Preliminary Study on Industry-Friendly and Native-IP Wireless Communications for Building Automation

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***Abstract*—Wireless communication technologies for building automation (BA) systems are evolving towards native IP connectivity. More Industry Friendly and Native-IP Wireless Building Automation (IF-NIP WiBA) is needed to address the concerns of the entire value chain of the BA industry including the security, reliability, latency, power consumption, engineering process, and independency. In this paper, the vision, requirements, and gaps of existing efforts are reviewed first. Then a hybrid architecture which can seamless support both Cloud-Based Mode and Stand-Alone Mode is introduced based on the 6LoWPAN WSAN (wireless sensor and actuator networks) technology and verified by a prototyping minimal system. The preliminary experimental results suggest that, 1) both the WSAN and Cloud communications can meet the requirements of non-real-time application of BA systems, 2) the reliability and latency of the WSAN communications is not sufficient for soft real-time applications but it is not far away to meet such requirements by sufficient optimization in the near future, 3) the reliability of Cloud is pretty sufficient but the latency is quite far from the requirement of soft real-time applications. To optimize the latency and power consumption in WSAN, design industrial friendly engineering process, and investigate security mechanisms should be the main focus in the future.**

Keywords—Fog-of-Things (FoT); Wireless Sensor and Actuator Networks (WSAN); 6LoWPAN; Native IP Connectivity (NIP); Wireless Building Automation (WiBA)

I. INTRODUCTION

Building Automation (BA) for residential buildings or homes, commercial buildings, and industrial buildings is one of the most promising application area of the Internet-of-Things (IoT) [1]. Thanks to the reduced cost of installation and maintenance and improved user experiences, Wireless Sensor and Actuator Network (WSAN) technologies are being actively applied or developed and therefore the Wireless Building Automation (WiBA) has become the new design paradigm of future BA systems [2]. To bring native support of Internet Protocol (IP), the so-called Native IP (NIP), to lightweight WSAN devices is a promising direction of the evolution of communication technologies for BA systems. It can not only ease the interoperability challenges during the system integration of various devices, sub-systems, and value-added services from different suppliers, but also tear down the walls that are hindering the BA industry to benefit from the vast amount of innovations in internet domain which evolves much faster. In practical standardization efforts, the evolution towards NIP connectivity has been clearly observed in most of the established or emerging BA communication standards, both wireless and wired, e.g. BACnet has released the BACnet/IP [3], KNX has released the KNXnet/IP [4], ZigBee has released the ZigBee IP [5], Bluetooth is developing the 6LoWPAN-over-BLE [6], and DECT ULE is developing the 6LoWPAN-over-ULE [7]. Given the standards which already have NIP connectivity such as the IEEE802.11ah Low Power WiFi [8], Thread Group [9], and the IETF IoT Suite (6LoWPAN, RPL, and CoAP) [10], the BA industry has reached a common consensus to enter the NIP era in near future even though the landscape of standardization is till fragmented.

To realize this vision of NIP-based WiBA, in addition to the technical challenges about reliability, latency, power consumption, and complexity, some important concerns from the standpoint of value chain should be addressed, e.g. "*Is that a good idea to connect everything in buildings to internet or cloud? How to reduce the security and privacy risks when enjoy the benefits from IP connectivity? How to inherit the experiences, best practices and tools for engineering and commissioning? How to strengthen their roles in the existing value chain which seems potentially to be disrupted by new entrants?*" In other words, the BA industry is demanding an Industry-Friendly and Native IP (IF-NIP) communication architecture which will not only meet the critical technical performances but also take care the business benefits of all the stakeholders in the value chain. However the existing efforts in this direction are insufficient due to the misinterpretation of "*NIP connectivity*", or lack of friendliness to system integrators and installers, or lack of support to engineering workflow (see section II for more details).

As a work in progress, this paper intends to present some preliminary thoughts and findings towards the vision of IF-NIP WiBA systems. In particular, the concerns of BA industry are interpreted from the standpoint of the whole value chain, and gaps of existing efforts are identified. Then the vision of IF-NIP WiBA is introduced and motivated. As a natural and specific derivative of this vision, a hybrid communication architecture is proposed to support flexible combination of Cloud-Based Mode and Stand-Alone Mode. Preliminary experimental results of a prototyping minimal system based on 6LoWPAN are presented with special respects with latency and reliability. The technical feasibility of the proposed architecture for non-real-time applications is confirmed and the needs of improvement for soft real time applications are

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suggested as well. Ongoing work about security, power consumption, and engineering process are discussed but without experimental results since they are out of the scope of this paper. This paper has figured out a visionary outline towards the next generation wireless communication architecture for future building automation systems. The industrial friendly considerations of the proposed vision and architecture can accelerate the market penetration since the major concerns of the entire industrial value chain are addressed better.

The rest of the paper is organized as follows: in Section II the vision, requirements, and gaps of existing efforts are interpreted, and the hybrid architecture is briefly introduced as well. The design and implementation of a proof-of-concept minimal system are presented in Section III. In Section IV, preliminary experimental results with respect to the latency and reliability are given. Finally the paper is concluded in Section V.

II. THE VISION, REQUIREMENTS, AND GAPS

A. *Evolution towards the NIP for BA Systems*

The two de facto standards of wired communication for BA systems, the BACnet and KNX, have both released the NIP edition BACnet/IP [3] and KNXnet/IP [4] respectively and achieved successful market acceptance. The evolution towards NIP is also clearly observed in the established or emerging wireless standards. First, the wireless technologies which already support NIP is trying to reduce the complexity, power consumption, and cost so as to be suitable for lightweight WSAN devices. For example, the WiFi Alliance has a plan to release a low power version IEEE802.11ah which works at sub-1GHz band dedicatedly for WSAN and IoT applications [11]. The IETF is trying to finish the application layer specification CoAP (Constrained Application Protocol) so as to provide a complete IoT Suite [12]. Second, the WSAN technologies which currently don't support NIP are turning to NIP by embracing the 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks). For example, the ZigBee Alliance has released the new generation specification of ZigBee IP [5] based on the 6LoWPAN and RPL protocols defined by IETF. The Bluetooth SIG has started to define the so-called 6LoWPAN-over-BLE together with IETF [6] based on the Bluetooth v4.1. Moreover, the DECT ULE is also working on their NIP version [7]. Given the facts, the IETF 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks) and RPL (IPv6 Routing Protocol for Low power and Lossy Networks) protocols have become the de facto standards of the transformation towards NIP [10]. It is valuable to mention, the battery-free EnOcean technology also supports IP but it is not looked as NIP since the EnOcean-over-IP gateway is needed [13]. KNX-RF is not NIP either since the RF/TP or RF/IP coupler is needed to interoperate with IP network [4].

B. *The Vision of IF-NIP WiBA*

Given the above technical survey of the established and emerging standards and deep market survey throughout the entire value chain, we have observed that, although the BA industry has reached the consensus towards NIP networks, the market penetration of wireless NIP technology are still not satisfactory. Besides the insufficient technical maturity of the standards, the lack of friendliness to the established value chain is pointed to be one of the root causes. In other words, an Industry-Friendly and Native IP (IF-NIP) wireless communication solution for building automation systems is not in place today. This has motivated our vision of the so-called IF-NIP WiBA. In an IF-NIP WiBA solution, the wireless communications should basically provide the same level of performances as the wired NIP technologies in terms of security, reliability, and soft real-time, and additionally provide years of battery life or even battery-free operation. At the same time, the IF-NIP WiBA solution should be compatible with the best engineering practices during system integration, commissioning, and maintenance. These requirements and gaps of existing efforts are detailed below.

C. *Buildings in the Fog-of-Things*

Compared with many other applications of IoT in consumer domains, the BA system is much more critical in terms of determinism, safety, security, and privacy. The term of *Internet-of-Things, Intranet-of-Things,* or *Industrial Internet* are misleading according to our experience when communicate with customers. Therefore we propose a new term of *Fog-of-Things* (FoT) (inspired by the concept of Fog Computing introduced by Cisco [14]) to avoid misunderstanding, emphasize crucial requirements, and be more friendly to industrial practitioners. First, it is obvious that FoT is not always to connect everything to the internet or cloud. Instead, in many cases, the networked devices can also be connected to isolated local networks or intranet. Second, the *fog* (the interconnected intelligence devices) is seamlessly surrounding on the *ground* (the physical objects in field) unlike the *cloud* which is far away floating over the *ground*. So the FoT is a better representation of the characteristics of IoT in critical applications, including the wireless connectivity, close loop control, embedded decision making, short latency, high reliability, high mobility, location awareness, and wide-spread geographical distribution. Third, professionals with industrial expertise become even more important than ever to make such FoT systems work in the field, which essentially strengthen the roles of system integrators and installers. Therefore it a more industrial friendly term.

D. *Technical Requirements and Gaps*

Given the requirements of future building automation systems under the context of FoT, we see after decades of efforts, the wired NIP technologies like BACnet/IP and KNXnet/IP have achieved acceptable performances of latency, reliability, and security at least for commercial buildings which are less cost-sensitive compared with residential buildings and less mission-critical compared with industrial buildings. But the wireless NIP technologies cannot yet reach the same level of performances as the wired NIP technologies [15, 16]. So the IF-NIP WiBA system must address the following technical challenges simultaneously.

- *Security:* Security is always the primary concern in any industrial communication system including the WiBA system. For an extreme example, a hacker or terrorist might send a command to start all the heavy loads (e.g. air conditioners) at the same moment to trigger an accident or trip of the distribution grid. Such commands should definitely be filtered or blocked by the WiBA systems. At the same time, the privacy concerns from end consumers are also important challenge faced by the suppliers when everything is connected by wireless because attack can be performed without physical access and the loss caused by the attack can be exponentially enlarged if it is connected to internet.

- *Reliability:* The fundamental limit of the reliability is the interferences and distortions of radio signals are complicated and highly dynamic due to the open nature of wireless media. Moreover the reliability of RPL as the de facto routing protocol of wireless NIP today is not satisfactory under the interference of a typical home or office environment [17].
- *Latency:* The latency is fundamentally limited by the physical layer bandwidth. Compared with the phical layer bandwidth of wired NIP technologies which is typically 100Mbps, the bandwidth of radios used in the wireless NIP standards is too narrow e.g. up to 250Kbps for ZigBee IP and IETF IoT Suite, 1Mbps for Bluetooth LE, and 1.152Mbps for DEC ULE. According to our experimental results (see section IV), the latency of wireless NIP is too long compared with the rule-of-thumb of *Soft Real-Time* for non-critical control application that suggests a maximum Round Trip Time (RTT) of 150ms. In more critical cases such as the future sustainable buildings as a part of Micro Grids. Many control loops in such buildings require bounded latency and guaranteed availability to manage the power generation, storage, and consumption.
- *Power Consumption:* Unlike the wired NIP devices, most of the WiBA devices are expected to be battery-powered or even battery-free to fully deliver the benefits of being "really wireless". So the above critical requirements must be met under the strict constraints of battery life e.g. no less than 3 years for non-permanently working devices. It is even desirable to have battery-free wireless NIP devices. It is challenging but the work in [18] has demonstrated the possibility of transmitting 6LoWPAN packets from a WSAN device powered by piezoelectric-based energy harvesting.

E. Non-Technical Requirements and Gaps

In nowadays BA value chain, system integrators and installers are playing essential roles to help the device manufacturers to reach end users or consumers. They integrate the devices into a usable solution by performing the complicated parameterization, configuration, installation, and commissioning according to the specific requirements of the users. Even though the do-it-yourself (DIY) market is developing quickly driven by some new entrants from out of BA domain like the Apple HomeKit [19], the role of system integrators and installers should be strengthened instead of weakened. So the IF-NIP WiBA system must be friendly to system integrators and installers. In particular the following requirements must be met.

- *Engineering Process*: The BA industry has established mature engineering process and tools based on the decades of best practices. For example, the KNX Association has standardized the engineering tool software ETS and standardized device description file format. The configuration parameters are described in such files by the device manufacturer in a machine readable language. The system integrator can conveniently configure the parameters after import this file to the ETS software, and interoperability of devices from different manufacturers are also guaranteed by this means [4]. This process has been praised as one of the best practices. KNX-RF naturally supports this engineering process but unfortunately it is not NIP, The EnOcean is going to define the similar engineering tools and file formats but unfortunately it is not NIP either [20]. Actually none of the existing wireless NIP technologies can meet this requirement. Although most of them intend to provide a cloud-based autonomous service discovery and configuration solution [21], the standardization progress is unclear. And we are doubtful about the effectiveness in practice because 1) it increases the dependency of cloud infrastructure and services which is conflicting with the next requirement below, and 2) it significantly increase security vulnerabilities since the users are blind to the process.
- *Independency*: An essential approach to keep the health of the BA value chain is to ensure the independency of the players. On one hand, the system integrator and installer don't want the WiBA system to rely on other infrastructure or services which are controlled by 3rd parties, e.g. the cloud service provided by the device manufactures or telecom operators. On the other hand, end users especially commercial users, don't like to tie their WiBA systems to one more contract with a 3rd party to reduce the business complexity and security and privacy issues. Some popular solutions in DIY market cannot meet this requirement. For example, the HomeKit platform provided by Apple requires all the configuration information to be distributed by the iCloud service provided by Apple. To realize any remote control of the HomeKit-enabled WSAN devices, an iOS terminal like the iPhone, iPad, or AppleTV box is needed [19].

F. Industry Friendliness of Cloud-Based vs. Stand-Alone

Established BA system suppliers which have rooted deeply in the value chain still emphasize the so-called Stand-Alone Mode where the WiBA devices are interconnected to each other directly or through a kind of local gateway, and users can monitor and control the devices locally without any involvement of internet or cloud server. First, it gets rid of the dependency of internet and cloud services, and therefore the issues about security and privacy can be significantly reduced. Second, the installation and configuration of such devices are more complicated for end users than Cloud-Based Mode. Thus, the role of system integrators and installers are strengthened by technical means. So it is looked as more industry-friendly.

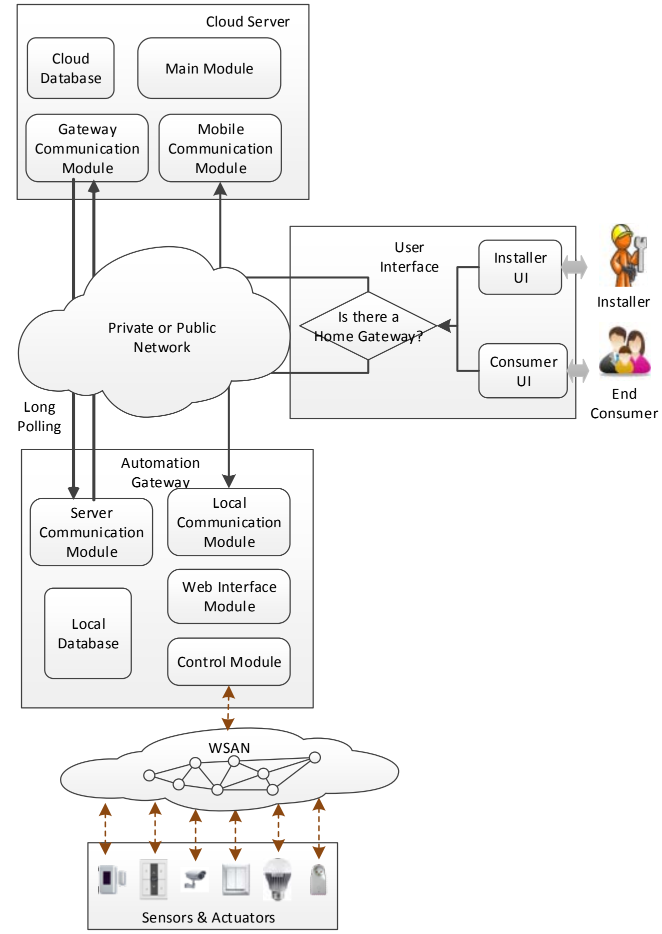

Fig. 1. A minimal system of the proposed hybrid IF-NIP WiBA architecture

Some solutions from new entrants have significantly simplified the configuration and commissioning efforts by the so-called Cloud-Based Mode where the WSAN devices of the WiBA system are all connected to a kind of server in the cloud and users can monitor and control the devices through the internet during configuration as well as usage. Traditional system integrators and installers become less important since all these work can also be done by the end users themselves, or the device manufacture if the cloud services are included in the product package, or the another service provider like telecom operators. So it is looked as not industry-friendly enough.

G. *The Hybrid Architecture*

Given the pros and cons of the Cloud-Based Mode and Stand-Alone Mode, the BA industry is demanding a hybrid WiBA architecture which can take the advantages of the both modes i.e. to simplify the system configuration and maintenance by the Cloud-Based Mode, to reduce the security and privacy issues by the Stand-Alone Mode, and to make the solution more friendly to both system integrators, installers, and dedicated service providers by offering flexible combination of the two modes.

The hybrid architecture for the IF-NIP-WIBA has been proposed in our previous work [22]. It can seamlessly support both Cloud-Based Mode operation, Stand-Alone Mode operation, and flexible combination of the two basic modes. Benefited from the Cloud-Based Mode, the system integrators can choose to provide remote services for engineering, commissioning, command validation, and maintenance by themselves through a private cloud, and they can choose to partner with 3rd parties for more value-added services like energy management and optimization, in home healthcare, and many more. Benefited from the Stand-Alone Mode, they can also choose to perform the engineering, commissioning, and maintenance in the field by professional installers utilizing exactly the same workflow as the wired BA systems so that the security issues and dependency can be minimized. Additionally, they can combine the Cloud-Based Mode and Stand-Alone Mode in a more flexible way, e.g. using the Cloud-Based Mode during commissioning to ease the engineering and configuration and using the Stand-Alone Mode after commissioning.

Data recorded in the database

Fig. 2 Implemented hardware of the minimal system including the Cloud Server, User Interface, Automation Gateway, and the WSAN devices, and the CO2 measurements collected over a normal working day in the office building

III. PROTOTYPES

A. *Design of a Minimal System*

To identify the technical requirements and verify the concepts, a minimal system of the proposed hybrid IF-NIP WiBA system architecture is designed as Fig 1. The minimal system is basically formed of four elements: an Automation Gateway, a Cloud Server, a User Interface (UI), and a series of sensors and actuators connected through WSAN. The users (end consumers or installers) can connect to the Cloud Server or the Automation Gateway directly from their UIs e.g. a smart phone or tablet, depending on user's choice and the network connection. The 6LoWPAN technology is used in the WSAN for native support of IPv6 connectivity over low power wireless communications. More details of the minimal system is given in [22].

B. *Implementation of the Prototype*

A prototype of the minimal system is being implemented. Some of the hardware setup is shown in Fig. 2. Details are descripted below.

- *Cloud Server*: The Cloud Sever application runs in an Ubuntu 12.04 image on Amazon AWS EC2 Platform. The service type is t2.micro, which contains one virtual CPU, 1 GiB memory along with 8 GB store. The server program is written in Python. It forwards any HTTP request (GET, POST) from the web interface to the Automation Gateway, and then sends the received HTTP response from the Automation Gateway back to users.

- *User Interfaces*: A static webpage is implemented as the User Interface of our system. From the table in the webpage, users can identify the sensors' name, as well as the IPv6 address, network connection status, average latency within the local WSAN network. Users can also control the sensors from the webpage. In our case, users can turn on/off a smart plug, get the current measurement from CO2 detector, etc. There is no difference between the user interface on cloud server and the user interface on automation gateway. Users can have the same controlling command on both user interfaces.
- *Automation Gateway*: A low cost Linus host, Raspberry Pi, is used to implement the Automation Gateway. It has 512 MB of RAM, two USB ports and a 100Mb Ethernet port. The Raspbian Image is used as the gateway operating system. The Server Communication Module, Local Communication Module and Control Module are implemented as Python program. A Python network engine is designed in the program. The Database is based on SQLite database running on the Raspberry Pi. A simple Web Interfaces is also provided. After giving the right user name and password, users can have a direct control to the WSAN devices. The Automation Gateway application integrates IPv4 socket and IPv6 socket harmoniously. The IPv4 socket manages the communication with the Could Server, as well as responds to the HTTP request from the Web Interface. The IPv6 socket manages the connection to the USB 6LoWPAN Border Router not only to control the devices within the WSAN but also to enroll a new devices to the network. In the Automation Gateway program, a daemon thread is set to monitor the current network status of the sensor, measuring the average latency of every sensor within the local sensor network.
- *WSAN Devices*: The 6LoWPAN devices from Watteco NKE Electronics are selected to implement the WSAN devices. Two smart plugs and one CO2 detector are used in the prototype system. All the devices are operates at 868MHz ISM band. The IPv6 adaptation layer is based on the IETF 6LoWPAN standard. The IETF RPL (routing protocol of the IPv6 packets over low-power and lossy network) protocol is used for mesh networking. In the application layer, the ZigBee Cluster Library (ZCL) format packets are inserted as the payload of UDP packets. Besides the sensor devices, a USB 6LoWPAN Border Router is used to provide the radio connection between the Automation Gateway and the sensor devices. It can be plugged on a Linux host and creates the link between standard IPv6 applications and 6LoWPAN devices. It also takes the role to setup the WSAN and in turn to allow new devices joining in.

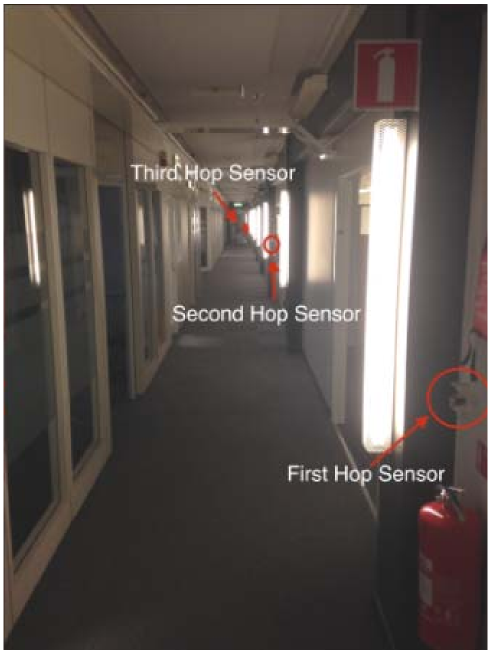

Fig. 3. Test setup in the office building

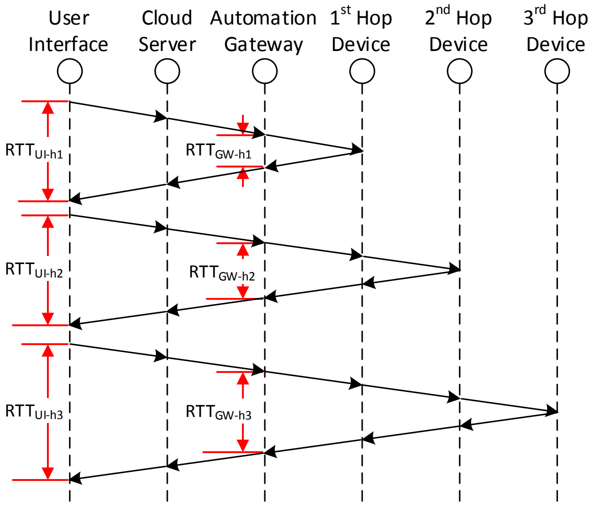

Fig. 4. Definition of Round Trip Time (RTT) between UI and Gateway and between Gateway and Devices with different number of hops

IV. PRELIMINARY RESULTS

A. *Experiment Setup*

As mentioned, latency and reliability are of the concerns when IP-based communication is applied due to the lack of real-time mechanisms. As shown in Fig.3, the hardware is setup in a corridor of our office building which is about 100 meters long, and the Automation Gateway is installed in the office aside. The WSAN is configured to be three hops. The Cloud Server which is deployed on the Amazon PaaS located in Ireland.

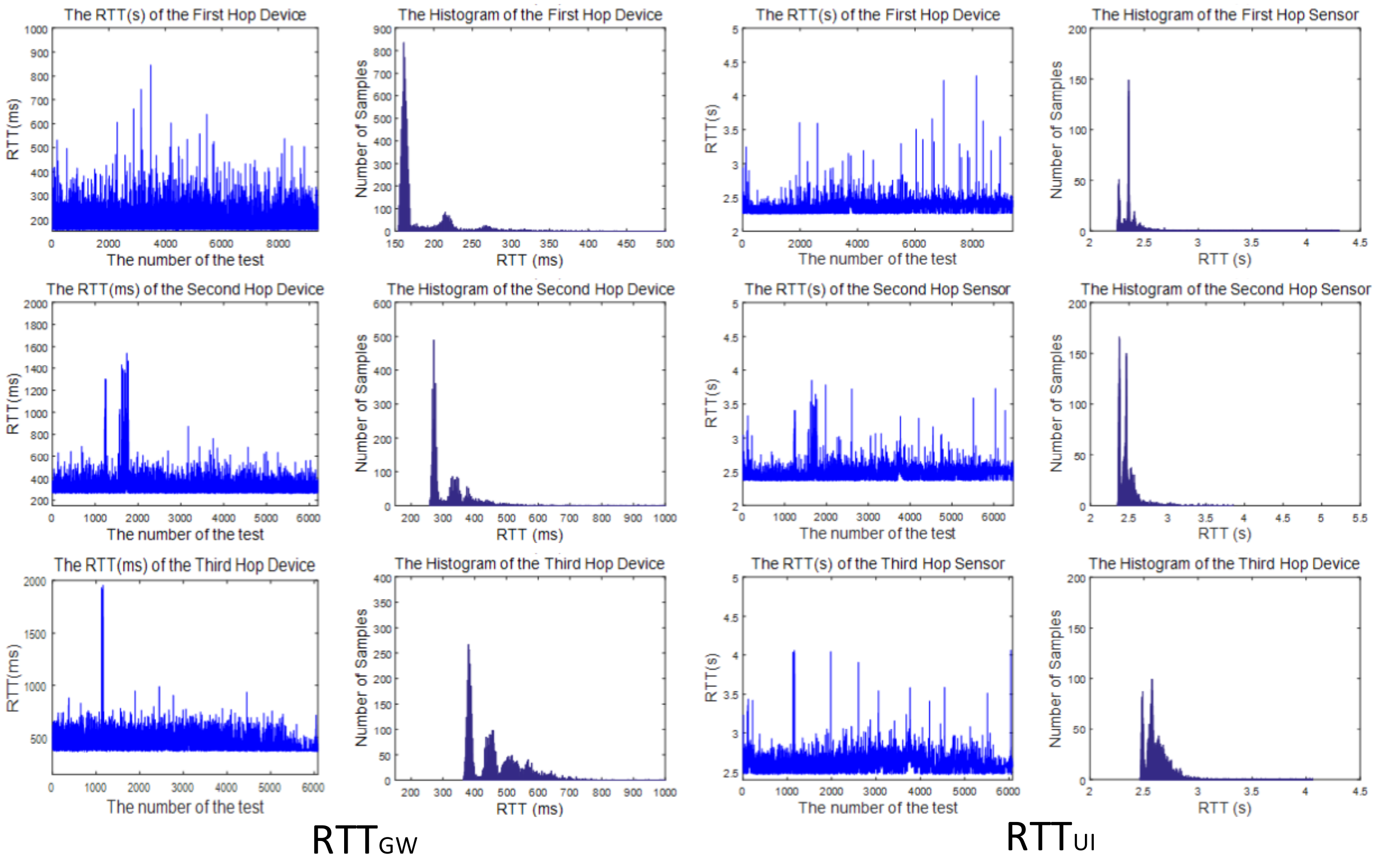

Fig. 5. Round Trip Time between Gateway and Devices (RTT_{GW}) and between User Interface and Devices (RTT_{UI}), and their histograms

B. *Definition of Evaluation Criteria*

In this experiment, the latency is measured by Round Trip Time (RTT). As shown in Fig. 4, two types of RTTs are defined. The RTTs are denoted by the number of hops in the WSAN. For example, the RTT between the User Interface and the 3rd hop device is denoted as $RTT_{UI\text{-}h3}$. They a

- *RTT_{UI}*: it starts from the moment when the User Interface sends out a command to one of the WSAN devices, and ends at the moment when the User Interface receives a response from the device. During the test, the User Interface software sends out a command to e.g. the 3rd hop Device, then the command is forwarded by the Cloud Server, Automation Gateway, 1st hop Device, and 2nd hop Device sequentially to the 3rd hop Device, then the 3rd hop Device sends out its response, then the response forwarded by the 2nd hop Device, 1st hop Device, Automation Gateway and Cloud Server sequentially back to the User Interface, finally the User Interface receives the response and records the time duration as $RTT_{UI\text{-}hop3}$.
- *RTT_{GW}*: it starts from the moment when the Automation Gateway sends out a command such as Read or Write to one of the WSAN device, and ends at the moment when the Automation Gateway receives a response from the device. During the test, the Automation Gateway software sends out a command to e.g. the 3rd hop Device, then the command is forwarded by the 1st hop Device, and 2nd hop Device sequentially to the 3rd hop Device, then the 3rd hop Device sends out its response, then the response forwarded by the 2nd hop Device and 1st hop Device sequentially back to the Automation Gateway, finally the Automation Gateway receives the response and records the time duration as $RTT_{GW\text{-}hop3}$.

Reliability is measured by the Round Trip Packet Error Rate (RT-PER) which is the percentage of the commands that are not responded correctly before timeout among the total commands sent during the period of test. The RT-PER are measured at the User Interface and Automation Gateway and denoted as $RT\text{-}PER_{UI}$ and $RT\text{-}PER_{GW}$ respectively.

C. *Data Analysis*

The test results from an experiment that lasted for about 15 hours are plotted in Fig. 5 and statistics of the data is collected in Table I. Some observations are described below.

- *Latency of WSAN.* RTT_{GW} represents the latency caused by the communications within the WSAN. 1) The average RTT_{GW} is on the order of hundreds of milliseconds, e.g. 184ms, 324ms and 465ms for 1st, 2nd hop, and 3rd hop respectively in this experiment. 2) The average RTT_{GW} increases proximately linearly when the number of hops increases. In experiment, the average RTT_{GW} increases by 140ms for each hop. 3) The distribution of RTT_{GW} is quite diverse. In experiment, the maximum RTT_{GW} is on the order of seconds and 4 to 5 times larger than the average RTT_{GW}.

Table I. Statistics of the Round Trip Time (RTT) and Round Trip Packet Error Rate (RT-PER)

		1st Hop Device	2nd Hop Device	3rd Hop Device
RTT_{UI}	Min(ms)	2247.2	2354.1	2463.9
	Average(ms)	2347.1	2473.6	2612.4
	Max(ms)	4300.7	3849.9	4061.6
	σ (ms)	94.3	118.7	123.2
	avg+σ (ms)	2441.4	2592.3	2735.6
	avg+2σ (ms)	2535.7	2711	2858.8
	avg+3σ (ms)	2630	2829.7	2982
	P@avg+σ	91.41%	91.63%	88.83%
	P@avg+2σ	97.43%	96.86%	97.43%
	P@avg+3σ	98.68%	98.17%	99.00%
RTT_{GW}	Min(ms)	154	258	364
	Average(ms)	184	324	465
	Max(ms)	846	1531	1950
	σ (ms)	47	96	101
	avg+σ (ms)	231	420	566
	avg+2σ (ms)	278	516	667
	avg+3σ (ms)	325	612	768
	P@avg+σ	89.76%	91.58%	86.52%
	P@avg+2σ	95.13%	97.35%	97.78%
	P@avg+3σ	97.87%	98.58%	99.59%
RTT_{Cloud}	Average(ms)	2163.1	2149.6	2147.4
$RT\text{-}PER_{UI}$	%	0.00%	3.15%	4.32%
$RT\text{-}PER_{GW}$	%	0.00%	3.15%	4.32%

- *Latency of Cloud.* The RTT_{UI} represents the total latency caused by the communications in the WSAN and Cloud. In this experiment, it is reasonable to assume that the statistic characteristics of the WSAN and Cloud environment is stable during the period of the two commands for RTT_{GW} and RTT_{UI} because they are sent almost at the same moment (the error is less than sub second). So the average latency cause by the Cloud (RTT_{Cloud}) can be proximately estimated by $average(RTT_{UI})- average(RTT_{GW})$. 1) The average RTT_{Cloud} is quite stable and not affected by the number of hops in WSAN. In this experiment, the average RTT_{Cloud} is all around 2000s for 1st hop, 2nd hop, and 3rd hop devices. 2) The distribution of RTT_{UI} is less diverse compared with the RTT_{UI}. In this experiment, the maximum RTT_{UI} is always less than twice of the minimum RTT_{UI}. 3) Occupying the major part of the total latency, the latency of Cloud is 4 to 10 times larger than the WSAN latency.
- *Reliability of WSAN.* The $RT\text{-}PER_{GW}$ represents the command failure caused by the communications within the WSAN. The $RT\text{-}PER_{GW}$ increases when the number of hop increases. In this experiment, we not have observed any command failure for the 1st hop device. However we are not sure about whether there is no packet loss because we are not clear if there is any re-transmission mechanism in the lower layers of the protocol implemented by the Watteco devices. The $RT\text{-}PER_{GW}$ increase up to 3.15% and 4.32% at the 2nd hop device and 3rd hop device respectively.
- *Reliability of Cloud.* The $RT\text{-}PER_{UI}$ represents the total command failure caused by the communications within Cloud and WSAN. Because in this experiment, the communications between the Cloud Server and User Interface and the Automation Gateway are based on TCP which has automatic retransmission and guaranteed end-to-end reliability, there is no command failure caused by the Cloud in fact. So the $RT\text{-}PER_{UI}$ is equal to the $RT\text{-}PER_{GW}$ in this experiment.

D. Performance Assessment

- *Communications of WSAN.* For non-real-time applications through local network, such as monitoring of status of sensors and configuration of operation parameters (e.g. schedule, work mode) of actuators by an in-home display (IHD) or smart phone, the latency and reliability of WSAN communications is acceptable. For example, in this experiment if we set the up bound of Maximum Acceptable RTT as 768ms which is the $Average\_RTT_{GW}+ 3*Standard\_Deviation$ of the furthest away 3rd hop devices, about 95.68% of the commands can receive correct responses, and 99.59% of the responses arrives within. However this cannot meet the requirement of soft real time applications such as remote control of dimmerable lights or curtains which need the latency to be *imperceptible* for human. According to the rule-of-thumb in practice, *imperceptible latency* usually is defined as >95% of the commands are responded correctly within 150ms. In this experiment, even for the nearest 1st hop device, 95.13% of the responses arrive within 278ms. But it is not far from the acceptable level.
- Communications of Cloud. The reliability of Cloud communications is pretty good for most of the applications. But the latency can only meet the requirement for non-real-time applications. It is quite far (10 time larger) from the requirements of soft real-time applications.

E. Limitations and Future Work

Due to the limitation of time, the proposed engineering process is not fully implemented on the prototype and therefore is out of the scope of this paper, but is one of the focus of the ongoing work. Another ongoing work is to evaluate and optimize the power consumption of the WSAN devices and Automation Gateway. As mentioned above, the WSAN latency cannot meet the requirement of soft real-time applications, but it is not far away, therefore we expect to solve it in the next step of our work. But since the latency of Cloud is quite far away for soft real-time applications, to optimize the latency in Cloud will not be the focus in our next step. Instead, we will look more into security issues and solutions of the Cloud communications.

V. CONCLUSION

Future building automation systems are typical practical cases of the Fog-of-Things (FoT) which represents the IoT for more critical applications. Wireless communication technologies for building automation systems are evolving towards native IP connectivity. To realize the vision of

Industry Friendly and Native-IP Wireless Building Automation (IF-NIP WiBA) systems, more industry friendly wireless communication technology is needed to address the concerns of the entire value chain of the BA industry, including the security, reliability, latency, power consumption, engineering process, and independency.

In this paper, the vision, requirements, and gaps of existing efforts are reviewed first. Then a hybrid architecture which can seamless support both Cloud-Based Mode and Stand-Alone Mode is introduced based on the 6LoWPAN technology and verified by a prototyping minimal system. The preliminary experimental results suggest that, 1) both the WSAN and Cloud communications can meet the requirements of non-real-time application of BA systems, 2) the reliability and latency of the WSAN communications is not sufficient for soft real-time applications but it is not far away to meet such requirements by sufficient optimization in the near future, 3) the reliability of Cloud is pretty sufficient but the latency is quite far from the requirement of soft real-time applications.

In the next step of this work, to optimize the latency and power consumption in WSAN, implement industrial friendly engineering process, and investigate security mechanisms should be the main focus.

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