ZigBee based Small-World Home Area Networking for Decentralized Monitoring and Control of Smart Appliances

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***Abstract*— This paper deals with the unique development of decentralized monitoring and control of smart electric appliances using ZigBee mesh topology for home area networking (HAN). All the communication nodes within the entire user's home are tied with ZigBee communication while the running status of individual smart equipment is displayed in a portable in-home-display (IHD) and/or in a smartphone through Wi-Fi Internet connectivity. In order to reduce the number of ZigBee nodes, a group of smart appliances is interfaced with one ZigBee module through a smart controller board while that controller unit will be housed inside the local switchboard. Few of such controller units are required for all the smart appliances for their monitoring and control. The maximum number of such controller units is thus equal to the number of maximum switch board in that house. Small World Mesh topology for ZigBee-based HAN with node degree greater than unity is used to provide the communication redundancy so that if any one of the ZigBee fails, the other portions can work uninterruptedly. The ZigBee Controller boards, IHD, and ZigBee to Wi-Fi gateway based small world HAN network is established in our laboratory which resulted in reduced transmission delay and robust network connectivity.**

***Keywords*— HAN, IHD, Small World, Mesh topology, ZigBee**

I. INTRODUCTION

Smart home deployment or even conversion of an ordinary home to a smart one is one of the research topics in order to implement smart grid concepts successfully. Smart home not only proposes for energy efficient usage of various electrical appliances but also takes crucial role in reduction of footprint of green house gases. Green Smart Home Technologies are thus being evolved in which efficient energy management in residential buildings are encouraged [1]. It is learnt that the display of real time information on electric power consumption can result in reduction of up to 30% by enabling the consumer to consume responsively with energy efficient manner [2]. The consumers are being encouraged to consume responsively with the various measures of demand side management implementation schemes of smart grid.

Home area networking is the building blocks of smart homes where various home energy management (HEM) communication and control strategies are adopted and being implemented with rapid growth rate on the basis of initiatives from government, industries and technology groups. The HAN connects devices that are capable of sending and receiving signals from a meter and/or HEMS applications using either wired or wireless medium [6] Amongst the existing medium, ZigBee wireless medium are widely used as HAN communication due to its inherent low power consumption, high noise immunity, robustness and highly reliable etc. features.

In this endeavour, the authors in [3] focuses on the MATLAB Simulink model of ZigBee transceiver design for communication between the smart meter and home appliances. The operating frequency of this model is 2.4 GHz. The Bit Error Rate (BER) performance was studied against Signal to Noise Ratio (SNR). The authors in [5] suggests development of an embedded board for virtual home robot server for efficient control of internal information and conditions of the house from a remote location with ZigBee sensor network. The usefulness of HAN to meet the requirements of daily life such as the control of commonly used household appliances and the real-time monitoring of family environment is discussed in [7]. The authors in [8] describe the design and implementation of an effective architecture for the dynamic integration of ZigBee home networks into OSGI-based home gateways, where ad hoc ZigBee devices are represented by device proxy services. A typical home energy control system design to provide intelligent services for the user or consumer for real environments is discussed in [9]. A remote-controllable and energy-saving room architecture to reduce standby power consumption and to make the room easily controllable with an IR remote control of a home appliance is proposed in [10].

A new type of HAN service like outdoor air quality monitoring system for collected data on carbonic oxide, nitrogen dioxide, sulfur dioxide, ozone, particulate matter, temperature, and humidity etc. is proposed in [11]. Smart home automation using IEEE 802.15.4 ZigBee and the standard of wireless networks and protocols are discussed in [12,13]. The use of Cognitive radio-based smart grid environments and survey of contemporary technologies for smart home energy management discussed in [14, 15].

The energy-efficient features with cluster tree architecture for the home area network for home automation system, dynamic control for multiple legacy IR controllable smart devices, etc. are discussed in [16, 20, 26]. Infrastructure monitoring and operation for smart cities based on IoT systems and a review of connectivity challenges in IoT-smart homes are discussed in [17,21]. Various communication topologies for establishing a communication network using WSN is discussed in [18].

The Role of Smart Homes in Intelligent Homecare and Healthcare Environments is discussed in [19]. The design of a wireless intelligent home system based on ZigBee source route technology in-home application for real-time monitoring system is discussed [23-25,26].

From this discussion, it is observed that ZigBee protocol is widely utilized as a HAN communication medium but in most cases, star topology [27,28] is utilized for implementing the network. The paper is organized is as follows

Section 2 discusses the different building blocks of small-world HAN. Section 3 discusses proposed HAN module operations. The performance of the proposed HAN is studied and analyzed in section 4. Section 5 concludes with the achievements of this proposed work..

II. Materials and Methods

The basic schematic of the decentralized ZigBee-based HAN is shown in the following fig.1. As shown, each node is equipped with a control board with a ZigBee module along with the number of load channels in order to control the functioning of the loads connected to it. The loads controlled through a switchboard in a room are clubbed together to form a group of loads. This group of loads can be connected through a ZigBee control board (ZCB) through each of its load channels. In order to construct the proposed meshed HAN, the maximum number of nodes or ZCB can thus be varied depending on the number of switchboards within the house. The mesh topology with non-beacon mode of ZigBee networking is proposed.

Any one of ZCB can communicate with the smartphone and IHD to exchange various information related to AMI services. One custom-developed ZigBee enabled (in-home-display) IHD also communicates with the ZCB so that the consumer can be intimated about the AMI services as well as present consumption status. The same can also be displayed from a smartphone through its customized App.

The communication between ZCB is followed by mesh networking so that decentralized monitoring and control becomes possible. The reason for utilizing mesh networking is that if one node starts malfunctioning then the information can relay through the other node to the IHD and gateway end.

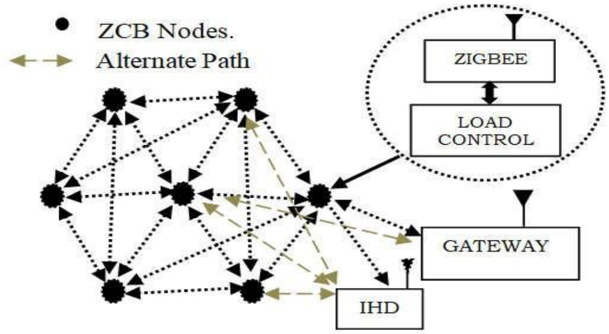


Fig. 1. Schematic diagram of proposed decentralized HAN.

i) **Load section**: In every electrical board the specific loads are connected via relay modules, as shown in fig 2.a In this hardware, the controller performs the task of On/Off operation of individual load on the basis of the energy-saving schemes (ESS). The ESS is adopted by the consumer by remote monitoring of the running status of the loads from IHD or from his/her smartphone. The control actions are generated from the smartphone and are transmitted to the controller board through various communication mediums. At the last mile of communication, ZigBee is interfaced with this controller board. Fig 2.b. Individual switches are put in parallel with the relay as a redundant control.

The basic components of a ZCB are as follows-

ii) **Signal conditioning unit:** In order to measure the overall power consumption by the group of loads through a ZCB, voltage, and current sensors are used and signal conditioning circuits are used for proper scaling and filtration of the signal. These signals are then fed to the controller for measuring purposes. This is shown in Fig 2.a.

iii) **Wi-Fi to ZigBee gateway**: ZigBee to Wi-Fi or vice- versa protocol conversion is done in this gateway, as shown in Fig.2.b. This conversion is needed for the smartphone to ZCB interface purposes. The HAN is designed such that there will be two gateway with any ZCB so that one can be used as a standby of the other.

iv) **IHD interface**: This portable unit is used as centralized monitoring of individual load consumption status, power supply quality, the status of renewable generation if available, the status of overall power consumption with its GLCD display screen in decentralized HAN as shown in Fig.2.c.

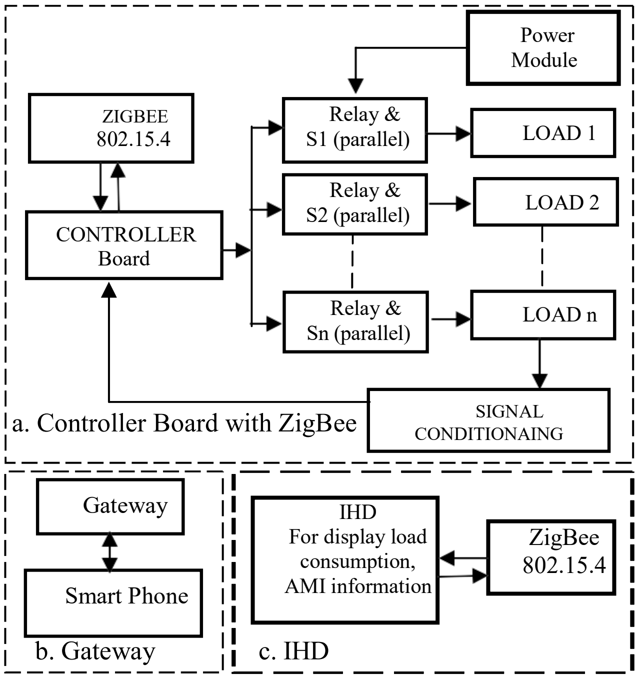


Fig 2. Detail schematic diagram of proposed decentralized HAN (a. Controller Board with ZigBee end b. Gateway c. IHD unit).

A. ZigBee HAN Generation Scheme

In the proposed decentralized ZigBee HAN model, networking structure follows small-world network theory [29] model. Network structure can be represented by the graph where any graph is a function of the number of edges and number of nodes present in the network and can be represented as *G(V, E)*. A random network model can be characterized by the total number of nodes *N* and the probability *p* that two nodes are connected. A random network can be generated or constructed by the following principle with *N* nodes and probability [29]. The following algorithm is used to generate small-world network model.

Step 1: Start with the *N* number of nodes.
Step 2: Connect *K* nearest nodes for all the nodes *i=1….N.*
Step 3: Reconnect the edges to a randomly chosen node with probability *p*. If a randomly generated number between (0, 1) is < *p*, then connect two nodes *i* and *j*.
Step 4: Repeat steps 3 for all possible *NK/2* edges in the network.

To evaluate the size of the network, the average path length in equation 1 is used and is defined as the average distance between two vertices, average all possible pair of vertices. The distance between a pair of vertices is defined to be the number of minimum edges or hops connecting the two vertices. The equation is given by,

$$L = \frac{W(G)}{N(N-1)} \tag{1}$$

$$W(G) = \sum_{i=1}^{N}\sum_{i=1}^{N} dist(i,j) \tag{2}$$

Where *N* is the total number of nodes in the network, *W(G)* is Weiner Index.

The clustering coefficient measures the cliquishness of a typical node friendship circle. The average clustering coefficient averaged over all vertices *i=1…..N* is given by [30].

$$C = \frac{1}{N}\sum_{i=1}^{N} C_i \tag{3}$$

Where C_i is the clustering coefficient for vertex *i* defined as

$$C_i = \frac{2E_i}{K_i(K_i - 1)} \tag{4}$$

Where E_i is the actual number of edges connecting the neighbors of vertex *i*, K_i is the total number of neighbor vertices connected to vertex *i*, and $K_i(K_i\text{-}1)$ is the maximum number of possible connections between the neighbor vertices. One of the important issues for the small-world network is that the average path length is always proportional to the *ln(n)* [30]. As an example, the following example is considered of a graph network of 10 nodes. From this network shown in Fig 3, an average path length *L*=2.288 is calculated and *ln*(10)=2.3025 which is nearly equal to 2.288 and thus the network is small-world in nature. The shortest path from one node to another node is shown in Table I. Eccentricity is the sum of all shortest path for corresponding nodes.

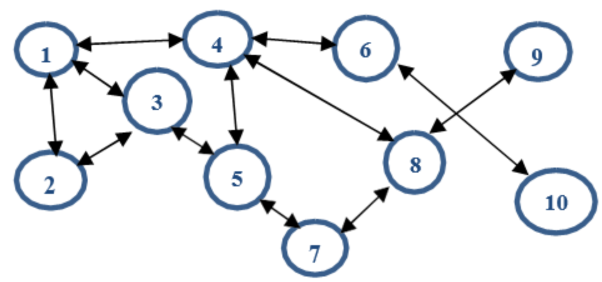


Fig 3. Graph network for calculation average length.

In a real scenario, the HAN network is very small i.e. few nodes are deployed for this network. The data to be sent from source to destination node depends on the edge connection of nodes. RSSI strength is also important to analyze the distance between the nodes.

TABLE I. SHORTEST PATH LENGTH FROM ONE NODE TO ANOTHER NODE

	1	2	3	4	5	6	7	8	9	10	Ecentricity
1	0	1	1	1	2	2	3	2	3	3	18
2	1	0	1	2	2	3	3	3	4	4	23
3	1	1	0	2	1	3	2	3	4	4	21
4	1	2	2	0	1	1	2	1	2	2	14
5	2	2	1	1	0	2	1	2	3	3	17
6	2	3	3	1	2	0	3	2	3	1	20
7	3	3	2	2	1	3	0	1	2	4	21
8	2	3	3	1	2	2	1	0	1	3	18
9	3	4	4	2	3	3	2	1	0	4	26
10	3	4	4	2	3	1	4	3	4	0	28

B. Decentralized Scheme

The proposed network structure is followed by small-world property which is not fully meshed one. A full mesh network takes more time to join the node in the network as well as to initialize the process as the routing table has to store large number of addresses of the destination nodes. But in the small-world model, the nodes are connected with shortest path principle for which a very low count routing table is sufficient. It is also shown from Table I that there is an alternate path to send the message from source to destination. The table will be updated with the reconnect feature of small-world network. This feature provides a decentralized monitoring and control of the HAN. When any new node wishes to join in the HAN then based on the reply of the adjoining nodes and the reconnect properties, it can join the network.

1. *Coordination to each other packet. (maintain the coordination between mesh connected nodes)*
   a) Periodic scan performs by each ZigBee node and maintains the neighbor ZigBee module. This operation is performed by n number nodes (ZCB) which are connected to each switchboard.
   b) In the neighbor table for a particular node using the MAC address, the RSSI value also measures to calculate the distance between the node in HAN.
   c) If any node is a failure or starts malfunctioning then ZigBee nodes again start scanning and establish a new network structure, thus by using this mesh decentralized method load cannot disrupt from the gateway end and there is also an alternate path to relay the message from load end to gateway meter or vice versa.
2. *Decision packet. (the decision was taken by an optimized technique which load is on or off)*
   a) A decision packet is needed for the load on/ off features. Depending on the demand of electricity needed in HAN and also in DSM from the utility end.
   b) In this packet in the RF payload section, the load on-off status is maintained by specific data on which load can be controlled to switch on or switch off. Transmit packet generates for this load control features.
   c) Reply packet will be generated for successful transmission.

C. ZCB Operation for

i) Load consumption packet. (Inform the load consumption data) Each ZCB measures load consumption and creates the transmit packet to the destination address where the destination may be another ZCB for multi-hop or an IHD or smartphone through gateway.

ii) The typical action perform by this ZigBee module are given below

a) Scan the neighbor ZigBee module.
b) Measure the RSSI value of each neighbor ZigBee module.
c) Send transmit request packet to the destination node.
d) The reply packet from the destination ensures the transmission status.

III. Experimental Result

In the following section, Fig 4 show different hardware development module for HAN in the laboratory. ZCB is connected for load control facilities, the IHD unit is for display purposes, Wi-Fi gateway is used to convert ZigBee to Wi-Fi protocol to send the power consumption data to the smartphone. Fig 4.c shows the current transformer waveform under different load connections, the data of CT secondary terminal voltage under different load is shown in Table III.

Data receive by IHD terminal and ZCB power consumption data: Power consumption by different ZCB under different load connections shown in Table II.

RSSI signal strength at a different distance:

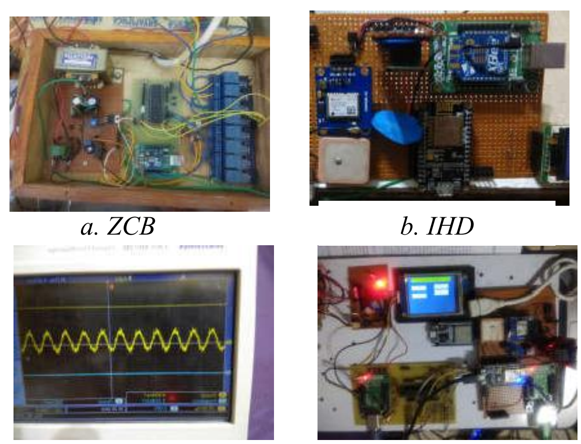
In this section, the RSSI value in dBm concerning the distance between the gateway and switchboard unit (ZCB) in HAN is shown in Table IV. The coverage area of HAN is very important for data collection from the load side (switchboard) to the monitoring side and also the gateway.

Delay for different hop value:

Transmit Request Frame: 18 bytes header with CRC + d (number RF payload bytes). Here d=4. Therefore in Tx frame consists of 22 bytes. Over the air data rate is 250 kbps, set Xbee baud rate = 115200. Transmit power mode 6.3 mW (+8 dBm), boost mode enabled.

Delay generate at different hop values shown in Table V.

It is evident from Table VI that the mesh topology is working with any combination of the nodes considering only node as master. However for the case of occurrence of two master nodes is also possible and that situation is explained below for a true decentralized mode of operation.



a. ZCB *b. IHD*

c. load waveform *d. Wi-Fi Gatewav*

Fig 4. Various hardware component like ZCB, IHD unit, CT secondary waveform, and Wi-Fi gateway.

TABLE-II
ZCB Power Consumption

ZCB No.	Power Consumption
1	28.5 w
2	44.7 w
3	59.3 w

TABLE-III
CT Secondary Voltage

Load Number	Amplitude in (p-p)
Bulb 15w	20.8 mv
Bulb 25w	32.8 mv
Bulb 100w	104 mv
Led Bulb (3w)	17.6 mv
Led Bulb(14w)	19.2 mv

TABLE-IV
VARIATION OF RSSI VALUE WITH DISTANCE

Distance between two nodes in meter	Average RSSI value in dBm	Average Power
3	-51	7.94 nw
5	-55	3.162 nw
10	-78	15.74 pw
25	-85	3.162 pw
30	-92	0.631 pw

TABLE V
DELAY GENERATE FOR DIFFERENT HOP

Hop Count	Delay in msec
1	1.90
2	3.81
3	5.73
4	7.64

TABLE VI
NODE TO NODE COMMUNICATION STATUS

Node to node transmission	Received packet
Node 1 to the gateway	yes
Node 1 fails from Node 5 to gateway	yes
Node 3 to Node 1	yes
Node 4 to Node 1	yes

Two Master Nodes: Two master nodes 1 and 5. Node 1 is IHD and node 5 is one ZCB. Now send the data from master 1 to the gateway node, now if this node 1 is a failure (here in practical scenario node 1 is power off) now it is observed that node 5 i.e. one ZCB sends the data to the gateway node. Some observations are shown in Table VI.

Compare star and mesh topology: Star topology is centralized but one hop is followed from source to destination. But the proposed small-world mesh networking is a decentralized one where the communication depends on number of hops with any arbitrary chosen paths. This basic advantage of arbitrary path establishment is illustrated in Table VI.

IV. CONCLUSION

The establishment of a decentralized HAN with small-world topology is described in this work. The advantages of both decentralized, as well as small-world networking, are inherently introduced so that smaller average transmission delay and robustness of the network is realized, as indicated in Table VIII. Besides, the number of ZigBee nodes is further reduced to only a very few by making groups of the appliances based on their switchboard connections. This arrangement further reduces the average transmission delay as well as packet loss. The centralized monitoring facilities of the running conditions of the loads through IHD helps the consumers to turn off the unwanted loads. The same centralized monitoring as well control is also proposed from a remote location with the help of a smartphone through its App. Thus decentralized monitoring and control with small- world HAN development is realized with this work for a robust, quicker in operation, energy-efficient, and green home.

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