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Bluetooth Mesh Networking: An Enabler of Smart Factory Connectivity and Management

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***Abstract*—Smart factory is an environment where machinery and equipment are able to work together to improve processes through automation and self-optimisation. Connectivity in smart factory is the key enabler to optimise operations through collection of data to accelerate automation in a factory setting. This paper proposes the use of Bluetooth wireless mesh networking to realise the vision of smart factory, providing efficient connectivity to collect data from the shop-floor in real-time. Downstream communication to the sensor devices can also be performed, thus creating a digital twin of the shop-floor and its process. A web-based visualisation dashboard is implemented to monitor the status of sensors and machinery in real-time. The developed system is also integrated with an indoor localisation mechanism to provision new sensors into the mesh network. An augmented reality dashboard enables a user who is physically patrolling the smart factory to view sensor status in real-time.**

I. INTRODUCTION

Smart Factory is a term that describes "*an environment where machinery and equipment are able to improve processes through automation and self-optimization*" [9]. With this, different parts of the production system, in particular the shop-floor can now be connected via Internet of Things (IoT) technologies, thus enabling the exchange of information and actuation of commands in real time to optimise the operations.

Over the years, factory manufacturing has evolved to increase efficiency in operations transiting from manual work processes to the introduction of machinery. Industry 4.0 is regarded as a new way of manufacturing today, as it has the capability to exploit digital technology with machinery to optimize operations and collection of data to accelerate automation in a factory setting. Real-time data can be collected through smart sensors, robots and machines that are used simultaneously in the production and assembly line. The collected data are then used for further analysis to optimise the production workflow, to perform predictive maintenance, and to keep track of the factory production processes in real time. Even though, it has been years since the introduction of the Industry 4.0 in 2013 [7], there has been multiple challenges in integrating it into the current manufacturing systems within the factories of today [2]. Industry is slow to adopt this technology because replacing existing assets with Industry 4.0-enabled assets can be complex and that it requires time.

Activities around the management of production processes include a low-level control layer (LLC) which facilitates real-time responsiveness and a high-level control (HLC) layer which makes decisions that impact the overall goals of the system as a whole [10]. The LLC is responsible for providing information about the state of the production at current time and important diagnostics data, e.g., errors and failures, to the HLC which then triggers the HLC to make intelligent decisions automatically, e.g., scheduling of machine maintenance.

This paper proposes the use of Bluetooth wireless mesh networking to implement smart factory connectivity, with an aim to (1) Establish a sensor network to collect data to be analysed by an IoT platform (2) Enable downstream communication from the IoT platform to the sensor devices (3) Create a digital twin of the shop-floor and its process, accompanied by an interactive visualisation of the smart factory and (4) Ensure secure communication in the mesh network to guarantee data integrity and authenticity. Additionally, we have also integrated an indoor localisation mechanism to provision new sensors into the mesh network and to facilitate the installation of new sensors in the smart factory in an efficient manner.

This paper is organised as follows: Section II provides a short overview of Bluetooth mesh networking and related work. Section III presents our architecture to enable Industry 4.0 smart manufacturing, while Section IV describes our prototype implementation. Section V discusses performance evaluation of the proposed system, and we conclude the paper with future work in Section VI.

II. BACKGROUND AND RELATED WORK

This section provides a brief overview of Bluetooth mesh networking and related work in smart manufacturing.

A. Bluetooth Mesh Networking

Bluetooth Mesh is a new type of networking technology built using Bluetooth Low Energy (BLE). BLE provides the wireless communications technology while Bluetooth Mesh provides the networking technology. Nodes in a Bluetooth Mesh network are arranged in a mesh topology. Unlike older Bluetooth technologies, nodes within a mesh network can have one-to-one (1:1), one-to-many (1:M) or many-to-many (M:M) relationship. There are many other types of mesh networks such as Zigbee and Thread, as Bluetooth Mesh is the newest of the three, this paper aims to demonstrate its feasibility for smart manufacturing use case.

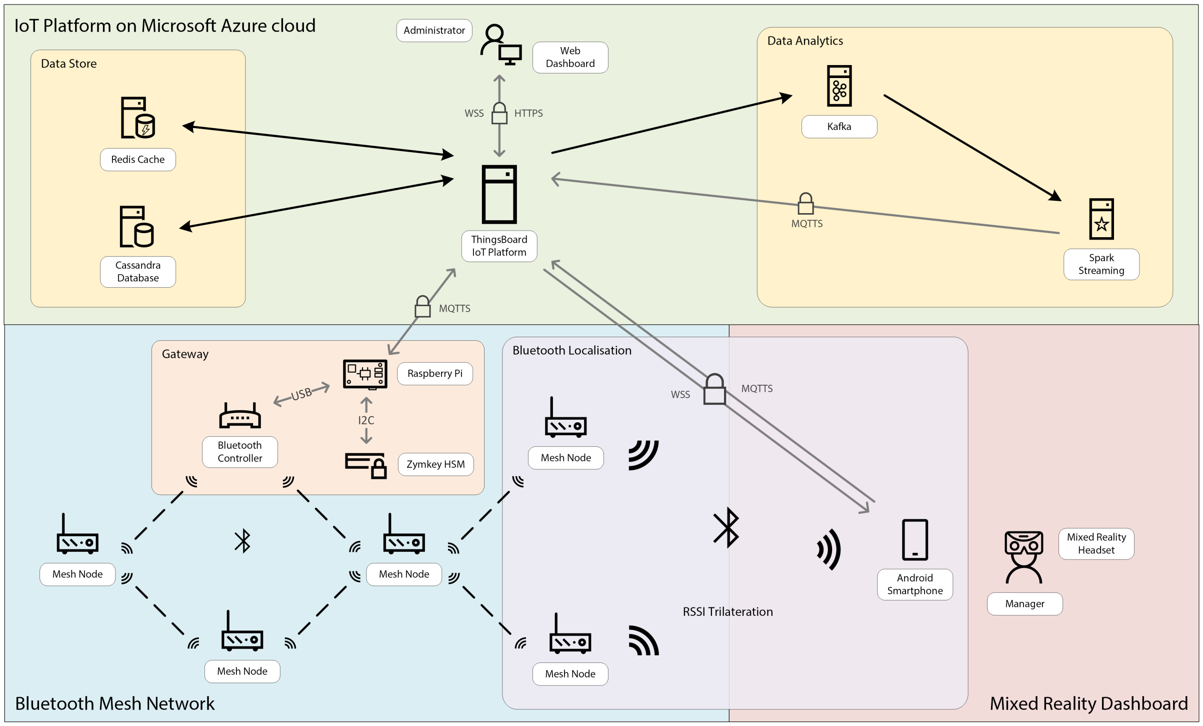


Fig. 1: Architectural Overview of Smart Manufacturing based on Bluetooth Mesh Networking

Bluetooth Mesh uses a client-server architecture. Each node can comprise of multiple servers and/or clients. Each server and client can contain multiple models. These models define the type of messages that the server and client may transmit or receive. Generally, clients will transmit messages to modify the state of a server. Bluetooth Mesh uses a publish/subscribe messaging system in which each device in the mesh network is given a unique unicast address. Devices can publish to this address for unicast communication. For multicast communication, devices can publish or subscribe to group addresses.

Bluetooth Mesh uses an approach called managed flooding to publish and relay messages. This means that messages are not routed but instead are broadcast to every other devices in range. These devices will then broadcast the message to other nodes until the message reaches the destination. One advantage of this technique is reliability as the failure of a single node will not affect the transmission path of messages. There will always be multiple paths that a message can use to reach its destination. There are also disadvantages in this method but the Bluetooth Mesh specification has provided a few countermeasures to optimise the flooding performance.

B. *Related Work*

Gandhi et al. [3] proposed a simple Bluetooth infrastructure for Smart Factory. A number of Bluetooth connected stationary nodes are deployed on the entire factory floor to collect data from Bluetooth enabled industrial sensors through polling. It relies on point-to-point connectivity, and it is seen as not scalable as compared to the newer Bluetooth mesh networking.

Garrido-Hidalgo et al. [4] proposed a collaborative BLE mesh network that has been deployed and evaluated, showing that mesh network can fulfill Industry 4.0 requirements with zero failures. The green I3A smart factory (GreenISF) scenario was used, highlighting the contribution of OperaBLE towards a sustainable digitalization of Industry 4.0.

Martínez et al. [6] presented a proof-of-concept implementation of Bluetooth Mesh to automate a smart doorbell. They have demonstrated the feasibility of Bluetooth as a technology that can be used for automation solutions.

Zafari et al. [11] reviewed many different indoor localisation techniques such as Angle of Arrival (AoA), Time of Flights (ToF), Return Time of Flight (RToF), Received Signal Strength Indicator (RSSI), etc. It is found that RSSI has low localisation accuracy though it is the easiest to implement. Among all the wireless localisation techniques, although Bluetooth has low localisation accuracy as compared to others, its seamless integration with BLE mesh network for data collection can be seen as an advantage for smart manufacturing.

Bertuletti et al. [1] tested a few regression models that can be used to convert RSSI into distance. The polynomial model has shown to be more accurate than the other models. In addition, Li et al. [5] proposed a more advanced technique, i.e., neural network based RSSI distance model, that greatly improves the localisation accuracy.

III. SMART MANUFACTURING WITH BLUETOOTH MESH NETWORKING

Figure 1 shows an architectural overview of the proposed smart manufacturing system. It consists of three major components, namely: (a) Bluetooth Mesh Network which collects and sends sensor data to the IoT Platform. (b) IoT platform, serving as the backbone of the system where data is stored, processed and analysed. (c) Visualisation dashboard which allows real time sensor data and the location of Intelligent Guided Vehicle (IGV) to be tracked.

A. Bluetooth Mesh Network

The Bluetooth mesh network consists of *Mesh Nodes* and a *Gateway* that bridges the communication between the mesh network and the cloud. The *mesh node* is a sensor capable of collecting sensor data such as *temperature, humidity, pressure, gas*, and *acceleration* in a smart factory setting. Each *mesh node* supports the following communication mechanisms:

- **Upstream communication** – Data collected from all the primary and secondary sensor in the mesh node will be read and published to the gateway using a sensor status message.
- **Downstream communication** – When a mesh node receives a message from the IoT Platform via the gateway, it will execute the operation encapsulated in the message.
- **Machine to machine communication** – A mesh node is able to communicate directly with another mesh node without relying on a central server.

The *Gateway* mediates the communications between the mesh nodes and the cloud securely. It operates on a publish-subscribe mechanism in which it subscribes to the IoT platform for attribute updates of the sensor device via MQTT. If the gateway application receives a message to send an actuation command to the specified sensor device, the message will be delivered through the mesh network. Conversely, when the gateway application receives data from the sensor devices, the sensor data will be parsed, formatted and then published to the IoT platform through MQTT.

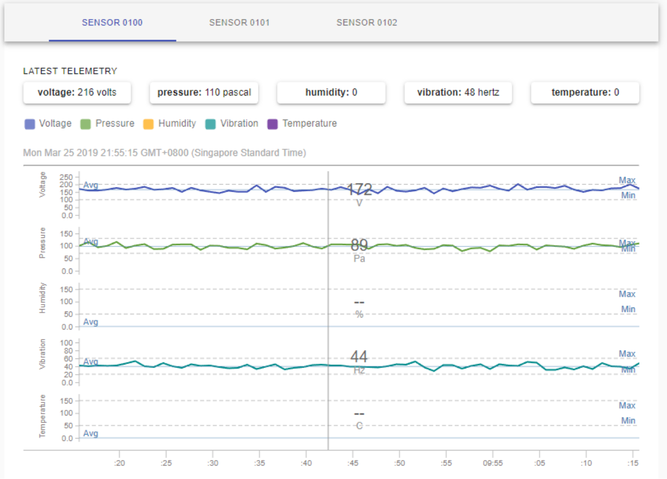
B. IoT Platform – ThingsBoard

The IoT Platform is required to store, process and analyse the data collected from the smart factory. In order to facilitate big data processing, both relational and NoSQL databases are supported by the IoT Platform. In addition, it has the capability to perform device management tasks such as getting the status of sensors and issuing actuation commands.

ThingsBoard is equipped with a powerful rule engine to process and analyse the data collected. This enables the average termperature, humidity and pressure for each sensor to be computed automatically, and then visualised on the dashboard for monitoring purposes.

C. Visualisation and Augmented Reality Dashboard

A smart factory interactive map is used to illustrate the real-time status of sensors and the IGV, thus creating a digital twin of the shop-floor. The IGV has four different states of automation, namely *Sending*, *Loading*, *Waiting/Charging*, and *Collecting*. Furthermore, the location of IGV is dynamically updated in real-time, and status information such as battery level, payload, and state will be shown when requested.



voltage: 216 volts
pressure: 110 pascal
humidity: 0
vibration: 48 hertz
temperature: 0

Fig. 2: Visualisation of sensor data

Based on the sensor data stored in the IoT Platform, the dashboard is able to display time series chart that is updated every 1000 ms in real time. The chart also shows the minimum and maximum baselines which indicate the range of each sensor value. With the baselines, the user can easily visualize the data output to ensure that the machine is running within the expected range as shown in Figure 2.

There is a augmented reality (AR) dashboard in the proposed system to allow for the user to visualise the status of sensors and machines in real-time using a AR headset when he/she physically walks around the factory. As the mesh nodes deployed on the shop-floor emit Bluetooth signals, the augmented reality dashboard made use of the signal strength of the mesh nodes to derive the physical location of the user within the mesh network in the factory using trilateration technique.

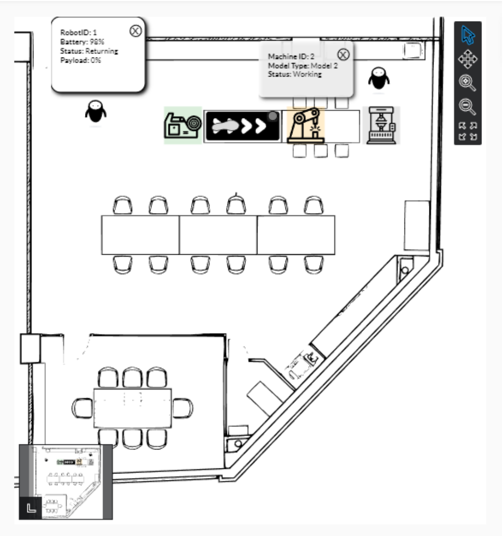
IV. IMPLEMENTATION

This section describes the implementation details of the proposed mesh networking for smart factory.

Fig. 3: (a) *Thingy:52* as a mesh node, (b) Raspberry Pi with *nRF52840 DK* as the gateway

A. Bluetooth Mesh Networking

We used *Thingy:52* in this prototype, running as a *mesh node*. The *Thingy:52* as shown in Figure 3(a) comes with a multitude of sensors to measure environment variables such as temperature, humidity, pressure, and many more. It is built around nRF52832 System on Chip (SoC) which is powered by


RobotID: 1
Battery: 98%
Status: Returning
Payload: 0%

Machine ID: 2
Model Type: Model 2
Status: Working

Fig. 4: A web-based interactive map showing the layout of the mock-up factory

an embedded ARM Cortex-M4F CPU running at 64 MHz, 512 kB of flash memory and 64 kB of RAM. The ARM Cortex-M4F CPU comes with a single precision floating point unit. The SoC supports Bluetooth 5 with a +4 dBm transmit power on the wireless radio.

A custom firmware was developed for the mesh node, i.e., *Thingy:52* using *Zephyr*, an open-source real-time operating system for embedded system to support efficient mesh networking.

The Raspberry Pi Model 3 running *DietPi OS* was used as the Gateway. As illustrated in Figure 3(b), in order to support longer Bluetooth transmission range, we flashed a custom firmware onto Nordic nRF52840 DK and attached it to the Raspberry Pi. The gateway also used a *BlueZ* mesh client library, and *jsmn* library to handle JSON operation, as well as the *Eclipse Mosquitto* library to handle Message Queuing Telemetry Transport (MQTT) connections.

The sensor data collected from the sensor devices needs to be timestamped. However, the sensor devices do not come with a Real-Time Clock (RTC). An emulated RTC on Raspberry Pi was used such that when the gateway receives sensor data from the sensor device, it will be timestamped with the current time. The main disadvantage of this method is that it does not account for latency between the sensor device and the gateway. However, this is not much of an issue as the latency between the sensor device and the gateway is negligible, i.e., $\leq$ 1s.

B. Interactive Dashboard

Figure 4 shows a web-based interactive map that allows for the tracking of IGV's location and the visualisation of sensor data in real-time.

C. Bluetooth Localisation

As the sensor devices periodically advertise Bluetooth packets, it is possible to measure the Received Signal Strength Indication (RSSI) values of these packets in order to estimate the distance between the user or IGV and the sensor device. The collected RSSI values are then smoothed using a Kalman filter:

$$x_k = Ax_{k-1} + Bu_k + w_{k-1} \tag{1}$$

where the predicted value, x_k is a combination of the previous value x_{k-1} plus a control input u_k and a process noise w_{k-1}. Based on x_k, we can then measure z_k using the equation

$$z_k = Hx_k + v_k \tag{2}$$

The coefficients A, B and H are general transformation matrices. As it was not possible to measure the movement of the user or IGV, it is assumed that there is no control input, and hence identity matrix was used. In this implementation, we also assumed that the process noise has a co-variance of 0.1 and that the measurement noise has a co-variance of 0.01 to place a higher emphasis on the measured values.

After smoothing the RSSI values, they are converted into distances. According to [1], a power regression based signal path loss model was used, and for convenience, our implementation adopted the coefficients used in Android Beacon library.

$$d = 0.42093 * RSSI^{6.9476} + 0.54992 \tag{3}$$

After converting the RSSI values into distances, the location of the user or IGV can then be computed using trilateration. This was done using the Levenberg-Marquardt algorithm. A moving average of the distance was used to smooth the computed location. The location information is then published back to ThingsBoard through MQTT. As the Bluetooth RSSI values have large fluctuations, this had caused the computed location to fluctuate too. Therefore, by using moving average of RSSI values, this provides some forms of stability to the location estimation.

D. Augmented Reality Dashboard

As shown in Figure 5, the augmented reality headset is powered by an Android smart phone. Content on the smart phone is reflected off a mirror and projected through a lens onto a tinted plastic screen in front of the user's eye. This allows for a real time augmented reality experience where virtual objects are overlaid onto the user's vision.

Fig. 5: Headset with phone mounted for augmented reality dashboard

Fig. 6: Interface of the augmented reality dashboard

With the ability to estimate the location of a user in the smart factory in real-time, a augmented reality scene showing the location of sensors as well as their corresponding status information can thus be rendered on the AR headset while the user is patrolling the shop-floor in a smart factory.

An augmented reality Android application was developed. The sensor location data and status information are retrieved from the IoT Platform, and then drawn onto the virtual world. This was done simply by first initialising a simple square with six vertices and two polygons using OpenGL ES. A blank texture is then drawn with the sensor data and then mapped onto the square. As shown in Figure 6, the second blue square shows the sensor device "0106". It can be seen that the sensor data is displayed below the name. and that the objects are overlaid onto the user's vision.

The Android application also subscribes to ThingsBoard for attribute changes. If any sensor device changes its location, the changes will be reflected immediately. The user is able to interact with the dashboard by using a Google Daydream controller. There are two modes of visualisation, namely (1) *Zone mode*: the sensors are colour coded according to their pre-defined zones (2) *Temperature mode*: the sensors devices are coded according to their temperature. The gradient starts at the colour blue with a temperature of 20°C. The gradient ends at the colour red with a temperature of 40°C. With the gradient, sensor devices and zones with a higher temperature will appear redder. Sensor devices and zones with a lower temperature will appear bluer.

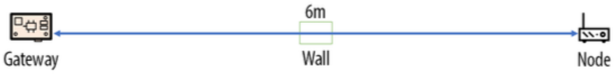
The second interaction is the ability to select and edit the position of any sensor devices. Using the controller, the user can select any sensor device and set its location to the position that the user is currently at as calculated by the Bluetooth localisation algorithm. When the user sets the location, the new position of the device is sent to ThingsBoard through the REST API. This can be useful to help position new sensor devices as they are added to the mesh network.

V. SYSTEM EVALUATION

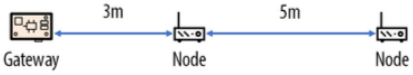
We have developed a prototype of smart factory with Bluetooth mesh networking and conducted preliminary feasibility tests on data rates, reliability and latency. Figure 7 shows five test set-up that were conducted. The nodes in test set-up 7(a), 7(b), and 7(c) are connected directly to the gateway, while the nodes in test set-up 7(d) and 7(e) are connected to the gateway via meshing.

(a) Test setup 1. Node is 15 cm from gateway.

(b) Test setup 2. Node is 3 m from gateway.



(c) Test setup 3. Node is 6 m from gateway with 1 wall in between.



(d) Test setup 4. Node is 2 hops from gateway with a total distance of 8 m.

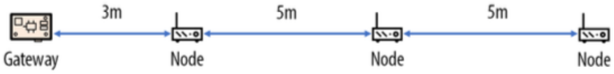


Fig. 7: Test setup with various topologies

A. Sensor Data Rates

The first test conducted was to measure the maximum sensor data rate that the system could handle. We programmed the sensor devices to send a burst of 100 and 500 messages containing sensor data via the mesh network to the gateway, which were then forwarded to the IoT platform.

As shown in Table I and II, our results clearly show that mesh networking is able to handle more than 50 messages a second.

TABLE I: Test results in handling a burst of 100 messages

Metric	**Test Setup 1**	**Test Setup 2**	**Test Setup 3**
Average Time Taken	1426 ms	1442 ms	2006 ms
Standard Deviation	294 ms	230 ms	606 ms
Average Message Interval	14 ms	14 ms	20 ms
Message Loss	0%	0%	0%
Message Data Rates	70 msg/s	69 msg/s	50 msg/s

TABLE II: Test results in handling a burst of 500 messages

Metric	**Test Setup 1**	**Test Setup 2**	**Test Setup 3**
Average Time Taken	6569 ms	8714 ms	9118 ms
Standard Deviation	617 ms	1074 ms	1256 ms
Average Message Interval	13 ms	17 ms	18 ms
Message Loss	0%	0%	0%
Message Data Rates	76 msg/s	57 msg/s	54 msg/s

B. Round Trip Time (RTT)

The second test conducted was to measure the round trip time of the system. A message was sent from the IoT Platform to the sensor device via the gateway. The sensor device then sends a message back to the IoT Platform. The time taken for this communication was measured.

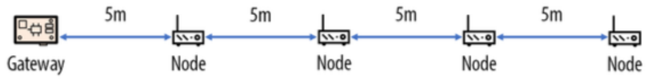
The results show that the RTT for the communication between the sensor device and the IoT platform via the gateway and mesh network is quite low and reasonable. The increase in latency per hop is pretty much in line with a study conducted by Silicon Labs on the performance of Bluetooth Mesh networks [8].

TABLE III: Test results of RTT measurement

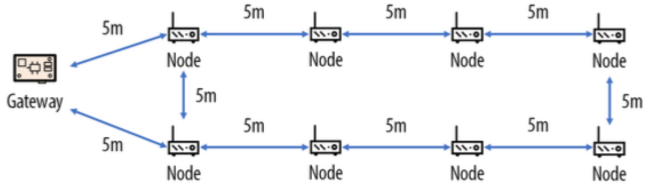
Metric	**Test Setup 1**	**Test Setup 2**	**Test Setup 3**	**Test Setup 4**	**Test Setup 5**
RTT	109 ms	115 ms	146 ms	250 ms	281 ms
Std Dev	22 ms	26 ms	37 ms	87 ms	65 ms

C. Reliability

A basic reliability test was conducted to demonstrate that mesh networking offers better reliability as it provides redundancy in the data transmission though controlled flooding.



(a) Test setup 6. Nodes are arranged in one line.



(b) Test setup 7. Node are arranged in two lines.

Fig. 8: Reliability of Bluetooth mesh networking

Figure 8(a) shows that four nodes are arranged in one line, and there is only one connectivity path between two nodes, while Figure 8(b) shows a simple mesh network consisting of eight nodes with multiple paths to the gateway.

A node failure was then simulated by randomly switching off one of the middle nodes. In the first setup, the message from the last node could not reach the gateway. In the second setup, the message from the last node could still reach the gateway. Even though we tested the prototype with only a small number of nodes, Silicon Labs has demonstrated that Bluetooth Mesh networks can be scaled to a much larger size [8].

VI. CONCLUSIONS AND FUTURE WORK

A reliable connectivity is crucial to ensure the success of smart factory. We have demonstrated the feasibility of Bluetooth mesh networking to facilitate data collection from the sensor devices to an IoT cloud as well as downstream communication. With a reliable communication infrastructure, management tasks can then be efficiently implemented, this includes visualisation of sensor and machinery status in real-time, tracking of physical location of the user and IGV on the shop-floor, and performing remote configuration of the sensors through downstream communication.

The developed prototype system also shows that Bluetooth Mesh has an added advantage over other competing mesh networking technologies, as it is interoperable with many devices in the market. In particular, the augmented reality dashboard is only possible as every smart phone comes with Bluetooth connectivity. Even though the current prototype system has not been deployed in a real factory setting, the architecture is scalable and it fulfills the requirements of a smart factory.

One of the main issues in the developed prototype is that the accuracy of localisation is rather low as a basic localisation technique was adopted. However, it is possible that the localisation component of the system is replaced with a more accurate technique by employing the new Bluetooth 5.1. We can exploit the capability of Bluetooth 5.1 that supports direction finding using AoA and AoD to improve the accuracy of the localisation in future versions of the system.

Apart from smart factory, the technologies and architecture demonstrated in this paper has the potential to be used in other areas or industries such as building automation. Even though the system was designed for industrial use in mind, the system could also be adapted to provide connectivity and management for a smart home and other IoT applications.

REFERENCES

[1] S. Bertuletti, A. Cereatti, U. Della, M. Caldara, and M. Galizzi. Indoor distance estimated from bluetooth low energy signal strength: Comparison of regression models. In *2016 IEEE Sensors Applications Symposium (SAS)*, pages 1–5, April 2016.

[2] B. Chen, J. Wan, L. Shu, P. Li, M. Mukherjee, and B. Yin. Smart factory of industry 4.0: Key technologies, application case, and challenges. *IEEE Access*, 6:6505–6519, 2018.

[3] M. Gandhi, H. Kour, D. Tandur, R. Gore, and A. Varghese. Bluetooth iot infrastructure network with immersive experience. In *2017 9th International Conference on Communication Systems and Networks (COMSNETS)*, pages 425–426, Jan 2017.

[4] C. Garrido-Hidalgo, D. Hortelano, L. Roda-Sanchez, T. Olivares, M. C. Ruiz, and V. Lopez. Iot heterogeneous mesh network deployment for human-in-the-loop challenges towards a social and sustainable industry 4.0. *IEEE Access*, 6:28417–28437, 2018.

[5] G. Li, E. Geng, Z. Ye, Y. Xu, J. Lin, and Y. Pang. Indoor Positioning Algorithm Based on the Improved RSSI Distance Model. *Sensors*, 18:2820, Aug. 2018.

[6] C. Martínez, L. Eras, and F. Domínguez. The Smart Doorbell: A proof-of-concept Implementation of a Bluetooth Mesh Network. In *2018 IEEE Third Ecuador Technical Chapters Meeting (ETCM)*, pages 1–5, Oct. 2018.

[7] M. Moore. What is industry 4.0? https://www.techradar.com/news/what-is-industry-40-everything-you-need-to-know, Apr 2018.

[8] Silicon-Labs. An1137: Bluetooth mesh network performance.

[9] C. Team. What is the smart factory and its impact on manufacturing? https://ottomotors.com/blog/what-is-the-smart-factory-manufacturing, June 2018.

[10] P. Vrba, P. Kadera, V. Jirkovsky, M. Obitko, and V. Marik. New trends of visualization in smart production control systems. In *Holonic and Multi-Agent Systems for Manufacturing. HoloMAS 2011. Lecture Notes in Computer Science, vol 6867. Springer, Berlin, Heidelberg*, page Chapter 7. Springer, Berlin, Heidelberg, 2011.

[11] F. Zafari, A. Gkelias, and K. K. Leung. A Survey of Indoor Localization Systems and Technologies. *IEEE Communications Surveys Tutorials*, pages 1–1, 2019.