manner to maximize the aggregate utility of all users and minimize the cost for the provider by keeping the total consumption below the generating capacity was proposed and confirmed using simulated results.

1.3. Advanced Metering Infrastructure

Advanced Metering Infrastructure (AMI) is needed to interconnect the smart meters connected at the customer premises with the control centers of the utility company. According to Saputro et al(2012)[10], A well designed AMI setup can be seen as having 3 different layer split across the three important functionalities addressed by the network as shown in Fig. 1.

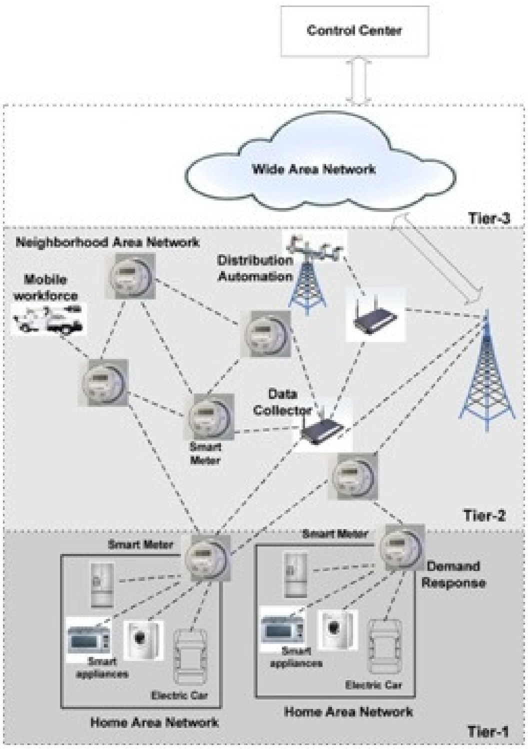

Fig 1 Schematic of a Communication architecture for smart grid (Saputro et al(2012)[10])

The AMI can also act as a data acquisition mechanism which can proactively diagnose and take necessary control actions related to grid maintenance on top of the support provided for DSM. An extended version of the AMI network is looked up on to interconnect large numbers of different intelligent electronic devices(IEDs) that are sensor based controllers of power system equipments (like feeder and substation transformers, circuit breakers etc) which are widely dispersed within the smart grid. Advances in Broadband wireless technologies have made it feasible to have data rates and network capabilities comparable to that of wired networks. Wireless Sensor Networks(WSN) provide significant advantages over traditional wired communications methods like PLCC by having higher flexibility, rapid deployment, low installation cost as well as aggregated intelligence via parallel processing as observed by Gungor et al (2010)[6]. Having large number of wireless nodes spread over a large geographic area makes it necessary to have an appropriate routing and data forwarding mechanism in multi-hop networks to find high quality network paths. These routing protocols must guarantee that the measured data as well as the dispatch of the control commands are carried out in a reliable and timely manner across devices. This requirement makes the design of an effective communication protocol difficult for WSNs deployed for AMIs

1.4. Smart Grid Communication

Significance of smart grid in the demand response management and the role wireless sensor networks can play is discussed by Sang-Hyun Lee et al(2014)[12].The role of communication based demand management techniques in shifting the consumer demands to off-peak hours and in-home Energy management using a fuzzy scheduling algorithms was simulated to arrive at a schedule cycle for certain high-power appliances. Erol-Kantarci & Mouftah(2011)[05] (2010)[15] observed that performance of WSN in terms of delivery ratio, delay and Packet Delay Variance for varying inter arrival-times and varying network sizes were studied and it was observed that delivery ratio, delay and PDV improves as the packet inter-arrival time of the sensing application increases. This leads us to conclude that the performance of DSM services increases as the intensity of other monitoring applications that share the WSN resources decrease. Erol-Kantarci et al(2010)[15] have modelled a energy demand following a Poisson process using a simulation program and wireless sensor based data collection using zigbee to analyze the effect of DSM for the consumer and found it to be much beneficial for the consumer. Smart grid communication technologies include both wired communication as well as wireless communication. Vehbi et al(2011) [7] discusses the advantages, disadvantages, reliability, security & robustness issues as well as the requirements in terms of scalability of different communication technologies for smart grid. The network topology and the routing technologies to establish the wireless sensor network for Automated Meter Reading(AMR) and the DSM is discussed by Li Li et al (2013)[8]

A protocol implementation based on the framework of the IPv6 routing protocol for Low Power and Lossy Networks and its suitability for AMI is discussed by Di Wang et al (2010)[4].RPL supports inward unicast as well as outward unicast data transfer which helps in transfer of meter reading as well as control data respectively from the consumer and the provider. A detailed study of the suitability of RPL in WSN for smart grid is discussed in Ancillotti et al (2013) [1],[2] by providing the RPL specification and the design principles together with routing algorithm. Results of experimental performance evaluation of RPL for different network settings to understand the impact of the protocol attributes on the network behavior, namely in terms of convergence time, energy, packet loss and packet delay are discussed by Gaddour & Koubaa (2012)[13]. Their study has concluded that RPL is a promising routing protocol for Low power Lossy Networks(LLNs) as they provide greater level of flexibility to deal with different requirements of the underlying applications. Comparative study of RPL against the Collection Tree Protocol(CTP) has been carried out by JeongGil Ko et al (2011)[14]. They have compared the performance of TinyRPL, an model implementation of RPL using TinyOS to that of the defacto routing protocol CTP used for mesh networking in TinyOS. It was concluded in their study that RPL performs equally well or better than CTP for most of the parameter. Moreover, RPL also provides additional flexibility which can be altered according to the need of the application

2. Routing Protocol for Low Power Lossy Networks(RPL)

Routing Protocol for Low power Lossy Networks(RPL) is a routing protocol which was recently standardized by the IETF working group for low power and lossy Networks. RPL finds neighbors and establishes routes using ICMPv6 message exchanges and manages routes based on a 'rank' value that represents nodes' relative position to the root of the routing tree. The key idea of RPL is to maintain network state information using one or more directed acyclic graphs (DAG). A DAG is a directed graph wherein all edges are oriented in such a way that no cycles exist. For each DAG created in RPL, there is a root. The DAG root typically is the gateway node in AMI networks or the sink node in sensor networks. All edges in the DAG are contained in paths oriented toward and terminating at one root node. Each node in the DAG is associated with a rank value. The rank of nodes along any path to the DAG root should be monotonically decreasing in order to avoid any routing loop. In order to construct a DAG, the gateway node will issue a control message called DAG Information Object (DIO). A DIO message conveys information about the DAG, including:

- A DAGID used to identify the DAG as sourced from the DAG root;
- Rank information used by nodes to determine their positions in the DAG relative to each other;
- Objective Function identified by an Objective Code Point (OCP) that specifies the metrics used within the DAG and the method for computing DAG rank

Any other node (called client node) that receives a DIO message and is willing to join the DAG should add the DIO sender (the previous node traveled by the DIO) to its parent list, compute its own rank (associated with the parent node) according to the OCP, and pass on the DIO message with the updated rank information. For a node having already joined the DAG, upon receiving another DIO message it may have the option to either

- discard the DIO based on several criteria recommended by RPL, or
- process the DIO to maintain a position in an existing DAG, or
- improve its position (by obtaining a lower rank) according to the OCP and current path cost.

After the DAG is constructed, each client node will be able to forward any inward traffic (destined to the gateway) by choosing its most preferred parent as the next-hop node. In order to support the outward traffic from the gateway to a client node, the client node should issue a control message called Destination Advertisement Object (DAO). The information conveyed in the DAO message includes 1) the rank information used by nodes to determine how far away the destination (the client node that issues the DAO message) is, and 2) reverse route information to record the node visited along the outward path. After passing this DAO message all the way from the client node to the gateway according to the inward path indicated by the DAG, and all the intermediate nodes record the reverse path information from the DAO message, a complete outward path is established from the gateway to the client node. The above data flow of a simple RPL implementation is discussed in Di Wang et al (2010)[4] and was modified to carry data from a serial port of an energy meter to the root node.

3. System Model

Most of the currently available Digital Energy meters stores various parameters of the energy consumed in their internal registers. These data are made available to the external world through a serial communication interface like modbus protocol. Modbus is often used to connect a supervisory computer with a Remote Terminal Unit(RTU) in a supervisory control and data acquisition systems. Slave devices responds to the various command issued in the form of function codes by the supervisory control center by providing the appropriate data or triggering the corresponding relays in the case of actuators. All these happen through a simple 2 wire serial communication. The architecture of the proposed system is given in Fig 2.

The root node is attached to a PC, which acts as the data accumulator. An application continuously monitors the serial port of the PC and unpack the serial data and updates the information into a database. The collected information is then made available to end users through a web interface. The same information can also be used to implement various DSM techniques

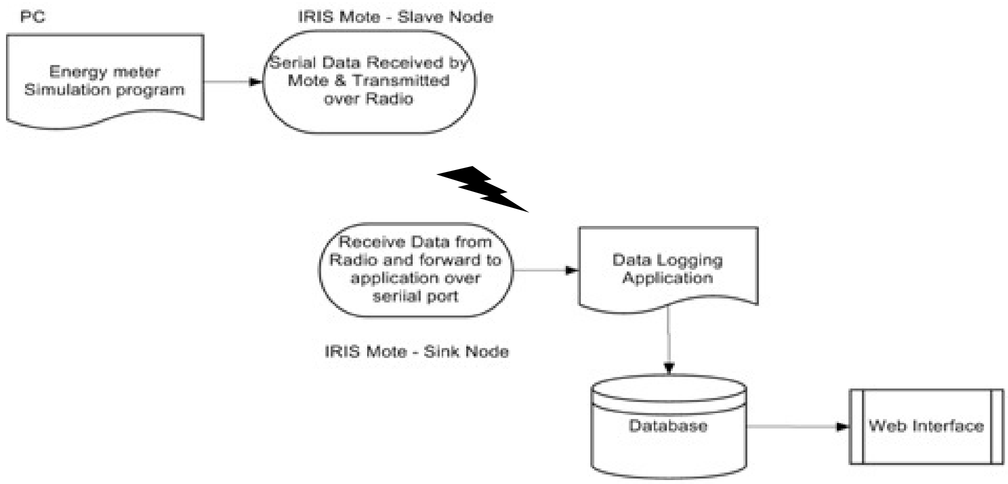

Fig. 2. Proposed System Architecture

4. Implementation

The NesC component and interfaces required for the implementation of the RPL are listed in the Table 1. Once a mote boots up with TinyRPL, TinyRPL will operate in the 'background' of an application to exchange route related messages with other RPL-using nodes. The RPL Routing Engine begins its operations once a global address is allocated using the DHCPv6 process. Once the RPL routing engine starts exchanging DIO and DAO messages, it can receive packets from the application layers. The packet-sending IP interface can be connected identically to the ways that they are wired in blip. Once the packet reaches the point to discover the next hop address (on the blip stack), RPL's routing table will be called to retrieve the next hop node's IPv6 address for the specified destination.

Table 1. NesC components available for RPL implementation(source:Github:TinyOs-main repository) .

Components	Interfaces
RPLRoutingEngineC	RPLRoutingEngine, RootControl
RPLDAORoutingEngineC	RPLDAORoutingEngine, StdControl, ICMP_RA
RPLRankC	IP_DIO_Filter, RPLRank, StdControl, ICMP_RA
RPLRoutingC	RootControl, StdControl,
RPLOFC	RPLOF

A test application using the above components was wired and configured to send data across the network using the RPL protocol. Topology discovery and updating of the routing table followed by packet forwarding was analyzed using a sniffing tool called Peryton Analyzer. Topology discovery and the frame details are given in the Fig.3. Smart meters are one of the most important components of the smart grid. Important design considerations that need to be taken care for the development of a smart meter and the role of wireless technologies to base station communication is discussed by Depuru et al(2011)[3]. Integration of smart meters to a wireless sensor network implemented using RPL protocol will form a efficient neighborhood area network(NAN) over which energy consumption details of consumers can be collected by the energy provider. The data collected is forwarded towards the root node across the ad-hoc network using the RPL protocol. Most of the current energy meters provide wide variety of serial interfaces to read the stored data available in the smart meter.We have used an energy meter which has implemented the simple modbus protocol to read the available data from the smart meter.

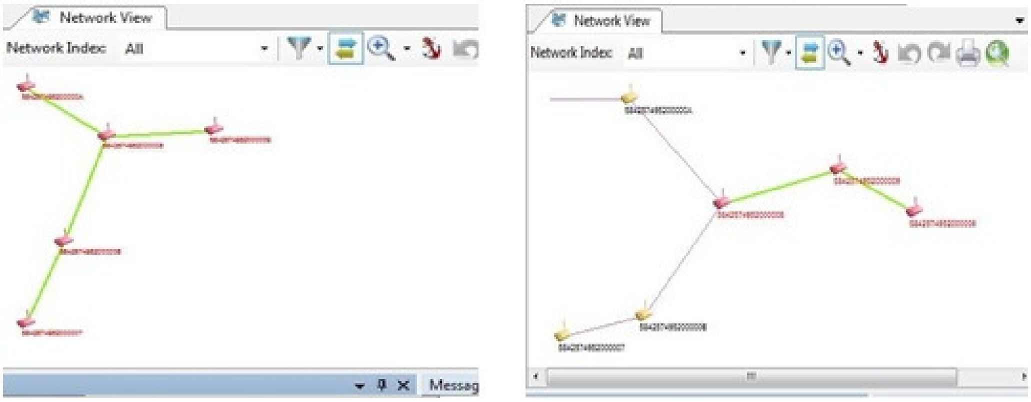

Fig 3. Topology discovery of the network by RPL

IRIS motes from Crossbow technologies were used as the notes that interact with the energy meters and form the wireless sensor network. IRIS motes have an inbuilt microcontroller Atmel AT1281 which has a serial port. TinyOS provides components that allow communicating with the mote through the serial interface. The component details and their respective interfaces are given in the Table 2

Table 2. Components and Interfaces of TestRPL Component.

Components	Interfaces
TestRPLC	Leds,Boot,Timer,
	RPLRoutingEngine, RPLDAORoutingEngine,
	RootControl,StdControl,
	SplitControl,UDP,
	Receive, AMSend, Packet

5. System Setup and Outcomes

Java applications were running on a PC and the motes were connected to the PC for serial communication

Fig.4. System setup for data aggregation using IRIS motes

through the USB port. System setup is as shown in the Fig 4. Instead of using a real energy meter, simulation software were used to generate and transmit the energy usage data through a serial port of a PC at periodic intervals to the motes. The application program will accept the port details over which the data needs to be transmitted and once initiated, it generates and sends serial data through these ports to the mote. Mote accepts these serial data and then forwards the data towards the sink node over the radio channel. At the receiving end, the mote acting as the sink node will accept the data coming over the radio and pass it on to PC through the serial port to which the sink

Fig. 5 Smart meter simulation program(serial data)

node is connected. A Java application will be running on a PC to which the sink node is attached to. This application will keep on monitoring the specified serial port to which the sink node is connected to and reads the packet data that it receives over the serial port. The packet data is then interpreted and updated to a database using JDBC as and when a packet is received by the sink node. Screen shot of data capture are given in Fig.5 and Fig.6

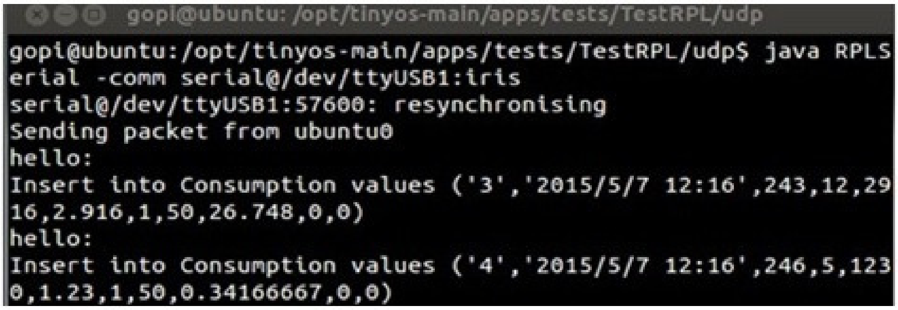

Fig 6 Application attached to the Sink node

The web interface provided for the end users to monitor their energy consumption was developed in Java/Jsp. Users are provided with a screen as given in Fig 7.The Web application can be modified for other complex DSM methods.

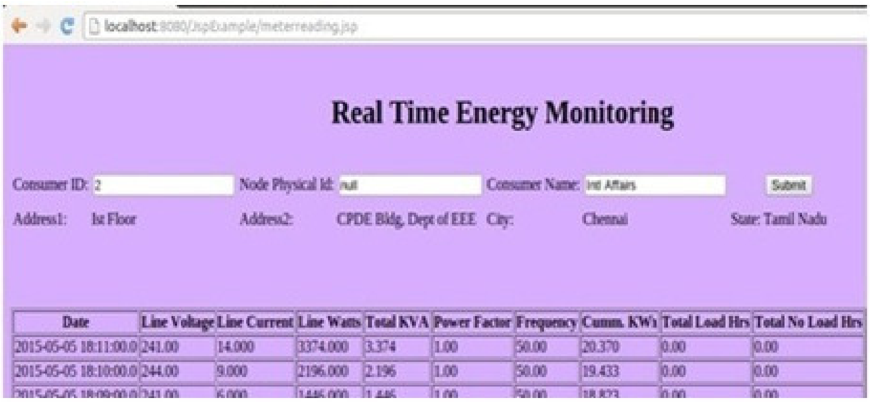

Fig.7 User interface to view real time energy reading

6. Conclusion & Future Scope

Smart grids can play a significant role in the Demand Side Management of power, whose efficiency depends on a robust communication mechanism between the grid components. Sensor nodes can be attached to the grid components to form a Wireless Sensor Network that can act as a communication backbone for the grid infrastructure. IETF has standardized RPL as a standard protocol for low power lossy networks. Due to the variable link quality between the nodes of the grid, these networks can be considered as lossy networks and hence RPL would be the ideal candidate for the data routing in such networks. Automated Meter Reading infrastructure was successfully implemented in this project and a web interface was provided for the consumer to know the real time consumption details. The following can be taken up as the further areas to work on to have full fledged AMI setup using the RPL for a smart grid infrastructure

- Objective Function based on properties like link quality, criticality of the node, remaining energy etc can be identified and implemented to calculate the Rank value. Results can then be compared with the standard implementations
- Possibility of Integration with hierarchical protocols to support aggregation
- Hardware interfacing of IRIS motes to Digital Energy meters implementing Modbus protocol
- Development of application to pass commands from the control center to the end devices using the Point to Multi Point data transfer capability of RPL
- Implementation of a switching system to control the demand at the customer premise

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