

Design and Implementation of a DASH7-based Wireless Sensor Network for Green Infrastructure

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ABSTRACT

Globally, a dramatic demographic shift towards urbanization is occurring. Between 2000 and 2050, the proportion of people living in urban areas is projected to rise from 46.6% to 69.6%. Urbanization poses problems through effects such as environmental pollution, accidents, heat island effects and climate change. With the rapid urban growth and development, the quality of green space available has been degrading. Furthermore, many land characteristics have been altered such that the whole water cycle has been significantly changed. Some of the considerable adverse effects of these changes include the increase in runoff which leads to flooding and poor quality of receiving waters. To improve storm water management, green infrastructures (GI) have become a promising solution by restoring the natural environments in big cities, creating a better living environment for the city's residents. In this paper, a wireless sensor network (WSN) was designed for the monitoring of green infrastructure in smart cities. A data acquisition system based on a new wireless network protocol – DASH7 for green infrastructure is evaluated, developed, and implemented. The DASH7 based WSN system is introduced as a better potential candidate in the case for midrange WSN/IoT green development use. The DASH7 WSN, integrated with a variety of sensors, including soil moisture, temperature, light, humidity, and pressure was designed and tested where sensor data was transmitted and displayed on a cloud server.

I. INTRODUCTION

Globally, more people live in urban areas than in rural areas, with 55% of the world's population residing in urban areas in 2018. In 1950, 30% of the world's population was urban, and by 2050, 68% of the world's population is projected to be urban (United Nations 2014). Cities continue to grow in size, increasing the demand for an upgrade of efficient green infrastructure and environmental monitoring systems. For example, the number of people living in Washington, D.C, has increased rapidly, from 601,723 in 2010 to 681,170 in 2016 (US Census Bureau 2017). Ongoing climate change and the growing population proportional to cities' sizes has led to the construction of more tall buildings integrated with vertical green garden/farm/green roof architectures. Carefully designed architecture along with the concept

of “blue and green infrastructures” (Gehrels et al. 2016) will increase opportunities healthier living in big cities.

Washington, D.C. is interested in making better use of green infrastructure in order achieve a healthy city. According to the District Department of Transportation website, the “Sustainable DC Plan,” adopted in 2013, sets long-range goals for making the District the greenest city in the nation. The plan calls for increased green infrastructure in the public right-of-way (ROW) and taking actions to improve the health of the city’s waterways (DDOT 2018). Green Infrastructure (GI) is the living network that connects landscape areas, natural areas, and waterways. In urban areas, GI captures rainfall; cools buildings and pavement; and creates natural pathways for wildlife. GI includes Low Impact Development (LID) techniques, which mimic nature to capture and treat stormwater as close to the source as possible (DDOT 2018).

In recent years, wireless sensor networks (WSNs) have been widely used in industrial, commercial, and consumer applications (Gruen 2013). In a wireless sensor network, sensor nodes are spatially distributed across an area of interest to sense, measure and collect information, and transmit the data to a base station for processing. The challenge of green infrastructure and environment monitoring sites is in reliable wireless data transfer over large distances. Reliability of wireless data transfer is the most significant factor when evaluating the applicability of wireless systems in industrial or similarly harsh environments. In many industries, wireless systems are often used for monitoring purposes (Koskinen et al. 2010; United Nations 2014). For metropolitan location like Washington, D.C., green infrastructure and the increase of construction of buildings with vertical gardens need WSNs that can operate over large distances. For green infrastructure monitoring, an easily deployable WSN would be very attractive, as it would save a lot of time from installing and dismounting a measuring system. In this paper, a new wireless protocol is developed for green infrastructure monitoring using DASH7 Wireless Sensor Protocol with multiple-sensor targets. These particular sensors can analyze multiple readings from soil moisture, light, temperature, humidity, and pressure.

The rest of this paper is organized as follows. In Section II, a general data acquisition system is proposed to explain important aspects of the green project development. The current WSN technologies and their limitations for green infrastructure and the environment are explained in Section III. In Section IV, the WSN using the DASH7 protocol for green infrastructure monitoring is introduced. Measurement data from the implemented WSN is shown in Section V. Finally, the conclusions and future work are provided in Section VI and VII, respectively.

II. PROPOSED SYSTEM OVERVIEW

Data acquisition for green infrastructure development and environment monitoring requires an implementation of a WSN. A general WSN architecture includes: node(s) or endpoint(s), gateway(s), and a cloud server, as shown in Fig. 1. In the proposed WSN, nodes or endpoints would be deployed at monitoring sites. A gateway or sub-controller would be deployed near the controlling site. Endpoints transmit readings via a defined network to the gateway, and gateway publishes those to a cloud server. Users analyze and monitor data by accessing the cloud server. Each node contains a powerful network modem to communicate with the

gateway, and it contains multiple functional sensors such as moisture sensor, light sensor, temperature sensor, humidity sensor, etc. Nodes can be deployed under a stationary or a mobilizing state. Gateways are deployed in controlling zones instead of monitoring sites. A controlling zone is an area where the gateway can be accessed directly by users. Gateways also contain a defined network modem, which is compatible with endpoints, and a protocol to acquire data published from endpoints. Moreover, data must be stored in cloud server for easy accessing and monitoring. Cloud server must be a part of WSN/IoT data acquisition. Transmitted data are received by the data collection server, which stores the type of physical/statistical quantity, the measured/calculated value, and the time stamp of the measurement in a dedicated database.

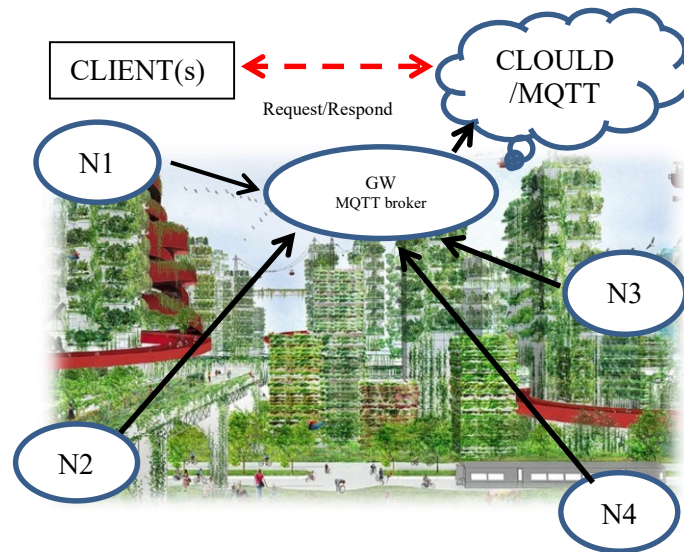


Fig. 1: Green project architecture with WSN implementation proposed

III. CURRENT WSN TECHNOLOGIES AND LIMITATIONS

Many wireless technologies have been used for the development of WSNs. The most widely used wireless technologies are RFID, Bluetooth, Bluetooth ULP (Ultra Low Power, also known as Wibree), and Zigbee. In addition, there are several high-speed communication technologies based on Ultra-Wide Band (UWB) radio. These technologies enable versatile applications. Many non-consumer applications require a longer radio communication range compared with technologies mentioned earlier. For instance, RFID, Bluetooth and UWB are typically suitable for short-range communication, where the range is less than 10 m. In industrial and infrastructure applications, the required radio range can be up to hundreds of meters. Besides, very low power consumption is required for systems where batteries are applied.

Many WSNs have been developed with short-range wireless communication capabilities (10 – 100 m) with emphasis on low-power operation. For example, communication protocols like Zigbee, and Wi-Fi are widely implemented in home automation design. Smart home interfaces and device definitions are introduced to allow interoperability among ZigBee devices produced by various manufacturers of electrical equipment, meters, and smart energy enabling products (Han and Lim 2010; Byun et al. 2012). Nevertheless, new technologies are constantly updated

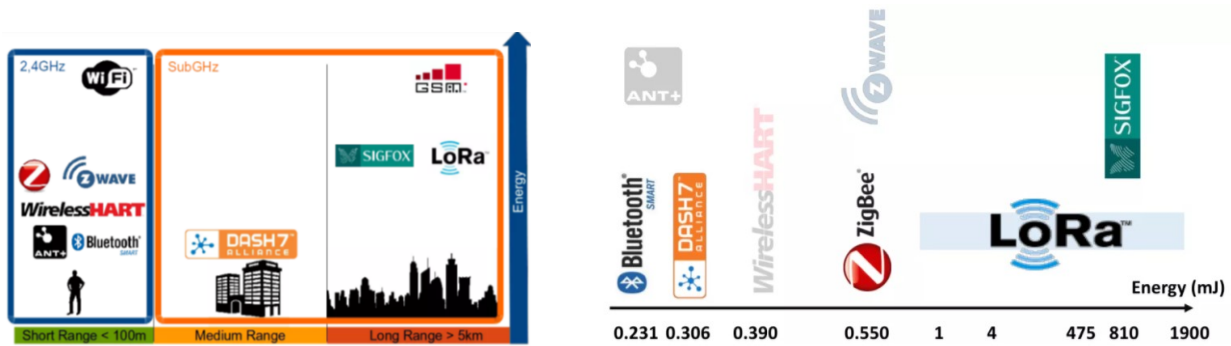
with compiled standards into connection such as Wi-Fi Alliance, Zigbee Alliance, and Z-wave pushing forward with their advantages to support smart cities and smart control. Wi-Fi Alliance standard has introduced HaLow for IEEE 802.11.a.h technology with low power, and long range Wi-Fi. It gives a city an effective coverage using HaLow's built-in meshing technology (Wi-Fi HaLow 2017; Hetting 2017). Zigbee Alliance has introduced Zigbee 3.0 standard for Smarter World, with also built-in meshing technology (Zigbee 2017). However, both Wi-Fi and Zigbee technologies have limitations for large-scale deployment in green infrastructure and environment monitoring. A large distance among a Gateway's and multiple Endpoints' localizations inside a wireless network challenges the limit of a number of nodes deployed across green project sites. Additionally, mesh technology requires complicated network establishments, which are involved with extensive defined algorithms for using routing to select a specific path through the network from one device to another.

IV. WSN Architecture Using DASH7 protocol

Due to those technologies' limitations listed above, DASH7 Wireless Sensor Network is proposed for green infrastructure and environment monitoring. To compromise a long range of data acquisition and bypass a complex setup for mesh network, DASH7 Protocol (D7AP) is proposed in this project to serve for design, evaluation, and implementation purposes.

D7AP

D7AP is designed to avoid using the busy 2.4 GHz frequency range used by many protocols such as ZigBee and Wi-Fi. Instead, DASH7 protocol uses the Sub-1GHz ISM band, operating in the 433 MHz, 868MHz and 915MHz. D7A was originally developed from ISO18000-7 standard for Military logistic purposes. D7AP is conceived as a medium range, asynchronous network protocol enabling communication with small and bursty data packets between devices in a request-response fashion. Endpoints are considered to be energy constrained and mobile within the environment. Moreover, the whole network of devices is assumed to be transitional and there is no need to maintain routing information or other management information. D7AP has a large communication range and hence it allows a star topology or a tree topology where there is a maximum of one hop between the endpoint and the gateway, making it less complex than a typical mesh topology. The endpoints have the option of enforcing a packet to be acknowledged by at least one gateway, and hence providing communication between the sensor and the cloud (Ergeerts et al. 2015).



As shown in Fig. 2a, D7AP fills the gap between the short range and the long range networks. D7AP excels in urban and industrial network installations connecting actuators and messaging applications, e.g. sensors, alarms, states, with ranges up to 1000 m. It is important to note that ranges are somewhat speculative, as they depend on the environment. The objective figures are estimated in link budget that is the maximum supported attenuation of the signal between the transmitter and the receiver. In standard D7A with 2-FSK modulation, the maximum link budget is about 125 dB and allows ranges from 150 m to 1 km (Weyn et al. 2015; Wizzilab 2017; DASH 7 Alliance 2017a). D7A is a BLAST Communication Protocol (DASH 7 Alliance 2017b), where BLAST stands for:

- Bursty: Data transfer is abrupt and does not include streaming content such as video, audio, or other isochronous forms of data.
- Light: Packet sizes are limited to 256 bytes.
- Asynchronous: D7AP method of communication is by request-response, which requires no periodic network "handshaking" or synchronization between devices.
- Stealth: D7A does not use discovery beacons, end nodes can choose to respond only to pre-approved devices.
- Transitional: A D7AP system of devices is inherently mobile or transitional. Unlike other wireless technologies, D7AP is upload-centric, not download-centric. Devices do not need to be managed extensively by fixed infrastructure (i.e. base stations) to respond only to pre-approved devices.

Fig. 2b shows the energy consumption of DASH7 compared to other well-known communication protocols. As shown in Fig. 2b, DASH7 Energy Consumption is 0.306 mJ compared to Zigbee, and Z wave (0.550 mJ), promising a low-power network communication. At standby mode, D7AP consumes 2 μ A, and the energy cost to send one packet is 260 μ A/s. Duration of one packet including start-up time of the microcontroller, two-time collision avoidance and transmitting of the data, is 17.7ms. In order to fulfill the constraint of a 1-year lifespan, battery has to have at least the capacity of 6.62 mAh (Ergeerts et al. 2015).

D7AP covers all OSI-layers, from the physical layer up to the application layer. Central to the D7AP stack is the concept of a file system. The D7AP file system is a collection of structured data elements together with their associated properties like permissions and storage class. Data elements are defined for D7AP configuration parameters used by the stack, like the encryption key or the access profiles (which may describe the channel, coding and TX power). Next to the D7AP System Files, there is a range of data elements, which are reserved for application usage, to store sensor readings for example. The application manages the data elements through the D7AP Application Layer Programming Interface (ALP). An ALP Command consists of one or more ALP actions and each action specifies an operation to be executed – e.g. read, write, or execute file, etc. A set of actions can be preceded with queries, where the Boolean output of the queries determines if the actions should be processed or not. A query is defined as an arithmetic comparison or string token search between data in a file and supplied data, or data in another file. Queries in ALP commands are used as a flexible addressing mechanism. A gateway or a sub-controller uses ALP commands to interrogate and manage the endpoint nodes in the environment. More complex

combinations using multiple query operands, chained together with Boolean operators, and multiple actions are possible as well. A network of DASH7 nodes effectively behaves as a distributed database, where the query is processed on the endpoint nodes transmitting the requested data only if needed. To maximize global availability, the D7AP PHY supports the 433, 868 and 915 MHz unlicensed ISM/SRD bands (Ergeerts et al. 2015). Three channel classes are defined: Lo-Rate, Normal and Hi-Rate, using a symbol rate of 9.6, 55.555 and 166.667 kbps, respectively. All channel classes are modulated with GFSK but using different frequency deviations and channel spacings. The number of channels available varies per band and per channel type on one hand, and local regulatory limitations, which might disallow usage of parts of the band on the other hand (Ergeerts et al. 2015). Unlike other available WSN technologies like Zigbee, D7AP is not a mesh technology. It is a one-hop option, which is natively embedded in the protocol, allowing a star topology. The D7AP based WSN has a star topology, namely, each unit has a direct connection to the data center. Transmission of measurements occurs individually for each sensor, using a D7AP network at low priority (i.e., data may be lost when the network is at peak load). Transmitted data are received by the data collection server, which stores the type of physical/statistical quantity, the measured/calculated value, and the time stamp of the measurement in a dedicated database.

D7AP-915MHz System Setup

1) Wizzikit D7AP-915MHz

The WizziKit is a full Wireless Sensor-Actuator Network prototyping framework based on Wizzilab hardware and open-source collaborative platforms. Wizzikit 915-MHz Kit is a whole kit design for WSN application, which tends to replace other WSNs (e.g. Zigbee) for green infrastructure and environment monitoring.

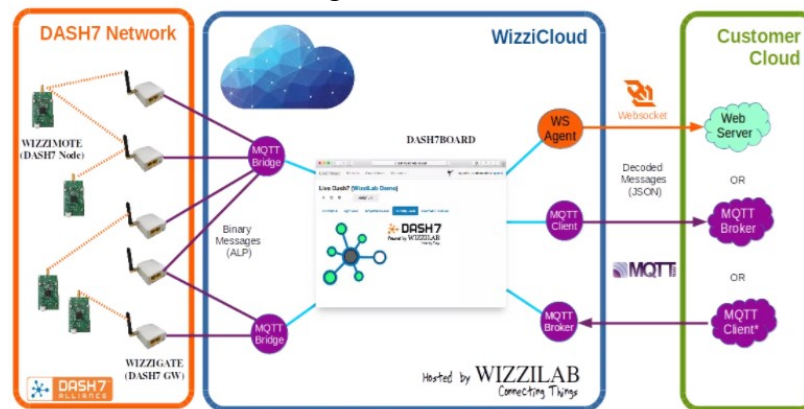


Fig. 3: Wizzilab's DPA7 Network Architecture (Wizzilab 2017).

Generally, Wizzilab's network architecture includes two parts: DASH7 network; and User network, as displayed in Fig. 3. DASH7 network includes two parts: Node(s), and Gateway (GW). Both devices have specific assigned Unique IDs (UID), and both are mounted with 915-MHz Antennas by SMA connectors to enable 915-MHz network communication.

2) Gateway (915-MHz)

Gateway plays a central role of monitoring and configuration of the WSN. Gateway v1.0 (WizziGate) is a Linux board implemented using a DASH7 modem filter. GW's hardware is based on GL-iNet AR150 Smart Router with enhanced MQTT firmware and 915MHz RF extension. Many communication protocols are available through the GW. As shown in Fig. 4 these include Message Queue Telemetry Transport (MQTT), DASH7, WIFI, and GSMA. Endpoints transmit and publish data to GW by D7AP, while GW maintains Data Acquisition through MQTT protocol. Data Acquisition from D7A network is stored in the Cloud, and it can be accessed via Dash7 Dashboard in WiFi network. As shown in Fig. 5, GW's have a UID, and MQTT is configured to subscript / publish data from node(s) via local website. Gateway has an IP address for WiFi network. In DASH7, each device has a unique identifier called UID. This is the equivalent of the MAC address for a network card. The UID is an 8-bytes identifier following the EUI-64 standard. The UID of this GW is obtained after setting up Ethernet connection via local address. This Gateway's UID distinguishes its own communication configuration of transmit and receive process in D7AP WSN system, as an address in D7A Star topology map.

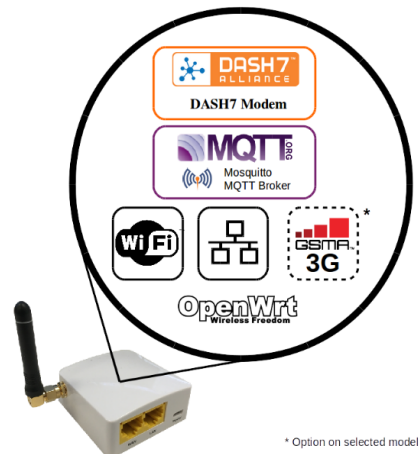


Fig. 4: 915MHz Wizzikit gateway with available communication protocols (Wizzilab 2017).

Administration

Gateway Status

Gateway UID:	001BC50C7010009B	Reboot Gateway
WizziCloud:	Connected	
MQTT Broker:	Up for 00:06:54	Restart
Gateway services:	Up for 8 days and 01:57:53	Restart

Gateway Software

	Current version	Update status
Package:	v1.2.106	up to date (v1.2.106)
Firmware:	20170224	up to date (20170224)

Fig. 5: Gateway's status in Wizzikit's local address

GW's UID is used to assign at star map in Dash7board Site. Dash7board GUI is designed by Wizzilab

to assign devices in Dash7 network by their UID(s), as well as give users an easy access and monitor through their DASH7-WSN. GW has to be assigned and allocated in WSN map as a communicational point between DASH7 network and User Application Site. In Fig. 6, GW's and Endpoint's UID, and statuses are displayed in Star map. GW is assigned in middle of the star map; with last 2-digit UID "9B", and one Endpoint's UID is "A27". This Star map also updates status of each device in network: e.g. connection, power, firmware, etc. D7AP Gateway always gives an access to configure Access Profile, and Access Class for DASH7 Protocol. An Access Profile defines the set of parameters allowing accessing a remote device over a channel scanned by the latter device.

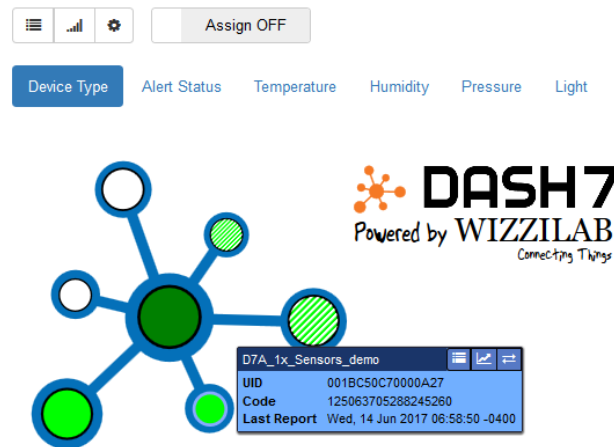


Figure 6: System deployment with Star topology.

The Access Profiles are identified by an index, called Access Class. Only the Access Classes are exchanged between devices while the Access Profiles are not. Consequently, in order to understand each other, all devices of a D7A network need to have a compatible list of Access Profiles that is identical Access Profiles corresponding to the identical Access Classes. Before the network deployment, the network administrator has to define the set of access profiles and sub-profiles used in the network. The administrator also associates an index (the access class) to every profile. This set shall be unique and known by all devices in the network. By default endpoints use access class 0x01, and GWs use 0x21.

3) D7AP-915MHz Endpoints

The endpoint node (WizziMote in Wizzilab's network) 915-MHz is introduced as a WSN endpoint which includes two boards implemented together: SH2050 shield and Host Nucleo-L432KC. SH2050 is an integrated circuit shield that is designed to have both DASH7 protocol modem, and a number of available functional sensors, which are useful for green infrastructure and environment monitoring. Based on Cortex M0+ (STM32L081KZ6) application processor, SH2050 is designed to give a connection between sensor/actuator devices (HOST) to the DASH7 network. It is controlled by the host application using a serial link and a few GPIOs. Serial data is encapsulated using serial protocol with serial configuration: 115200 bauds, 8 bits, 1 stop, and no flow control. It is pre-programmed to operate with FSK modulation with data rate of 55.6 kbps (normal data rate). SH2050 operates from a single 2.4V to 3.6V power supply by a Nucleo32-L432KC development board from ST-Microelectronic. Nucleo32-L432KC has ARM Cortex M4 processor, and MBED enabled. Improvement of technology has provided the ability to integrate multiple small scale sensors altogether in the same circuitry board. SH2050 includes: Light sensor (TEMT6000), Pressure sensor

(LPS25HB), Accelerometer and Magnetometer (LSM303C), and Humidity and Temperature sensor (HTS221). A Soil Moisture sensor is implemented to SH2050 to detect water in soil, which plays a key role in the life of plants. At endpoint integration, each of the sensors is given a specific ID, and all involved parameters that must be used in transmit/receive process under DASH7 network. An update is required at both GW's and endpoint's services. An update at firmware, hardware configuration, reading values, sensors' thresholds, MQTT protocol, and dash7board GUI takes place to acquire data properly under the current available established network. Fig. 7 shows an Endpoint (UID: A27) is deployed on testing site. The top board is SH2050 with multiple sensors, powered by Nucleo32-L432KC (bottom). Fig. 8 shows D7AP WSN architecture setup that was implemented for the green infrastructure.



Fig. 7: Endpoint (UID: A27) with multiple sensors deployed to a monitoring area.

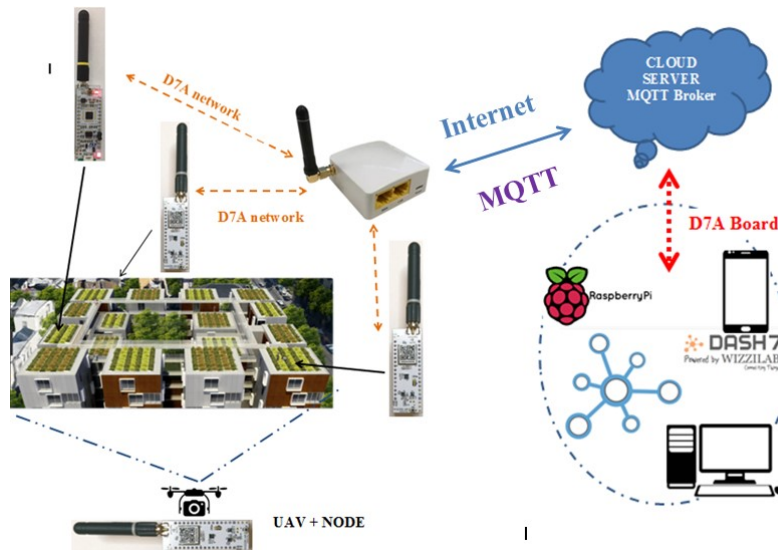


Fig. 8: D7AP WSN architecture setup for green infrastructure.

V. RESULTS

In this application, endpoints with UIDs: A27 (modified) and A26 are deployed on a green monitoring site. Figure 8a, b, and c, show the real time visualizations from multi-sensors in SH2050

at users' dashboard monitoring website. Fig. 9 displays the visualized data of temperature (under Fahrenheit and Celsius units) sensor based on D7A network. Fig. 10 displays data acquisition of light measurement based on D7AP network, with unit-less scale 0:1000. Those valid data are measured based on algorithms programming in the Mbed environment and complied into endpoints. Fig. 11 displays data of relative humidity (100%) and pressure (mbar/100) measurements obtained from the network. Fig. 12 displays messages reported by endpoints to the monitoring website using MQTT protocol in GW's local website. Endpoints transmit data to GW using D7AP. Monitoring website subscribes data from GW, and GW publishes all data and parameters to monitoring website. MQTT protocol, which is installed at the two-ends (GW and monitoring site/cloud), subscribes and publishes the data. The reported message of endpoint A27 subscribed by MQTT client has extra data compared to A26 due the additional soil moisture sensor.

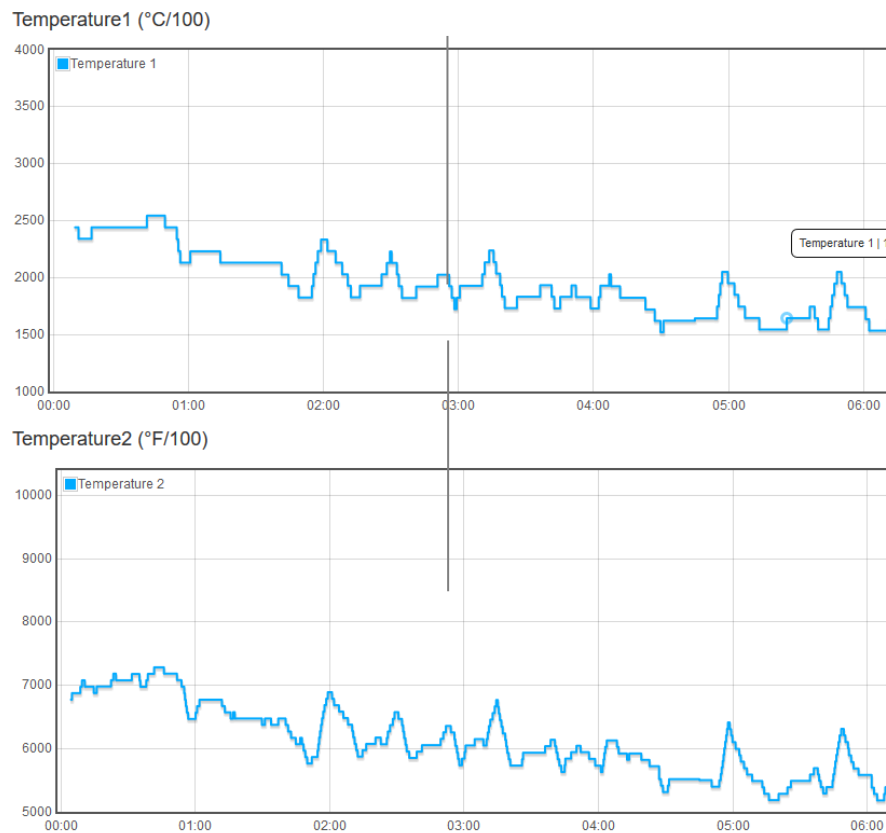


Fig. 9: Data acquisition of Temperature sensor (F/C) based on D7A network.

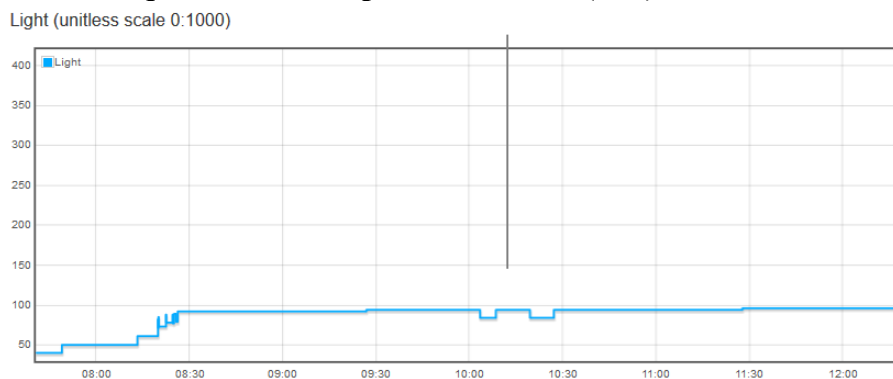


Fig. 10: Data Acquisition of Light sensor based on D7A network.

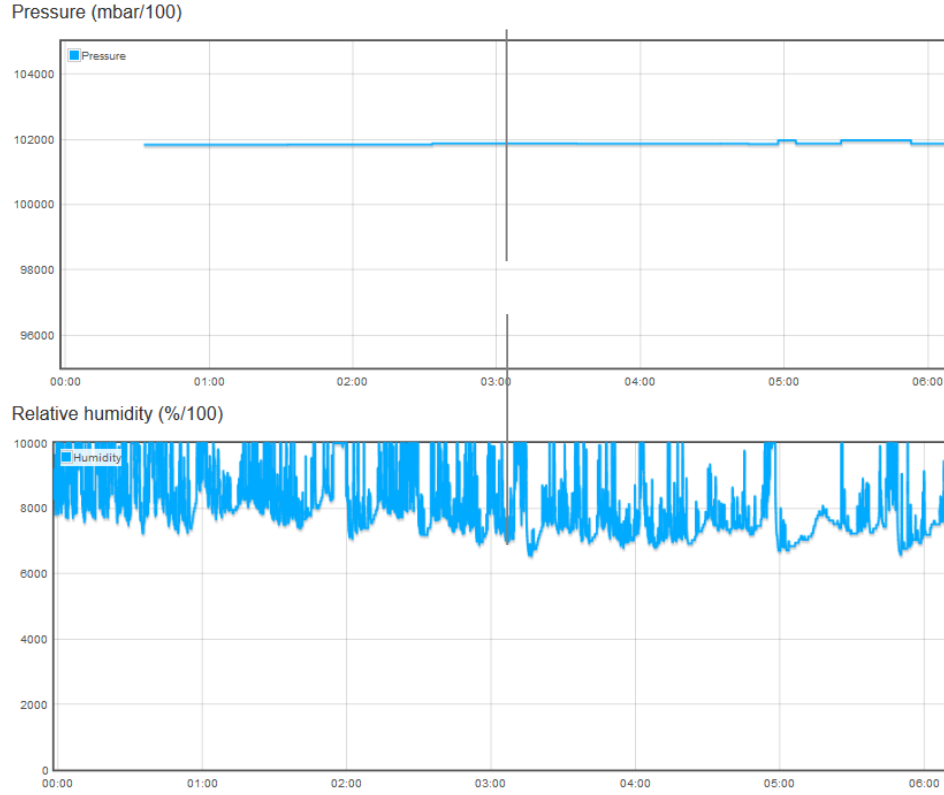


Fig. 11: Data acquisition of Pressure (mbar/100) and Humidity (%/100) based on D7A network.

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Fig. 12: Messages reported by endpoints to the monitoring website using MQTT protocol in GW's local website.

VI. Conclusions

In this paper, D7AP v1.0 based Wireless Multi-sensor Network Wizzikit 915 MHz is introduced as a better solution to midrange WSN/IoT use cases for green infrastructure and environment monitoring. D7AP is designed specifically for use in mid-range, and low-power WSN/IoT networks.

With extended communication range, compared to IEEE 802.15.4 networks, and low power operation, D7AP broadens the area of possible applications. Moreover, D7AP architecture of routing information maintained by nodes of the network simplifies complex mesh topology used in large networks that extend beyond the communication range of a single gateway. The use of D7AP improves operation of localization and monitoring systems based on RSSI measurements. Larger link budgets and better penetration of sub-GHz waves through obstacles make D7AP also more suitable for indoor localization applications while still ensuring low-power operation. Particularly, Wizzikit D7AP-WSN 915-MHz with the implementation of soil moisture sensor and D7AP technology promises a better wireless multi-sensor network for green project monitoring. An update when adding an extra sensor must follow the design of SH2050's and D7AP's architecture for data acquisition.

VII. Future Work

Data Acquisition of Endpoint A27 based on D7AP network needs an improved Mbed program in order to transmit and publish soil moisture data properly. Deployment of D7AP WSN of 915-MHz deployment has to be studied and measured carefully in order to avoid signal interference in a hostile environment. Furthermore, an energy harvesting system such as solar panels can be implemented to power this WSN in a green infrastructure.

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REFERENCES

- Byun, Jinsung, et al. (2012). "An intelligent self-adjusting sensor for smart home services based on ZigBee communications." *IEEE Transactions on Consumer Electronics*, vol. 58, no. 3 pp. 794-802, 2012.
- DASH7 Alliance. (2017a). <http://dash7-alliance.org/>
- DASH7 Alliance. (2017b). DASH7 Alliance Wireless Sensor and Actuator Network Protocol VERSION 1.1. <http://dash7-alliance.org/>
- DDOT (2018). District Department of Transportation, <http://ddot.dc.gov/GreenInfrastructure/>
- Ergeerts, G. et al. (2015). "DASH7 Alliance Protocol in Monitoring Applications," 10th International Conference on P2P, Parallel, Grid, Cloud and Internet Computing (3PGCIC), Krakow, 2015, pp. 623-628.
- Gehrels, H., et al. (2016). "Designing green and blue infrastructure to support healthy urban living."
- Gruen, A. (2013). "SMART Cities: The need for spatial intelligence.", 3-6.
- Han, D., and Jae-Hyun Lim. (2010). "Smart home energy management system using IEEE 802.15.4 and zigbee." *IEEE Transactions on Consumer Electronics*, vol 56, no. 3, pp. 1403-1410, 2010.
- Hetting, C., (2017) Giant strides to connect all thing with Wi-Fi 802.11ah (HaLow). <http://wifinowevents.com/>
- Koskinen, J., P. Kilpeläinen, J. Rehu, P. Tukeya and M. Sallinen. (2010). "Wireless Sensor Networks for infrastructure and industrial monitoring applications," 2010 International Conference on Information and Communication Technology Convergence (ICTC), 2010, pp. 250-255.

United Nations (2014). Department of Economic and Social Affairs. World Urbanization Prospects, the 2014 Revision. Available online: <http://esa.un.org/unpd/wup/CD-ROM/> (accessed on 7 November 2016).

United States Census Bureau (2017). District of Columbia. <http://census.gov/>

Weyn, M., G. Ergeerts, R. Berkvens, B. Wojciechowski and Y. Tabakov, (2015). “DASH7 alliance protocol 1.0: Low- power, mid-range sensor and actuator communication,” 2015 IEEE Conference on Standards for Communications and Networking (CSCN), Tokyo, 2015, pp. 54-59.

Wi-Fi HaLow. (2017). <http://wi-fi.org/>.

Wizzilab. (2017). <http://wizzilab.com/dash7-technology/>

Zigbee (2017). <http://zigbee.org/>