# An IoT Implementation for Manufacturing Using Wi-Fi, 6LoWPAN, and MQTT

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## Abstract

Traditional automated manufacturing environments employ multiple machines that do not necessarily communicate with a central supervisory system. As suggested by the initiatives such as Industry 4.0 and Smart Manufacturing, it is more important than ever to access real time machine performance and environmental data to accurately track, maintain and improve manufacturing automation. We present a use case where WiFi and 6LoWPAN based sensors are introduced to collect environmental and machine health data in an existing manufacturing line to minimize the downtime and maintenance costs.

## 1 Introduction

### *Data Tracking for Manufacturing*

Increased demand for goods in emerging markets, concerns on energy use, and overall demand for utmost quality are pushing the automated manufacturing environments towards a better tracked, connected approach where individual automation machines and processes can be orchestrated as a whole system. Initiatives like Industry 4.0 and Internet of Things (IoT) set the guidelines for the transformation from the traditional factory automation to the next generation automated manufacturing solutions. Industry 4.0 concept envisions a term called Smart Manufacturing, where all materials can interact with the equipment and processes, and each process can seamlessly transfer the work in progress to the next process until the finished goods are produced. This requires decentralized self-organizing skills and minimizes the need for human input and labor [16]. Any process irregularities and automation issues will be detected and corrected in a prompt fashion to ensure a seamless production line, and minimize the downtime and maintenance costs of the line [15]. Vast amounts of data should be collected, analyzed, and quickly transferred between the individual processes of the production environment to achieve the goals of Smart Manufacturing.

Several industries such as power generation and distribution have long been using Supervisory Control and Data Acquisition (SCADA) systems to track the entire process in real time to prevent accidents that can have catastrophic consequences. The SCADA systems are also recently evolving to handle more inputs and process “big data” to meet the needs of Industry 4.0[12]. However, many industries have long avoided using SCADA due to the high cost associated with the communication infrastructure of these systems[11].

### *Communication Challenges and IoT*

A manufacturing environment can consist of manual stations, simple machines controlled by hardware, and Programmable Logic Controller (PLC) or PC based automation machines that use a broad range of protocols to communicate. The communication may be via simple lights, audible alarms, and human machine interfaces (HMI) to interact with humans; discrete I/O connections to adjacent machines; serial communication, several industrial field buses; USB; and several protocols over Ethernet backbone. These communication methods are not designed to be interoperable with each other and each equipment manufacturer tends to use a proprietary communication solution. A multitude of incompatible control environments and communication methods pose a challenge to collect the data in a centralized fashion. Several solutions have been proposed to make the data transportation more abstract and platform agnostic. One such solution is Open Platform Communications – Unified Architecture (OPC-UA). The original OPC was developed in 1990s as a communications standard between PC based world and industrial automation devices such as PLCs, however it was constrained to only a small subset of industrial control systems. OPC-UA strives to create a platform, language, and protocol independent communications platform for universal use [20]. It should be noted that OPC-UA is not suitable for resource constrained systems due to the high memory demand and processing requirements of the server implementations. Although one recent development claims to reduce the OPC-UA stack down to 200KB, it has not been in widespread use [15]. The IoT initiative has taken a quick start for consumer oriented sectors such as smart appliances, but it is still in its early stages for manufacturing and automa-

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tion [4]. As IoT strives to be a low cost solution for seamless data transfer regardless of the types of the objects, it is worth considering for the next generation manufacturing and industrial automation where every existing process could be treated as a "thing". This concept is called Industrial Internet of Things "IIOT" and it might be the key to the next industrial revolution [13]. There are a few communications protocols such as Advanced Message Queuing Protocol (AMQP) [21], Message Queuing Telemetry Transport (MQTT) [18], and Constrained Application Protocol (CoAP)[17], which are better suited for power and network constrained embedded IoT applications due to their low communication overhead and reduced processor use [8].

*Use of WSN for Manufacturing*

Wireless Sensor Networks (WSN) utilization is on the rise for manufacturing environment data acquisition and transfer due to their lower cost and ease of integration to existing processes [7]. Some of these sensors use the existing IEEE 802.11 WLAN network infrastructure[1], widely known as WiFi. However, these sensors are often battery powered and expected to perform for extended periods of time with no human interaction, thus using WiFi is not energy efficient enough to fulfill this purpose. Therefore more energy efficient wireless protocols are being utilized such as Bluetooth Low Energy (BLE) utilizing the IEEE 802.15.1 standard, ZigBee, and 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks) that are built on the IEEE 802.15.4 Low-Rate Wireless Personal Area Network standard [6]. Protocols such as ZigBee and BLE use the Media Access Control (MAC) layer for hardware addressing, and do not traditionally implement the Internet Protocol (IP). The lack of IP addressing is acknowledged as a shortcoming and some recent developments such as ZigBee IP [14] are offered, but are not yet popular. 6LoWPAN, on the other hand, implements the native IPv6 stack on a low-power 802.15.4 based network, and makes it much easier to pass the information to widespread IP based protocols such as TCP or UDP with minimal effort. Since only 25% of the entire Internet has IPv6 support as of 2018 [3], interim translations to the legacy IPv4 domain are still necessary using methods such as IPv6 to IPv4 tunneling. It should also be noted that a border (edge, gateway) router is usually necessary to translate the information to the desired network structure and push it to the final destination for most of the existing low-power network solutions.

## 2 Existing Manufacturing Environment

The targeted manufacturing environment is the production lines of a sensor company which operates around the world. These lines are often in humidity, temperature, and dust controlled clean rooms. They consist of some fully automated assembly and calibration machines, some semi-automated assembly and test machines, and some manual stations that are capable of producing 20,000 to 40,000 pressure sensors per day. Some of the machines such as the calibrators are controlled by PCs, connected to the manufacturing network and push individual sensor data into a central production database via company Local Area Networks (LAN). Other machines have no network access and they only communicate to the operators about the process information via alarms, lights, and HMIs that require the operators to correctly feed the materials in and out of the machines. Machines are supplied from a variety of vendors and come with incompatible architectures. No SCADA or a similar system is present for the central control of the manufacturing lines. The company has recently invested in an IoT initiative and is looking to collect more data from the automation machines, processes, and the ambient environment to improve the quality, efficiency, and minimize the unforeseen downtime. The data is collected by a commercial IoT gateway based on the Eclipse Kura IoT Edge Framework. This gateway natively supports MQTT and OPC-UA for data transmission among other protocols. The hardware also contains a wireless receiver that supports IEEE 802.11. Some development is already completed so that several networked machines are pushing effectivity data such as cycle time and lot yields into the company IoT cloud over the OPC-UA framework via the gateway using wired LAN.

## 3 Design Methodology

The company IoT group has chosen MQTT for all the external data acquisition devices that OPC-UA implementation would be impractical. MQTT is a publisher-subscriber architecture where the publisher publishes the data as a message under a topic of choice to the broker, which acts as a gateway. The Quality of Service (QoS) of the messages could be chosen so that the delivery of the message can be guaranteed for mission critical applications or just be transmitted once to conserve network bandwidth and energy. A subscriber can subscribe to any number of topics and receive the data that is provided by the publisher via the broker. It should be noted that any node can be a subscriber and publisher simultaneously. Figure 1 illustrates a simple data transaction using MQTT for temperature data under the topic `Temp`.

**Figure 1. Message transfer over MQTT**

The formatting of the MQTT message is further standardized to a custom JSON format so that the messages can be abstracted and stored in the IoT cloud while complying to the templates used for data analytics.

The networked machines consist of ~20% of the entire production line, and rest of the automated equipment and semi-automated processes lack any performance data. Furthermore, even the networked machines sometimes lack the necessary sensors to collect certain data. One of the needed metrics is the cycle time and Overall Equipment Effectiveness (OEE), which is a metric of equipment availability, performance, and quality[2]. A cost effective way of introducing OEE tracking is to use embedded WSNs that have built-in motion sensing capability via gyroscopes and accelerometers. The small profile wireless node can be placed on a periodically moving part such as a pneumatic cylinder, a guard door, a crimping head, or a servo motor and detect the mean-time between periodic motions and determine the machine effectiveness. The same hardware can also measure the irregularities in the vibrations and alert the maintenance personnel ahead of time before machine breaks down. Especially the oven and chiller fans display excessive vibration that can be tracked long before they have total breakdown. The collected data can also be used to benchmark a particular equipment against similar equipment and determine the bottlenecks in the production lines. As the sensors are often placed in clean rooms; temperature, ambient pressure, and humidity sensing capability will also be handy to monitor and map the environmental conditions as a whole. Based on the immediate business needs an IoT based solution is sought to effectively track the following cases:

1. Cycle time monitoring for non-networked machines and processes based on repeated motions of machine actuators
2. Maintenance prediction based on the vibration and noise intensity of the actuators and oven heating and refrigeration systems
3. Monitoring of the environmental variables such as ambient temperature, pressure, and humidity to determine clean room conditions

## 4 Proposed Manufacturing Sensor Network

An extensive hardware comparison study of the existing commercially available WSNs was conducted. The key requirements were accurate acceleration and vibration sensing, ambient temperature sensing, ambient pressure sensing, ambient humidity sensing, noise sensing, low-power consumption, ease of integration to MQTT protocol, ability to work extended periods of time with internal power, and over-the-air firmware update availability. The hardware also need to be low-cost as potentially thousands of units will be deployed. Based on the study, three hardware platforms were chosen as a basis for our initial test platforms.

### *NodeMCU Platform*

The first platform is the NodeMCU. Based on the Espressif ESP8266 wireless module, it is an inexpensive and easy to use development platform for applications using 802.11 WLAN. Open source libraries are available for direct MQTT support, however no on board sensors or power storage are available. We connected this platform to an external InvenSense®MPU-6050 Inertial Measurement Unit (IMU) to be able to monitor acceleration data. Due to the ease of development, and low hardware cost this platform is used as the test bed for the continuous monitoring of the acceleration due to machine motions and vibrations. This platform was not considered for the final application due to the lack of internal sensors and power.

### *CC2650 Sensortag Platform*

The second platform is TI CC2650 SensorTag. This platform is designed as an all-in-one WSN for IoT applications. It has dual support of 802.15.1 (BLE) and several protocols using 802.15.4 such as 6LoWPAN and ZigBee. It has a built in accelerometer, gyroscope, magnetometer, IMU, and sensors for humidity, temperature, air pressure, light, and noise. The platform is powered by a standard CR2032 coin-cell battery, and is designed especially for ultra-low power consumption. The manufacturer claims that under certain conditions the battery can last several years [5]. The software platform is open source, easy to use, and supports several operating systems for embedded devices. To further maximize the battery life, we chose to design with the 6LoWPAN option and Contiki operating system. Contiki is a small operating system designed for tiny, resource constrained nodes utilizing 6LoWPAN[10]. It uses a duty cycle protocol called ContikiMAC, which enables it to achieve ultra-low power consumption by turning off the wireless transceivers 99% of the time [9]. Its ultra-low power consumption makes it possible to have multiple nodes in a production line without adding the burden of additional maintenance. One disadvantage of this platform is the lack of native MQTT support as there is no direct 802.11 connection. There is a flavor of MQTT called MQTT for Sensor Networks, however even that does not provide a direct access to outside networks [19].

### *XDK-110 Platform*

The third platform is Bosch XDK-110. This platform is also designed as an all-in-one WSN for IoT applications. It has dual support of 802.15.1 (BLE) and 802.11 (WLAN) standards, however it does not have native support for 802.15.4. It has a built in accelerometer, gyroscope, magnetometer, IMU, and sensors for humidity, temperature, air pressure, light, and noise. The unit has abuilt-in rechargeable 560 mAh battery. The software platform is based on Eclipse open-source, easy to use, and has native MQTT support. The unit is not as cost effective as it is five times more expensive than a TI CC2650- SensorTag.

The diagram in Figure 2 illustrates how the networked machines and the chosen wireless sensors provide their data to the corporate IoT cloud via the existing commercial IoT gateway. The WSNs eventually use the 802.11 WLAN connection to push their data using MQTT and the networked machine controllers use OPC-UA to complete the same action. It should be noted that the TI SensorTag needs an additional edge router to translate the messages sent over 6LoWPAN to MQTT and relay them to the IoT gateway. The abstracted data is stored in the cloud to be used by data analytics teams regardless of the source.

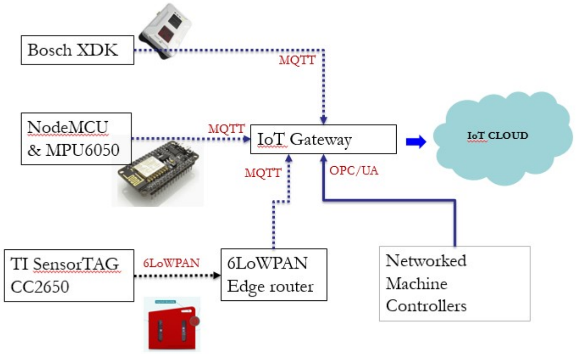

**Figure 2. Proposed IoT network diagram**

## 5 Status and Results

An ESP8266 based WSN equipped with an external MPU6050 3-axis accelerometer is currently mounted at a sensor calibration machine to analyze the the vibrations of the machine and determine the wear and tear as well as the performance of the motion components. The vibration data is also used as a basis for our cycle time determination algorithm. This setup is powered by an external power supply, which is not desirable for the final application, however is ideal for continuous streaming of raw data for development purposes. We have found that in order to accurately track the cycle time, the sensors need to be specifically placed as close as possible to the actuators of the machines. For the pressure sensor calibration machines, a location near the pneumatic rams that seal the devices under test at the calibration station was found to be suitable. Figure 3 shows the sensor location in such a machine.

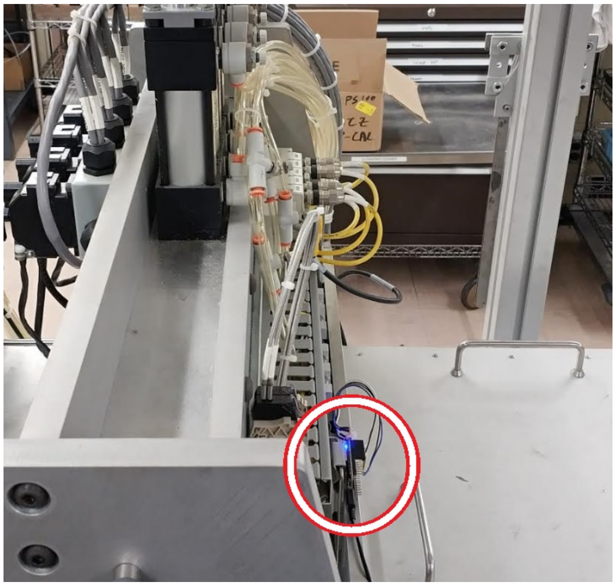

**Figure 3. Sensor placement on a calibration machine**

Based on the raw accelerometer data analysis, we were able to pick up distinct patterns that occur when the pallets containing the devices under test are indexed, and the sealing rams are engaged. For this specific machine type, there are a few spikes by the multiple actuations in between cycles to disengage the previous devices, move the pallets containing the next devices, and engage the new devices. Such pattern is captured live in Figure 5. In this figure it could be seen that the cycle time is around 16 seconds for the monitored period. We have developed an algorithm that captures the timestamp of when these frequent acceleration spikes start and end. This determines the indexing time. The period between the start times of the acceleration spikes is recorded as the cycle time. In order to conserve power, the battery powered nodes publish results once when each cycle is determined. An example message of a cycle time event with additional sensor parameters is shown below. The message payload is formatted as a specific JSON structure according to the company IoT standards.

```
{
   "metrics":{
      "AcX":"10",
      "AcY":"19",
      "AcZ":"1027",
      "mag":{
         "x":"-1098",
         "y":"2563",
         "z":"-3173"
      },
      "gyr":{
         "x":"38",
         "y":"5",
         "z":"-27"
      },
      "env":{
         "r":"8",
         "p":"101375",
         "t":"-618475291"
      },
      "LastCycleTime":"14.1",
      "location":"CR1"
   }
}
```

A Bosch XDK-110 WSN is prepared to monitor the vibration on the same machine to study the machine health and provide the basic cycle-time tracking functionality via its built-in accelerometer. The environmental parameters such as relevant humidity and ambient air pressure is also monitored using the built in sensors and a sample output is plotted in Figure 4. It should be noted that although the sensor provided the pressure data in `Pa`, the live visualization chose to display in `psia`.

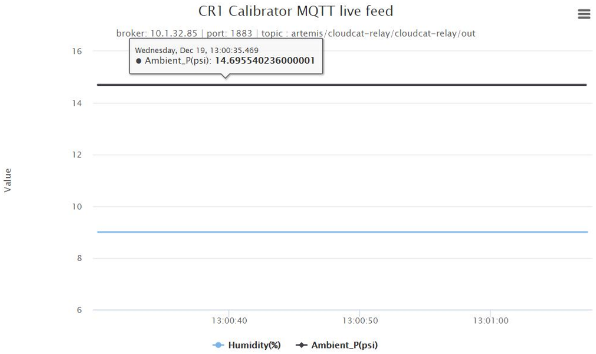

**Figure 4. Live visualization of environment variables**

A TI SensorTag CC2650-STK WSN is being developed for the same purpose as the Bosch XDK-110 WSN. Since it utilizes 6LoWPAN, its lower cost and ultra-low power properties make it an attractive option for this purpose. The Contiki based approach as discussed by Yang et. al. [22] was chosen to be the architecture of choice to get the data from the 6LoWPAN network to the manufacturing LAN and transfer it to the existing IoT gateway [23, 24]. Contrary to the BeagleBone based border router in Yang's study, several industrial IoT gateways are considered that will provide native

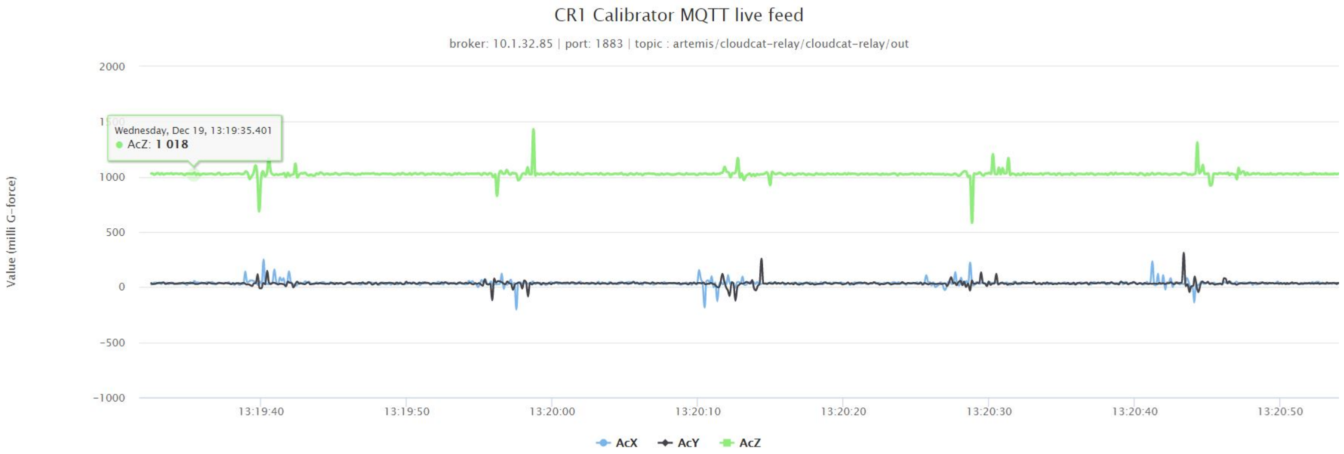

**Figure 5. Live visualization of accelerometer data**

6LoWPAN border router capability over 802.15.4 protocol so that the infrastructure can be provided by the corporate IT services and multiple sensors can be deployed seamlessly.

## 6 Conclusion

This study has investigated several WSN platforms for potential use in an industrial manufacturing environment for cycle time and OEE tracking, machine maintenance prediction, and environmental variable monitoring. Three WSN platforms have been developed and tested for the intended application, where two of the finished prototypes use the existing 802.11 WLAN, and the one in development uses ultra-low power 6LoWPAN. It was found that cycle time and machine health can be detected from the obtained sensor data for the machine type that the prototypes were tested. It should be noted that different types of automation machines and processes may require distinct algorithms to determine the same information and more data analysis should be done to generate a more generic solution.

Upon the completion of the 6LoWPAN based prototype WSN, further studies related to power consumption, communication robustness, and susceptibility to ambient electrical noise should be made to determine the most applicable solution.

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