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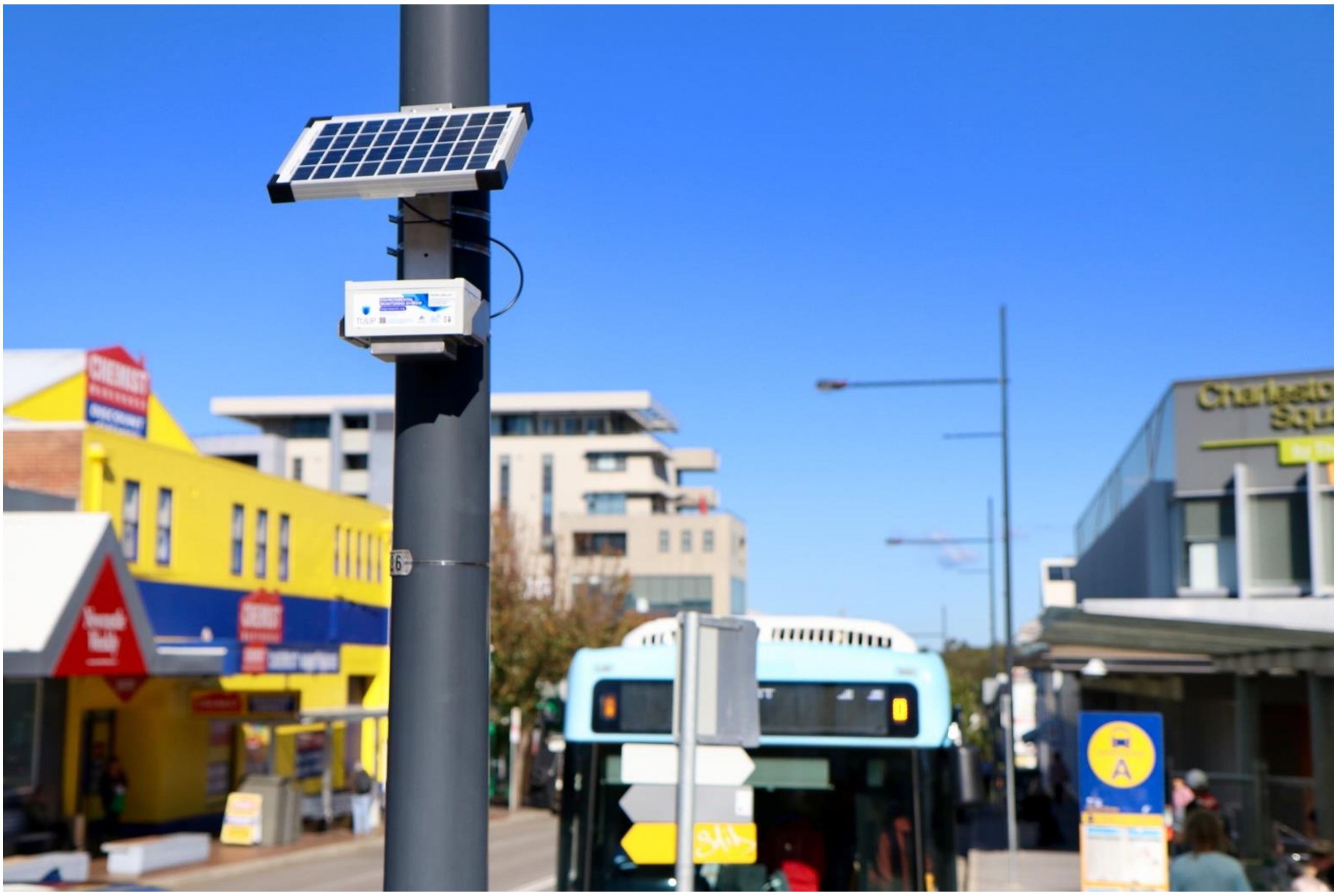
Operational Network of Air quality Impact Resources



A reference architecture for smart air quality monitoring: detailed guide

SR204

Table of Contents

Introduction

An air quality sensing network collects, manages, and stores data, and makes this data available to one (or more) end users. The design and implementation of any air quality sensing network depends upon different technology reference architecture layers, and underpinning components. These include software and hardware components, Internet of Things (IoT) sensing devices, network and communications infrastructure, and data management platforms and databases, as well as more advanced data analytics and visualisation platforms.

These layers and components form a complete, integrated system that is called a ‘system architecture’ (or ‘technology stack’), through which data flows. Various users will access and make use of that data at different layers of the architecture. The design of a technology stack for air quality sensing should be informed or guided by an IoT reference architecture.

A ‘reference architecture’ is a generic framework or structure that describes how components of a complete IoT solution (such as an air quality monitoring system) relate to each other. It describes the type of technology and functionality at various layers of a technology stack. A reference architecture is useful when designing your own, tailored air quality system architecture and solutions. It provides you with a map of the layers and functions you are likely to need.

This supplementary resource builds on the overview provided in the OPENAIR Best Practice Guide chapter *IoT reference architecture for smart air quality monitoring*.

Who is this resource for?

This detailed guide aims to assist local government staff involved in the strategic planning and delivery of an air quality monitoring project. It is a practical tool for people responsible for designing and implementing an IoT architecture and solution for an air quality monitoring project, including:

- information, communication and technology (ICT) professionals
- data custodians.

It is also intended as a useful general reference for:

- people leading new air quality monitoring projects
- local government leadership
- smart city professionals
- planners
- environmental officers.

How to use this resource

This supplementary resource extends the overview provided in the Best Practice Guide chapter *IoT reference architecture for smart air quality monitoring*. You can use this more detailed guide as a reference to assist with the development of an IoT architecture solution that meets the needs of your air quality monitoring project.

Please note that the reference architecture framework used throughout this guide is based on the more general *IoT Reference Framework v1.0* developed by the IoT Alliance of Australia (IoT Alliance Australia, n.d.).

What is the purpose of this guide to reference architecture?

- To establish a common language and to help stakeholders become familiar with the associated technical terminology, in order to facilitate discussions among the air quality sensing community
- To help local governments planning air quality sensing projects to understand and articulate the structure and functional needs of prospective IoT solutions
- To support the design of detailed IoT solutions for sensing projects.

There are two types of reference architecture referred to in this resource:

1. A simplified reference architecture. Intended to convey the concept of a layere architectural framework - this is primarily for non-technical readers. (Figure 1)
2. A full reference architecture. Intended for readers with greater technical knowledge. (Figure 2)

A simplified reference architecture for low-cost air quality monitoring

Figure 1 presents a simplified version of the reference architecture for low-cost air quality monitoring, intended for a non-technical audience. It highlights the distinct types of technology products and services that need to be procured to build a complete air quality monitoring system.

You can review Figure 1 by starting from the bottom layer (the ‘physical world’ that hosts the IoT end points for air quality sensing), and working your way up. Observe how different layers of technology used for different purposes are stacked together, to support different applications and users. This enables the flow of data from the bottom layer (the ‘physical world’), through the various technology components, to the top layer (‘data users’).

Data users		
User interfaces (laptop, mobile, tablet, etc.)		
Application enablement	**Air quality data applications**	End user business and IoT applications: • data discovery and sharing (e.g. public dashboard; open data portal; custom API) • developer services.
Intelligence enablement	**Analytics and visualisation platform**	A user-facing dashboard that might incorporate maps, customisable graphs, and more advanced data analytics tools (e.g. GIS; digital twins; machine learning/AI).
	Data management and storage *[Data platform]*	Device telemetry (sensor readings) must be structured and stored in a way that is secure, searchable, and accessible. Storage options tend to be cloud-based third-party services (commonly Amazon or Microsoft) that are connected to data management systems, which structure data and manage user access.
Connection management	**Device hosting and management + basic data interpretation** *[IoT platform]*	You will need a contract with a service provider that hosts devices in a digital platform. Device management involves the onboarding and commissioning of new devices and their subsequent management, with alerts in place for failures and errors. Be aware of your basic data interpretation requirements (like humidity interference correction for particulate data, and calibration and drift correction for gas data), and communicate these before proceeding.
Connectivity + edge gateway	**Communications**	You will need a contract with a communications provider that supports the transmission of live data from devices to a central online management location. Your chosen communications solution might involve local government-owned infrastructure (gateways), or you might engage a telecommunications provider and make use of their existing infrastructure.
IoT end point	**Devices** (IoT end point)	Physical digital hardware that produces and transmits data.
The physical world		

Figure 1. Basic components of data architecture for a sensing network

Data users

Data users are the top layer of the reference architecture. Users include anybody who will interact with the air quality data applications through the user interfaces, via the services and technology provided through all lower layers.

User interfaces

User interfaces provide interaction points to end users via various devices (e.g. laptops, or mobile devices). These interfaces enable data users to access and utilise different air quality monitoring applications and data. For example, a mobile device and user interface software could provide a map of air quality in a particular local government area that is colour-coded, based on an average air quality measure of the previous 24 hours.

Application enablement

The application enablement layer represents any air quality data applications that are utilised by end users for business purposes. Examples include data search, discovery, visualisation, and sharing through public dashboards, open data portals, and custom ‘application programming interfaces’ (APIs).

Intelligence enablement

The intelligence enablement layer has two types of applications. The first is the *analytics platform*. This is responsible for processing, visualising, and interpreting sensor data at different granularities (e.g calculating an hourly average, or generating air quality reports). The applications used in this layer can be simple visualisation-based maps, reports, and graphs, or more advanced analytics tools (such as GIS, or machine learning-based systems that predict future air quality trends). Google Analytics, PowerBI, and Tableau are some examples of widely used data analytics platforms.

The second type of application is data management and storage, or the *data platform*. This is where the device telemetry (air quality sensor readings) is formatted and stored in a way that is secure, searchable, and accessible. While air quality data can be stored on-site, most of the storage options tend to be cloud-based third-party services (e.g. AWS RDS, Microsoft Azure Data Lake, AWS S3, Hadoop, and PostgerSQL) that are connected to data management systems. The data platform provides a complete solution for managing the data life cycle, and controlling access to different applications by users.

Connection management

The connection management layer is important to maintain the IoT devices (and network connections) that communicate live data from sensors to the intelligence enablement layer. This layer is responsible for device hosting and management, as well as basic data interpretation.

Device management involves the onboarding and commissioning of new devices, and their subsequent management (with alerts in place for failures and errors related to devices, connection, and data). You need a contract with a service provider that hosts these device management and communication tasks typically in an IoT platform. For example, vendors like PurpleAir, Aeroqual, Geoscada, and Clarity provide IoT platforms for handling air quality data.

Basic data interpretation includes modifications and corrections to sensor data, based on your requirements (e.g. humidity interference correction for particulate data measurements, or calibration and drift correction for gas data). These requirements should be clearly communicated to your IoT platform provider before proceeding.

Connectivity and edge gateway

The connectivity and edge gateway layer is responsible for the overall communication between the IoT devices and connection management layers. Connectivity is enabled via different communication protocols (e.g. LoRaWAN, 4G/5G, or Wi-Fi). Through connectivity and gateways, the data is collected from IoT end points, and transmitted to a central online management location (e.g. a database). This can be done using local government-owned infrastructure (e.g. gateways), or by engaging a telecommunications provider and using their existing infrastructure.

IoT end point

The IoT end point is the layer that interacts directly with the physical world, and captures the state of the environment in real time. It represents physical digital hardware, such as air quality sensing devices (containing sensors), which produce and transmit air quality data. For example, vendors like PurpleAir or The Things Network provide different sensing devices that can be used in this layer. A standard PurpleAir sensor can measure particulate matter (0.3µg to 10µg), temperature, humidity, and air pressure.

The physical world

The physical world represents the actual environment you want to sense for air quality data, as well as the infrastructure available for installing sensing devices (such as street lights or buildings). For air quality monitoring the location of sensing devices may be specific traffic intersections, airports, public transport hubs, schools, construction sites or neighbourhoods of interest.

A full reference architecture for low-cost air quality monitoring

Figure 2 presents the full reference architecture for low-cost air quality monitoring. This is based on the generic *IoT Reference Framework v1.0* (Iot Alliance Australia, 2018).

This reference architecture is organised into ten layers, with industry solutions at the top, and IoT end points at the bottom. Each layer provides a list of example component types in an air quality monitoring context.

There are also four functional capabilities that are applied across all ten layers in Figure 2: **operations**, **security**, **data governance**, and **data sharing**.

10	Industry solution	• Construction monitoring and compliance • Transport and infrastructure planning/management • Precinct planning • Energy demand management	• Indoor air quality management • Bushfire management • Automated water-sensitive urban design (WSUD) • Public health management
9	Stakeholders	• Local governments • Health authorities • Regulators • Local community	• Landowners • Research institutions • Transport authorities • Public/community
8	IoT users	• Planners • Asset/operations managers • Coompliance officers • Designers	• Health administrators • Researchers • Citizens
7	User interface	• Browser • Tablet/smartphone • Laptop/personal computer	• HDM (AR/VR) • Actuated display • User communication
6	Application enablement	• Apps • API • Public dashboard	• Digital twins/GIS • Operations dashboard
5	Intelligence enablement	• Data ingestion • Data interpretation and correction • Data validation • Temporal interpolation • Spatial interpolation	• Heterogenous data synthesis • Model integration • Data management • Data analytics platform • Data sharing
4	Connection management	• Device management • Configuration management • Identity management	• Asset management • Firmware over the air (FOTA) • Representational State Transfer (REST) API support
3	Connectivity	• Long Range Wide Area Network (LoRaWAN) • NB-IoT	• Sigfox • Wi-Fi • 4G
2	Edge gateway	• Air quality monitoring device	• Weather station
1	IoT end point	• Wall/building (fixed) • Pole (fixed)	**Actuations** • BMS • Automated mitigation • Actuated display
		Sensors • Heat • Humidity • Particulates (PM1/PM2.5/ PM10) • NO_x • SO_x • O_3 • VOC	• Weather • CO_2 • CO

Figure 1. Full reference architecture for low-cost air quality monitoring (adapted from IoTAA, 2022)

Reference Architecture layers

Layer 10: Industry solutions

The industry solution layer at the top of Figure 2 represents a set of eight business use cases (or solution examples) for air quality monitoring.

This layer provides context for an air quality solution and may include details about the social, economic, safety, security, and legal/regulatory environments, and how these might affect and/or influence the design and choice of an IoT solution. Include any specific laws, regulations, or other obligations you must comply with when designing your project's own IoT solution.

This layer helps stakeholders to consider factors (such as privacy, safety, and compliance with laws and regulations) associated with your specific context, at the early stages of design and implementation of an IoT solution. This information encourages users and service providers at each layer (from 1 through 9) to investigate their solution's compliance with laws and regulations specific to their industry, and outside that industry.

Some of these industry solutions are described in more detail below. Please note that this is not an exhaustive list, and additional use cases or solutions can be added as required.

Construction monitoring and compliance

Air quality monitoring solutions can help to monitor the environment around construction sites (including additional traffic, dust, or air pollution associated with particular building materials). Local governments can monitor the compliance of construction projects with air quality standards and regulatory requirements. This information can be used at the IoT solution design stage, to purchase IoT devices that capture all necessary measurements to evaluate air quality and regulation compliance. It can also be used to establish network connectivity, to gather air quality data at the desired time intervals for local governments to be able to evaluate and act on that data.

Precinct planning

When local governments are informed about the air quality in specific areas, they can make informed decisions about precinct planning and development approvals. Proposals to locate vulnerable people in aged care facilities and schools near busy road intersections or other busy transport routes should be assessed in light of air quality in the specific locations proposed.

Indoor air quality management

Indoor air quality management is another use case for an air quality monitoring IoT solutions for local government (e.g. monitoring indoor air quality in public buildings, schools, recreational spaces, or restaurants). There are different requirements and regulations associated with indoor air quality compliance, often the responsibility of building management. This may require different sets of IoT devices, connections, and data platforms, when compared to an outdoor air quality monitoring solution. Information privacy and security can be a significant concern when monitoring indoor air quality.

Water-sensitive urban design (WSUD)

Water-sensitive urban design (WSUD) is an approach to integrate urban water cycle management into urban planning, design, and development processes. The goal of WSUD is to manage the effects of urban development on the urban water cycle, by considering the management of natural water resources, potable water, waste water, and storm water in an integrated manner. Heat and humidity data provided by weather stations, air quality sensing devices or dedicated heat monitors can be combined with other measurements such as soil moisture to understand the effectiveness of WSUD implementations.

Transport and infrastructure planning/management

Transport and infrastructure planning and management projects may require monitoring and meeting certain air quality standards and regulations. Motor vehicles, diesel powered trains, and aeroplanes are a major contribution to air pollution, and emit significant levels of greenhouse gases.

Infrastructure managed and approved by local governments can contribute to air quality, whether positively or negatively (e.g. a factory may increase air pollution, while a park with greenery can reduce it). This information can be used to identify opportunities to improve air quality, or to impose regulations to control air pollution in particular precincts.

Bushfire management

Bushfires are a major cause of air pollution in Australia. Wind can carry the smoke from bushfires across vast distances, affecting the quality of life and health of many residents. Air quality monitoring in real time can help to improve understanding of bushfire impacts on air quality, and to provide timely notifications to the public (e.g. to stay indoors, or use air filtration masks). Air quality information can be used to guide future bushfire planning and management processes.

Public health management

Air pollution is a major public health concern. Pollutants (e.g. particulate matter, carbon monoxide, ozone, nitrogen dioxide, and sulphur dioxide) can cause respiratory problems, heart disease, and lung cancer. Children, the elderly, and other communities from low socio-economic backgrounds are more susceptible to such illnesses. It is thus critical to monitor and maintain air quality around public areas, schools, aged care facilities, and hospitals. There are local and national policies and regulations in place to safeguard public health and safety in this domain.

When designing and implementing your IoT solution, ensure it meets the requirements of any associated public health regulations, and that it captures the data and information necessary for ongoing regulatory compliance. Keep in mind that healthcare professionals and researchers may also be interested in investigating how air quality data affects public health, and this may require data to be captured at different granularities, over a set time period.

Layer 9: Stakeholders

Identifying the relevant stakeholders, their needs, expectations and responsibilities will help you to define and deliver an air quality monitoring solution that provides meaningful impact in your community.

In Figure 2, the layer representing stakeholders outlines eight core types of stakeholders. This layer – together with the industry solution layer – provides a solid business context for the remaining layers of the reference architecture.

Core stakeholders are individuals or organisations with an interest in air quality solutions and data (e.g. local governments, health authorities, regulators, local communities, landowners, research institutions, transport authorities, and the general public). In addition to these core stakeholders, secondary stakeholders (such as industry solution or service providers, consultants, and systems integrators) may also need to be considered as they may be delivering parts of the air quality monitoring solution.

It is important to understand the responsibilities, roles and expectations of each stakeholder. This will help you define the necessary governance and management processes for air quality solution components, across all the different architecture layers. For example, in the IoT device layer, you will need to decide: *who will sponsor, supply, deliver, and support your IoT devices for an air quality monitoring solution?*

This information will help to identify underlying complexity of any air quality monitoring solution, including auxiliary needs (e.g. security, privacy, data integrity, solution resilience, availability, and resources).

The eight core stakeholder groups are described below;

Local governments

Local governments can be the primary business owner of an air quality monitoring solution. You may have staff with an interest in certain types of air quality data, or who play a key role in planning, designing, implementing, and managing air quality solutions and data. Local governments may need to recruit and coordinate external service providers, while ensuring data privacy and security requirements are met, and that data is stored and shared responsibly and ethically with internal and external stakeholders.

Health authorities

Local, district or state-level health authorities may have an interest in air quality data, and have specific requirements for the data collected by an air quality monitoring solution.

Regulators

Regulators may have regulatory compliance requirements that influence the design and implementation of your air quality monitoring IoT solution (e.g. specific air quality regulatory compliance for construction, industrial emissions, or infrastructure planning). By understanding these requirements early on, you can design solutions that meet the regulator's needs. This may include sourcing appropriate IoT devices or intelligence enablement platforms that collect/analyse the right kind of data to ensure regulatory compliance. Regulators may also be the end users of air quality monitoring data.

Local communities

Local communities are stakeholders who can experience both direct and indirect benefits from any air quality monitoring solutions. As direct users, they might be interested in monitoring air quality in real time to make everyday decisions (e.g. configuring indoor air circulation and filtering systems to reduce air pollutants during bushfire season). Indirectly, they may benefit from decisions made by other stakeholders (such as regulators, planning or transport authorities).

Landowners

Landowners as stakeholders may use an air quality monitoring solution to observe the air quality around or near their properties/landholdings, and to take action to improve air quality in their local area.

Research institutions

Research institutions (or individual researchers) as stakeholders will mainly be interested in the data generated by an air quality monitoring solution. This data can be used in various research projects (e.g. analysing impacts of air quality on public health and well-being). Research institutions may also potentially be interested in accessing larger volumes of historical data for their research.

Transport authorities

Transport authorities may be interested in using air quality data to inform planning and infrastructure decisions, and to ensure regulatory compliance. They may have particular requirements for an IoT solution (e.g. placing air quality sensing devices near motorway tunnels).

Layer 8: IoT users

This layer identifies different users who interact directly or indirectly with an IoT-enabled air quality monitoring solution. Users can be categorised as ‘primary’ or ‘secondary’. Primary users act upon the information produced by the solution (e.g. a local government planner in an air quality monitoring solution owned by local government).

Secondary users are the individuals who operate and manage the solution, or have a business interest in the solution (e.g. researchers, emergency responders, and other government agencies that may request access to the data).

The IoT users layer in the architecture can help to identify and understand who is going to use your air quality data. An IoT solution can then be designed to meet user requirements and access needs.

The stakeholders layer in Figure 2 highlights seven key IoT users associated with an IoT-enabled air quality monitoring solution. More details about these users are provided below. Please note that this is not an exhaustive list, and additional users can be added as required.

Planners

Planners might use data and insights provided by an air quality monitoring IoT platform to plan development projects (e.g. transport or community infrastructure). They will generally want to use historical air quality data to understand the current situation, and to ensure that future development plans comply with any associated laws and regulations. Planners could be direct users (from local government), or indirect users (from transport or health authorities).

Asset, operations and compliance managers

Asset or operations managers are responsible for managing and maintaining infrastructure and assets. They may be aware of the impact their assets/operations have on local air quality, and can use IoT-enabled air quality monitoring solutions to ensure regulatory compliance.

Compliance officers can use an air quality monitoring solution to monitor air quality levels and related compliance in various sectors (including construction, transport, infrastructure, and energy). By accessing air quality data with a certain granularity, accuracy, and frequency, they can more easily perform any compliance assessment duties, and take necessary remediation actions.

Planners

Designers of different local government infrastructure (e.g. parks, waste management facilities, or transport infrastructure) can use the data generated by an air quality monitoring solution to guide their design of spaces to reduce the emission of air pollutants, or to take remedial actions. For example, public parks with trees and green space can be designed close to high-polluting industry areas, to reduce CO_2 accumulation.

Health administrators

Health administrators can use an air quality monitoring solution to monitor air pollution in specific local government areas, and to assess the public health implications. They can take necessary actions to mitigate any health issues (e.g. encouraging the public to wear masks during bushfire events), or can advocate for policy or regulations to control and minimise air pollution and avoid health hazards.

Researchers

Researchers can use an air quality monitoring solution to generate data for relevant research projects. They can use the intelligence enablement layer of the architecture to collect and analyse air quality data for a variety of research tasks in different domains (e.g. public health, agriculture, and transportation).

Citizens

Air quality monitoring solutions can be used to provide public access to air quality data. Air quality monitoring solutions should be simple and easy for the public to understand. Understanding how the public will use this data is essential to design appropriate user interfaces such as dashboards and alerts.

Layer 7: User interface

The user interface layer enables user access to different applications in the air quality monitoring solution. This layer defines how users access data and information via different hardware devices and software interfaces.

The most common user interfaces use commercially available devices (e.g. smartphones, tablets, laptops, and desktop computers). However, there are new types of interfacing devices rapidly emerging, such as headset-mounted displays (used in virtual reality or augmented reality applications), and home devices (such as Google Home or Amazon Alexa). In certain industry solutions, a complete, customised user interface may be required to serve specific IoT user requirements. Information kiosks and displays installed in public spaces are another type of hardware that can be used to provide air quality information.

Identifying different elements and requirements of the user interface layer also helps in making design decisions at lower layers. For example, if the user interface is a mobile device, the application enablement layer should contain a cloud- or web-based mobile application accessible via the internet.

The user interface layer in Figure 2 highlights six key user interface components. More details about these user interfaces are provided below. Note that this is not an exhaustive list, and additional user interfaces can be added as required.

Browser

Browsers are the web interfaces (e.g. Firefox, Safari, Google Chrome, or Microsoft Edge) that people use to access websites and web services. Browsers are installed on a range of hardware devices such as desktop and laptop computers, mobile phones and tablets.

Tablet/smartphone

Users can utilise tablets or smartphones to access air quality applications. These applications can be accessible via related browsers, or can be downloaded to a tablet or smartphone.

Laptop/PC

Laptops and PCs (personal computers) are also a common user interface device. They can use air quality applications via the browser, or traditional on-device installed applications.

Headset-mounted displays (virtual reality/augmented reality)

Headset-mounted displays are a relatively new type of hardware device, used in virtual reality or augmented reality applications. They are particularly useful for immersive experiences, such as visualising air quality data and other environmental information in three dimensions.

Actuated displays

Actuated displays provide visual information, and they also serve as mechanical actuators that generate signals. For example, an actuated display could involve using LED lights integrated with sensor data to visually indicate the current level of air quality in a particular area, using different colours (e.g. a red light indicates that air quality level is below the expected threshold, and a green light indicates the air quality level is good).

User communication

User communication represents the custom end-user interfaces and communication methods that are not covered in the above categories. These include the use of virtual private networks (VPNs), file transfer (FTP), short message service (SMS) and email-based user communication methods. Your IoT solution can design or adapt one or more user communication methods, to best fit the intended users' needs.

Layer 6: Application enablement

The application enablement layer provides access to air quality monitoring applications. It can include end user business and technical applications.

Business applications refer to air quality monitoring apps, application programming interfaces (APIs), dashboards, digital twins/geographical information systems, and operations dashboards. Technical applications include those that help your organisation to operate and manage the IoT solution and associated devices. This layer also includes other supporting applications (e.g. user interface security management, and developer services).

This layer can support a variety of activities, such as network connection management for devices, raw data storage and processing, monitoring events, managing any associated issues, and providing interfaces to external systems for data extraction. The application enablement layer is backed by two underlying layers: intelligence enablement, and connection management.

The application enablement layer in Figure 2 highlights five key types of applications associated with an air quality monitoring solution. More details about these application types are provided below. Please note that this is not an exhaustive list, and additional applications can be added as required.

Apps

This includes mobile and web apps, which can be hosted on-premises, or in cloud infrastructure. These apps can be accessible via the internet. When designing apps, it is important to consider user experience, and to use simple and minimalistic design to ensure the app is reliably working on required devices, and with supporting operating systems.

Application Programming Interfaces (APIs)

APIs are web-based interfaces that allow applications to access and use air quality data and services. For example, a local government can publish an API (to share air quality data) that can be accessed by software developed by a different government agency (e.g. a public health authority). APIs can be publicly accessible, or can be made available for a price (charged based on usage, or number of API calls). APIs provide data and services, and can be used to develop new customer air quality monitoring-enabled applications. Information security and access control are important aspects to be considered with API design and implementation. Local governments may also want to consider an API management platform, to systematically publish and manage air quality solution APIs.

Dashboards

Dashboards are applications that make available air quality data and services readily available to public users. An example of application enablement of data platforms are the SEED dashboards run by the NSW Government’s Central Resource for Sharing and Enabling Environmental Data in NSW. This is a web portal that publishes NSW environmental data (such as bushfire data) for public access. Users can access the air quality data sets for their own purposes, or develop further applications and conduct analysis on those data sets.

Digital twins/geographical information systems

Digital twins are virtual replicas (or simulations) of physical devices and their environment. These can be used by data analytics experts to understand a system and its behaviour. As part of an air quality monitoring solution, a digital twin/GIS application can use air quality data – together with an intelligence enablement layer – to understand, analyse, and simulate air quality patterns within a certain area. Digital twin applications can also be used to represent lower layers of the reference architecture (IoT end points, edge gateway, and connectivity), which can help in identifying performance bottlenecks, and possible failures.

GIS (geographic information systems) specifically are computer-based tools used to record, visualise, and understand geographic data. Google Maps and ArcGIS are two popular GIS applications. In the context of air quality monitoring, GIS applications can be used to visualise and analyse air quality data, alongside other geographic information.

Operational dashboards

Operational dashboards are applications that can be used internally by local governments to support their day-to-day operations involving air quality data. This could include operational reports of current air quality levels, or monitoring the health of IoT devices.

Layer 5: Intelligence enablement

Air quality monitoring applications produce and use large amounts of data generated by air quality sensing devices. A major challenge for local governments is how to manage and process this data to generate insights, and make decisions.

This capability is realised through the intelligence enablement layer. Intelligence enablement is what enables the use of data and analytics technologies to analyse, cross-reference, detect behaviour and patterns of interest, and learn/predict future behaviour and patterns that might drive actions and outcomes related to air quality monitoring.

The intelligence enablement layer involves three main activities; (1) collecting and storing the raw data coming from sensing devices, (2) transforming that data into a format that is suitable for components in the application enablement layer, (3) performing data processing or analysis to extract information from the data that would be useful at the application enablement layer.

The intelligence enablement layer in Figure 2 highlights ten key components to support air quality data management and analytics needs. More details are provided below. Please note that this is not an exhaustive list, and additional components can be added as required.

Data ingestion

Data ingestion is the handling of data that is collected by air quality sensing devices and then communicated through connection gateways. This data is accumulated into the data storage repository, for further processing and use.

Data interpretation and correction

Data interpretation and correction elevate the quality of the raw data coming from IoT devices, by putting it into a structured format (i.e. a data model), and by conducting device-specific corrections to the data, so it is fit for the intended use.

Data validation

Data validation is required to make sure no erroneous data is stored. Validation can be conducted against pre-defined rules and requirements (e.g. acceptable data formats, or ranges for a specific data point). Ideally, unvalidated data should not be used in the intelligence enablement or application enablement layers, as the results can be inaccurately interpreted by the intended users.

Temporal interpolation

In the context of air quality monitoring, temporal interpolation is determining the air quality at a point in time between two measurements. For example, measurements may be taken at say 8am and another at 8:30am. The air quality at 8:15 can simply be interpolated by taken an average of the 8am and 8:30

readings. Median values or more sophisticated techniques can be used when there are many measurements available.

Spatial interpolation

Spatial interpolation is similar to temporal interpolation but relates to space instead of time. The likely air quality at a location between two monitoring stations can be interpolated. As with temporal interpolation there will always be some uncertainty in the interpolated value. This may be due to variations in local topography and other factors such as location of air pollution emission sources.

Heterogenous data integration

Air quality monitoring solutions may comprise a mixed population of air quality sensing devices from different manufacturers. In these cases it will be important to provide capabilities integrate data from different makes and models of sensing device into a common data format.

Model integration

Model integration refers to combining existing air quality simulation or analytical models into a single, new model. This can be done to enhance or extend existing air quality models, where air quality data can be easily discovered, interpreted, and integrated, and rules and algorithms can be automatically applied to the combined data.

Data management

Data management includes overall data life cycle management, ensuring security and reliability, as well as managing user access to data.

Data analytics platforms

Data analytics platforms refer to the smart technologies and/or techniques (e.g. artificial intelligence [AI] and machine learning [ML]) used to produce actionable insights for decision makers. The benefit of AI and ML is their capacity to derive insights from air quality data automatically (or semi-automatically), within a short time period, and with minimal human effort. Common applications of AI and ML in the air quality monitoring domain could include automatic early identifications and alerts of abnormal air quality measures, and automatic corrections of errors in sensor readings due to external factors (thus reducing system downtime).

Data sharing

Data sharing is a specific component that ensures the data is available to relevant users, based on existing data sharing contracts. This component can be designed for real-time, batch, or bulk data sharing to support users' needs for analysis and decision-making.

Layer 4: Connection management

The connection management layer specifies a set of key components for managing IoT devices, and the connection between IoT devices and the intelligence enablement layer. This layer includes IoT device management, device configuration management, identity management of devices (and users who access them), asset management, and firmware management, as well as supporting the APIs that transfer and transform air quality data across different layers.

The success of the connection management layer depends on its ability to scale into a range of devices operating on different communication protocols (detailed in the connectivity layer). It should also support low-level device configuration, and provide security through access management and data encryption. This layer is the bottom layer of an IoT-enabled air quality solution (commonly referred to as an 'IoT platform'). Within this framework, the IoT platform scope can extend from here into the direct user interface layer.

The connection management layer in Figure 2 highlights six key components for an air quality monitoring solution. More details about these components are provided below. Please note that this is not an exhaustive list, and additional components can be added as required.

Device management

Device management involves the onboarding and commissioning of new IoT devices including air quality sensing devices, and their subsequent management. Device management includes monitoring device operations and sending alerts to technical personnel when failures and errors occur.

Configuration management

Configuration management involves the configuration of new IoT devices to work with components from other layers, and to communicate with other devices. It is necessary to keep the configurations up to date, to accommodate any changes to other parts of the IoT solution.

Identity management

Identity management involves the registration of new devices, users, and roles, and the provision of access to different users and roles (based on their level of privilege).

Asset management

There are many different physical assets associated with an IoT solution, in addition to the devices discussed under device management. Asset management includes the monitoring and maintenance of physical assets.

Firmware over the air (FOTA)

FOTA, or 'firmware over the air', enables engineers to update and maintain IoT end points (distributed across different locations) remotely and wirelessly.

REST API support

An IoT-enabled air quality monitoring solution relies on internet connectivity and information exchange. REST APIs are typical programming interfaces set up to facilitate a secure and reliable information exchange over the internet, across multiple computing devices. There will be REST APIs implemented to integrate different components of an IoT solution implementation. For example, a REST API can be established to enable communication between the air quality data storage platform and the data analytics platform. Through REST APIs, the data analytics platform can request specific data (e.g. air quality data for a specific location, and a specific period).

Layer 3: Connectivity

The connectivity layer provides the network connection between end point/gateway devices installed in the field and the IoT platform. This layer supports connectivity technologies, such as Bluetooth, Wi-Fi, Ethernet, LoRaWAN, Sigfox, LPWAN, 3G/4G LTE, LTE-M (Cat-M1), NB-IoT (Cat-NB1), and other proprietary radio technologies.

This layer also represents the internet access network for IoT client devices (which could be fixed or mobile broadband), as well as connectivity to the internet service provider. There could be more than one connectivity technology that can be used in an IoT-enabled air quality monitoring solution that is designed for a specific purpose. When selecting a connectivity technology, it is necessary to consider key factors, such as coverage (how far the connection signal will reach), mobility (is the IoT device portable?), network capacity, power consumption, bandwidth, and security, cost and network and availability concerns.

The connectivity layer in Figure 2 highlights five key technology components for an air quality monitoring solution. More details about these components are provided below. Please note that this is not an exhaustive list, and additional components can be added as required.

See the OPENAIR Best Practice Guide chapter *Data communications procurement* for more information about the relative advantages and disadvantages of different communications options within the device connectivity layer.

Layer 2: Edge gateway

Solution components in the edge gateway layer provide one or more of the following services:

1) They can aggregate data communication and management for a group of sensors and actuators to coordinate their connectivity to each other, and to an external network in the connectivity layer.

2) They can act as *protocol gateways* that perform communication protocol conversion between devices and the centralised IoT platform.

3) They can be *edge computing gateways* that perform a subset of functions from layers 4, 5, and 6 in Figure 2 (e.g. data storage, analytics, and machine learning). A typical edge gateway should have the ability to back up data, to avoid data loss due to a communication interruption with upper layers. Instead of transmitting data in real time, an edge gateway will store, aggregate, and/or integrate different measurements, and pass the data into upper layers as batches (via an internet connection).

The edge gateway layer in Figure 2 highlights two example gateways that can be used in an air quality monitoring solution. More details about these gateways are provided below. Please note that this is not an exhaustive list, and additional gateway types can be added as required.

Air quality monitoring devices

Air quality monitoring devices that combine or connect multiple IoT devices are also identified as edge gateways. They accumulate different sensor readings over time (such as $PM_{2.5}$ [1], air temperature and humidity), store the data temporarily and then transmit the data over the internet in batches, at a frequency defined by the device's configuration (e.g. every 1 minute, 5 minutes, or daily).

Weather station

A weather station edge gateway should be able to store and process air quality data coming from multiple sensors and measuring instruments (such as the IoT end points of an air quality monitoring solution).

Layer 1: IoT end point

The IoT end point layer represents physical devices that can be remotely managed, and perform specific tasks. These end points can either be a simple, stand-alone sensing devices, or more complex products that have a single (or multiple) end points embedded in them. The IoT end point layer can be further expanded into an architectural functional stack, comprising hardware (e.g. sensors, actuators, communications, memory a central processing unit), operating systems, a hardware abstraction layer, and firmware.

For example, a low cost sensing device may have a display to indicate air quality. It will also have a set of sensors to measure specific attributes of the environment such as particulate matter, temperature, humidity, and air pressure.

The IoT end point layer in Figure 2 highlights four key types of components of an IoT-enabled air quality monitoring solution. More details about these components are provided below. Please note that this is not an exhaustive list, and additional components can be added as required.

Wall/building (fixed)

Wall/building represents the physical location where IoT devices are mounted or installed. Many air quality sensing devices are mounted on rooftops, as this enables unobstructed access to ambient air. A critical aspect to consider (when deploying and calibrating sensing devices) is how heat radiated from the rooftop can affect sensor readings.

Pole (fixed)

Poles represent another possible physical location where IoT devices can be mounted. Many air quality monitoring sensing devices can be mounted on existing poles (e.g. street lights or traffic lights), which may save time and money.

Sensors

Sensors collect data about the environmental and are therefore essential to any air quality monitoring solution. An IoT-enabled solution can use a combination of different air quality sensors, based on local

[1] PM (particulate matter) refers to airborne solids or liquids. Its size is measured in micrometres and is indicated by the subscript. E.g. $PM_{2.5}$ has a diameter of 2.5 micrometres or less. (NSW Health, 2020)

government requirements. Common examples include sensors that measure heat, humidity, particulates, NO_x, SO_x, CO_2, CO, O_3, VOCs, as well as various weather sensors.

Actuators

Actuators are in some ways the opposite of sensors. Rather than collect data, they act on data they receive. For example, an alarm device is an actuator than can be integrated into a CO censor, so that an alarm will sound if the CO level in the environment exceeds a defined threshold (e.g. a smoke alarm). These kinds of actuations are frequently used in air quality monitoring solutions (e.g. in building management systems to warn users of toxic particles, or overall air quality).

Some sensing devices include displays (a type of actuator) that indicate the level of air quality through numerical readouts or coloured LED lights.

Actuation could also be used to automatically activate air filters or close windows when air pollution levels exceed certain levels.

Functional cross-layers

This section discusses four functional layers that can be applied across the different reference architecture layers presented in Figure 2: **operations**, **security**, **data governance**, and **data sharing**.

Operations

Air quality monitoring solution operations need to be managed across all layers: from physical devices, through the various platforms, databases, and applications, and all the way up to end users.

Operational functions include monitoring, assessing, and maintenance, as well as tracking and resolving issues related to IoT devices, networks, and platforms. This may include conducting planned maintenance and upgrades, troubleshooting, resolving problems, and managing settings and users. There can be different operational needs within each architectural layer, so it is important to ensure that IoT system operations are part of your overall IT operations and service management frameworks.

A local government organisation may use industry standard operational approaches and frameworks such as ITIL and IT4IT. Air quality monitoring solutions can generally be managed using these existing IT operational frameworks.

> WHAT ARE IoT SYSTEM OPERATIONS?
>
> IoT system operations are where IoT initiatives become ‘operationalised’, meaning they are integrated into an organisation’s standard day to day operational procedures.

Security

Any air quality monitoring solution is theoretically open to attack from internal and external threats, and is at risk of unapproved data access at any layer of the reference architecture. Security needs to be a consideration from the top to the bottom of your technology stack.

Security requirements are established based on local government risk assessments, and tailored to assets in different architecture layers, according to the scope set by your project and/or organisation. Additional levels of security may be required if your air quality monitoring solution deals with sensitive data, or operates within national security and/or critical infrastructure space.

It is important to ensure that the security of your chosen IoT system aligns with the broader IT security strategy and policy of your organisation. Using the reference architecture framework provided, you can assess the security vulnerabilities of different layers of your IoT solution.

For more guidance on cybersecurity measures, see the OPENAIR Best Practice Guide chapter *Cybersecurity for smart air quality monitoring networks*.

Data governance

An air quality monitoring solution requires end-to-end oversight, and control over the management and flow of data across the reference architecture layers. This is called data governance, and it can include the following factors:

- **data lineage** – provides the ability to trace data from its origin to its destination.
- **data quality** – ensures the monitoring, maintenance, and improvement of data accuracy, completeness, consistency, timeliness, validity, and uniqueness.
- **metadata management** – metadata describes data, and it has its own management requirements. Metadata within a smart sensing network can include contextual information relating to sensing devices and their deployment; information associated with the interpretation of raw sensor telemetry; information associated with the format, exchange, and storage of data; information associated with data users and access privileges; and information associated with the display and analysis of data.

> WHAT IS DATA GOVERNANCE?
>
> Data governance is about end-to-end oversight and control over the management and flow of data.

Data sharing

An air quality monitoring solution is composed of layers that exchange or share data *internally* (with other components of the architecture). Each layer also has the potential to share data *externally* (with other systems and users).

> WHAT IS SECURITY?
>
> Security is the protection of technology and data assets from internal and external threats, based on a thorough risk assessment.

Data sharing is something that needs to be managed at every level of the IoT solution architecture. This ensures that only appropriate data is made available to end users, and that more sensitive data is shared only with approved users. A data sharing policy, plan, agreement, and supporting set of guidelines and/or procedures are required to operationalise appropriate data sharing. These plans should also cover any pre-processing of data, before it is shared.

You should ensure that the data sharing functionality and settings applied to your project align with any pre-existing data management and sharing policies within your organisation. For more details, see the OPENAIR Best Practice Guide chapter *Sharing air quality data*. The *Data Sharing and Privacy Guide* published by the NSW Information and Privacy Commission is also very useful (Information and Privacy Commission, 2020).

> WHAT IS DATA SHARING?
> Data sharing is a process of making data available to individuals or external organisations.

References

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Associated OPENAIR resources

Best Practice Guide chapters

IoT reference architecture for smart air quality monitoring

This Best Practice Guide chapter introduces the OPENAIR reference architecture for smart air quality monitoring. The reference architecture is a framework that identifies the various components and data flows that make up a complete technical solution for smart air quality monitoring. It is a generic reference that can help local governments to design and implement their own technical solutions.

Data communications procurement

This Best Practice Guide chapter explores the various communications technologies that can support smart low-cost air quality sensing, and provides advice on selecting technologies that are appropriate to a project and organisation.

Cybersecurity for smart air quality monitoring networks

This Best Practice Guide chapter provides guidance on key cybersecurity considerations for local governments establishing smart low-cost sensing networks and supporting platforms and services.

Sharing air quality data

This Best Practice Guide chapter provides guidance on the sharing of air quality data. It explores the process by which a local government might assess data to determine its shareability, and presents a series of practical options for implementing data sharing.

Further information

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This supplementary resource is part of a suite of resources designed to support local government action on air quality through the use of smart low-cost sensing technologies. It is the first Australian project of its kind. Visit www.openair.org.au for more information.

OPENAIR is made possible by the NSW Government's Smart Places Acceleration Program.

Document No: 20231207 SR204 A reference architecture for smart air quality monitoring: detailed guide Version 1 Final