SMART METERING SYSTEM FOR HOME AREA NETWORK USING ZIGBEE

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Abstract—* ZigBee technology was developed for special wireless networks where Bluetooth & wi-fi technologies are not showing much better results. In wireless personal area networks (PAN) where we need to transmit low data rate information in comparatively large area (10-100 m). A multi-interface ZigBee building area network (MIZBAN) for a smart metering infrastructure (SMI) for high-rise buildings was developed. This leads meter management functions such as Demand Response for smart grid applications. To cater for the high-traffic communication in these building area networks (BANs), a multi-interface management framework was defined and designed to coordinate the operation between multiple interfaces based on a newly defined tree-based mesh (T-Mesh) ZigBee topology, which supports both mesh and tree routing in a single network. To evaluate MIZBAN, an experiment was set up in a two-floor building. Based on the measured data, simulations were performed to extend the analysis to a 23-floor building. These revealed that MIZBAN yields an improvement in application-layer latency of the backbone and the floor network by 75% and 67%, respectively.

***Index Terms*—Smart Metering Infrastructure (SMI), building area network (BAN), multi-interface, smart grid, ZigBee.**

I. INTRODUCTION

SMART metering infrastructure (SMI) is an important milestone of smart grid development [1]–[4].Different smart-grid communication technologies and standards have been introduced [2]. Apart from smart metering, SMI also facilitates utilities to perform demand response, and thus energy demand is reduced [5]–[7]. Therefore, various AM pilot projects have been implemented around the world, e.g. in Australia, Japan, the United States, and Europe, and most of these are designed for individual homes.

Recent trials of SMI in Asian countries involved high rises in which signal penetration is much more difficult because of the typical hard reinforced concrete structure in such buildings. Moreover, the large amount of electric meters scattered in high rises drives the need to accommodate high data flow which supersedes ordinary slower data flow SMI in the U.S or Europe, where normally data will be sent back to a utility from a single house. Such a huge aggregation of data creates the need to investigate building area networks (BANs) to cater for high-traffic SMI (HTSMI) [8]–[10]. A successful BAN requires good connectivity. A wireless sensor network is a potential candidate for BAN, and it has been widely adopted in industrial automation which transmitted the data over large areas using its multi-hopping ability [11].

ZigBee is one of the well-known wireless sensor network standards, and it has been widely adopted in different SMI projects as a result of its intrinsic mesh property, which provides good scalability and connectivity. In addition, the wireless characteristics facilitate a "plug and play" behaviour which benefits retrofitting into existing premises. As a matter of fact, in May 2009, ZigBee was recognized by the USA government as an open standard for the smart grid [12]. In light of the development of BAN, a generic architecture of ZigBee BAN (ZBAN) is proposed in this paper. The proposed ZBAN may be easily, accurately, and efficiently deployed in high-density-traffic BANs, such as in high rises. Based on the discussion of a ZBAN design for HTSMI, this paper set up a role model for BAN, which handles the inter-floor and infra-floor communication separately by using the Backbone Network (BN) and Floor Network (FN), respectively. As a result, BN and FN can adopt different designs in order to cater for their own traffic characteristics. For example, a multi-interface design has been proposed for the BN of ZBAN, while a single interface design has been adopted for the FN. It is because the traffic loading of BN is much heavier than FN. The design of BN and FN is not limited to ZigBee development but can apply any communication media, including wire line and wireless technology. To support the multi-interface BN development of ZBAN a multi-interface management framework (MIMF) was defined and designed such that it coordinates the operation between multiple interfaces, rendering the DR latency requirement [13] fulfilled. It is important to highlight that the development of MIMF is not the original intention of this paper. However, the previous work of dynSMIc channel management algorithms focused on the single interface device [14], [15] which did not handle the adjacent channel interference from multi-interfaces, and, thus, they cannot be applied in this case. Even though some multi-interface Wife designs have been discussed recently [15], [16], these designs cannot be directly adopted to ZBAN because the network characteristics of ZigBee and Wife are the same. Wife is a star network while ZigBee is a mesh network. Owing to these reasons, MIMF has been in development for the BN development of ZBAN.

The novelty in the MIMF design is twofold. First, MIMF minimizes the impact of adjacent channel interference by proposing a brand-new channel-selection mechanism for network formation. Second, a transmission interface-selection algorithm has been defined on top of the ZigBee route-selection procedure to ensure the device always transmits with the best condition interface and balancing the traffic load between different interfaces. By adopting the standard tree address assignment, MIMF supports a newly designed tree-based mesh (T-Mesh) network which provides both tree and mesh routing to maximize routing strength. Such a T-Mesh design is the first of its kind. The detailed design of the MIMF will be discussed in later sections. We will explain that the developed multi-interface ZBAN (MIZBAN) can be efficiently adopted in high-traffic BANs (e.g., high rises) to facilitate demand side management (DSM), which in turn improves the electricity generation efficiency. This paper is organized as follows. The design of ZBAN for HTSMI is discussed in Section II.

II. HIGH TRAFFIC ZIGBEE BAN FOR HTSMI

ZigBee belongs to the class of wireless sensor networks whose adoption bears a crucial meaning. It was discussed that, because of the inherent nature of scalability and mesh capability of ZigBee, ZBAN for SMI can be established and set up quickly in most existing buildings at a lower cost. Such an adaptive and scalable wireless structure will certainly help to build up an efficient demand response smart metering infrastructure for various smart grid applications. A good demand and response smart metering system will help the gross domestic product (GDP) grow healthily (less carbon emission) to a great extent.

Attention should be drawn to the fact that traffics in a BN in a high-rise BAN is a few hundred times more than in a traditional SMI network used for individual houses or low rises. Since data are normally collected every 15–30 min, the major challenge presented to the SMI system in a high-rise BAN is the design of high density traffic for smart metering. From the HTSMI system design perspective, high-density meter data aggregation in the backbone yields high traffic. In addition, it is not uncommon that wireless local area networks (WLANs) are normally used in households. WLANs operate in the same frequency band as ZigBee at 2.4 GHz. Under such circumstances, closely packed packets of different standards around the same general area may cause inference to the target SMI system. However, it was well documented that ZigBee and Wife may coexist [18].

Hitherto, the remaining issue is to design a mechanism for high traffic. To tackle the challenge of high traffic, the network structure of a multi-interface ZigBee BAN (MIZBAN) is proposed, and its conceptual architecture is illustrated in Fig. 1. MIZBAN is divided into two parts: the multi-interface backbone, in short, BN (vertical), and the single-interface mesh floor network, in short, MFN (horizontal).

Each interface represents a frequency channel. Components: in-home displays (Z-IHD) and ZBAN meter terminals (Z-BMT). Referring to Fig. 1, Z-IHD and Z-BMT belong to an MFN (horizontal) and are located at different premises o each floor. The Z-BMT is the interception point of the MFN and the BN. It connects to multiple electric meters using data buses, since electric meters are normally centralized into the meter room. If the Z-IHDs/Z-BMTs are situated at locations where the coverage cannot be reached by the MFN, a ZigBee router is added to relay the message to target devices. Z-IHDs, Z-BMTs and ZigBee routers are configured to form a ZigBee mesh network that can be easily established in each premise on a floor. The timely energy consumption and the price rate information can be delivered to users at any time when a user presses a button on the Z-IHD.

On the other hand, the BN consists of many Z-BMTs and a ZBAN Gateway (Z-BGW). A Z-BMT on a floor deals with horizontal traffic as well as vertical traffic. While the horizontal traffic allows energy audit and profiling, the vertical traffic facilitates a batch-mode data aggregation, thus rendering DSM. It is thus seen that a Z-BMT embraces traffic for both the MF and the BN.
The BN (vertical) is now discussed. It consists of two basic components: Z-BMT and Z-BGW. The incorporation of these units furnishes the features of load profiling and meter management. In the BN, meter readings are collected from the electric meters via a Z-BMT located on the corresponding floor. Meter data are aggregated (wirelessly) from Z-BMT to Z-BMT until they finally reach the Z-BGW. The Z-BGW is a unique device in a BAN that aggregates energy data from Z-BMT and transmits the data to the backend serve of the utility. The most challenging mission of MIZBAN is that the BN must ensure that the data flow between Z-BMTs in a BAN bear sufficient signal strength. and the signal transmission be accomplished with reasonably low latency. Based on the demand, a multi-interface framework accommodating

multiple channels is developed. To facilitate fast data delivery (and thus low latency), a ZigBee MIMF was devised in the MIZBAN BN. The vision is to enable parallel transmission by using multiple interfaces. Thus, the transmission time will decrease dramatically as the number of parallel channels is increased. However, parallel channels may incur potential adjacent interference.

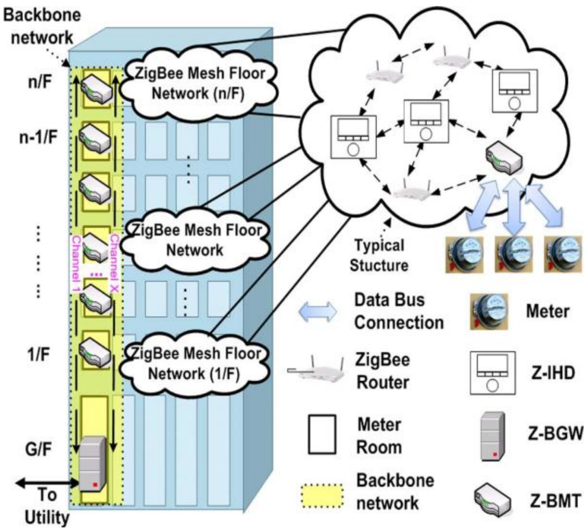

Fig.1 MIZBAN Design for HTSMII

Block Diagram Explanation:

Here, microcontroller is backbone of our project. We used ATmega16 microcontroller which is from AVR family & manufacturer of Atmel Co. and all the peripherals are connected to the microcontroller. ATmega16 is 8-bit microcontroller with RISC architecture. Also it has inbuilt ADC. It has +5V.
Fig. 2 shows the block diagram of two meters of building collecting the meter reading for zigbee BAN. communication.

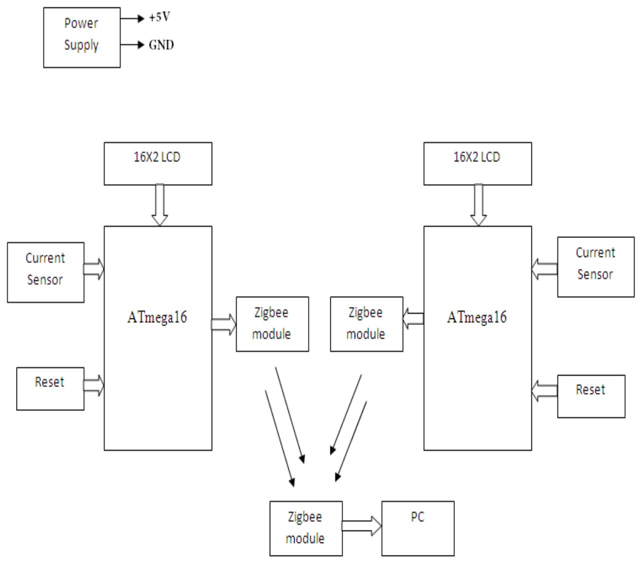

Fig. 2 Block Diagram

There are two transmitters and one is receiver which is connected to PC. Zigbee module is connected serially to microcontroller which is used for wireless interface framework accommodating multiple channels is developed.

III. ZIGBEE

ZigBee, a technical overview of wireless technology:

Why wireless? They claim it saves costs because no wires need to be installed, saving on installation costs. This view is a bit short. Wireless adds new problems. There can be much kind of problems: devices do not respond to each other, noise disturbance, neighbour interference, and many more. The biggest problem however is that if it does works today, it might give you problems tomorrow. Most progress on the technical part has been in prevention of all possible problems. So at this moment my personal experience is that it's very good already. However, you really need 'site survey tooling' to be able to pinpoint problems at customer locations. Remember that there are no wires to follow and measure.

In very few words I would say: "low cost, low power, very diverse possibilities".

What is Zigbee? Zigbee is a wireless networking standard that is aimed at remote control and sensor applications which is suitable for operation in harsh radio environments and in isolated locations. It builds on IEEE standard 802.15.4 which defines the physical and MAC layers. Above this, Zigbee defines the application and security layer specifications enabling interoperability between products from different manufacturers. In this way Zigbee is a superset of the 802.15.4 specification.

Zigbee is organized within the Zigbee Alliance. Many companies (>150) already adapted this technology, to get an impression just look here. 9 companies are called 'promoters' and they are the actual promoters of the Zigbee standard. These companies are: BM Group, Chipcon, Ember, and Free scale, Honeywell, Mitsubishi, Motorola, Philips and Samsung. On the right you will find a direct link to those companies. Standard is primarily aiming at monitoring and control applications. Low power consumption is the most important feature that makes battery operated devices operates for a long time. The amount of data throughput (bandwidth) is relatively low compared to wireless land for example, but with

250kbps for many applications more than enough. The distance between 2 nodes can be up to 50 meters but be aware the each node can relay data to the next making a very big network, covering significant distances, possible.

Hardware (Physical and MAC layers) at the moment all solutions work on 2.4GHz but specified is also 915MHz for North America and 868MHz for Europe. The 2.4GHz frequency band is a license free band, so a ZigBee product may be used all over the world. All current products seem to be using the 2.4GHz band at the moment. Take a look at the next table for a few differences between the bands:

Frequency	868 MHz	915 MHz	2.4GHz
Bandwidth	20 kbps	40 kbps	250 kbps
Nr. of channels	1	10	16
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In all bands DSSS (Direct sequence spread spectrum) is used. 868 and 915 MHz are using Binary Phase Shift Keying and 2.4GHz uses O-QPSK (Offset Quadrature Phase Shift Keying).

These license free frequencies are becoming more and more crowded and noisy. The 802.15.4 specification has many features to ensure a reliable operation under the worst environmental conditions. Some keywords: Clear Channel Assessment, Quality Assessment and Receiver Energy Detection. To prevent problems caused by it, a technique called Carrier Sense Multiple Access (CSMA) is used to only transmit when this does not cause problems (collisions).

Like in any network data is transmitted in packets. ZigBee's packets have a maximum size of 128 bytes including protocol overhead. In total there is room for a maximum of 104 bytes. Compared to Ethernet this is rather small but for most applications that ZigBee will be used for this is more than enough (how many bytes do you need to switch on a light? (No, this is not a light bulb joke)).

For real-time features, ZigBee has the possibility to define high priority messages. This is achieved by use of a guaranteed timeslot mechanism so that the high priority messages can be sending as fast as possible.

ZigBee uses 2 kinds of addressing. There is a 64 bit IEEE address that can be compared to the IP address on the internet. There is also a 16 bit short address. The short addresses are used once a network is setup so this makes a total of 2^16 = ~64000 nodes within one network possible. This is enough for almost anything imaginable. If you need more than you can off course design a gateway node.

The ZigBee upper layer the layers above that what 802.15.4 specifies is what we call the ZigBee standard (look above for a graphical overview). Many aspect of the network are specified in this layer, like: Application profiles, security settings and the messaging.

ZigBee is known because of its mesh network architecture but it does also support a star topology or cluster tree or hybrid architecture. Depending on the application or situation each kind of topology has its own advantages and disadvantages. A star topology is very simple, all nodes directly communicate with one central node (like a star...). The mesh topology is more complicated, each node may communicate with any other node within range. It's easy to understand that this gives many possible routes through the network; this makes it a very robust topology because bad performing routes can be ignored. The cluster tree topology is basically a combination of star and mesh. A small-scaleMIZBAN was set up to obtain the baseline data of the system performance. This is referred as minimum effort. The baseline data includes the FN tree and the signal propagation path. The FN tree and the signal propagation distance is a logical term determined by the transmitter power and the sensitivity of the receiver.

- XBEE MODULE XB24-Z7WIT-004:

This is the XBee XB24-Z7WIT-004 module from Digi. Series 2 improves on the power output and data protocol. Series 2 modules allow you to create complex mesh networks based on the XBee ZB ZigBee mesh firmware. These modules allow a very reliable and simple communication between microcontrollers, computers, systems, really anything with a serial port! Point to point and multi-point networks are supported.

These are essentially the same hardware as the older Series 2.5, but have updated firmware. They will work with Series 2.5 modules if you update the firmware through X-CTU.

Features:

- 3.3V @ 40mA
- 250kbps Max data rate
- 2mW output (+3dBm)
- 400ft (120m) range

- Built-in antenna
- Fully FCC certified
- 6 10-bit ADC input pins
- 8 digital IO pins
- 128-bit encryption
- Local or over-air configuration
- AT or API command set

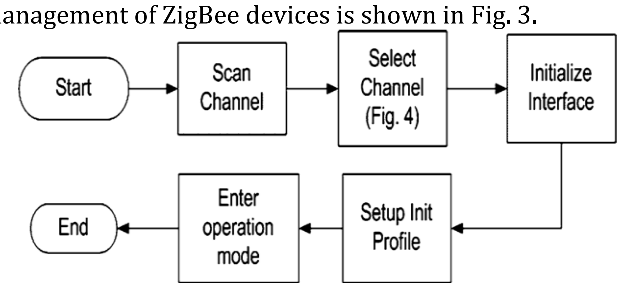
The electric grids components, energy production plants, distribution lines and loads need to become "smart". Smart grid is a new concept that refers to technologies devoted to modernising the electric grids, creating an intelligent system that responds to peaks of energy usage, controls power demand, better incorporates local production of clean energy and accurately measures consumption. Automatic Meter Reading (AMR) and Automatic Meter Infrastructure (SMI) are smart metering technologies that contribute to the smart grid.

AMR technology enables energy meters to autonomously report customer consumption, hourly or even more frequently in a day, while SMI provides an infrastructure to aggregate, record and send that information to a service provider. SMI goes even further; it creates a two-way network between the smart energy meters and the service provider, allowing individuals and companies to improve their energy usage. In-home energy displays, thermostats, light switches and load controllers are already a reality. Utilities also beneath from this two-way networking since it improves reliability, and allows for dynSMIc billing and appliances control.

Wireless technologies are becoming more common since they avoid the hassle and cost of installing and maintaining a cable infrastructure to support a network. Regarding SMI/AMR, GPRS, Wi-Fi, Bluetooth and ZigBee are the most promising wireless technologies. General Packet Radio Service (GPRS), has the advantage of using an already existing infrastructure, but it is an expensive solution. Hardware costs as well as power consumption (transmission requires bursts of more than 2 A) are higher than in other wireless technologies. In addition, utilities need to pay for the communications service, subscribing it from a telecoms provider.

IV. MULTI-INTERFACE MANAGEMENT FRAMEWORK

It was explained in Section II that a MIMF is required to speed up the traffic by enabling parallel transmission with multiple interfaces in a MIZBAN BN. The MIMF is an application management module to coordinate the operation of different interfaces for the initialization of network formation and data transmission. It is vital to stress that the MIMF is an application module that may be implemented on top of any ZigBee protocol core, thus it is interoperable with new and old versions of the ZigBee standard. As a result, MIMF inherits MAC and network-layer characteristics of ZIgBee including routing, address assignment, and media access control. The proposed MIMF is a service sub-layer that interacts with the application profile and multiple network layers. By taking these factors into consideration, a MIMF design incorporating the Z-BGW and the Z-BMT was introduced to support the backbone communication of MIZBAN. Since MIMF is created for HTSMI, a smart metering device is powered by the main supply in order to support a low-latency and high-reliability service. Therefore, energy efficiency is not the main concern for the MIMF design. The MIMF architecture for the management of ZigBee devices is shown in Fig. 3.



.Fig. 3. Network formation procedure of multi-interface coordinator

ZigBee supports both tree and mesh routing, as does MIMF. Outstanding from ZigBee, MIMF considers tree routing as a backup path of mesh routing. When mesh routing fails (for instance, as a consequence of routing table overflows), MIMF simply forwards the message to its parent (next hop of tree route which is defined by address assignment). The parent node can further handle message with mesh routing. Under such a curriculum, the service would not be suspended, and transmission delay would slightly increase. Such a novel design will be referred to hereafter as T-Mesh. In the present design of the MIMF for MIZBAN, the Z-BGW is configured as the coordinator and the Z-BMT is configured as the router. Thus, the Z-BGW takes care of the network formation and mitigates potential interference. In essence, the Z-BGW initializes a personal area network (PAN) and governs the router discovery and provides permission for members joining the PAN. The Z-BGW and the Z-BMT will determine the best transmission interface to achieve a low latency which renders an efficient DSM. [14], [19] [20].

A. Network Formation:

In brief, the network formation procedure of the MIMF ZigBee Coordinator (Fig.6) is similar to the formation of an ordinary ZigBee network. First, the coordinator performs the channel scanning via the master interface in order to acquire the LQI of the channel. LQI, similar to the ordinary meaning of receive signal strength indicator (RSSI), is defined in the ZigBee standard as a measure of the channel signal strength. After the channel scanning is performed, the coordinator selects the operating channel for each interface. To minimize the adjacent channel interference and ensure the channel quality, a channel selection algorithm was developed. The algorithm is shown in Fig. 4.

After every interface has been initialized, the coordinator enters the operation states and other ZigBee devices such as routers and end devices may join the network. On the other hand, the multi-interface router, which is a unique device, also performs channel scan with its master interface. The master interface of the router initializes with the best LQI channel and joins the multi-interface network. The router then receives an all-operation channel ID from the master interface, and, subsequently, the router initializes the rest of the interfaces with given channel IDs. The initialization process of a ZigBee router is summarized in Fig. 5.

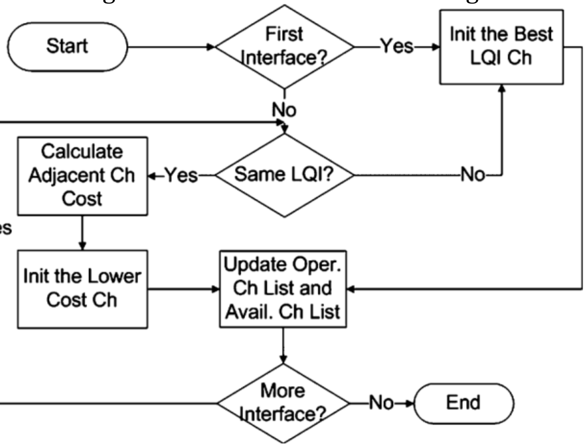


Fig. 4. Channel selection algorithm

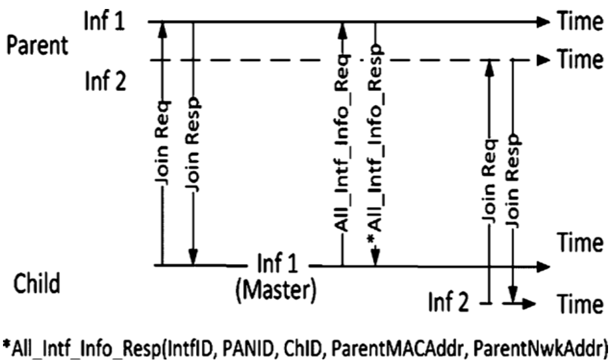


Fig. 5 Initialization process for a multi-interface router

B. Data Transmission:

To further enhance the network performance, the MIMF devices select the interface with the lowest transmission cost for data transmission. The interface selection algorithm is applied to both the coordinator and routers. The details of the data transmission are illustrated in Fig. 6.

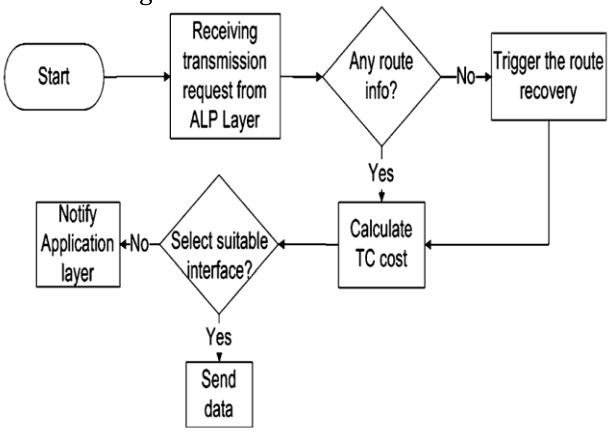


Fig. 6. Transmission interface selection algorithm for MIMF.

After receiving the data transmission request, MIMF checks its route database which records the transmission cost of every interface for a specific destination. If MIMF does not find any record in the database, it instructs all interfaces to initiate a ZigBee standard route discovery to record path cost (C{P}) and round-trip time (RTT). RTT generally defines the period of time from sending out data/request to receivingthe corresponding acknowledgment/ response. Path cost indicates the link quality of routing path, and it is defined by ZigBee standard[21]. With end to end routing path information, the transmission cost (TC) of every interface can be calculated. For interface , the transmission cost (TC_i) is given as

$$TC_i = RTT_i * \{CP\}_i \tag{1}$$

Certainly, the lowest transmission cost interface will be selected and the selection result will also be recorded in the route database. Typically, the transmission will be updated after every transmission has been completed because the new RTT can be recorded. Adoption of RTT has several advantages. Firstly, the RTT measurement is only carried by sender and so no extra network traffic has been generated. Second, RTT provides the updated transmission condition of the entire path because the path cost cannot be updated frequently because it can only be updated by performing route discovery, which may degrade the network performance. Furthermore, RTT can also indicate the workload of every interface because a long RTT may imply a high queuing delay. Therefore, it is a good indicator for load balance to avoid overloading a single interface.

Apart from RTT cost (C{P}) is another parameter for interface selection. Before going into details of path cost, the concepts of path and link must be introduced. A path of length refers to a routing path with L – 1 hops which consists of L devices [D_1, D_2...D_L].

V. CONCLUSION

To facilitate efficient deployment of SMI for existing buildings, a first BAN is presented in this paper which suggested breaking the network into backbone and floor network to handle inter-floor and infra-floor communication separately. To gain more insight, this paper discussed the practical design of a BAN based on ZigBee. To cater to high traffic and meet the U.S. government latency requirement, a MIMF was defined and designed to coordinate the operation between multiple interfaces based on a newly designed T-Mesh ZigBee. As a result, a ZigBee MIZBAN is proposed for HTSMI. A pilot was conducted. By conducting an experiment and using a simulation model, the ALL of the backbone network and the floor network was investigated. From the experimental results, it has been proved that the performance of the backbone and floor network improved by 40% if the number of network interface increases from one to two. By adopting the quadric-interface ZigBee module in a measurement in a twenty-three floor building, the SMI improved the ALL of the backbone and the mesh floor network by 75%(at 0.7 s) and 67%(at 0.09 s) respectively. To help designers to design HTSMI, this paper has made seven recommendations for MIZBAN (refer to SectionV). Such recommendations ensure the design of SMI to fulfil the tightest US government Demand Response requirement for a latency value of less than 0.25 s. There are two directions for future work. First, the BAN design will further applied to other communication media including wire line and wireless in order to conduct a comparative study. As a result, the full picture of the HTSMI development and recommendations can be provided. Second, the performance of MIZBAN will further be improved by conducting a coexistence study with other wireless technologies in order to strengthen its anti-interference capability.

REFERENCES

[1] A. Ipakchi and F. Albuyeh, "Grid of the future," *IEEE Power Energy Mag.*, vol. 7, no. 2, pp. 52–62, Mar.–Apr. 2009.

[2] V. C.Gungor, D. Sahin, T. Kocak, S. Ergut, C.Buccella, C.Cecati, and G. P. Hancke, "Smart grid technologies: Communication technologies and standards," *IEEE Trans. Ind. Inf.*, vol. 7, no. 4, pp. 529–539, Nov. 2011.

[3] P. Siano, C. Cecati, H. Yu, and J. Kolbusz, "Real time operation of smart grids via FCN networks and optimal power flow," *IEEE Trans. Ind. Inf.*, vol. 8, no. 4, pp. 944–952, Nov. 2012.

[4] W. Su,H. Eichi,W. Zeng, andM.Y.Chow, "Asurvey on the electrification of transportation in a smart grid environment," *IEEE Trans. Ind. Inf.*, vol. 8, no. 1, pp. 1–10, Feb. 2012.

[5] F. Benzi, N. Anglani, E. Bassi, and L. Frosini, "Electricity smartmeters interfacing the households," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4487–4494, Oct. 2011.

[6] J.Haase, J.M. Molina, andD.Dietrich, "Power-aware system design of wireless sensor networks: Power estimation and power profiling strategies," *IEEE Trans. Ind. Inf.*, vol. 7, no. 4, pp. 601–613, Nov. 2011.

[7] P. Palensky and D. Dietrich, "Demand side management: Demand response, intelligent energy systems, smart loads," *IEEE Trans. Ind. Inf.*, vol. 7, no. 3, pp. 381–388, Aug. 2011.

[8] Y. H. Jeon, "QoS requirements for the smart grid communications system," *Int. J. Comput. Inf. Sci.*, vol. 11, no. 3, pp. 86–94, 2011.

[9] Y. Simmhan, Q. Zhou, and V. K. Prasanna, "Chapter: Semantic information integration for smart grid applications," in *Green IT: Technologies and Applications*. Berlin, Germany: Springer, 2011.

[10] Z. M. Fadlullah, M. M. Fouda, N. Kato, A. Takeuchi, N. Iwasaki, and Y. Nozaki, "Toward intelligent machine-to-machine communications in smart grid," *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 60–65, Apr. 2011.

[11] P. T. A. Quang and D. S. Kim, "Enhancing real-time delivery of gradient routing for industrial wireless sensor networks," *IEEE Trans. Ind. Inf.*, vol. 8, no. 1, pp. 61–68, Feb. 2012.

[12] U.S. DOE, "Locke, Chu Announce Significant Steps in Smart Grid Development," 2009. [Online]. Available:http://www.energy.
gov/news2009/7408.htm.

[13] Dept. Energy Commun., "Communications requirements of smart grid technologies," Oct. 5, 2010.

[14] E. Toscano and L. L. Bello, "Multichannel superframe scheduling for IEEE 802.15.4 industrial wireless sensor networks," *IEEE Trans. Ind. Inf.*, vol. 8, no. 2, pp. 337–350, May 2012.

[15] Q. Yu, J. M. Chen, Y.-F. Fan, X.-M. Shen, and Y.-X. Sun, "Multichannel assignment in wireless sensor networks: A game theoretic approach," in *Proc. INFOCOM*, Mar. 2010, pp. 1–9.

[16] I.Ho, P. Lam, P. Chong, and S. Liew, "Harnessing the high bandwidth of multi-radio multi-channel 802.11n mesh networks," *IEEE Trans. Mobile Comp.*, vol. PP, no. 99, 2013, DOI: 10.1109/TMC.2013.9.

[17] D. J. Yang, X. Fang, and G. L. Xue, "Channel allocation in non-cooperative multi-radio multi-channel wireless networks," in *Proc. IEEE INFOCOM*, Mar. 2012, pp. 882–890.

[18] Y. Peizhong, A. Iwayemi, and Z. Chi, "Developing ZigBee deployment guideline under Wife interference for smart grid applications," *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 110–120, Mar. 2011.

[19] Z. Hanzálek and P. Jurčík, "Energy efficient scheduling for cluster-tree wireless sensor networks with time-bounded data flows: Application to IEEE

802.15.4/ZigBee," *IEEE Trans. Ind. Informat.*, vol. 6, no. 3, pp. 438–450, Aug. 2010.
[20] C. Caione, D. Brunelli, and L. Benini, "Distributed compressive sampling for lifetime optimization in dense wireless sensor networks," *IEEE Trans. Ind. Inf.*, vol. 8, no. 1, pp. 30–40, Feb. 2012.
[21] "ZigBee-2007 Specification," ZigBee Alliance, ZigBee Doc. 053474r17, Jan. 17, 2008.
[22] T. Y. Chen, J. Burnett, and C. K. Chau, "Analysis of embodied energy use in the residential building of Hong Kong," *Energy*, vol. 26, no. 4, pp. 323–40, Apr. 2001.
[23] OPNET University Program [Online]. Available: http://www.opnet. com/services/university/
[24] S. Y. Seidel and T. S. Rappaport, "914 MHz path loss prediction models for indoor wireless communications in multifloored buildings," *IEEE Trans. Antennas Propag.*, vol. 40, no. 2, pp. 207–217, Feb. 1992.
[25] E. Toscano and L. Lo Bello, "Cross-channel interference in IEEE 802.15.4 networks," in *Proc. WFCS*, May 2008, pp. 139–148.
[26] L. Lo Bello and E. Toscano, "Coexistence issues of multiple co-located IEEE 802.15.4/ZigBee networks running on adjacent radio channels in industrial environments," *IEEE Trans. Ind. Inf.*, vol. 5, no. 2, pp. 157–167, May 2009.