# Flexible Indoor Environmental Quality Monitoring for Interoperable Subsystems in Buildings

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***Abstract*— In urbanized areas most humans spend 90% of their time indoors, which makes the quality of indoor environments a major concern. While there have been many separate sensors which report specific parameters such as temperature, humidity, illuminance, CO2 etc., a flexible platform onto which ad-hoc ensembles of sensors can be deployed is missing. The flexibility in sensor selection for the ensemble translates to flexibility in cost incurred. Also, interoperability with other subsystems, such as air-conditioning and mechanical ventilation systems, in the building becomes a requirement for achieving useful system-level integration. A novel platform containing new hardware and software is proposed in this work to satisfy the environmental quality requirements, with a flexible architecture for interoperability. The platform achieves plug-and-play of sensors along with minimal energy expenditure to maintain the indoor environmental quality.**

***Keywords—smart buildings; indoor environmental quality; internet of things; sensors; edge-computing;***

## I. Introduction

Indoor environmental quality (IEQ) implies the quality of the environment inside buildings, pertaining to factors such as – air quality, temperature, humidity, lighting, sounds, odors, and factors that influence human well-being and health. The main factors contributing to IEQ are depicted in Fig. 1. IEQ has a significant impact on productivity and health of a human. For example, CO reduces oxygen delivery to the body's organs (like the heart and brain) and tissues, and causes harmful health effects.

This work proposes a novel flexible system for IEQ monitoring. It includes both hardware and software. The intended integration of the monitoring system is with other subsystems are such that the energy expenditure by a supervisory control system to satisfy the IEQ needs would be minimal.

The main gap in achieving real-time indoor environment quality monitoring and subsequent controlling system is the lack of sensor arrays that can respond in real-time. Most of the solutions for sensing an array of values use cloud-computing solutions that form isolated silos of their own.


Fig. 1. Main factors contributing to Indoor Environmental Quality (IEQ).

The most advanced air quality sensors, as claimed here [1], are used to monitor the environment in a test-bed. It has been used as a reference to identify the lacuna of existing sensor arrays, and a new sensor array design is proposed to overcome the issues. The designs for the sensor array and its container/packaging have also been performed with flexibility in mind. The design of interface for the new sensor array has also been implemented, along with corresponding local server. The platform architecture follows the philosophy of edge computing [2] and edge analytics, rather than following cloud-based computing. This is expected to give buildings higher control over own data and operation. It would also contribute to having real-time feedbacks for control systems [3-4] within the building that ensure the quality of indoor environment.

In this work, the proposed device contains an array of sensors and is equipped with a wireless transceiver for communicating with the local server. The sensors are extendable based on different scenario of real-life applications.

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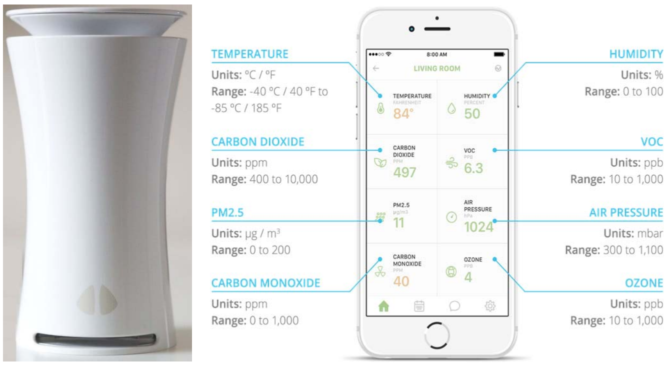
The communication protocol is Wi-Fi as it is readily available in most of the buildings / home environment. However, it can be changed to either Bluetooth or Zigbee if required.

The next section discusses an existing sensor array to note the drawbacks, and the need for sensor emulation in developing a supervisory control. Also, emulators fill the gaps in the ensemble of sensors selected when certain sensors are absent. Section III details the novel IEQ monitoring system and its architecture. Section IV contains the results of the proposed system. Section V is the conclusion and future work.

## II. Drawbacks of Reference Sensor Array, and the Need for Emulators towards Testing

Existing sensor array platforms for indoor sensing were explored. The most comprehensive one found was 'uHoo' [1]. The example of its physical configuration and the main display of the app associated with it are shown in Fig 2(a) and 2(b) respectively. uHoo devices follow a cloud computing paradigm, with web service hosted by a cloud provider. That means the indoor environmental data collected locally are possibly being transferred to a location in another far away country. If a local digital platform is seeking the data, there is no direct access possible to the devices. The data has to be drawn from the remote location, which is probably in another continent. While this mechanism is convenient in many ways and demands minimal local infrastructure, it goes against the very idea of a real-time cyber-physical system for the buildings.




(a) (b)

Fig. 2. uHoo IAQ monitoring system
a) physical uHoo device b) uHoo app's display [1].

The browser-based display system for uHoo is as shown in Fig. 3. This interface is but restricted since it accesses the cloud, and it is not locally configurable. The interface is tied to a user account, and lacks programmatic access to historical data so that further analytics can be performed by a building's supervisory control system or a building management system. But the mobile app did allow manual downloading of limited historical data.

Hence, open source dashboard platforms were explored for the display of collected data. The best choice among them was Grafana [5], an open-source, general purpose dashboard and graph composer, which runs as a web application. An example of a graph generated through Grafana connected to a MySQL database is shown in Fig. 4.

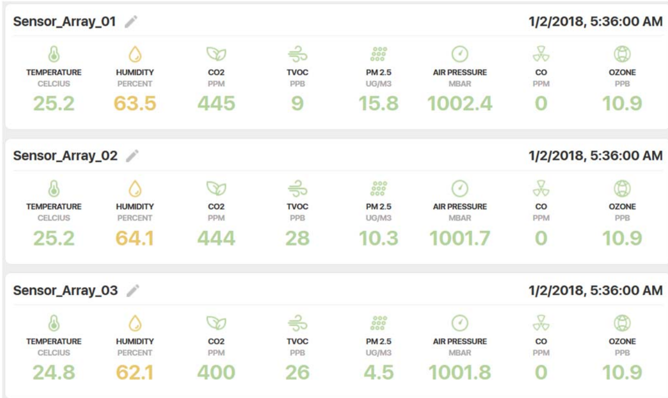



Fig. 3. Browser-based display of certain IEQ data from three hardware instances of reference sensor arrays.

The plot on $CO_2$ shows multiple peaks that indicate prolonged human presence during those periods. There are five peaks that appear together with gap of two in between, indicating five working days and the two holidays. The graph is interactive and automatically gets updated as new values are inserted into the local database. But the ability to handle data other than time-series data is poor in Grafana.

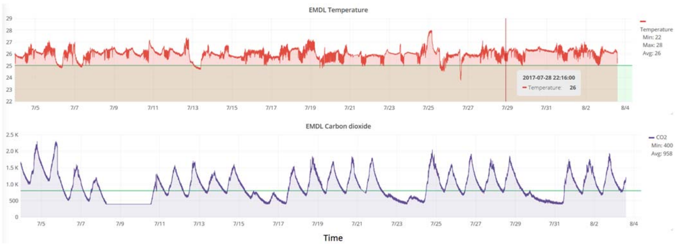



Fig. 4. Measured data from the reference sensor array visualized using Grafana. The upper plot is for temperaure and the lower one is for $CO_2$.

The inference of human presence from the peaks, and coupling that knowledge with a calendar of working days is possible by a smart analytical system. But to manifest such functionality for a building and to realize it in a manner which minimizes dependency on infrastructure that are external to the building, a new system with focus on edge-computing [2] must be available.

Another important observation available is the extremes of temperature which are measured by the reference array. An example of it is shown in Fig. 5. It is noticeable that the minimum temperature of the room on a particular day was 24.1 °C, while the maximum on that day was 27.3 °C. This indicates the unused scope of understanding human comfort through sensing and through occupant engagement. It also indicates the scope for intelligent control based on real-time user feedbacks. Such an IEQ-oriented system must be able to provide meaningful data to a supervisory control system for control of actuators related to lighting, Air-conditioning and Mechanical Ventilation (ACMV), air cleaning units etc.

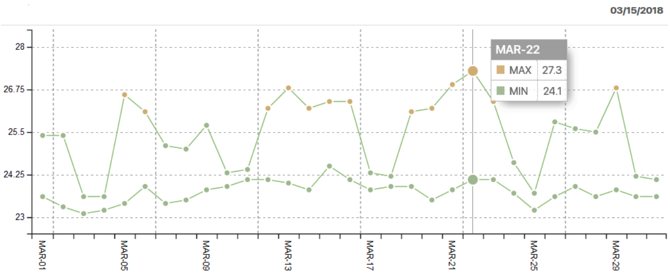


Fig. 5. Measured data on temperature for March 2018. The difference between minima and maxima imply the opportunity to improve human comfort through real-time occupant engagement and feedback.

For development of a control system, the mathematically rigorous method would be to model the overall system of sensors, their dynamics, the dynamical communication network, and the supervisory controllers together. But such systems are slow and have variable time-delays in sending feedback. To reduce the complexity of developing controllers and other interfacing programs, an alternate method would be to use sensor data in real-time to test a controller model/algorithm.

A typical schematic of a wireless sensing is shown in Fig. 6, which is a common network strucuture when using Zigbee communication.

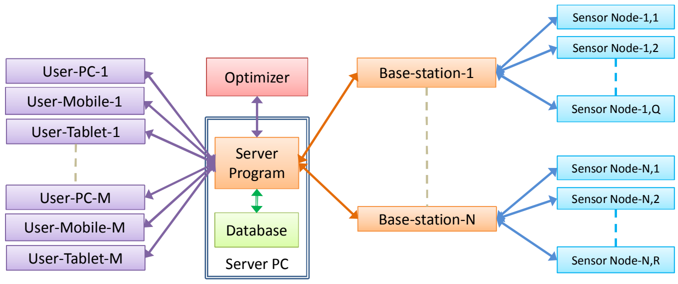


Fig. 6. The typical scheme of communication and connectivity for a wireless sensor network for M users and N base-stations contacting many sensor nodes

The actual physical sensors might be inherently slow for purposes of testing a controller, and most probably will not cover the entire range of each parameter measured. This problem is overcome through the development of emulators. The emulation of sensors were done by developing emulator programs and then and testing their communications with the server. Through this technique, the variable communication delay gets realistically reflected in the measurements. An illustration is shown in Fig. 7.

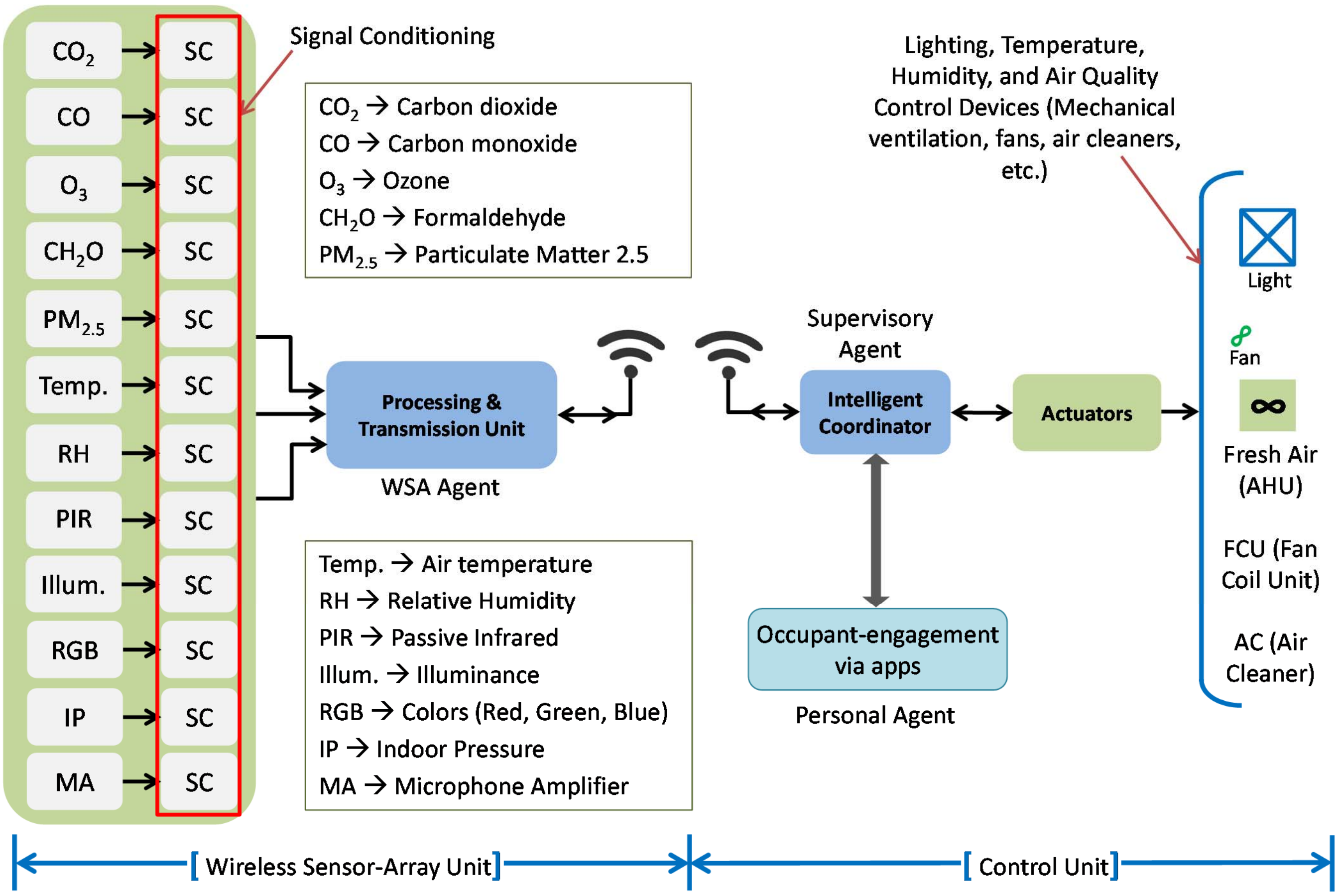


Fig. 8. Scheme of integration between IEQ monitoring and corresponding actuations are shown.

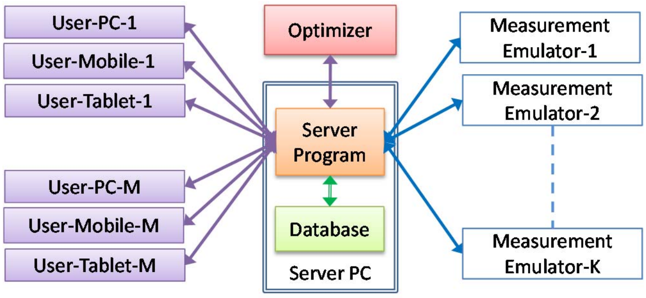



Fig. 7. Emulated communication and connectivity for the wireless sensor network designed for sensor array

The emulators can then act as flexible generators of data-points for an IEQ system. The design of the sensor array, which acts as a flexible node, is detailed next.

## III. Flexible IEQ Monitoring System

As shown in both Fig. 6 and Fig. 7, the server program acts as the communication bridge between users and sensed values. In this architecturem an optimizer is assumed which takes optimal decisions based on data from from both humans and sensors, so that heavy energy consuming systems like ACMV can be actuated to consume lesser energy. The design focus here is to make a sensor-array that is interoperable with a local server program, since the data collected by the sensor arrays could not only be used for monitoring and analyzing ambient environment but also fed back to air quality control system [6-7] including the mechanical ventilation, air purifier, etc. Fig. 8 represents the schematic of a system consisting of the proposed sensor array which interfaces with such a control system and its actuators.

A minimum of 12 indoor environmental parameters are targeted in the schematic. This includes carbon dioxide ($CO_2$), carbon monoxide (CO), ozone ($O_3$), formaldehyde ($CH_2O$), particulate matter 2.5, temperature, relative humidity, infrared motion sensing, illuminance, color values of light, air pressure, and ambient sound level. The values of parameters generated by the sensors are acquired using a processing unit. They are then collated and sent to a coordinator program, which then computes the actuation required to improve IEQ. A list of sensors selected for the making of sensor-array is given in Table I.

TABLE I. Sensors used in the making of the sensor array

| Parameter | Sensor | Interfaces | Power Supply Specification |
|---|---|---|---|
| CO2 | SenseAir LP8 [8] | UART | 3.3V |
| CO | SPEC CO [9] | UART, Analog | 3.3V |
| $O_3$ | SPEC $O_3$ [10] | UART, Analog | 3.3V |
| $CH_2O$ | DFRobot Gravity SEN0231 [11] | UART, Optional DAC | 3.3V-6V |
| PM2.5 | Telaire SM-PWM-01C [12] | PWM output | 5V |
| Temperature and Relative Humidity | Sensirion SHT31 [13] | I2C | 3.3V |
| Motion | SE-10 PIR Motion Sensor [14] | Digital (High/Low) | 3.3V |
| Illuminance | TAOS TSL2561 [15] | I2C | 3.3V |
| RGB | TAOS TCS34725 [16] | I2C | 3.3V |
| Pressure | NXP MPL3115A2 [17] | I2C | 3.3V |
| Sound | Maxim MAX4466 [18] | Analog | 3.3V |

Even though there are plenty of sensors to choose from, other than those given in Table I, assemblies such as the uHoo reference sensor array face the inflexibility that changes to the sensor combination requires redesign of the sensor array and are not possible by the end-user of the IEQ monitoring system. This implies that users looking for an inexpensive solution with reasonable compromise in accuracy and users looking for more accurate measurements using higher quality sensors – both these categories of users are left without options to customize their IEQ monitoring. These lacunas, along with the ones noted in the previous section, are overcome by the proposed IEQ monitoring hardware and corresponding software.

The hardware architecture of the proposed sensor array follows a system of a single main-board hosting a few sensor-boards (SB). A hardware instance of the sensor-array with five sensor-boards is shown in Fig. 9.

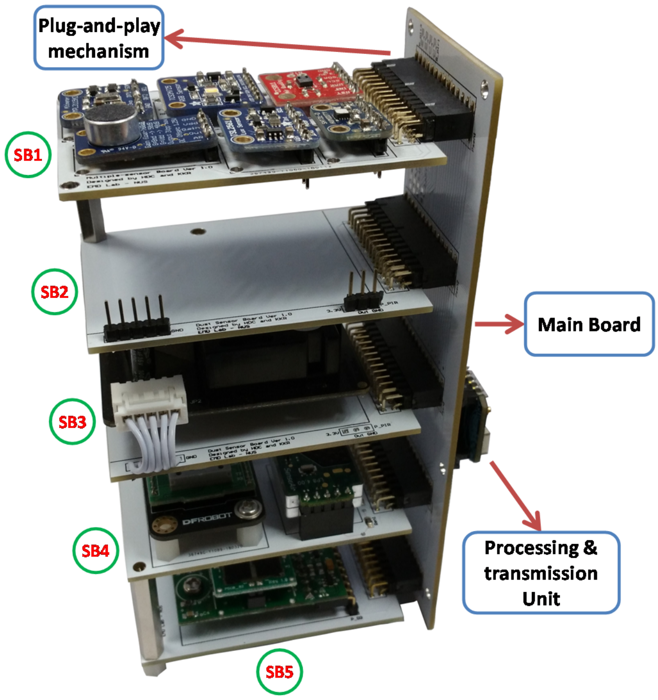



Fig. 9. Hardware instance of the proposed sensor array for flexible IEQ monitoring and interoperability.

The main board hosts the processor and the communication device. Since Wi-Fi is very common in the modern world, it has been chosen for communication here. This new design has SBs that can be optionally plugged in or pulled out of the main board. New SBs can be designed depending on whether the end-user is looking for lesser cost or for higher accuracy. SB-2 is shown as empty to indicate the option to add more sensors there. In large facilities where multiple sensor arrays have to be deployed, such feature could be especially useful since a few of the sensor arrays placed at non-critical areas could have inexpensive SBs attached to the main board. The embedded software in the processor can correspondingly accommodate multiple sensors, and allows over-the-air programming so as to update sampling and data-handling for new sensors.

The operation of the IEQ monitoring hardware relies on local servers, and it is locally hosted such that the interface is easily reconfigurable for interoperability. The data of the building would then stay within the building, unless they are opted for sharing. The IEQ data could be then coupled in real-time with data from other measurements of appliance usage, air-conditioning, their carbon footprints, and associated information thus making the IEQ system interoperable instead of reductionist or silo-based. The scheme of such an edge-based operation is shown in Fig. 10. Proposed sensor arrays do not send directly send data to any cloud service.

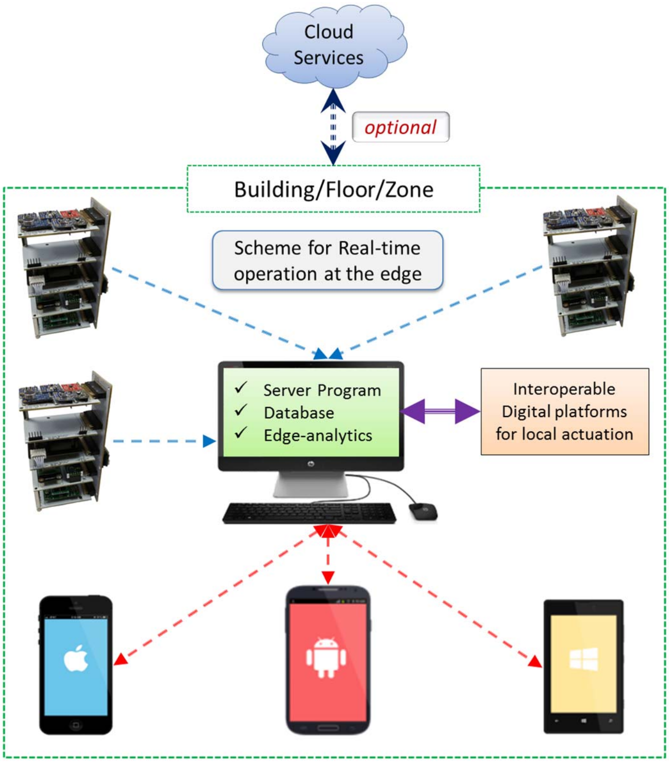



Fig. 10. Scheme of integration of the proposed sensor arrays for interoperability with other subsystems in the building.

The customization of sensors would be reflected in the power levels and energy cost of the design. The main board with only the processor and communication modules consumes 0.4-0.5 W when the Wi-Fi is ON for a 5V input. In the power-save mode of the processor, with Wi-Fi ON, the power can be as low as 0.09 W. In deep sleep mode, the power consumption could go as low as 0.4 mW. These imply that the proposed sensor array would incur low energy consumption, depending on the rate at which sensors data are acquired. Assuming a transmission of data every minute, the main board is estimated to consume around a single kWh of energy in a year.

## IV. Conclusion and Future Work

This research proposes a new indoor environmental quality monitoring platform which can operate based on an ad-hoc ensemble of sensor boards on a sensor-array. Unlike the reference sensor array, the proposed array is flexible to allow different sensors and allow interoperability with other subsystems in the building. The operation of the developed system validates its suitability to act as a local real-time system. This also indicates the opportunity of modeling intelligent local multi-agents that act in real-time, before using them in a closed-loop control towards performing actuations.

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