Interference-Mitigated ZigBee Based Advanced Metering Infrastructure

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Abstract—An interference-mitigated ZigBee based Advanced Metering Infrastructure solution, namely IMM2ZM, has been developed for high traffics smart metering. The IMM2ZM incorporates multi-radios multi-channels network architecture and features an interference mitigation design by using multi-objective optimization. To evaluate the performance of the network due to interference, the channel swapping time ($T_{sw}$) has been investigated. Analysis shows that when the sensitivity ($P_{rx}$) is less than -12dBm, $T_{sw}$ increases tremendously.

Evaluation shows that there are significant improvement in the performance of the application layer transmission rate ($\sigma$) and the average delay ($D$). The improvement figures are: $\sigma > -300\%$ and $D > 70\%$ in a 10-floor building; $\sigma > -280\%$ and $D > 65\%$ in a 20-floor building; and $\sigma > -270\%$ and $D > 56\%$ in a 30-floor building. Further analysis reveals that IMM2ZM results in typically less than 0.43 sec delay for a 30-floor building under interference. This performance fulfills the latency requirement of less than 0.5 sec for SMs [31] in the USA. The IMM2ZM provides a high traffics interference-mitigated ZigBee Advanced Metering Infrastructure solution.

Index Terms—Smart Grid, High traffics AMI, ZigBee, Interference mitigation, Multi-objective optimization, Multi-radios, Multi-channels.

I. INTRODUCTION

The development of smart Grid is imperative and is identified by the USA Department of Energy as the key development revitalizing USA’s electric infrastructure. Smart metering (SM) supports distributed technologies and consumer participation, and extracts energy data using two-way communication [1]-[2]. Pertinent to the nature of SM, the wireless sensor network (WSN) is a vital component in smart grid communication [3]-[4]. The ZigBee wireless protocol is commonly used in WSN and adopted as one of the standards in SM [5].

In most smart cities, there are many tall buildings. These high rises normally present a hostile environment for wireless signals. ZigBee is dedicated to smart energy applications and has been extensively adopted in smart energy applications. By taking advantage of ZigBee Smart Energy open standard and its mesh capability for scalability, researchers find it advantageous and efficient to adopt ZigBee in SM applications. It was pointed out that, in urban area, a huge aggregation of data created the need to investigate building area networks (BANs) [6, 7]. However, high rises are typically comprised of hard reinforced concrete, rendering signal propagations are difficult in general. A modern smart city is normally full of civilians with enriched lives that normally demands communication using WiFi or Bluetooth for wireless delivery in the same frequency band. Thus, the application of ZigBee to Advanced Metering Infrastructure (AMI) in high traffic areas needs to be handled with special consideration to mitigate the potentially hostile interferences.

A former design of HTAMI did not consider interference [8]. However, the high attenuation and dispersive characteristics of concrete construction in ZigBee BAN (ZBAN) demands AMI features that mitigate interference. In this investigation, an interference model will be investigated. A new design and implementation of interference-mitigated ZBAN for HTAMI will be proposed and developed.

In the design, there are multiple parameters that are indicative for consideration, for instance, high power and high throughput for fast data transmission and low latency for good QoS etc. However, the magnitude of these factors may bear contradictory meanings, for example, the high power transmission that causes the feeling of potential health hazard versus the well accepted low power, the high throughput demanded by users versus the low throughput generally achieved in a hostile environment, the low latency commonly requested versus the high latency normally occurs in noisy communications. A salient solution can be achieved by optimizing these key parameters. In this investigation, prior experimental work was conducted to acquire the background data pertinent to the characteristics of the ZBAN.

In the experiment, measurement data of a five-storey building was conducted to collect prime data to pave the way for the large scale modeling and analysis of the complicated high traffics scenario. The interference mitigation model for ZigBee transmission will also be derived. It will be explained that the Non-Dominated Genetic Algorithm-II (NSGA-II) is customized to obtain the pareto fronts from which the appropriate design will be developed. The OPNET is then employed for a large scale evaluation and analysis. The measured data are used for optimization and model generation in the OPNET environment. Measurement results show that the developed IMM2ZM satisfies the demand for high traffics interference mitigation.
response requirement of the US standards amongst the hostile environments of HTAMI.

The contribution of this paper is as follows:
1. A prior measurement was performed to obtain the prime data for the formulation of objective functions of the optimal solution at large scale;
2. An interference mitigation model has been derived;
3. A customization to NSGA-II [26] optimization has been developed;
4. OPNET evaluation has been implemented for large scale analysis;
5. A channel swapping interference-mitigated multi-radio multi-channel ZigBee metering (IMM2ZM) system has been implemented for IMM2ZM system for high traffics AMI.

This paper is organized as follows: The introduction of the related work is given in Section II. The design of IMM2ZM is presented in Section III and the system IMM2ZM model in Section IV. The multi-objective optimization for the IMM2ZM using NSGA-II is described in Section V. The analysis and evaluation of the IMM2ZM are shown in Section VI. Finally, a conclusion is given in section VII.

II. MIZBAN AND RELATED WORK

The demand for HTAMI in modernized cities has been significantly increasing. Wireless data delivery basically meets the “versatility” need of HTAMI. By virtue of the open standard nature and mesh capability, ZigBee is the populated candidate adopted by the industry [8]. It is evidenced that ZigBee has been applied to SM [1].

Derived from practical needs, a generic design for HTAMI, namely multi-interface ZigBee building area network (MIZBAN), was developed by partitioning the network into two parts, namely the Backbone Network and the Floor Network and multiple interfaces were developed [8]. In the MIZBAN, interference was not particularly treated. It is well evidenced that WiFi, Bluetooth and ZigBee operate in the same frequency band [12]. In addition, mobile signals such as 3G, LTE also operate in the vicinity which may cause adjacent channel or cross channel interference. In order to provide a good quality of service, interference mitigation for HTAMI must be developed.

Limited former work was devoted to interference in ZigBee. For instance, ZigBee deployment guidelines which include the safe distance and the safe offset frequency for smart grid applications were developed in an attempt to mitigate the potential WiFi interference [13]. However, the WiFi interference in high rises environment is much more complex since the apartments are close to one another and WiFi signals scatter around the environment. Therefore, deployment guidelines alone as captioned in [13] are not sufficient. In general, an optimal solution to mitigate interference is difficult to be obtained.

A generic cross layer optimization for caching was also discussed for multi-interface multi-radio (M2) WSN [18]. However, only a few discussions focused on IEEE 802.15.4. A comparative study of WiFi and IEEE 802.15.4 for M2 was provided in [19]. A M2 MAC layer design for IEEE 802.15.4 was also presented in [20] but the discussion was only based on the MAC layer of ZigBee and the network layer and application layer were not considered. It is seen that there is still much room for further development. In this paper, based on IEEE 802.15.4, a cross layer design into the network layer and application layer will be investigated. Particular interest will be devoted to the interference mitigation design for HTAMI. In this investigation, an interference mitigation solution, namely IMM2ZM, has been developed and analysis will be discussed.

III. DESIGN OF IMM2ZM

A. IMM2ZM Basic Structure

Akin to MIZBAN [8], the proposed architecture of IMM2ZM is also divided into the backbone network and the floor network (Fig. 1). The backbone network refers to a multi-radio ZigBee mesh network that is formed by a Reading Centralizer (RC) with multiple Reading Meter Terminals (RMT) deployed into the meter room on each floor (this is a common configuration in Asia). Multiple-radio was devised in the IMM2ZM backbone network to share the traffic loadings to facilitate fast data delivery. The backbone network interacts with the Meter Data Management System (MDMS) to provide the utility services such as meter management (MM), Meter Record Oder (MRO) and Load Profile (LP). Apart from the backbone network, RMTs are connected wirelessly with In-Home Displays (IHDs) to form another ZigBee single-radio network, namely floor network, to facilitate end users to obtain real time meter readings. The functions of each component are summarized as follows:

- Fig. 1 Architecture for IMM2ZM.

The IMM2ZM incorporates multiple channels to achieve good latency [8]. Also, channel swapping is incorporated to facilitate interference mitigation.

B. Multi-Layer Design of IMM2ZM Backbone Communication

The network layer and the application layer of the M2 backbone network have been designed to interoperate with the current ZigBee standard. ZigBee implements two layers on top of the 802.15.4 MAC layer, namely the Network layer and the Application security layer. The IMM2ZM design consists of the followings: network initialization, swappable
channel registration, address distribution, routing control, application security. The process tasks and protocol architecture will be described.

The Network layer is situated above the IEEE 802.15.4 MAC. One of the missions of the network layer is to empower IEEE 802.15.4 devices to deal with a variable network size application. There are three main tasks for the network layer: (1) network initialization, (2) address distribution and (3) routing control. The network initialization includes the management of network formation and the devices. Address distribution aims at arranging a unique network address to each device in a ZigBee network. Routing control is a mechanism to maintain the end-to-end reliability and transfer packets through the network.

1) Network Initialization

Basically, this design is mainly applied to multi-radio devices, e.g. the RC and RMTs. Generally, RMT is the backbone infrastructure which aims to relay the information across different floors to the RC.

When an interference source is detected at an occupied channel, the channel-swapping process will be activated to ensure the reliability of the IMM2ZM system. For example, if the ZigBee radio I of RMT A at channel B is jammed by strong interference and thus experience continuous transmission failure, the ZigBee radio I of RMT A will issue the Channel_Jam_Report to the RC with the jammed channel ID. Then the RC will broadcast the Channel_Scan_Req (channel ID) to all RMTs through channel A. After the channel scanning, the RC will send Channel_Result_Req to each RMT to collect the scan results and then select a new channel and broadcast Channel_Update_Req to all RMTs.

The selection of the new channel is mainly based on the principle that channels with larger frequency separation intercept less co-channel interference. Normally there are 16 frequency channels available in IEEE 802.15.4, namely channel 1 to channel 16.

Initially, channel 1 will be assigned as the operating channel. If a traffic jam is detected, the channel swapping will be incurred based on (1).

\[
CH_{\text{new}} = \begin{cases} 
17 - CH_{\text{old}}, & CH_{\text{old}} \in \{x \mid x = 2k - 1, k \in Z^+\} \\
19 - CH_{\text{old}}, & CH_{\text{old}} \in \{x \mid x = 2k, k \in Z^+ & k > 1\} \\
1 & CH_{\text{old}} = 2
\end{cases}
\] (1)

where \(CH_{\text{new}}\) refers to the channel to be selected, \(CH_{\text{old}}\) is the previous channel with jam before channel swapping.

The channel jamming issue will be detected on the new channel until no Channel_Jam_Report is received.

1) Address Distribution

When a device joins the network, it is given a 16-bit short address (network address). Such address is a unique address in the ZigBee network. Two distributed addressing schemes are available in the ZigBee Network – the Tree Address Assignment Scheme and the Stochastic Address Assignment Scheme.

2) Routing Control

Basically, ZigBee supports two routing mechanisms: hierarchical (also known as tree) and table driven (also known as mesh) routing. In particular, Mesh Network Routing (Table-driven routing) is basically similar to the Ad hoc On-Demand Distance Vector (AODV) routing protocol [22] for general multi-hop ad hoc networks. For the design of IMM2ZM, the address distribution and routing mechanism should be considered together since these two schemes affect each other.

IV. THE IMM2ZM MODEL

In this section, a system model of IMM2ZM is presented. The purpose is to aid a system designer to estimate the performance of IMM2ZM. Let’s consider an IMM2ZM with \(k\) channels in an \(n\)-floor building experiencing the interference from \(x\) WiFi devices, \(y\) ZigBee devices, \(z\) Bluetooth devices and \(m\) other wireless devices such as 3G and LTE devices from both adjacent channel of IMM2ZM and non-IMM2ZM network. The total interference power, \(P_{\text{int}}(x,y,z,m)\), received by a single IMM2ZM ZigBee receiver is calculated as [22]:

\[
P_{\text{int}}(x,y,z,m) = P_{\text{int}} + \sum_{i=1}^{17} P_{\text{int}} + \sum_{i=1}^{y} P_{\text{int}} + \sum_{i=1}^{z} P_{\text{int}} + \sum_{i=1}^{m} P_{\text{int}}_{\text{others}}
\]

where \(P_{\text{int}}, P_{\text{int}}, P_{\text{int}}, P_{\text{int}}, P_{\text{int}}_{\text{others}}\) are the noise power, WiFi interferer power, ZigBee interferer power, Bluetooth interferer power and interferer power from other sources respectively.

The Bit Error Rate (BER) of a single IMM2ZM ZigBee receiver interfered by \(x\) WiFi devices, \(y\) ZigBee devices, \(z\) Bluetooth devices and \(m\) other wireless devices including from both adjacent channel of IMM2ZM and non-IMM2ZM network, \(B_{x,y,z,m}\), is then evaluated as:

\[
B_{x,y,z,m} = Q\left(\sqrt{2\gamma}\sum_{i=1}^{17} P_{\text{int}} + \sum_{i=1}^{y} P_{\text{int}} + \sum_{i=1}^{z} P_{\text{int}} + \sum_{i=1}^{m} P_{\text{int}}_{\text{others}} + PG - P_{\text{fade}}\right)
\]

Where [23]

\[
Q(x) = \frac{1}{\sqrt{2\pi}} \int \exp(-\frac{u^2}{2})du
\]

\(P_{\text{fade}}\) is the fading loss, and PG is the process gain, and \(\gamma \approx 0.85\) [25].

Special consideration is drawn to the derivation of BER of ZigBee packets amongst the interference of all potential sources. The extreme cases that packets are transmitted successfully (\(P_{\text{succ}}\)) as well as the case that all IMM2ZM devices are busy (\(P_{\text{bs}}\)) are considered. Assuming the packet length is \(L\) bits and \(h\) IMM2ZM devices are competing. Denote \(P_{\text{succ}}\) be the probability of successfully transmitted a correct packet (with every bit in the packet correctly transmitted) and \(P_{\text{bs}}\) be the probability that all IMM2ZM devices are busy when a packet is sent to a specific ZigBee transceiver of IMM2ZM devices. \(P_{\text{succ}}\) and \(P_{\text{bs}}\) are evaluated as:

\[
P_{\text{succ}} = (1 - B_{x,y,z,m})^h
\]

\[
P_{\text{bs}} = (1 - \tau)^h
\]

ZigBee performs Clear Channel Assessment (CCA) four times before reporting failure, thus the transmission probability, \(\tau\), is evaluated from the channel busy probability, \(\alpha\). In this work, four channels are used, hence \(\alpha\) is defined as follows:

\[
\tau = 1 - \alpha^4
\]

For performance evaluation purpose, the packet error rate, \(P_{\text{err}}\), is evaluated by incorporating \(P_{\text{bs}}\) into consideration. Hence \(P_{\text{err}}\) is now defined as:

\[
P_{\text{err}} = 1 - P_{\text{succ}}\frac{1}{P_{\text{bs}}}
\]

In IMM2ZM, the channel busy probability, \(\alpha\), is then
derived as:
\[ \alpha = 1 - (1 - \alpha_{IMM2ZM})^2 (1 - \alpha_{WiFi}) (1 - \alpha_{IMM2ZM}) + \alpha_{IMM2ZM} \]
where \( \alpha_{IMM2ZM} \), \( \alpha_{WiFi} \), \( \alpha_{IMM2ZM} \), and \( \alpha_{IMM2ZM} \) denote the CCA busy probability of a given IMM2ZM devices due to Bluetooth devices, Wi-Fi devices, ZigBee respectively. \( \alpha_{IMM2ZM} \) refers to other interferers such as 3G and LTE devices.

The tagged IMM2ZM device is modeled as M/G/1 queueing system. It is assumed that: (i) \( h \) IMM2ZM devices are competing; (ii) each IMM2ZM device generates packet conforming to Poisson process of packet generation rate \( \lambda_h \); (iii) Data packet size is constant with \( b_m \) seconds. By incorporating \( T_{BO} \), \( T_{Turn} \), \( T_{SW} \), \( T_{ACK} \), and following [24], \( \alpha_{IMM2ZM} \) is expressed as:
\[ \alpha_{IMM2ZM} = \frac{(h-1)(1-\alpha_{IMM2ZM})}{\lambda_h} + \frac{1}{E[D_i]} \]  

(10)

where \( T_{BO} \), \( T_{Turn} \), \( T_{SW} \) and \( T_{ACK} \) are the time for backoff, turn around, switching and transmit acknowledgement respectively. In (10), channel swapping is specifically addressed to ensure the busy probability of IMM2ZM devices has taken consideration of interference. \( E[D_i] \) is the average number of packets served by the tagged IMM2ZM device in a busy period and is defined as \( E[D_i] = 1/(1-\rho) \) where traffic intensity \( \rho = \lambda_h E[D_i] + b_m + 2T_{SW} + T_{ACK} + T_{BO} \). \( E[D_i] \) denotes the queueing delay which refers to the duration that the packet in the system queues before transmission or discarded. Substituting \( E[D_i] \) to (10), \( \alpha_{IMM2ZM} \) is manipulated as:
\[ \alpha_{IMM2ZM} = \frac{\lambda_h (h-1)(1-\alpha_{IMM2ZM})}{\lambda_h} + \frac{1}{\lambda_h (b_m + 2T_{SW} + T_{ACK} + T_{BO})} \]  

(11)

With the newly defined \( P_{err} \) in (8), the single hop transmission channel throughput, \( S \), for an IMM2ZM device with single radio is expressed as:
\[ S = 8L_p P_i \]  

(12)

\[ P_i = (1 - \tau)^h \]  

(13)

\[ P_j = h \tau (1 - \tau)^{j-1} (1 - P_{err}) \]  

(14)

\[ P_j = h \tau (1 - \tau)^{j-1} P_{err} \]  

(15)

\[ P_j = 1 - P_i - P_j \]  

(16)

where \( L_p \) is the payload of packet in bytes; \( P_i \) is the probability that the time slot is idle; \( P_j \) is the probability of successful transmission without channel error and collision in a time slot; \( P_j \) is the probability of channel error occurs in a time slot; \( \delta \) is the duration of idle time slot; \( T_i \) is the average channel busy time due to successful transmission; \( T_i \) is the average channel busy time due to collision; and \( T_f \) is the transmission failure time due to channel error. \( T_i \), \( T_f \), and \( T_f \) follow the meanings from [21] and the relationship between \( T_i \), \( T_f \), and \( T_f \) are given by:
\[ T_i = b_m + T_{ACK} + 2T_{IFS} \]  

(17)

\[ T_f / T_f = b_m + T_{ACK} + T_{IFS} \]  

(18)

The overall transmission of IMM2ZM with \( k \) radios is now investigated. Consider a high rise building with \( n \) floors and each floor has \( N \) apartments. Assuming a smart meter stores \( N_i \) records for data recovery and the record length is \( N_i \) bits. The sleep-to-join time for each node is \( T_{CS} \). Therefore, the meter reading collection duration for a specific floor demanding \( c \) hops from transceivers, \( T(c) \), is newly derived according to the detail construction of the building as:
\[ T(c) = \left( \frac{N_i N_i + T_{CS}}{S} \right) \times \left( \frac{c}{k} \right) \]  

(19)

Thus, \( T(c) \) gives an account of multiple hops and multi-channels. The general knowledge of the average delay, \( D \), is the amount of time required to transmit all of the packet's bits successfully. \( D \) is the primary parameter for wireless communication network design For SM, a large \( D \) largely impacts the effectiveness of the system [24]. To facilitate more advanced applications such as real-time pricing, a low value of \( D \) is demanded. In IMM2ZM, \( D \) is also defined as the time of collection of the meter readings of the entire building.

\[ D = \frac{\sum_{c=1}^{n} \left( \frac{(N_i N_i + T_{CS})}{S} \times \frac{c}{k} + T_{CS} \right)}{n} \]  

(20)

where \( T_{CS} \) is the Channel Swapping Time of the respective \( N_i \)-th, \( T_{CS} \) will be defined in section V.

In general, the transmission rate, the number of bits transmitted successfully in a unit time, is an important performance indicator for wireless communication. In essence, data overlay the entire network on the application layer from which they are processed. With high traffics in high-rises, the quantity of data transmitted in a time slot is bulky. Thus the transmission rate on the application layer affects significantly the network performance.

Therefore, the application layer transmission rate, \( \tau \), a pertinent descriptor of IMM2ZM, is defined as:
\[ \sigma = \frac{N_i N_i + T_{CS}}{D} \]  

(21)

From the captained analysis, \( D \) and \( \sigma \) are pertinent descriptors providing a holistic view of the latency performance that take account of the total number of hops and the interference mitigation. Thus, \( D \) and \( \sigma \) are indicative figures to quantify the performance of the IMM2ZM in BAN.

V. MULTI-OBJECTIVE OPTIMIZATION BASED ON NSGA-II

To synthesize the performance of IMM2ZM, the system requirement will be formulated and an optimization is needed. As such, a method that fulfills all the objective requirements is sought for. It is well known that the Genetic algorithm (GA) is genetically powerful and is a searching mechanism which imitates the natural procedure of evolution. In most practical engineering problems including wireless network design, global optimum does not exist. Therefore the problem cannot be formulated into single objective optimization problem. Also, most of the problems in engineering demand the consideration of multiple conflicting objectives in order to give a comprehensive and excellent performance; Compared with single objective optimization, multi-objective optimization has super advantages as: The diversity of multi-objective optimization is much wider than single objective optimization [9]. As a result, the multi-objective problems render the launch of Multi-Objective Evolutionary Algorithms (MOEAs). The MOEA is a kind of GA that

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always searches for a set of nondominated optimal solution which is referred as Pareto-Front (PF) [9].

MOEAs was successfully applied to the optimization of Wireless Local Area Network (WLAN) [10]. It is well evidenced that Nondominated sorting genetic algorithm II (NSGA-II) is proven to outperform other MOEAs in terms of convergence and diversity functional analysis [11]. It is envisaged that NSGA-II is powerful and will provide a wider distribution of the solutions during the search of optimal solutions. Thus NSGA-II [26] is employed in this paper for custom design of an optimal IMM2ZM. The developed model will minimize the influence of potential interference with optimal throughput and minimal latency.

The following tasks illustrate the main design concept:

A. Initialization

During the initialization, the population size, constraints, objective functions and number of parameters are determined. The crowding distance, the average distance of the two nearest points representing optimal solutions, is calculated to estimate the density of the optimal solutions.

B. Multi-Objective Searching Process

The main scope in the Multi-Objective Searching Process aims at generating a new population for further optimization to reach the optimal solutions. Selection, crossover and mutation imitate the process of natural evolution [26]. The objective values of each objective function of the individuals in the new population are estimated based on the designed objective functions. The ranking of the individuals in the same population is based on domination. Recall from [9] that solution u dominates solution v, if and only if two conditions are true: (1) all the objectives in u should perform no worse than v; (2) at least one objective in u should perform better than v. Solution u does not dominate solution v if either of the conditions is violated. Solutions that are not dominated by other solutions in the population have the highest ranking.

The iteration process will be completed when the maximum generation is reached or the output converges, and thus the PF is obtained. Every solution in the PF is an optimal solution and does not dominate each other.

Owing to the simplicity of computation in optimization, prioritized objective functions are sometimes used and weighting factors are assigned to the objective functions. In contrast, multi-objective optimization has a wider diversity to search for optimal solutions in wider range. An investigation is made to explore the effectiveness between these two schemes. The comparison will be shown in later context.

C. Network Representation

To start with, the network needs to be modeled. Important information such as the number of floors, maximum number of channels etc will firstly be obtained. The NSGA-II optimization will then be customized and incorporated to evaluate the optimal solution.

D. Design Constraints

To facilitate the search, it is necessary to assign reasonable upper and lower limits of the parameters which conform to the unique design of the network. Reasonable limits may effectively reduce the quantity of undesirable individuals during the operation, thus reducing the computing time significantly.

E. Design of Fitness Values

In general, for multi-objective optimization, the objective functions are expressed as [26]:

Minimize \( F(x) = (f_1(x), ..., f_m(x))^T \) 

Subject to \( x \in \Omega \)

where \( f_m(x) \) is the objective values for each individual in the whole population, and \( \Omega \) is the variable range.

A feasibility study was carried out. However, it is impracticable, if not impossible, to perform a full scale measurement in high rises. Therefore, prior measurement was performed for the provision of realistic data to support the model construction of IMM2ZM. For the same reason described in [8], the performance of the large scale IMM2ZM is analyzed using OPNET model and simulation [27]. Interference mitigation model developed in section IV will be incorporated into the OPNET to achieve a full scale performance evaluation of IMM2ZM.

There are mainly two parts in the feasibility study. 1) a small scale IMM2ZM prior measurement using four ZigBee physical channels; and 2) A large scale simulation of the IMM2ZM using OPNET model. The feasibility study is mandatory since it analyzes the performance of developed IMM2ZM. Besides, the measured data in the prior measurement also plays an important role in the initialization of the parameters in objective functions for the optimization. For example, in (2), \( P_{Wyb} \), \( P_{Bf,Wf} \), \( P_{Rx,ZB} \), \( P_{Rx,BT} \) and \( P_{Rx,others} \) each varies at numerous wireless environment within floors of buildings. These parameters will be estimated based on the measured data in the prior measurement to give a more accurate formulation for ZBAN at large scale. In essence, \( \alpha \) in (9), \( T_{BO} \), \( T_{Turn} \), \( T_{SW} \) and \( T_{ACK} \) in (11) and \( T_{SD} \) in (19) were evaluated in the prior measurement in the feasibility study and thus provided good estimates in the large scale model.

To facilitate testing, an IMM2ZM was set up in a residential building. In the prior measurement, a five-floor IMM2ZM using four ZigBee physical channels was developed and measured. The 5-floor IMM2ZM consists of five 4-radio RMTs and one 4-radio RC. The experimental setup is illustrated in Fig. 2.
each floor, i.e. \( n = 30 \) and \( N_f = 8 \), is considered at large scale. The RC collected the meters data once every 30 minutes and the smart meter stored the latest 10 records, i.e. \( N_t = 10 \). The system specifications of IMM2ZM for both the experiment and simulation are summarized in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SYSTEM SPECIFICATION OF IMM2ZM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Experimental data</td>
</tr>
<tr>
<td>Number of floor, ( n ) (a-floor)</td>
<td>5</td>
</tr>
<tr>
<td>Number of apartment per floor, ( N_t )</td>
<td>8</td>
</tr>
<tr>
<td>Number of record stored by smart meter, ( N_t )</td>
<td>10</td>
</tr>
<tr>
<td>Record length, ( N_r ) (bits)</td>
<td>32</td>
</tr>
<tr>
<td>AES 128bit enabled Payload length, ( L_p ) (Bytes)</td>
<td>60</td>
</tr>
<tr>
<td>Packet length, ( L_p ) (Bytes)</td>
<td>127</td>
</tr>
<tr>
<td>Transmission Power ( P_{tx} ) (dBm)</td>
<td>19.6 [-20,20]</td>
</tr>
<tr>
<td>Receiver Antenna Gain ( G_{rx} ) (dBi)</td>
<td>0</td>
</tr>
<tr>
<td>Transmitter Antenna Gain ( G_{tx} ) (dBi)</td>
<td>0</td>
</tr>
</tbody>
</table>

In the prior measurement, a testing was carried out in the meter room on 1\(^{st}\) – 5\(^{th}\) floor to identify the potential WiFi, Bluetooth, ZigBee, LTE, 3G and other interference sources. The measured data from the prior measurement serves as important trustworthy parameters for objective function analysis. Based on the measured data, important parameters such as the transmitter and receiver gains, the packet generation rate as well as the transmission power are optimized (“genes” in the algorithm) for the network and device design. On the other hand, \( D \), BER and \( \sigma \) are designed as the objective functions.

The objective functions are designed as: (1) minimize average \( D (F_1) \); (2) minimize average BER \( (F_2) \); (3) maximize average \( \sigma \) \( (F_3) \). The three objective functions are formulated as:

\[
\text{Minimize } F_1 = \frac{\sum_{i=1}^{num} D_i}{num} \tag{23}
\]

\[
\text{Minimize } F_2 = \frac{\sum_{i=1}^{num} B_{i,j,x}}{num} \tag{24}
\]

\[
\text{Maximize } F_3 = \frac{\sum_{i=1}^{num} \sigma_i}{num} \tag{25}
\]

Subject to

\( G_{tx} \in [0,2] \text{ dBi}, \ G_{rx} \in [0,2] \text{ dBi} \), \( P_{tx} \in [-20,20] \text{ dBm} \)

where \( num \) is the number of replication of the experiment.

Constraints for each objective function:

\( D \leq 0.5 \text{ sec} \) [28] to fulfill the demand response (DR) requirement for SM;

\( \text{BER} \leq 5 \times 10^{-4} \); and

\( \sigma \geq 20 \text{ kbps} \).

*In the Hong Kong environment, a data rate of \( 10-20 \text{ kbps} \) is normally adopted, hence \( \sigma \sim 20 \text{ kbps} \) is employed for evaluation.

The NSGA-II scheme is then customized to optimize the network. The key parameters are listed in Table II.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>PARAMETERS SETTINGS OF NSGA-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population size</td>
<td>100</td>
</tr>
<tr>
<td>Maximum number of generations</td>
<td>200</td>
</tr>
<tr>
<td>Crossover type</td>
<td>Uniform</td>
</tr>
<tr>
<td>Crossover rate</td>
<td>1</td>
</tr>
<tr>
<td>Mutation rate</td>
<td>0.2</td>
</tr>
</tbody>
</table>

With the inclusion of number of floors \( n \) and number of channels \( k \), the performance of the IMM2ZM is optimized for \( n = 5, 10, 20, 30 \) and \( k = 1, 2, 3, 4 \), and simulated values for each objective are obtained to search for optimal solutions.

![Fig. 3 (a) PF of BER versus \( D \) for 5-floor; (b) PF of BER versus \( \sigma \) for 5-floor.](image)

As an illustration, the PF for \( n = 5, k = 4 \) is shown in Fig. 3. It is reiterated that every solution in PF does not dominate each other. As a representative value for SM wireless communication network, BER is chosen as \( 5 \times 10^{-4} \) [2]. From Fig. 3 (a), \( D = 0.04 \text{ sec} \) and \( \sigma = 2.1 \times 10^4 \) bps. Coupled with the objective functions (22) (23) (24), \( P_{tx} = 100 \text{ mW} \).

The comparison between prioritized objective functions multi-objective optimization is now investigated.

Objective functions with prioritized weighting factors are formulated as [9]:

\[
\text{Minimize } F(x) = \sum_{m=1}^{M} \omega_m f_m(x) \tag{26}
\]

Subject to

\( g_j \geq 0, j = 1,2,...,J \)

\( h_k (x) = 0, k = 1,2,...,K \)

\( x_i^{(l)} \leq x_i \leq x_i^{(l+1)}, i = 1,2,...,n \)

where \( \omega_m \) is the weight of the \( m \)th objective function. \( f_m(x) \) is the normalized objective function, \( g_j, h_k \) and \( x_i \) are constraints.

The prioritized objective function is now investigated, and weighting factors are assigned to explore the effectiveness to obtain the optimum solution. As an illustration, indicative
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For $\omega_1 = \omega_2 = 0.1$, $\omega_3 = 0.8$, the priority of transmission rate $\sigma$ is defined to be the highest amongst $D$, BER and $\sigma$, the BER exceed the limitation of SM (i.e. $5 \times 10^{-4}$). Similarly when $\omega_1 = \omega_3 = 0.1$, $\omega_2 = 0.8$ (i.e. the priority of delay is defined to be more important). Besides, when $\omega_1 = \omega_2 = 0.1$, $\omega_3 = 0.8$, BER can be guaranteed within the SM requirement, in contrast the delay $D$ will be increased and thus exceeding the limitation ($0.5s$). For cases with average priority of three objectives, BER is confined to an acceptable level. From Table III, it is analyzed and concluded that if the priority of the objectives are assigned, there are negative impacts as follows:

a). the limitation of BER, $D$ may not be guaranteed.
b). the diversity of pareto-front will be reduced.
c). $D$(multi-objective) – $D$(Prioritized)>43%;
d). $\sigma$(multi-objective) – $\sigma$(prioritized)>9%.

Thus, it is seen that the performance of multiple objective optimization surpass the priority based optimization.

The same optimization process was applied to IMM2ZM and reiterated for $n = 6,\ldots, 30$ and the corresponding PFS were obtained. The respective optimized values, namely $D$, BER, $\sigma$, and $P_{\text{bw}}$ are evaluated and plotted in Fig. 4.

Fig. 4 (a) shows the variation of $P_{\text{bw}}$ and $\lambda_n$ versus the network size $n$. When $n$ increases, a higher received power, $P_{\text{bw}}$, is needed to overcome the complex interference environment and significant fading.

Fig. 4 (b) shows the variation of $D$ and $\sigma$ versus $n$. It is seen that $D$ increases and $\sigma$ decreases when $n$ increases. It is important to point out that $D < 0.5$ sec in all cases and thus fulfills the US standard for SM. As an illustration, from Fig. 4 (a) and (b), when $n = 10$ and $N_o = 8$, $P_{\text{bw}} = 91$ mW and $\sigma = 2.1 \times 10^{10}$ bps, $D = 0.2$ sec (which falls within specifications).

Alternatively, when $n = 10$ and $N_o = 8$, $P_{\text{bw}} = 93$ mW and $\sigma = 2 \times 10^{10}$ bps, $D = 0.4$ sec (which also falls within specifications). Thus, the optimization analysis in this section provides the design platform for the scalable and versatile development of IMM2ZM model pertinent to HTAMI. The large scale OPNET study will then be studied.
overshoot (mainly caused by channel swapping. After the lapse of delay overshoot aims at combating interference and is signifying that the channel swapping process has been increasing or when

also observed that when the number of interference sources thus requiring long transmission time between nodes. It is

Fig. 5 Simulated $D$ for $n = 5, 10, 20, 30$ by OPNET. Define $P_{RX}$ as the receiving sensitivity of the IMM2ZM. $P_{RX}$ is related to the gains and losses incurred in the link budget, the transmitting power of interference sources and its associated distance, as well as the distance away from interference sources. $P_{RX}$ is expressed as:

$$P_{RX} (dBm) = P_{ZB} + G_{TX} + G_{RX} - L_{FS} - L_{TX} - L_{RX} - L_{XX} - L_{XX}$$  (27)

where $P_{ZB}$, $G_{TX}$ and $G_{RX}$ are captioned Table I. $L_{FS}$ (dBm) is the path loss and fading, which is related to the transmission distance and wavelength. $L_{TX}$ (dBm) refers to the loss due to interference and $L_{RX}$ (dBm) and $L_{XX}$ (dBm) are the transmitter loss and receiver loss respectively. It can be concluded from (27) that $P_{RX}$ increases with an increasing $P_{ZB}$ or a hardware design of larger $G_{TX}$ and $G_{RX}$. However, with fixed $L_{TX}$ and $L_{RX}$, as well as $L_{FS}$, $P_{RX}$ certainly decreases tremendously due to serious interference.

The relationship of $T_{CS}$ versus $n$ and $P_{RX}$ is plotted in Fig. 6 using OPNET when $P_{ZB} = -20$ dBm to 20 dBm and $n = 1$ to 30. From Fig. 6, it is seen that $P_{RX}$ and $n$ affect $T_{CS}$ significantly. When $n$ increases, $T_{CS}$ increases significantly because the channel swapping process necessitates time to detect channel condition and reiterates network traffics information between RC and RMT in high traffics networks in HTAMI. The improvement of $P_{RX}$ will reduce $T_{CS}$. It is evaluated that when $P_{RX} = -12$ dBm, $T_{CS}$ will be increased tremendously because of the link budget reaches the bottom margin of the sensitivity of the IMM2ZM.

VI. ANALYSIS AND EVALUATION

To investigate the performance of IMM2ZM, an interference mitigation study and a latency study were conducted. It was shown that the latency study accounted for the IMM2ZM system performance.

A. Interference Mitigation Study

Interference under high traffic condition weakens signal reception. However, the potential interference cannot be ignored for high rises as a result of the ever increasing number of wireless users. As a result, interference mitigation is important for high performance and thus a study is a necessary.

With the experimental setup shown in Fig. 2, the interferers were established in the vicinity of the RMT. The RMT was located in the meter room and the access point operated at the same frequency channel as the operating channel of IMM2ZM. During the experiment, $D$ and $T_{CS}$ were measured for meter reading collection. In order to investigate a comprehensive performance of IMM2ZM, five buildings with $n = 3, 4, 5$ respectively were measured. The results are presented in Fig. 7.

Fig. 7 (a), (b), (c) depict the real time performance of $D$ with the introduction of interferers into buildings for $n = 3, 4$ and 5 respectively. On each floor, the real time delays of a maximum of 10 individual hops (referred as “Hop_<floor_No.>_<hop_No.>”) are recorded and analyzed.

It was captioned that the interference will cause delay overshoot and thus the IMM2ZM will activate “Channel Swapping”. Define $T_{CS}$ as the “Channel Swapping Time” for the duration of channel swapping. Fig. 5 shows the simulated results (from OPNET) of $D$ against time for $n = 5, 10, 20, 30$ under the wireless environment shown in Table IV. Fig. 5 reveals that, at the turn of the IMM2ZM, there is an unstable period of delay overshoot due to $T_{CS}$. It is seen that $T_{CS} = 21$ sec, 25 sec, 30 sec, 80 sec for $n = 5, 10, 20, 30$ respectively. The delay overshoot aims at combating interference and is mainly caused by channel swapping. After the lapse of delay overshoot ($T_{CS}$), the transmission remains stable, hence signifying that the channel swapping process has been completed. It is seen that $T_{CS}$ increases significantly with an increasing $n$ due to the large network cluster size in HTAMI, thus requiring long transmission time between nodes. It is also observed that when the number of interference sources increases or when $P_{ZB}$ is smaller, $T_{CS}$ increases.
It is seen that $D$ increases by 60% - 70% between $t = 0$ and $t = 5$ sec for $n = 3, 4$ and 5. Such a performance is trivial since IMM2ZM collects meter readings using a single channel. The channel swapping period ends at $t = 15$ sec, 20 sec, 25 sec for $n = 3, 4, 5$ respectively and $D$ becomes relatively constant afterward. This phenomenon is attributed to the fact that the IMM2ZM has successfully found a channel with insignificant interference for transmission. When $t \leq T_{cs}$, the delay is high since data delivery enters the overshoot period. As an illustration for analysis, $T_{cs}$ ($n=5$) = 25 sec is longer than $T_{cs}$ ($n=3$) and $T_{cs}$ ($n=4$) by 10 sec and 5 sec respectively. Thus a larger network obviously occupies a longer swapping period, rendering a higher delay. Nevertheless, for all scenarios, IMM2ZM recovers its normal transmission after channel swapping is completed. It is noted that $T_{cs}$ is relatively small with respect to the data collection period (i.e. 15-30 min typically). Therefore, an IMM2ZM with small $T_{cs}$ generally is a figure of merit reflecting a robust HTAMI.

Fig. 7 (a) Real time $D$ under interference for $n = 3$ when the maximum of hop = 10; (b) Real time $D$ under interference for $n = 4$ when the maximum of hop = 10; (c) Real time $D$ under interference for $n = 5$ when the maximum of hop = 10.

B. Latency study

In this investigation, analysis of IMM2ZM with $n = 5, 10, 20$ and 30 have been studied to give a holistic view of the effectiveness. The results of $D$ and $\sigma$ versus $k$ ($k = 1, 2, 3, 4$) are plotted in Fig. 8 and Fig. 9 respectively. The performance improvement of IMM2ZM ($k = 4$) (with interference mitigation) over MIZBAN [8] (without interference mitigation) is shown in Fig. 10.

Fig. 8 Investigation of $D$ when $k = 1, 2, 3, 4$. 
The strength of IMM2ZM versus MIZBAN is now analyzed. The maximum capacity should be examined and seen that the gradient increase when $k = 4$ is investigated. Fig. 10 shows the performance improvement of IMM2ZM ($k = 4$) (with interference mitigation) over MIZBAN [8] (without interference mitigation). From Fig. 10, it is seen that as $n$ increases ($n = 5, 10, 20, 30$), $\sigma$ increases from 174% when $n = 5$ to: 329% when $n = 10; 280%$ when $n = 20; 274%$ when $n = 30$. It is seen that the gradient increase of $\sigma$ is tremendous from $n=5$ to $n=10$. Thus, it is concluded that IMM2ZM performs very well at increasing network size (say $n = 30$). The performance of $D$ is also investigated. It is seen, that the improvement of $D$ increases rapidly from 37% at $n = 5$ to: 72% when $n = 10; 65%$ when $n = 20; 56%$ when $n = 30$. Hence, it is concluded that the performance of the optimized IMM2ZM well surpasses MIZBAN. In Hong Kong, the Hong Kong Housing Authority of the Census and Statistics Department of the Government of Hong Kong [30] revealed that $n \sim 12$ in 2014. Apparently $n$ will increase significantly with urban modernization in the future. From the analysis in the paper, it is evidenced that the IMM2ZM should be adopted for high performance HTAMI.

**VII. CONCLUSION**

Current smart metering (SM) solutions focus on low traffic for individual houses. SM traffics are ever growing, in particular for buildings in Asia. This paper proposes the IMM2ZM, a new multi-objective optimization interference-mitigated ZigBee based Advanced Metering Infrastructure (AMI) as a smart metering solution for high traffics data. The contribution of this paper is five-folded. Fourthly, the OPNET evaluation has been implemented for large scale analysis. Fifthly, a channel swapping IMM2ZM system has been implemented and analyzed for high traffics AMI. The delay ($D$), BER (PER) and application layer transmission rate ($\sigma$) are pertinent descriptors providing a holistic view of the latency performance that take account of the total number of hops and the interference mitigation. These indicative figures have been optimized to synthesize the IMM2ZM performance. The channel swapping time ($T_{cs}$) has been analyzed. $T_{cs}$ evaluates the efficiency of channel swapping, hence giving an account of the latency performance of the network due to interference. It is concluded that when the IMM2ZM sensitivity ($P_{th}$) is less than -12 dBm, $T_{cs}$ increases tremendously.

Fig. 8 investigates the variation of $D$ against $n$ ($n = 1~30$) and $k$ ($k = 1~4$). In general, $D$ increases as $n$ increases since the average number of hops for the routing path as well as the traffic loading increases. In contrast, $D$ decreases as $k$ increases because the traffic loadings can be shared by the multiple operation channels. It is seen from Fig. 8 that the improvement of $D$ for 5-floor $n = 5$ buildings is approaching saturation when $k = 2$. At $k = 2$, the improvement of $D$ for 5-floor buildings is not significant when compared to 10-floor and 20-floor buildings. This findings are attributed to the low density traffic characteristics at $n = 5$. Besides, when $k$ increases, in particular at $k = 4$, it is seen that the probability of finding a busy channel for RMTs is extremely low. The channel access delay will be minimized and thus $D$ reaches minimum.

Fig. 9 investigates the variation of $\sigma$ against $n$ ($n = 5, 10, 20, 30$) and $k$ ($k = 1, 2, 3, 4$). In general, $\sigma$ increases as $k$ increases since IMM2ZM transmits data in parallel via multiple channels simultaneously.

Fig. 10 Performance improvement of IMM2ZM ($k = 4$) (with interference mitigation) over MIZBAN [12] (without interference mitigation).
It is important to highlight that the IMM2ZM achieves an effective performance in a HTAMI and results in a significant improvement in the performance of the application layer transmission rate ($\sigma$) and the average delay ($D$). The improvement figures are: $\sigma > ~300\%$ and $D >70\%$ in a 10-floor building; $\sigma > ~280\%$ and $D >65\%$ in a 20-floor building; and $\sigma > ~270\%$ and $D >56\%$ in a 30-floor building. Analysis also reveals that the IMM2ZM results in typically less than 0.43 sec delay for a 30-floor building under interference. Such figures have fulfilled the latency requirement of less than 0.5 sec for SMs [28] in the USA. Thus the IMM2ZM features a high traffic interference-mitigated ZigBee Advanced Metering Infrastructure solution.

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**VIII. REFERENCE**


[27] OPNET University Program: http://www.opnet.com/services/university/


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His current research interests include radio frequency circuit design, mobile communication network design, and energy management and wireless automation protocol design.

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