Milestone 1 Report

A low-cost IoT-based Solution for Tracking and Monitoring Freight Consignments

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Glossary

Freight consignment
Goods/products that are transported from one place to another by ship, aircraft, train, or truck.

Supply chain
The stream of processes for moving goods, starting with the customer order through to the raw materials stage, supply, production, and distribution of products to the customer [1].

Supply chain management
Managing the chain of events in the supply chain process.

Supply chain visibility
The ability to discover a specific shipment's location and monitor its condition as it moves through the supply chain.

Shipment
A good/product/commodity that is being transported along the supply chain.

Item
An individual good/product/commodity/unit, especially one that is part of a collection of articles being shipped together.

Good/goods
All items that are movable and sold to a particular buyer, which can range from merchandise, supplies, and raw materials to already completed products.

Shipments
Plural of shipment.

Modular design
Modular design refers to a device architecture that comprises separate independent units that can be added or replaced as needed by the use case and context.

Hybrid architecture
Hybrid architecture in the context of this report refers to a supply chain management solution that allows the integration of multiple different visibility technologies.

Internet-of-Things (IoT)
A network of physical objects— "things"—that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet.

Cellular network
A land-based communication network where the link to and from end nodes is wireless.

Contents

1.0 Introduction

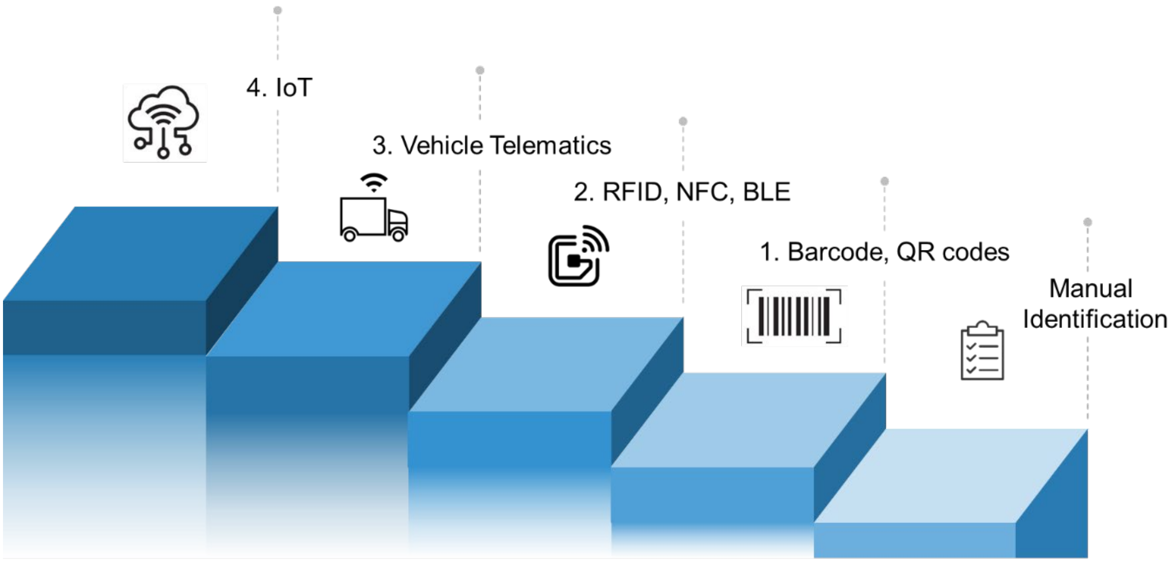
Supply chains are the backbone of the domestic and global trade and service economy. Modern day supply chains are increasingly complex with globally distributed networks of parties involving suppliers, manufacturers, and customers. While there is a need to meet the unprecedented customer expectations on receiving their goods on-time and in good condition, there are complex challenges in terms of regulatory compliance, tariffs, safety, quality, and accountability of the goods along the supply chain. These reasons have highlighted the need for increased visibility into the supply chain. **Supply chain visibility** refers to the ability to discover a specific product's location and monitor its condition as it moves along the supply chain. This ability to get information about the location, status, and condition of a product instantaneously at every time point has become essential to the efficient management of production, distribution, quality, and customer needs of modern-day complex and distributed supply chains.

Recent research and industry reports have highlighted the following benefits of supply chain visibility [2, 3]:

1. **Improved accountability** – through improved capabilities for controlling and tracking damage, loss, or theft of goods during transport.
2. **Condition maintainability** – preventing and tracking damage along the supply chain including preventing adulteration or substitution.
3. **Compliance assurance** – by ensuring regulatory compliance of goods that are sensitive to environmental conditions (e.g., temperature, humidity, vibration, shock).
4. **Enhanced customer satisfaction and consumer loyalty** – by providing improved visibility to customers regarding the location, condition, delivery times, and condition of the goods.
5. **Improved internal decision making and operational performance** – via freight operators delivering the highest standards of customer service, assuring service quality, and optimising business processes.

1.1 Project Background

In a typical supply chain, a **freight consignment** (goods/items) is sent by a customer to a destination. The transportation and delivery of the freight consignment is handled by a freight operator. The shipment process may include movement of the freight consignment by a single or multiple freight operators through several logistics checkpoints (e.g., depots, warehouses, seaports and airport entries and exits). The information about the location and condition of the freight consignment as it moves along the supply chain provides key information for supply chain visibility. Supply chain visibility is achieved through technologies that facilitate the tracking and monitoring of these goods as they transit along the supply chain. Several supply chain visibility technologies have evolved over the years, such as barcodes, RFIDs, NFCs, vehicle telematics, and IoT devices. Figure 1 shows the different **supply chain visibility technologies** that have evolved over time.



Barcodes, QR codes, and RFID tags have been conventionally employed to encode product information that can be read across different checkpoints of a supply chain, which is then fed into a centralised database. While Barcode and QR codes are very cost-effective approaches for tracking goods along the supply chain (based on manual scan events), these have several drawbacks including intensive labour, time inefficiency, scanning errors, the inability to be networked, and the inability to track individual consignments in real time and during transit [2]. RFID (Radio Frequency Identification), BLE (Bluetooth Low Energy), and NFC (Near Field Communication) support automatic scanning at entry/exit points of key transit checkpoints. To a certain extent, an integrated approach, involving information from Barcode, RFID, BLE, and NFC along with vehicle-based telematics into supply chain management information, has helped reduce manual processes and the tracking of shipments during transport respectively [4].

However, significant gaps in location tracking and condition monitoring continue to exist in terms of end-to-end supply chain visibility. This includes:

- Real-time information visibility
- Location and condition monitoring and tracking of individual consignments.

These are discussed in succession in the following paragraphs.

REAL-TIME INFORMATION VISIBILITY

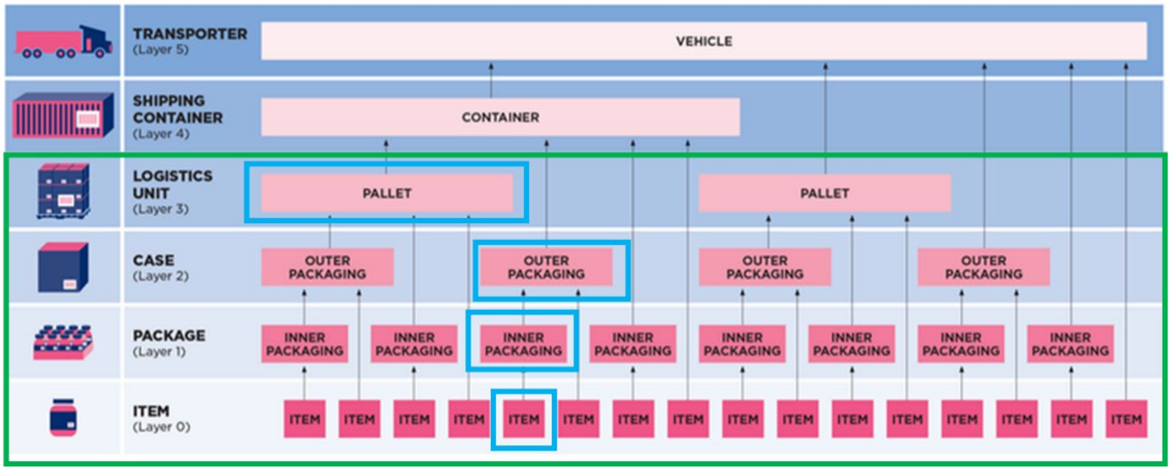
Real-time information visibility is of significant interest and relevance to all parties including manufacturers, freight operators, and customers along the supply chain [5]. Monitoring real-time shipment (i.e., goods that are being transported along the supply chain) helps track the location and/or condition of individual consignments at all time points along the supply chain. Real-time shipment monitoring is particularly important to track goods while in transit, and in between supply chain checkpoints [6, 7]. Monitoring the condition of goods in transit verifies the quality of incoming goods and facilitates the fulfilment of safety and environmental regulations. The real-time insights from shipment monitoring can help efficiently coordinate supply chain processes (e.g., planning, sourcing, manufacturing, delivering, returning) and optimise these processes to improve operational performance, resolve customer queries, and potentially reduce damage to goods and assets.

LOCATION AND CONDITION MONITORING OF INDIVIDUAL CONSIGNMENTS

Tracking individual freight consignments or freight parcels refers to the tracking of consignments that are transported individually (e.g., TVs, fruits, vegetables, canned products) that are packaged into individual consignments such as pallets and crates. Typically, these individual consignments are transported in a container. Individual consignment (or freight parcel) monitoring refers to the location tracking and condition monitoring of the smallest consignment unit which forms the lowest layer of the transport hierarchy.

As per the report on *Single Freight Data Standard for the National Digital Framework* by the Australian Logistics Council, GS1 standards [8] are used to identify different shipment units in terms of the cargo layers of a typical transport hierarchy [7, 9]. This GS1 model [7] shows six cargo layers comprising: item (layer 0), package (layer 1), case (layer2), pallet (layer 3), logistic unit (layer 4), container (layer 5), and transporter (layer 5). While this generic model captures all possible logistic units during transportation, the identified logistic units for each layer are not essentially applicable to all supply chains. For example, agricultural produce such as fruits and vegetables are typically transported in crates forming layer 0 of the hierarchy. On the other hand, medical devices, such as incubators, are transported as individual items and may not be aggregated into larger logistic units. Hence, this causes the hierarchy to just have three layers, item (layer 0), container (layer 1), and transporter (layer 2). Along these lines, the aim is to address the important limitation of existing supply chain management systems to track and monitor the location and condition of the shipment quantity at the lowest cargo layer of the transportation hierarchy.. Based on customer requirements, the scope of this project is limited to: (1) Item, (2) Package, (3) Case and (4) Logistics Unit levels. Shipping containers and transport assets are not included, as there are other solutions that address the location- and condition-related visibility requirements of these layers. Figure 2 shows the individual consignments that are the focus of this project.

Figure 2: Individual freight consignments that form the focus of this project [7]



Tracking of individual freight consignments during transportation in real time is a problem that was not addressed by barcode, RFID, NFC, and BLE-based visibility solutions. While vehicle telematics allows for real-time monitoring and tracking during transportation, it is mostly achieved at the container level and does not apply to the monitoring and tracking of individual freight consignments. Additionally, current transportation containers do not provide consistent transportation conditions and environment information about all the individual freight consignments included in the cargo [8]. For example, maintaining consistent environmental conditions is essential for food and agricultural products, because significant variation in temperature, humidity or other conditions during transportation may adversely affect product quality and shelf life. Furthermore, such temperature and humidity requirements are often specific to individual productions, in order to ensure quality preservation. Unstable temperature ranges across a refrigerated container results in chilling, frost or heat damage [9]. This may be owing to frequent opening during pick-up and loading, and/or goods' closeness to the vent or door.

Additionally, some agricultural, pharmaceutical, and medical equipment are sensitive to other environmental conditions such as vibrations and shock. Previous research has reported that vibration levels are not uniform in different parts of a container during transportation. Traceability may also be needed to identify damage due to varied environmental condition requirements of individual freight consignments in a mixed cargo. This problem of uneven distribution of controlled environmental variables in a refrigerated container has been acknowledged by the CSIRO. In their recent study, it was reported that tracking individual freight consignments can help to overcome these limitations [10].

Monitoring of individual freight consignments in real time will help to reveal the condition of the goods during transportation in between logistics checkpoints. Real-time monitoring of individual consignments also helps to: (i) verify the quality of incoming components, (ii) monitor the fulfilment of safety and environmental regulations, (iii) allow users to make immediate decisions when conditions are unsuitable, (iv) coordinate supply chain processes more efficiently and optimise them to increase agility in resolving issues (such as (iii)), (v) minimise costs, and (vi) increase operational efficiency.

In the context of supply chains and logistics, Internet-of-Things (IoT) solutions allow for enhanced visibility, which could improve supply chain productivity while enabling businesses to make decisions based on real-time data information. IoT refers to a collection of networked physical devices capable of sensing and exchanging information with other devices over the internet. IoT is capable of providing real-time end-to-end supply chain visibility. Recent developments in the area of IoT technology have built-in networking capabilities to upload status, location and condition information about the goods to the cloud at regular time intervals and be instantaneously accessed remotely (in real time). IoT can help achieve the real-time monitoring of individual freight consignments. IoT solutions empower supply chain management decision making by collecting and analysing data from various points along a logistics network, ultimately providing “visibility” and “context” to both customers and freight operators. By means of connecting sensors, IoT devices can be used in a variety of ways to enhance the visibility of a supply chain and report multiple condition monitoring parameters such as temperature, vibration, humidity and location.

While promising, IoT technology is still evolving, and there is a lack of clarity with regards to its functional requirements, use cases and contexts, architecture, and integration with existing infrastructure. Currently, there are a limited number of commercially-available IoT devices that support real-time tracking and condition monitoring of individual freight consignments.. There is a need to better understand aspects related to their cost, application contexts, sensing capabilities, integration with existing processes, security, and network architecture.

IoT solutions are being actively considered to provide real-time tracking and condition monitoring via the use of devices, sensors, platforms, networks, and data analytics. Examples of global navigation satellite system (GNSS) receiver-based IoT devices with cellular connectivity for tracking locations using low-cost components can be found. However, some of the shortcomings in the current hardware and software solutions are related to:

1. Device form factors that do not support easy attachment to freight consignments;

2. Cost effectiveness concerning device reusability, as it involves extra costs for the users (customers and freight operators) to return and manage the devices;
3. Some devices need to be plugged into a power source, hence they are not practical when continuous access to power cannot be guaranteed;
4. A lack of software support for device management (e.g., trajectory monitoring) to maximise device operating time and battery consumption.

The objective of this project is to explore the role of emerging IoT technology to fill visibility gaps, optimise costs, and improve efficiency in existing tracking and monitoring practices in supply chains.

1.2 Project Objectives and Methodology

The aim of this project is to investigate, research, and develop a low-cost IoT-based solution for the tracking and condition monitoring of freight consignments, which will provide enhanced visibility across supply chains.

To achieve this objective, the project will identify, assess, devise and trial appropriate IoT technologies for tracking and monitoring the condition of freight consignments in real time. The main milestones of the project are:

1. Conduct a consultation with the industry partner to identify the functional and technical (hardware and software) requirements for developing a low-cost IoT-based solution for the live tracking and condition monitoring of freight consignments. The consultation will aim to elicit prioritised requirements from the industry partner and use these to assess the trade-off between costs and features of the IoT solution.
2. Design the IoT-based solution for the tracking and condition monitoring of freight consignments.
3. Implement the IoT solution, including hardware, embedded software and cloud-based data analytics.
4. Undertake field trials to assess the IoT solution against the requirements identified in (1).

1.3 Milestone Description

This project is motivated by the need to enhance end-to-end supply chain visibility through IoT solutions. The first milestone aims to conduct desktop research to identify the functional requirements of an IoT-based solution that will guide the design and implementation.

The objectives of this milestone are as follows:

1. Information requirements for IoT-based solutions to track and monitor the condition of consignments related IoT technology review and selection.
2. Identify and document the IoT-based solution’s functional requirements (through a joint workshop with the industry partner and relevant stakeholders) to guide its design and development.

3. Review and assess commercial off-the-shelf IoT devices (or alternative combinations of IoT sensors, microcontroller and networking modules) that can address the functional requirements identified for tracking and condition monitoring.
4. Select the most suitable/"best" commercial off-the-shelf IoT devices (or alternative combinations of IoT sensors, microcontroller and networking modules) based on the above requirements.
5. Present the recommendations and obtain approval to proceed to Stage 2.

The steps below describe the methodology adopted to meet this project's objectives:

1. Identify the monitoring and technical requirements through literature and technology scan, based on two application areas:
    - Food & Agriculture, and
    - Pharmaceutical & Medical
2. Review existing solutions for their suitability in meeting the requirements identified in the previous step.
3. Provide recommendations for suitable commercial off-the-shelf or custom-designed IoT devices and use cases.

1.4 Milestone Scope

The aim of this milestone is to identify the functional requirements of an IoT-based solution for the tracking and condition monitoring of individual freight consignments during transportation. In particular, this work focuses on the role of IoT in augmenting supply chain visibility in three contexts that are described in detail in Section 1.1:

- Individual freight consignment monitoring
- Real-time tracking and condition monitoring
- In-transit monitoring

2.0 Identification of Use Cases and Functional Requirements

This section describes the use cases for the real-time location tracking and condition monitoring of individual freight consignments while in transport using IoT devices. The use cases will help identify the functional requirements for specific applications, which is essential for the development of IoT solutions in the next stage of this project. IoT-based real-time location tracking and condition monitoring of individual freight consignments during transit is applicable to a wide range of users and market domains. While the requirements derived from this report for the purposes of an IoT solution may apply to various industries and scenarios, the scope of this project focuses on the food and agriculture, and pharmaceutical and medical product supply chains. To support our functional requirement identification, example use cases are provided and discussed in detail for each of these domains in the following sections.

This report adopts the approach of eliciting functional requirements from use cases with a focus on high-level actions and requirements. The specific focus is on sensing requirements, traceability requirements, and action taking through real-time tracking and condition monitoring for preventing damage [11, 12].

In comparison to other sectors, food, agricultural products, pharmaceutical, and medical goods are more sensitive in nature and/or have a limited shelf life. Hence, the goods in these domains are more susceptible to damage, due to temperature fluctuations, shock/impact, and delays caused during transportation. This could also pose health-risks for consumers and incur significant losses for producers, manufacturers, freight service providers, and distributors. Hence, food, agriculture, pharmaceutical, and medical products are representative of a wide spectrum of complex location and condition monitoring needs.

2.1 Food and Agriculture

Food and agriculture industries comprise of a wide variety of consumable products that serve the nutritional and sustenance requirements of humans and animals. The Australian food and agriculture sectors combined generate close to $190 million revenue annually [13, 14].

Food and agricultural product supply chains involve transferring unprocessed farm produce to processed products which are categorised into agriculture and food products respectively. While there are rising consumer expectations on quality assurance at a domestic level, increased requirements for compliance, quality monitoring, and traceability presents both opportunities and challenges for global trade and export [15]. Food and agriculture products are sensitive to environmental conditions, and therefore to prevent damage, loss, and maintain quality, they need to be handled, stored, and transported in appropriately controlled environmental conditions for each particular product. This section explores the supply chain visibility needs in food and agriculture domains. The following subsection will identify the functional requirements, specifically for real-time location tracking and condition monitoring solution for individual freight consignments based on two use cases: strawberries and meat.

2.1.1 Use Case 1: Strawberries

Australian strawberry produce represents a more than A$400 million industry with approximately 82,300 tonnes of strawberries grown annually [15]. Strawberries are a delicate fruit with an extremely fragile skin and short shelf life. As per the industry recommended guidelines, the shelf life of strawberries reduces in above 0°C temperatures and low humidity conditions [16]. Therefore, it is recommended that they are stored and transported at temperatures maintained at 0°C and 90-95% humidity levels. In addition, modifying the storage atmosphere by increasing carbon dioxide (15-20%) and reducing oxygen is recommended to extend the shelf life and control decay. These regulatory requirements are outlined in the *Code of Practice for handling fresh fruit and vegetables in refrigerated shipping containers for Australian exports* [8] which outlines the recommended settings for transportation of fresh fruits and vegetables. While not part of product compliance regulations, in-transit vibrations are another source of damage to strawberries during transportation due to skin abrasion and bruising that leads to discolouration and decay [17]. In-transit vibrations could be caused by road conditions, suspension quality of the vehicle used for transportation, and packaging.

From these recommended guidelines for environmental conditions and reported causes of damage, the following functional requirements can be identified for tracking and condition monitoring of a pallet of strawberries during transportation:

1. Monitor (and record) temperature, humidity, gases, and vibrations;
2. Track location with a timestamp of events;
3. Provide real-time alerts when environmental conditions exceed pre-specified limits.

2.1.2 Use Case 2: Meat

The meat and livestock industry in Australia produce close to 2.4 million tonnes of meat products annually and contribute to up to 1.4% of Australia's GDP [18]. Meat processing involves the breaking down of livestock, extraction and preparation of their parts for human consumption.

Meat is a perishable product, and its shelf life is highly sensitive to the environment in which it is stored and transported. In particular, transportation of meat products is required to adhere to the compliance standards that are outlined in the Australian Standard for the Hygienic Production and Transportation of Meat and Meat Products for Human Consumption (AS 4696:2007) [19]. Under these standards, different meat products have different compliance requirements. For example, the standards recommend beef (stockinet) carcasses, sides and quarters be maintained at 7ºC, and all other portions of meat are required to be kept at 5ºC or less. Fresh meats also absorb odours readily, so it is recommended that meat not be loaded in vehicles retaining strong residual odours from other odour-producing/emitting products, such as fish, apples, or onions [20].

Therefore, some of the requirements for tracking and monitoring the transportation of beef (stockinet) can be summarised as follows:

- Monitor (and record) temperature and humidity;
- Track location with a timestamp of events;
- Detect and report the product compatibility in terms of condition monitoring, contamination, and odour transfer needs during mixed cargo transportation;
- Provide real-time alerts when set environmental conditions are out of range.

2.2 Pharmaceuticals and Medical

The pharmaceutical and medical supply chain involves the delivery of medicine, hospital and lab products, biological samples, medical equipment, etc. Quality maintenance of the products in this category is of great significance as even a slight degradation can have direct implications on human life and patient safety. Therefore, since these products are sensitive to environmental conditions, there are stringent regulatory requirements for their storage and transportation. Considering almost 90% of Australia's medicine supply is imported [21], a vast majority of products are a part of complex globally distributed supply chain, adding challenges to traceability. These reasons make pharmaceutical and medical products ideal candidates for the adoption of IoT-based technologies for improving visibility, quality assurance, and traceability. This section examines the medical and pharmaceutical domains to determine how supply chain visibility and traceability can be improved. The following section will identify the functional requirements, specifically for real-time location tracking and condition monitoring solutions for in-transit individual freight consignments based on appropriate use cases. Two use cases – COVID-19 vaccine transport and medical devices transport – are presented, representing the pharmaceutical and medical sectors.

2.2.1 Use Case 3: Vaccine transport

The COVID-19 global pandemic highlighted the role of vaccines in battling life-threating diseases. Vaccine production and delivery is central to disease management and mitigation. Considering its relevance in recent times, we take the example for COVID-19 vaccine transport as a use case under the pharmaceutical domain. In terms of condition monitoring, the temperature storage requirements are known to vary across different COVID-19 vaccines. After reaching a temperature at which the vaccine thaws (~25°C-30°C), it becomes useable for a limited time (~2 hours) [22]. In case the temperature changes during transit, the vaccine expiry will need to be adjusted accordingly. Following exposure to a higher temperature [23], in some cases, the vaccine may be returned to a lower temperature but only a single time. Certain vaccines are also sensitive to light, making it necessary to track exposure to light and trigger notifications in case of out-of-range fluctuations [24].

Accordingly, vaccine functional transport requirements can be summarised as follows:

1. Monitor (record) and alert temperature changes;
2. Monitor (record) and alert light intensity fluctuations where applicable;
3. Track location with a timestamp of events;
4. Provide real-time alerts when set environmental conditions are out of range.

2.2.2 Use Case 4: Medical equipment

Medical equipment ranges from diagnostic kits and surgical equipment to x-ray & MRI machines, all of which are sensitive in nature and likely to be impacted by small variations in storage conditions, handling, vibrations, and shock. Such impacts could affect their functionality, render them inoperative, or pose health risks to patients. Location tracking and condition monitoring during medical equipment transportation is critical because vibrations and shocks during transport can render high-value equipment inoperative. Additionally, the temperature range that needs to be maintained for a medical device during transportation varies by type, with some device components requiring storage at temperatures below -80°C, while others require storage at 15-25°C [25]. Temperature and humidity fluctuations arising from a variety of factors (e.g., storage location, transfers between modes of transport) can impact the medical device's quality and functioning. Due to the sensitive nature of medical devices, they are also impacted by vibration and shocks, calling for close monitoring during transport [26].

Based on the above information, the functional tracking and monitoring requirements of transporting medical devices can be summarised as follows:

1. Monitor (record) and alert temperature, vibrations, shocks, and humidity changes;
2. Track location with a timestamp of events;
3. Provide real-time alerts when set environmental conditions are out of range.

2.3 Key Functional Requirements Summary

From the functional requirements identified in the above-mentioned use cases, the following insights are provided into tracking sensitive and high-value goods:

1. **The condition monitoring requirements** are guided by the regulatory compliance guidelines stipulated for that particular commodity. Accordingly, the condition monitoring requirements vary by the type of product. As highlighted in the use cases earlier, sensitive and high-value goods are susceptible to being damaged in transit if the required transportation and handling conditions are not adhered to. While condition monitoring includes

several parameters (e.g., temperature, vibration, shock, gas, light), not all of these conditions need to be monitored for all goods. Depending on the product type, only a subset of condition sensing may be needed.

2. **Location tracking and recording of events**, such as when an item was received and dispatched from a particular location, or when abnormal ranges of environmental conditions were recorded, are common requirements for all use cases. This is expected considering the increasing emphasis on traceability, delivery time management, and the negative effect of delay on sensitive goods.
3. **The types of customisation in condition monitoring and alerts** vary based on the type of product and even among their subtypes. For instance, different COVID-19 vaccines have different temperature storage requirements, and alerts need to be customised and generated in case of changes outside of the range mandated for that particular vaccine.
4. **While alerts based on condition changes** can help identify variations in transport conditions, actual business decisions depend on additional factors such as product type, and there is a need for complex condition monitoring which includes, but is not limited to, the following:
   a. There is the need to monitor conditions over time based on analytics that take into account multiple parameters, rather than simple threshold-based analytics for single parameters. For instance, the Pfizer COVID-19 vaccine can be left at room temperature for up to 2 hours, beyond which it is considered not fit for use.
   b. Further, the nature of information conveyed by the alert may also vary depending on product type. For instance, in the case of the Pfizer COVID-19 vaccine, if a box of vaccine vials is exposed to a high temperature and then returned its ultra-low temperature storage conditions, the vials are considered suitable for use. However, this is does not hold if the vials have been exposed repeatedly, i.e., more than once [27].
5. It is desirable to have tracking and condition monitoring solutions that can be **reused and customised** as this will help with cost.

A summary of functional requirements for different use cases is provided in Table-1 below.

Table-1 Summary of tracking requirements from use cases examine

Domain	Sample use case	Sensing parameters							Alerts		
		Macro-location	**Micro-location**	**Temperature**	**Humidity**	**Gas**	**Vibration**	**Shock**	**Threshold-based**	**Parameter combination**	**Monitoring over time period**
Food & Agriculture	Strawberries	✔	✔	✔	✔	✔	✔		✔	✔	
	Meat	✔	✔	✔	✔				✔	✔	
Medical & Pharmaceutical	Vaccines	✔		✔					✔	✔	✔
	Equipment	✔		✔	✔		✔	✔	✔		

Based on the above insights and use cases, we identified the following **key functional requirements**:

1. **Flexible condition monitoring** to support product specific requirements via customisation of the sensing parameters.
2. **Complex rules and alerts based on product type** and more than one sensing parameter that (i) combine data from multiple related parameters (rather than a single parameter), (ii) are based on condition changes monitored across a time period (rather than a short time window), and (iii) customise alert types or levels based on product types.
3. **Real-time event detection and alert mechanisms** for monitoring and acting on sensed information in real time. This is important not only because of the sensitivity of the products, but also because many of the complex alerts discussed previously make use of the values of the sensing parameters over certain time periods. Hence, in the case of the Pfizer COVID-19 vaccine, the temperature values over a period of two hours determine whether or not the vaccine is still fit for use. This implies that the temperature values would need to be updated at an interval of less than two hours or preferably shorter.

While the above requirements follow directly from the use cases described earlier, we further note the following requirements arising from the nature of the supply chains:

1. **Device form factors**: Devices for location tracking and condition monitoring need to be suitable for tracking all types of freight, ranging from large equipment to small strawberries. Devices that are too large or heavy may not be suitable for small and light shipment.
2. **Battery life**: Due to the long distances over which freight consignments are shipped, from within cities to across countries, and the potential time in transit (up to weeks or months), devices need to be powered by long-lasting batteries to support extended device operation.
3. **Visibility across supply chains**: Due to the highly decentralised nature of supply chains, there is a need for tracking solutions to support a high degree of visibility, of tracking and condition monitoring information, across all stakeholders.
4. **Reusability**: We note that transport providers are some of the key stakeholders in the supply chain who are likely to reuse vehicles and product packaging, such as crates, for different products, which may have different sensing requirements. Tracking solutions need to be as reusable as possible to ensure adaptability to such dynamics.

3.0 Technology Scan and Survey

This section presents the results of the technology scan across commercial IoT solutions and standards for real-time tracking and condition monitoring of freight consignments. A brief introduction to IoT architecture is provided below prior to discussing the capabilities of commercial IoT solutions for tracking and condition monitoring. Figure 3 below depicts a generic IoT architecture for real-time tracking and condition monitoring. The three main components of an IoT solution are as follows:

- **IoT devices** are battery-powered devices consisting of one or more sensors along with a micro-controller. Two configurations of IoT devices are: (i) those which possess the capability to directly upload sensor data to the cloud via IoT gateways, and (ii) local IoT devices, which send data locally to IoT gateways, which then upload the data to cloud platforms.
- **Cloud-based platforms** with multiple functionalities, from long-term storage of sensor data and real-time processing, to analytics and alerting.
- **Real-time tracking and condition monitoring applications** which include use case-specific tracking and condition monitoring functionalities that utilise data from cloud-based platforms. These are typically mobile or web-based applications which provides user interfaces for individual supply chain stakeholders including producers, transport operators, and consumers

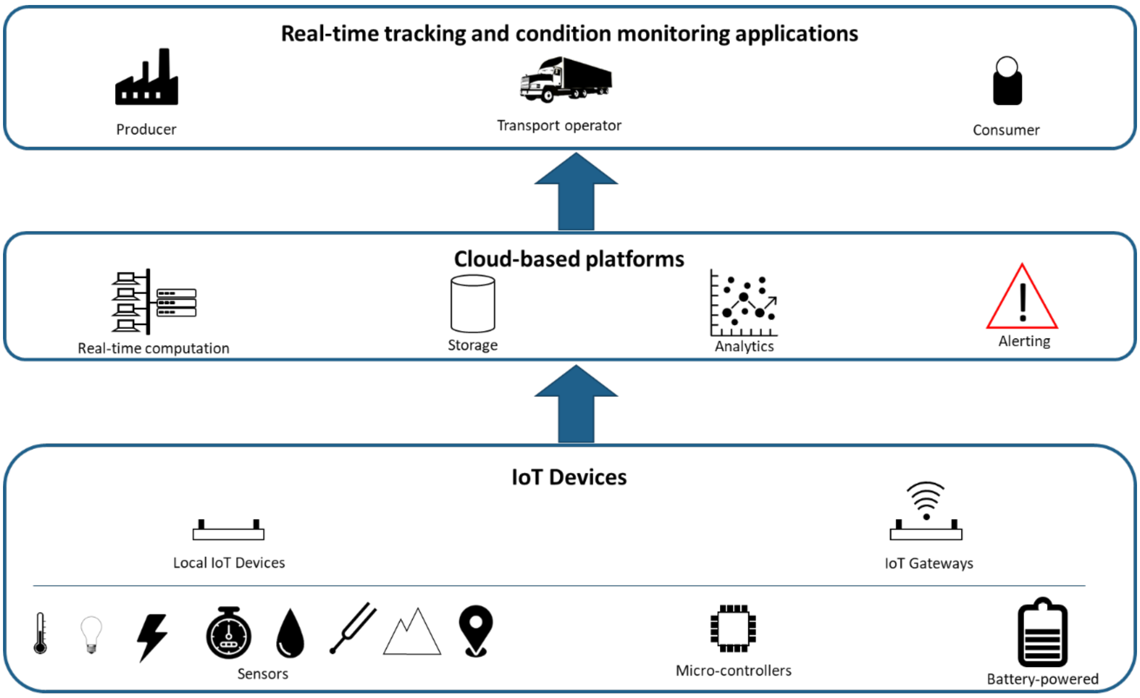


Figure 3: IoT Architecture

In the remainder of this section, we examine the existing IoT solutions and their capabilities vis-à-vis each stage of the IoT solution described above, and also include a discussion on battery considerations.

3.1 Survey of Commercial IoT Solutions

A technology scan was conducted to identify commercial IoT solutions that support real-time tracking and condition monitoring in supply chains. In particular, the capabilities of the IoT devices and cloud-based platforms included within existing commercial IoT solutions were studied. The support for tailoring their capabilities to individual use cases was also explored in the technology scan. This review did not consider research prototypes of IoT devices.

3.1.1 IoT Devices

The commercial solutions identified in this report represent the breadth of existing real-time tracking and condition monitoring capabilities. These are listed in Tables-2 & 3. We note that the report does not aim to do an exhaustive survey of existing commercial IoT solutions as this is beyond the scope of this report.

IoT devices form the core components of commercial IoT solutions which involve:

1. Sensing capabilities, for location tracking and condition monitoring;
2. Networking communication, for making the data available on cloud-based platforms;
3. Batteries to meet the power requirements of the IoT device, keeping in mind the duration of use on single charge and the modes of transport it can sustain (e.g., road, air, and sea transports).

3.1.1.1 Sensing capabilities

Existing commercial IoT solutions were found to encompass a range of sensing capabilities, which can be categorised into location tracking and condition monitoring:

- Location tracking: The tracking of location is considered an underlying need of all existing IoT solutions for real-time tracking and condition monitoring. Location tracking can, in turn, be categorised into the following sensing parameters:
  - **Macro-location:** Macro-location tracking refers to the geographical location of the freight consignment, widely supported by GPS technology. However, since GPS can have high power consumption, many solutions make use of cellular or Wi-Fi-based location tracking to conserve battery.
  - **Micro-location:** While macro-location provides information regarding the location of a shipment within a geographical area, typically with an accuracy of 10-20m, micro-location provides the location of the shipment within a localised space, such as within a truck, container, or building. Among the commercial solutions that were surveyed, only a subset were found to offer micro-location

capabilities, using Bluetooth Low Energy (BLE)[1] as the underlying technology. In such solutions, BLE-based IoT devices provide the micro-location information and connect to gateway devices that are capable of recording macro-location.

- **Condition monitoring:** Existing approaches for condition monitoring in commercial devices covered a wide range of sensing parameters, most common among which are temperature, humidity, and light. Other sensing parameters include shock, motion, pressure, tilt, and vibration. Some commercial devices also included additional sensing capabilities for organic gases, altitude, tamper detection, and even detection of GSM signal jamming. While most commercial tracking devices include a subset of these sensing parameters, some allow customisation of the sensing parameters to be enabled on a device.

Table-2 below provides a summary of sensing capabilities in existing commercial solutions.

[1] https://www.bluetooth.com/learn-about-bluetooth/tech-overview/

Table-2 Summary of sensing capabilities in existing commercial solutions

Sensor (Sensing parameters)↓/ Company→	**Sensitech**	**Tive**	**Kizy**	**MOST**	**Hanhaa**	**Lightbug Ltd**	**e2Link**	**Roambee**
Macro-location	Cellular	GPS, Cellular, Wi-Fi	Cellular, Wi-Fi	Cellular	GPS	GPS, GLONASS, BEIDOU, GALILEO, QZSS, Wi-Fi	GPS, GLONASS, BEIDOU, GALILEO, QZSS, Wi-Fi, Cellular	GPS
Micro-location	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes, 5m range
Light	0 to 400 lux	Yes	Yes	0.5 to 2000 lux	> 4 lux	N/A	Yes	Yes
Temperature	-20 °C to 55 °C	-20°C to 60°C	Add-on	-20 ° C to 55 ° C	-30°C to 50°C	Yes	-20°C to -60°C	-20°C to 65°C
Shock	N/A	N/A	N/A	0 to 15 g	2 to 16 g	N/A	N/A	Yes
Motion	N/A	Yes	Yes	N/A	N/A	Yes	N/A	N/A
Pressure	N/A	N/A	N/A	Yes		N/A	N/A	Yes
Tilt	N/A	N/A	N/A	N/A	Yes	N/A	N/A	Yes

Vibration	N/A	N/A	N/A	N/A	N/A	N/A	Yes	Yes
Humidity	10-100%	N/A	Add-on	0 to 100%	0 to 100%	N/A	20%-90%	0%-99%
Organic Gases	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes
Altitude	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes
Tamper detection	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes
GSM Jamming detection	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes
Dimensions	Smallest model: 101 mm x 65 mm x 29 mm Largest model: 121.5 mm x 115.5 mm x 25.5 mm	96 mm x 58 mm x 19 mm	87 mm x 56 mm x 8.5 mm	Diameter: 125 mm Thickness: 30 mm	162 mm x 100 mm x 19 mm	Smallest model: 56 mm x 37 mm x 12.9mm Largest model: 85 mm x 44 mm x 28.4 mm	Smallest model: 96 mm x 50mm x 11.2mm Largest model: 120 mm x 69 mm x 19.5 mm	Smallest model: 42.5 mm x 23.5 mm Largest model: 130 mm x 80 mm x 25 mm
Weight	Smallest model: 115 g Largest model: 240 g	N/A	42 g	220 g	144 g	Smallest model: 35 g Largest model: 140 g	Smallest model: 70 g Largest model: 166 g	Smallest model: 7.1 g Largest model: 317 g

Target supply chain sectors	Food, Life Science, Industrial	N/A	Food & Beverage, Textiles, Automotive	N/A	N/A	N/A	N/A	Food & Beverage, Agriculture, Pharmaceutical, Automotive, High-tech & Consumer goods
Link	https://www.sensitech.com/en/products/monitors/realtime/	https://tive.co/compare/	https://www.kizytracking.com/supply-chain-tracker/	https://most.tech/cargo-monitoring-system/	https://hanhaa.com/tracker-functions/	https://thelightbug.com/products/lb-pro.html	https://www.eelinktech.com/gps-tracking-devices/	https://www.roambee.com/sensors/

3.1.1.2 Network Communication

In order to achieve real-time and remote tracking of freight consignments, IoT devices are required to periodically transmit the location and condition monitoring data to cloud-based platforms. The communication capabilities of IoT solutions include networking technologies that are paired with appropriate data-exchange protocols.

Networking technologies: Most existing commercial solutions rely on existing cellular 2G/3G/4G/5G [28] networks. Low-power long-range networking technologies such as LoRaWAN [29] and NB-IoT [30], which use the cellular network, have also been considered for some solutions. A primary challenge with cellular networks is the network unavailability during sea and air transportation. In order to address this issue, some solutions make use of satellite or proprietary communication channels. Other solutions overcome loss of network connectivity by storing the location and condition monitoring information in on-device storage during periods of network unavailability; upon restoration, this information is uploaded to a cloud platform. Some commercial IoT solutions combine the above long-range networking technologies with short-range networking technologies such as Wi-Fi [30] and BLE. In typical deployments of such solutions, multiple IoT devices with short-range networking capabilities are paired with a single IoT device with long-range networking.

Data-exchange protocols: The commercial IoT solutions surveyed were found to incorporate a range of data-exchange protocols in conjunction with the networking technologies described above. However, these IoT solutions were found to use standards-based protocols, which are described later in detail. These include protocols for uploading data from IoT gateways to cloud-based platforms, as well as local data exchange among devices.

3.1.1.3 Battery

The choice of battery for an IoT device is dependent on multiple factors relating to both the device usage as well as the intended transportation mode. Firstly, both sensing and data transmission operations consume significant amounts of power; therefore, the battery life of the tracking device depends on the configured sensors and the data reporting frequency. Among the commercial solutions surveyed, the advertised battery life ranges from a minimum of 2-3 days to a maximum of more than 10 years, which corresponds to an update frequency of every few days. Further, while Li-ion is the most commonly used type of battery, this is not considered suitable for air transport due to the risk of catching fire in case of a short-circuit [31]. Hence, alternative battery technologies need to be considered for shipments being transported by air. A subset of the commercial solutions surveyed were found to support both Li-ion and non Li-ion options, even though Li-ion continues to be the predominant technology. Apart from the above, printable batteries have been looked at as an alternative technology. Although they are yet to see widespread deployment, some smart labels have been developed using printable batteries with battery life up to 2 years [32].

Table-3 provides a comparison of the networking technologies and battery life of some of the surveyed commercial solutions.

Table-3 Comparison of the networking technologies and battery life of some commercial solutions surveyed

Battery & Connectivity↓/Company→	**Sensitech**	**Tive**	**Kizy**	**MOST**	**Hanhaa**	**Lightbug Ltd**	**e2Link**	**Roambee**
Min Battery Life	7 days	30 days	10 days		20	19 days		90 days
Max Battery Life	90 days	3+ years	1 year	100 days	65	14.8years	5 years	3 years
Battery Type	Alkaline non Li-ion	Both Li-ion and Non Li-ion options available	Li-Ion	Li-Ion	Li-Ion	Li-Ion	Li-Ion	Both Li-ion and Non Li-ion options available
Connectivity	2G	2G/4G/5G/NB-IoT/BLE	2G/3G/Wi-Fi	2G/3G	Hanhaa XG (Proprietary)	2G/4G/ Bluetooth/NFC	4G LTE, NB-IoT	2G/3G/Wi-Fi/BLE

3.1.2 Cloud-based platforms

The existing cloud-based platforms in commercial IoT-based tracking solutions include the following features:

- **Analytics & Insights:** Some cloud-based platforms include analytics based on the data obtained from devices. Such analytics can generate information including the Estimated Time of Arrival (ETA), mean temperature and dwell time at various locations.
- **Visualisation:** Cloud-based platforms include real-time visualisation of location and condition monitoring data obtained from tracking devices to enable remote monitoring of shipments. A commonly used visualisation depicts the shipment location on a map, often with other condition monitoring data such as temperature.
- **Alerts:** In addition to real-time visualisation, cloud-based platforms enable defining thresholds for individual condition monitoring parameters, as well as the triggering of alerts if these are surpassed.
- **User interfaces:** Cloud-based platforms include user interfaces, such as navigable dashboards and mobile apps, for accessing the abovementioned visualisations, alerts, and analytics.

Existing cloud-based platforms include secure authorisation and authentication features to ensure that the above functionalities can only be accessed by intended users. For instance, certain functionalities monitoring the entire supply chain may be made available to only administrative users.

3.1.3 Real-time tracking and condition monitoring applications

While cloud-based platforms provide some information for supply chain stakeholders, these functionalities do not include information tailored for individual use cases. In order to achieve this, some cloud-based platforms allow integration of data with other cloud platforms, thereby enabling businesses to integrate real-time tracking data with other business processes and ERP systems to enable use case-specific functionalities.

3.2 Relevant standards

3.2.1 Food transportation requirements

Regulatory requirements for conditions in which food items must be stored and transported are mandated. CargoHandbook.com is a collection of guidelines for the transportation of over 800 commodities. It is the world's largest platform that outlines the environmental needs of commodities during transportation. While these are published in the context of overseas transportation, the needs of transportation are applicable to other transportation contexts as well.

3.2.2 Smart container data standards

Smart containers are traditional containers which are equipped with electronics to enable advanced monitoring encompassing location, identification, and sensing parameters, such as temperature and humidity.

The Smart Containers Project initiated by the United Nations Centre for Trade Facilitation and Electronic Business (UN/CEFACT) aims to promote adoption of smart container solutions through the definition of data elements required to enable real-time monitoring and visibility across different stakeholders throughout the end-to-end supply chain.

The smart container data elements are detailed in the Smart Container Business Requirements Specifications (BRS), which is the first formal standard published as part of the Smart Containers Project. The BRS sets out three technical pillars underpinning smart container solutions including: (i) an active smart device with an embedded set of sensors, (ii) platform for data collection, processing and sharing with different stakeholders, and (iii) communication protocols enabling data exchange. Subsequently, the BRS first outlines multiple use cases to guide the definition of data elements. The use cases are categorised by one or more case types, which are operational, security awareness, compliance, green maintenance, quality, and sovereign. They cover various aspects of smart container solutions including real-time condition monitoring of smart containers, such as the triggering events when sensing parameters (e.g., temperature, humidity, shock) go above or below a threshold. They also cover data exchange requirements across stakeholders such as during the changeover of the mode of transport.

The BRS identifies data elements and groups them into the following:

- Device
- Sensor
- Container
- Event
- Transport Booking
- Means of Transport

3.2.3 GS1 standards

GS1 defines a system of standards for the digitalisation of logistics [7], which consists of three layers that group standards into:

1. **Identification**: The identification layer includes the standardised identifiers for individual entities that need to be managed, encompassing different levels of the transport hierarchy such as items, cases, pallets and vehicles, as well other parts of the supply chain from manufacturer to consumer via distributors and distribution centres.
2. **Capture**: The capture layer includes standards for mechanisms to capture identity and additional attributes of an object. Currently, this primarily includes barcodes, QR codes and RFID, which require scanning with another device such as a smartphone.
3. **Share:** The information sharing layer includes standards for data exchange across stakeholders, which recognise three kinds of information, namely, the *Master* data, *Transactional* data and Visibility *Event* data.

The figure below depicts the GS1 system of standards

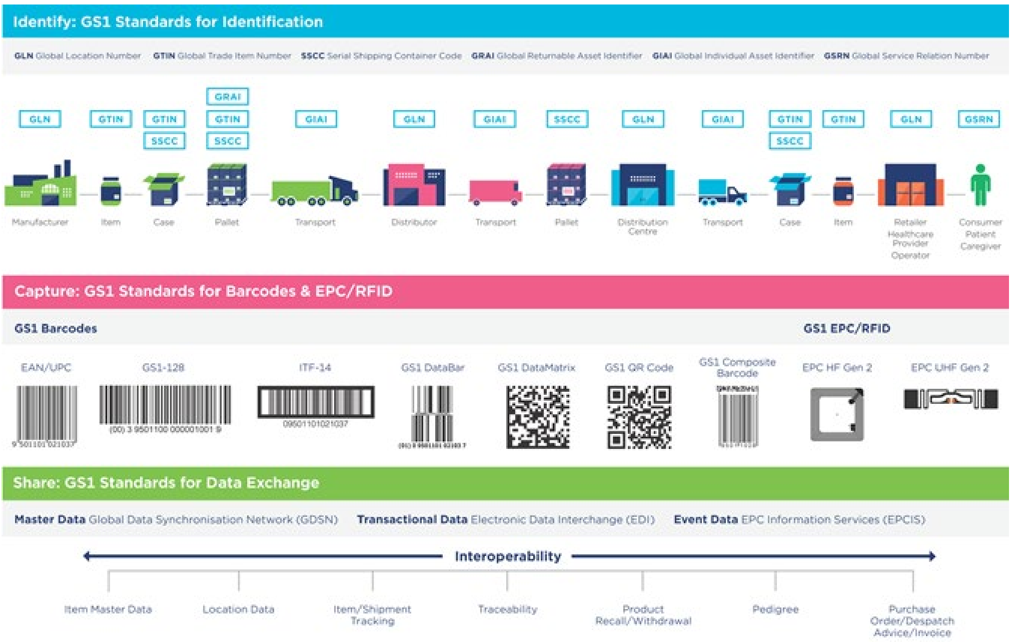


Figure 4: GS1 standards framework

3.2.3.1 IoT standards

Existing IoT standards for network communication include the following:

1. Networking technologies:
    - *Long-range networking technology:* Along with legacy cellular technology, this includes low-power long-range technologies such as NB-IoT [33], SigFox [34], LoRaWAN [29]), and Wi-Fi HaLoW [35]. All of these have range, starting from at least 1km and going up to 40km.
    - *Short-range networking technology:* This includes technologies intended for short-range communication, starting from around 30m for BLE to around 100m for Wi-Fi.
2. **Data exchange protocols:** Existing data exchange protocols for IoT can be grouped as follows:
    - *Device-to-cloud protocols:* These include protocols suited for uploading data from devices to cloud platforms, so as to make device data available in real time for other applications. While HTTP [36], which is the de facto standard of data exchange for the internet, is also used in IoT scenarios, MQTT [37] has gained greater popularity. MQTT uses a broker-based system for quick dissemination of IoT sensor data to multiple recipients. Both HTTP and MQTT data exchanges can be encrypted using Transport Layer Security (TLS)[2], which is a cryptographic protocol to provide a secure communication channel between device and cloud endpoints.

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[2] https://datatracker.ietf.org/wg/tls/documents/

- *Device-to-device protocols:* This includes IoT protocols which are only focused on data transfer locally among devices, such as from local IoT devices to IoT gateways. An example of such a standard is the Apple iBeacon[3] data format, targeted for use by BLE beacons. The GATT protocols defined by the Bluetooth SIG [4] are targeted for use by BLE-based peripheral devices. Constrained Application Protocol (CoAP)[5] is designed to be used over IP-based networks, such as Wi-Fi.

The above mentioned IoT standards are depicted in Figure 5 below.

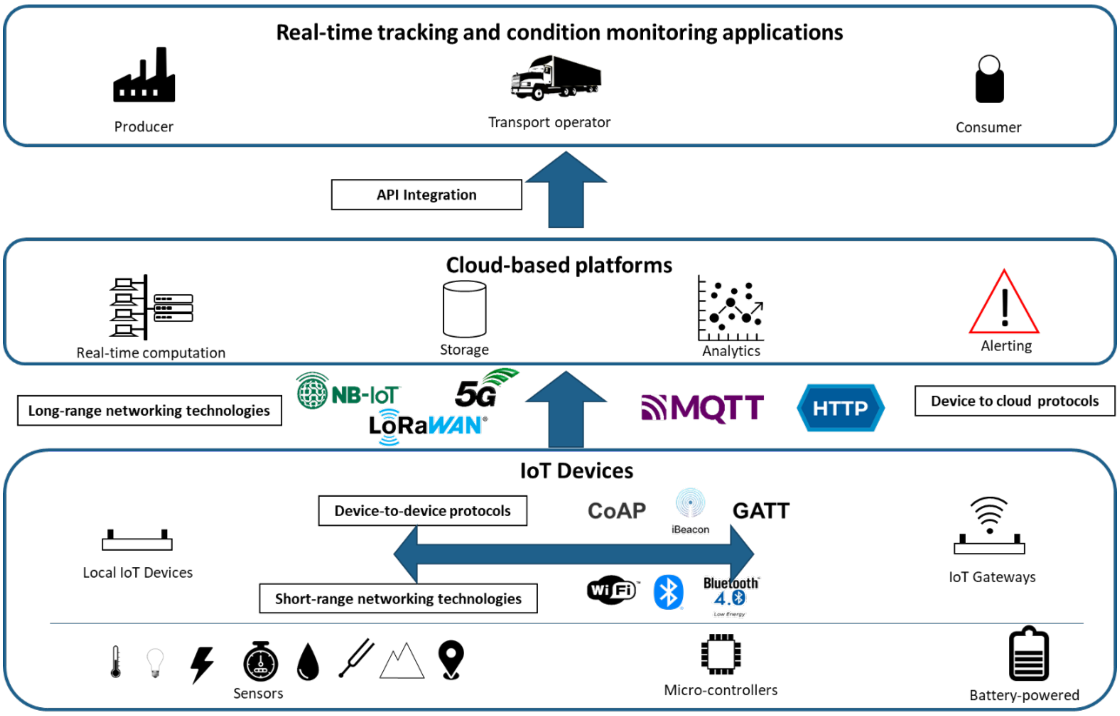

Figure 5: Data Exchange Protocols of IoT Standards

3.3 Summary of Technology Scan

Existing commercial IoT solutions for the tracking and condition monitoring of freight consignments discussed in the above section include IoT devices and cloud-based platforms. The following key capabilities were noted in the existing solutions:

1. Sensing capabilities: While a wide range of sensing capabilities exist across the breadth of commercial IoT solutions, macro-location was found to be the only sensing parameter included in the IoT devices that are part of the IoT solutions that were surveyed. Beyond macro-location, individual IoT devices were found to include a subset of all the sensing parameters. This implies that, for the purpose of any use case with specific sensing requirements, the

[3] https://developer.apple.com/ibeacon/
[4] https://www.bluetooth.com/bluetooth-resources/intro-to-bluetooth-gap-gatt/
[5] https://coap.technology/

choice of IoT device is typically limited. On the other hand, use cases that require a broad set of sensing requirements would likely need to use a combination of multiple IoT devices to ensure all requirements are covered.

2. Cloud-based platforms: Existing cloud-based platforms provide visualisation and alerting functionalities, which allow supply chain stakeholders to monitor shipments in real time and get notified of any deviations from expected shipping conditions. However, these capabilities are generic and there is limited support for tailoring to use case specific requirements.
3. Suitability **to transport hierarchy:** IoT devices themselves are agnostic to the product being monitored, even though they may sometimes be customised to better suit the tracking and condition monitoring requirements. Based on device characteristics, including the sensing capabilities as well as the weight and form factor, they may suit one or more levels of the transport hierarchy, such as:
    - A tracking device with macro-location monitoring capabilities may be used to monitor the vehicle. Thus, there may be only one such device for each vehicle, attached on the container or the vehicle dashboard.
    - Other tracking devices with broader sensing capabilities, including micro-location and other sensing parameters, may be attached at the level of outer or inner packaging. In some commercial IoT solutions, local IoT devices are targeted for such package level monitoring, wherein they connect to IoT gateways using short-range networking technologies, which in turn upload data to cloud-based software platforms over long-range networking technologies such as cellular data.

Figure 6 below outlines the key capabilities of commercially available IoT-based real-time individual freight consignment tracking devices identified in our technology scan.

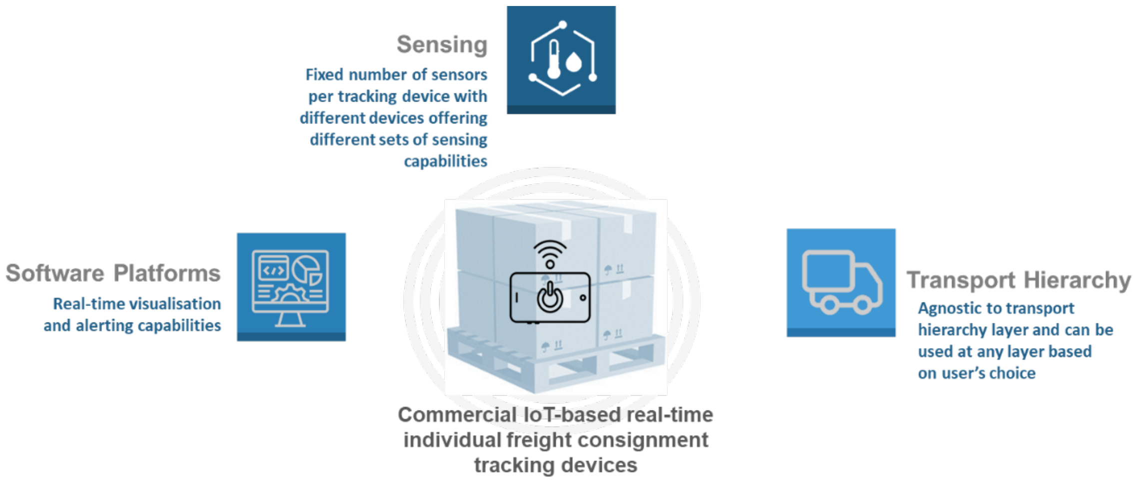

Figure 6: Capabilities in commercially available IoT-based real-time individual freight consignment tracking devices

4.0 Gap Analysis

Given the functional requirements identified in Section 2.0, the following section highlights the key gaps that the technology scan helped identify, and the potential opportunities for designing and developing a low-cost IoT solution for the tracking and condition monitoring of freight consignments.

4.1 Complex condition monitoring

As described earlier in Section 2, supply chain use cases discussed in this report require complex condition monitoring that involve a combination of sensing parameters and monitoring over a period of time. However, existing solutions for tracking and condition monitoring provide much less capability in this regard, and only include the ability to define alerts for single parameters using thresholds, such as temperature thresholds. Further, they lack the ability to define complex alerts that involve: (a) monitoring parameters over a period of time, (b) repeated events, and (c) combining information from multiple parameters and sources. Complex alerts that are based on analytics, patterns, and previous events for a single or a combination of multiple sensing parameters will make the system more intelligent and efficient, leading to improved uptake.

GAP: Inability to perform complex condition monitoring.

4.2 Open software architecture

Existing supply chain standards, such as the UN/CEFACT smart container standards as well as GS1 standards, highlight the need to ensure traceability across various supply chain stakeholders. However, existing real-time tracking software platforms are mostly proprietary and siloed, thereby limiting the visibility of condition monitoring information to stakeholders. Although some existing platforms provide APIs for business integration, they enable integration with applications specific to individual stakeholders. Protocol standardisation, on the other hand, primarily focuses on device-to-cloud data exchange. Some blockchain-based platforms targeted for supply chains work independently of the real-time tracking devices, and hence, are limited in their abilities. Thus, there is a current gap to fill (to achieve open software platforms) that will ensure end-to-end condition monitoring across the supply chain.

GAP: Limited stakeholder visibility of condition monitoring information to all stakeholders due to proprietary and siloed tracking software platforms.

4.3 Multi-source data integration

Electronic product information is the primary source of product identification in a supply chain. This is currently coded in the form of Barcodes, RFID tags, etc. The current practice is to manually or automatically scan these data carriers using dedicated scanners or readers, and upload the data to a database. When considering the scenario of tracking a consumer device using IoT-based trackers, there is no provision to include this electronic product information directly or from existing barcode/RFID-based devices into the IoT workflow in existing consumer devices. This can lead to a situation that involves accessing individual freight consignment tracking data from an IoT device without knowing the content included inside the package that is being tracked.

GAP: Inability to know the content included inside the package that is being tracked.

4.4 Micro-condition monitoring

While the transport hierarchy proposed by GS1 differentiates the different cargo levels, existing tracking solutions do not provide a way to determine the level being monitored, i.e., whether conditions being monitored relate to an item, package, container or vehicle. Further, large containers and vehicles often transport mixed cargo, which necessitates condition monitoring at different parts of a vehicle/container. This is especially important for transporting certain types of cargo, such as food, which can get impacted by excessive vibration in parts of a vehicle, its closeness to a vent, cross-contamination with other cargo, etc. The variation of controlled environmental variables in a refrigerated container is also acknowledged by a CSIRO study which reports that, while work is needed to rectify air distribution problems, or establish zoning, uneven temperature distribution issues can be overcome using a minimum of 12 sensors per truck (probably installed permanently at key positions within the truck) or at least one sensor per pallet of product [10]). While micro-condition monitoring has been explored to some extent by some commercial IoT solutions, the gap here is the inability to adapt to regulatory compliance requirements in real time. Take for instance, a mixed cargo scenario in which a product such as meat is transported alongside another non-compatible product such as fish. Since co-transporting fish and meat is reported to impart the odour of fish in meat and reduce its quality, this presents the risk of product damage and loss. In such a situation, micro-location tracking can help detect and send alerts, in real time, when the two incompatible products are in proximity (e.g., when 2nd product is loaded). Subsequently, other functionalities like complex condition monitoring may be performed, such as monitoring both temperature and micro-location together.

GAP: Adapting micro-condition monitoring to suit business requirements in real time.

4.5 Battery life

Battery life is another critical component of an IoT-based tracking system. Sufficient battery life ensures that the sensors and gateways are powered throughout the transit period. While existing solutions provide a range of batteries with varying battery lives that suit all types of short and long-term requirements, the size and weight of existing batteries limit their deployment to shipments that are large enough. Further evolution of batteries, such as printable batteries with relatively good efficiency, can help address the form factor issue and allow them to be deployed on smaller shipments.

GAP: Limited battery life and size and weight of batteries.

4.6 Reusability

As identified in the functional requirements, there is a need to support customisable features, such as the ability to select the sensing parameters, define normal and abnormal ranges, set the frequency of alerts, and input the location and persons to be alerted. The ability to support such customisations can enable tracking solutions, including tracking devices, to be reused easily in an on-demand manner across various domains and use cases, while also improving the sustainability of such solutions. Currently, while some solutions allow the ability to customise sensing parameters, this appears to be only possible during a one-time configuration of an IoT device. Hence, this implies that the same IoT device may not be used for more than one product type. This limits the reusability in situations that require repeated use for different product types, such as when a logistics provider undertakes shipment for different products using the same vehicles at different times.

GAP: On-time (one-off) device configuration and the lack of support for customisable features.

Figure 7 below shows the summary of the gaps identified through our technology scan of commercially available IoT-based real-time individual freight consignment tracking devices.

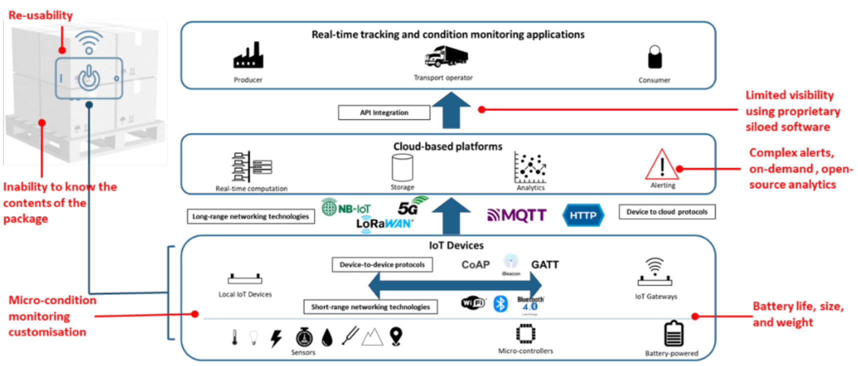

Figure 7: Gaps in commercially available IoT-based real-time individual consignment tracking devices (shown in red).

5.0 Recommendations

Based on the gap analysis presented in the previous section, some key recommendations for a low-cost IoT-based solution for the tracking and monitoring of freight consignments are proposed in this section. Details of the recommendations for the IoT solution are provided, followed by a discussion on cost considerations.

5.1 IoT solution recommendations

Some key recommendations for IoT devices and cloud-based platforms are detailed below.

5.1.1 Recommendations for IoT devices

1. **Customisable/modular design:** A customisable modular design that allows use case specific sensor selection is a key capability that is needed in IoT devices for tracking and condition monitoring. As seen in the above sections, one of the first functional attributes that needs to be defined for an IoT-based solution concerns the identification of sensing parameters. These sensing requirements can be derived from:
    - The regulatory controlled transportation environment variables, and requirements.
    - Additional sensing requirements identified from research and industry reports.

    In order to ensure that the IoT device can be adapted to and interoperable across different use cases, it is necessary to have customisable sensing parameters depending on the use case (by using applicable device management capabilities).

2. Form factor: Existing IoT devices are suited for vehicle or package-level monitoring, owing to their form factor and weight-related attributes. We recommend that the form factor of IoT devices be kept small in order to ensure micro-condition monitoring, especially in scenarios where items are small in size.

3. Battery: The key recommendation is for the IoT device battery to be lightweight and small in size to ensure that the above form factor recommendations can be realised. Further evolution of batteries, such as printable batteries with relatively good efficiency, can help address the form factor issue and allow them to be deployed on smaller shipments.

5.1.2 Recommendations for Cloud-based Platform

1. Complex condition monitoring: It is necessary for cloud-based platforms to support complex condition monitoring in order to adequately address a wide range of supply chain scenarios. In particular, two complex conditions are emphasised: (i) extended monitoring of sensing parameters, over time and location, and (ii) simultaneous monitoring of multiple sensing parameters. Such complex condition monitoring may involve determining patterns that are not possible through simple threshold-based rules and alerts; hence, there is a need to support condition monitoring based on machine learning and data analytics involving information that is acquired from more than one sensor.
2. Transparency and privacy preservation: Another recommendation for cloud-based platforms is to enable the transparent flow of data, with the objective of traceability across the supply chain. We identify the need for privacy preserving open APIs, which enable decentralised data sharing across supply chain stakeholders, while ensuring that information sensitive to individual stakeholders is kept private.
3. Hybrid architecture: Current supply chain management systems have a number of systems and practices in place and in use. There is growing interest in adopting emerging technologies such as IoT in this area. This is due to their ability to provide higher information visibility in real time, to enhance sensing (e.g., temperature, shock, humidity) and to improve networking capabilities (e.g., GPS, GPRS). However, there is a need to consider hybrid approaches that allow them to be integrated with existing solutions. Due to their low cost, the barcode and RFID methods are considered to be appealing and a preferred method of choice, likely to continue into the future. As such, experts suggest that adopting a more hybrid model that combines existing methods such as RFID and other novel solutions such as IoT at a systemic level will contribute significantly to end-to-end supply chain visibility [38, 39].

5.2 Cost considerations

Cost can be a major barrier in real-time tracking and condition monitoring, due to the scale of supply chain use cases. Here, we outline the key cost considerations for an IoT solution, by examining both direct and indirect costs.

5.2.1 Direct cost considerations

1. While direct costs relate to the costs of tracking solutions or associated operational costs (e.g., subscription costs, network charges), determining the acceptable price point depends on multiple factors (e.g., operational factors). Direct costs in the current IoT-based real-time monitoring systems can be classified into the following categories:
    - device costs (sensors and gateways)
    - subscription charges
    - network/communication charges
    - postage charges for returning devices
2. While these are the direct costs of current systems, it can be understood that the direct costs are directly proportional to: the number of sensors,

architecture (e.g., private or public cloud), modularity, sensor networking methods, communication type and its associated cost.

The cost incurred for a use case depends on the number of devices as well as the duration for which the monitoring capabilities are required. Determining the number of devices required depends on deployment considerations, such as what is the level of transport hierarchy at which tracking is required and whether IoT devices can be reused. For instance, while an IoT device attached to a vehicle may continue to be used for different shipments, this may not be true for containers or packages which get moved from one vehicle to another at different stages of the supply chain. In case of the latter, it might require a separate device for each container/package, potentially leading to high operational costs, or reusing devices so as to optimise costs. The latter has been the focus of some smart packaging solutions, which collect used packaging and reuse them for other products.

5.2.2 Indirect cost savings considerations

While there are significant concerns regarding the direct costs of IoT-based tracking, it is also important to consider the following indirect cost savings because of efficient and improved visibility solutions:

- Reduced environmental costs due to product loss and damage
- Reduced produce/product damage and loss to stakeholders
- Improved quality – attracting high market price, reducing damage, and disposal
- Saved staff time – doing manual checks, management with damaged product
- Increased health and safety – reducing medical management costs
- Improved traceability – reducing future occurrence of similar incidents
- Improved return on investment – for farmers and manufacturers

IoT solutions are capable of providing real-time end-to-end supply chain visibility. While advanced sensing capabilities of IoT solutions can help address the information visibility gaps in the existing technologies, the cost increases exponentially based on the sensing, communication, and application-level requirements. This cost does not just pertain to the device but to the entire infrastructure. This view is supported by an industry study on German manufacturers, which identified that upgrading existing business processes to more digital means requires substantial changes to the entire existing infrastructure [40]. Nevertheless, companies that embark on the design of IoT solutions to support improvements in their operational performance have to create a "business–technology alignment", which involves translating their specific application scenario into technical requirements for these solutions [41]. As part of this, the key cost impacts arising from a lack of tracking information need to be accounted for. Take for example, while tracking individual COVID-19 vaccines may not be cost-effective, a lack of such valuable information can result in a large number of vaccines being deemed not suitable for use, which, in turn can impact the wider socio-economic landscape, e.g., through imposition of other pandemic control measures such as lockdowns.

6.0 Conclusions

This milestone report has identified and presented the functional requirements for an IoT-based solution for real-time tracking and condition monitoring of individual shipment units. Four use cases: strawberries, meat, vaccines, and equipment transport, were considered under the food and agriculture and pharmaceutical and medical industries.

These use cases were considered to better understand the sensing, communication, visibility and traceability-related functional requirements. A technology scan of existing commercial off-the-shelf IoT devices in this area was conducted to understand their capabilities in meeting the functional requirements for the identified use cases.

Our review found a limited number of commercial devices comprised of fixed sensing capabilities, real-time visualisation and alert capabilities.

A gap analysis of the functional requirements and existing solutions revealed the need for customisable, modular, and hybrid solutions that can meet the needs of a different types of products.

These findings and recommendations will inform the future work towards achieving an IoT-based solution with an open-architecture comprising hybrid and reusable solutions, for real-time tracking and condition monitoring of individual shipment units.

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