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Wireless sensor networks consist of physically distributed autonomous sensor nodes that cooperatively monitor physical or environmental conditions. The key benefit of wireless sensor networks is that they are capable of generating a more complete view of the sensed environment by acquiring larger quantities of correlated data than independent sensor monitors. This makes them ideally suited for applications where a complex environment with many interdependent factors must be monitored. The aircraft cabin is one such example of a highly dynamic environment which necessitates the use of an advanced sensing system. Thus, in order to gain a better understanding of the aircraft cabin environment, a wireless sensor network was designed and prototyped. The network is comprised of a variable number of nodes, and each node is capable of adapting to monitor a wide variety of environmental parameters. The system, as described in previous publications, has now entered the testing phase. The current configuration includes twelve nodes sensing temperature, humidity, carbon dioxide, and barometric pressure. This paper discusses the results from a series of tests conducted with the prototype hardware/software in a mockup of the 767 cabin environment. Tests involved the use of humidifiers, heaters, and carbon dioxide to simulate changes in the cabin environment.

I. Introduction

In recent years, embedded systems technology has advanced to enable the development of new environmental sensing tools. One such technology which has opened many possible improvements in environmental sensing is wireless sensor networks. Wireless sensor networks (WSN) consist of physically distributed autonomous sensor nodes that cooperatively monitor physical or environmental conditions. Recently, environmental sensing systems have been placed in aircraft cabins to enable a better understanding of the baseline characteristics of the environment.[1,2] Additionally, work has been done to develop computer models of the airflow characteristics within the aircraft cabin.[3,4] While this work has provided some information, it does not provide a full view of the environmental conditions within an aircraft cabin, and generated computer models require experimental validation. Previous sensing systems provided only single node measurements. However, the aircraft cabin environment is highly dynamic, and as such, characteristics vary greatly depending on the spatial location of the sensor node. This problem can be directly addressed with a broad WSN deployment within the cabin. In the following sections we discuss the design of a wireless sensor network for the aircraft cabin environment and the results of testing the WSN in a mockup of the 767 cabin environment.

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II. Aircraft Cabin Environment

The aircraft cabin is a semi-enclosed structure with a mixture of outside and re-circulated air similar to homes and offices. The aircraft cabin differs, however, in that it is a low humidity, low pressure environment with passengers in close proximity. Passengers and crews may be exposed to various concentrations of ozone (O_3), carbon monoxide (CO), carbon dioxide (CO_2), and organic chemicals. The exposure level of contaminants introduced from outside sources depends greatly on the location of the aircraft (e.g. on the ground, in ascent, at cruise, or in decent).[5] With so many variables, it is clear that the aircraft cabin is a very dynamic environment that requires new tools to effectively monitor conditions.

A. Need for Wireless Sensor Networks in the Aircraft Cabin

In previous research,[1,2] the aircraft cabin environment was characterized by single node measurements. Single node measurements provide a basic understanding of the environment, but there are many factors in the aircraft cabin that can affect the results. In previous non-wireless systems, the sensor node was carried by a passenger and attached to the seat-back pocket to collect data throughout the flight. As the cabin is a semi-enclosed environment, there is a continuous exchange of outside air with cabin air.[5] This results in air flow patterns that are spatially dependent, and as such, the environmental quality measurements can be expected to differ depending on node location. Coordinated measurements in a distributed fashion would enable the characterization of air flow effects and validation of proposed computer models.[3,4] In addition to enabling more accurate estimation of the environment due to the increased area monitored, WSN deployment would enable characteristic measurements that are not possible with single node measurements. One of the possible abilities gained by WSN deployment would be identifying the source of an airborne contaminant as it traverses the cabin. Since the sensor nodes can communicate with each other, a disturbance can be tracked cooperatively by the network.

B. Wireless Concerns

Wireless sensor networks have been proposed for use in structural health monitoring of the aircraft itself.[6-8] In much the same way we propose the use of WSN to provide a picture of the environment of the passengers and crew by distributing environmental sensors throughout the cabin. One question raised when considering WSN deployment in the aircraft cabin is whether there could be any adverse interference with flight instruments. Several studies over the years have indicated that the wireless frequencies typically used in WSN systems, such as 2.4GHz ISM band systems, do not interfere with flight systems.[9,10] The broad deployment of Wi-Fi networks within the commercial aircraft is also a strong indicator of the accepted safety of radio transmissions in the 2.4GHz band.

III. Deployment of the WSN

In designing our wireless sensor network, we focused on creating a flexible system that could be quickly and easily reconfigured to meet a variety of sensing needs. The goal was to ensure that new sensor types and upgraded technology could be added to the system as our research needs evolved. In order to achieve the desired system flexibility, we had to design flexibility into both the hardware and firmware of the sensor nodes. The following subsections detail the design of our current prototype and the setup for the first test of the WSN in a cabin environment. A detailed description of the design methodology and our earlier prototypes can be found in our previous publications.[11]

A. WSN Hardware

The current hardware is both modular and reconfigurable. The level of modularization implemented in our hardware evolved over the course of our research. The current design represents the best configuration identified to this point. The primary dividing lines used for modularization in the current system are between the processing, communications,

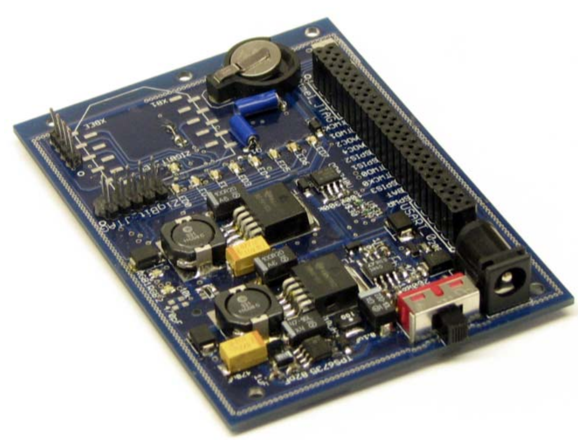

Figure 1. System board for WSN node

power management, storage system, and the sensor interfacing system. In this way, the core functionality of the WSN node is independent of any sensors connected to it. Thus, we have a single system board that has all necessary components for the WSN except for the sensors. Sensor interfacing boards can be created that provide any necessary support circuitry for the sensors as well as any sensors that are required for a particular application.

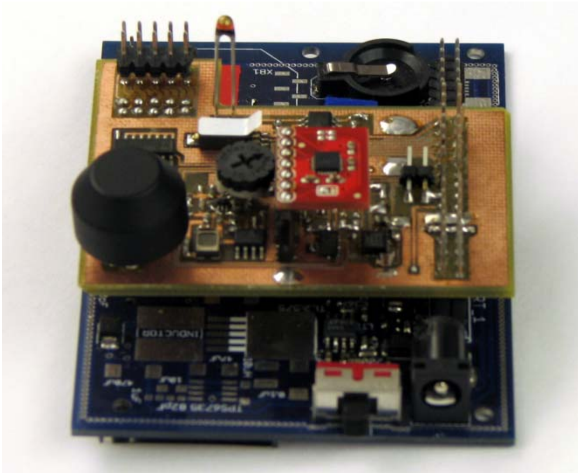

Figure 2. Example sensor interface board. *The sensor board shown provides ultrasonic detector / emitter, accelerometer, gyroscope, magnetometer, temperature, and humidity sensors* **(***6.85 x 9.5 x 3.5cm*).

Figure 1 shows the current system board for our WSN sensor nodes, whereas Fig. 2 shows a sensor interface board attached to the system board. The system board provides 3.3V and 5V switching- regulated power supplies which we have found to meet the typical requirements among a wide cross section of sensor types. The input power can range from 6V to 15V. The board utilizes either a microSD or standard SD card for local data storage (one or the other can be attached at board build time). Beyond the components discussed thus far, the board also has a real-time clock that is useful for correlating measurement times across the network. The sensor interface board attaches through a board-to-board connector that supplies all of the necessary communication protocols to interface with sensors or computer systems, as well as the main power busses.

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B. Network

The network topology chosen for this research is a simple mesh. Our network is comprised of multiple sensor nodes all communicating to a single base station node (or coordinator). The key benefit gained from using this topology is flexibility. The mesh topology allows sensor nodes to be moved out of range of the coordinator without loss of data. As long as sensor nodes are within range of other networked nodes, data can be relayed through the sensor nodes back to the coordinator.

C. Test Setup

On August 2nd 2011, we deployed our Fusion wireless sensor network[11] within Kansas State University's Boeing 767 mockup cabin section to verify the feasibility of capturing measurements of highly dynamic environmental conditions present in airliner cabins utilizing wireless sensor networks. The sensor network consisted of 12 wireless sensor units and a base station. Each wireless sensor unit was configured to measure four environmental conditions: CO_2, temperature, humidity, and atmospheric pressure. The 12 sensor units were uniformly distributed across the cabin section such that each seating section had sensor modules located at 100" intervals down the length of the cabin. This configuration resulted in a 76" spacing laterally between modules. The modules were placed on the top of the seatbacks to provide proximity to seated passenger head level. Figure 3 shows a diagram of the sensor module locations within the cabin section. The actual cabin and sensor nodes can be seen in Fig. 4.

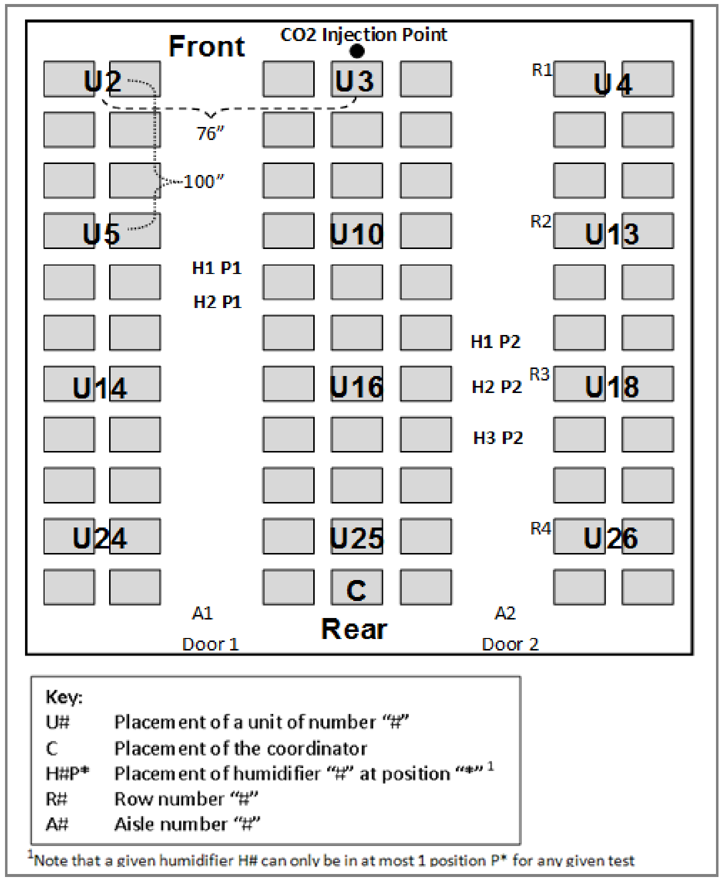
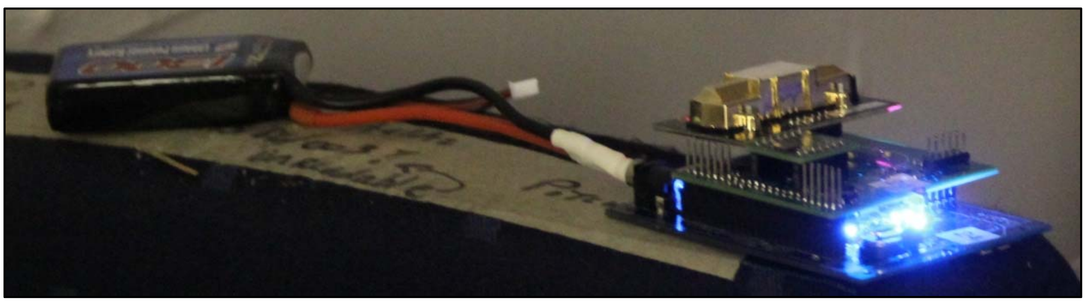


Figure 3. Cabin Layout and Test Configuration

Two test series were performed. The first test series (Series 1) primarily tested humidity dispersion and provided a basic test of the system. During Series 1, humidifiers were located in two different areas within the cabin (refer to Fig. 3). For the first part of the test, two humidifiers were used at positions H1P1 and H1P2. For the next part of the Series 1 tests, a third humidifier was added and the positions were changed (H1P2, H2P2, and H3P2). It should be noted here that the other three environmental parameters were also acquired during the humidity testing. The second test series (Series 2) primarily tested CO_2 dispersion through the cabin. For these tests, CO_2 was injected into the cabin at a fixed location at the front of the cabin (see Fig. 3).

(a) Cabin Interior with Active WSN



(b) Sensor Node

The sensor board shown provides CO_2, pressure, temperature, and humidity sensors as well as the option to support a CO sensor **(***6.85 x 9.5 x 3.5cm).*

Figure 4. Mockup Cabin and Sensor Nodes

IV. Results

The results for each test series are discussed in the following subsections.

A. Test Series 1

Test Series 1 was composed of five humidity cycles: two cycles with humidifiers at P1 and three cycles with humidifiers in position P2 (as shown in Fig. 3). For the first two cycles two humidifiers were placed at P1, while the remaining three runs were conducted with three humidifiers at P2. Figure 5 shows the humidity changes over the last three humidity runs in Series 1. For this portion of the test, we added an additional humidifier at P2 in order to allow for the generation of greater humidity perturbations. This is evident in the peak humidity measurements which exceeded 60%.

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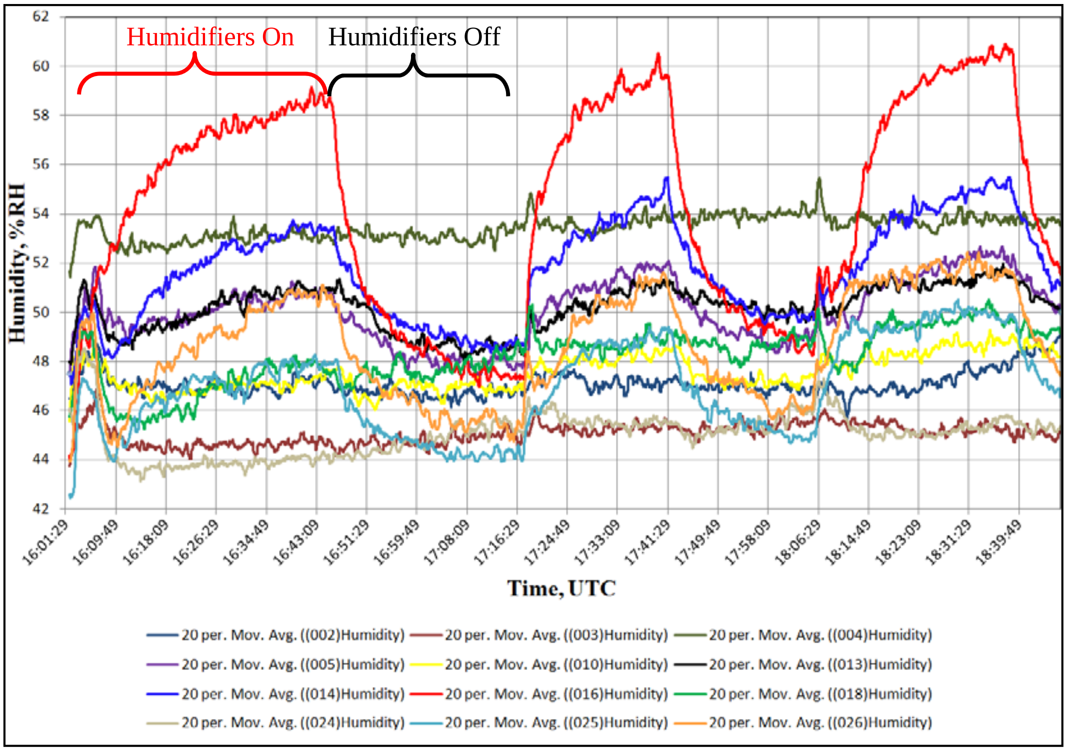

Figure 5. Humidity Test Series 1 P2

With the increased volume of humidified air being generated at P2, a larger portion of the sensor modules showed measureable changes in humidity. Units located in rows 2 (U5, U10, and U13), 3 (U14, U16, and U18), and 4 (U25 and U26; excluding U24) showed increased humidity during each run, with units U14, U16, and U26 showing the largest increase. Notice that only the rows closest to the humidifiers saw an increase in relative humidity. The cabin is designed such that air circulates in circular pattern parallel to the seat rows on each side of the cabin. Thus, lateral air exchange is kept to a minimum. Since the source of the humidity was in the middle and towards the back of the cabin, the results as shown in Fig. 5 were as expected.

Figure 6 shows the CO_2 over the Series 1 test runs. In Fig. 6, a peak in CO_2 corresponds with the time during which four occupants placed humidifiers within the cabin. Figure 6 also shows that there was a maximum of approximately a 150 ppm spread among sensor nodes, with most sensors within a 50 ppm spread. Units U26 and U2 read low whereas U14 read high. The CO_2 sensor used on the sensor nodes provides accuracy of ±75 ppm or ± 10%, whichever is greater. In this case, we see that the sensors are behaving within specification as we expect that the cabin at that time to be uniform. The CO_2 sensors could have been calibrated to the same baseline reading using a predetermined offset. However, at the time of the experiment, an efficient means of performing this kind of calibration in the field was not available. As previously stated, during the course of this test, we were also measuring atmospheric pressure and temperature. Since we were not adjusting these environmental variables, the data gathered from the sensors is largely uninteresting and, consequently, not presented in this document. However, we did notice an inverse relationship between humidity and temperature that can be clearly seen in Fig. 7. Figure 7 shows the temperature and humidity at U16. It should be noted that these tests were conducted in July when the out-door temperature was over 38º C.

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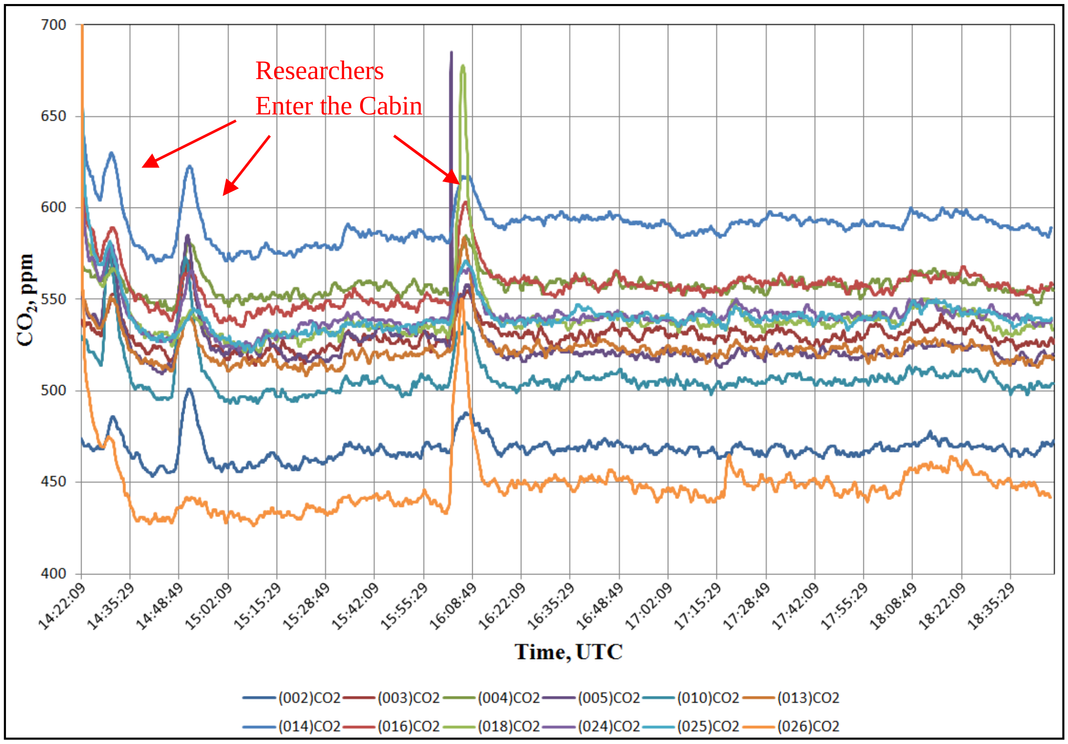

Figure 6. CO2 Measurements during Series 1 Tests

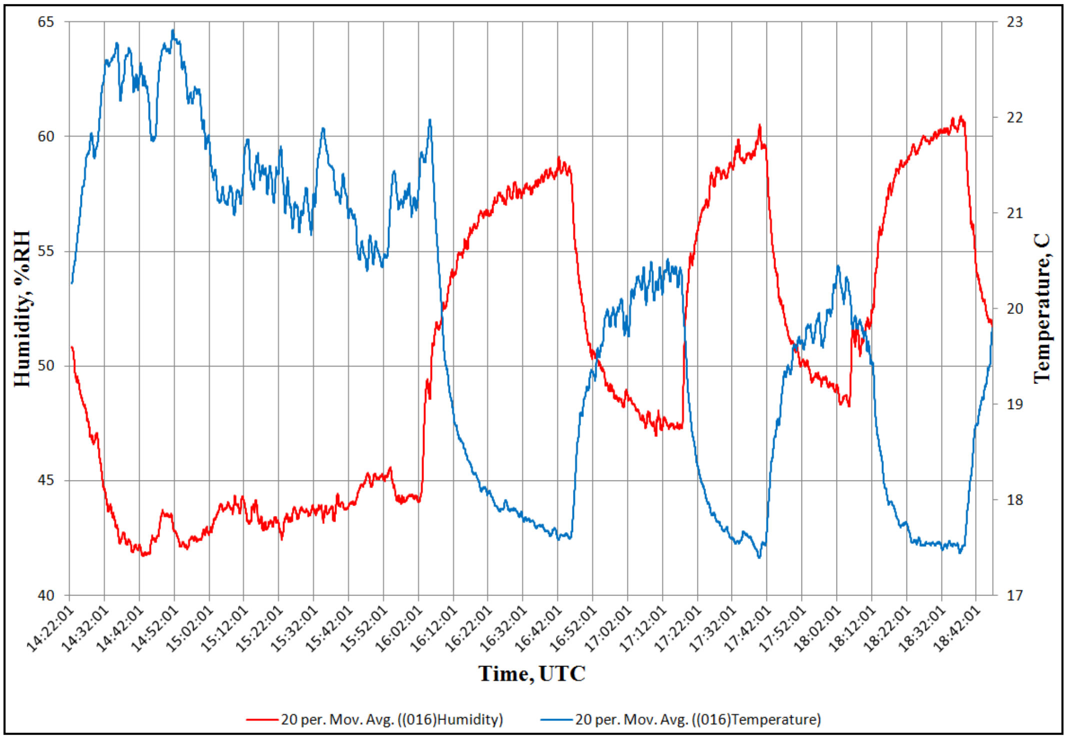

Figure 7. Humidity/Temperature Relationship

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B. Test Series 2

Test Series 2 was composed of four tests where CO_2 was flowed into the cabin. For the final two tests, in addition to flowing CO_2, the humidifiers were cycled, and heaters were used to simulate the body heat of passengers.

As seen in Fig. 8, CO_2 concentrations were well distributed through the cabin. As stated in the preceding subsection, the cabin is designed such that air circulates along the rows of the cabin but not between the front and back. Consequently, since the CO_2 injection point was at the front of the cabin (refer to Fig. 3), we expected the majority of the increased concentration to be sensed in the first few rows. From our results in Fig. 8, as the CO_2 was flowed into the front of the cabin, we see the highest concentration of CO_2 nearest the front of the cabin, tapering off toward the rear of the cabin. Thus, our expectations were correct. More testing would need to be completed to fully characterize airflow within the cabin, but these results show promise that the WSN could be used for such a purpose. From Fig. 8, we see that the last two runs which included humidity and temperature variations, U2 showed a significantly higher concentration of CO_2 than the other tests. Which effect (increased heat or humidity) may have caused this reaction is not clear.

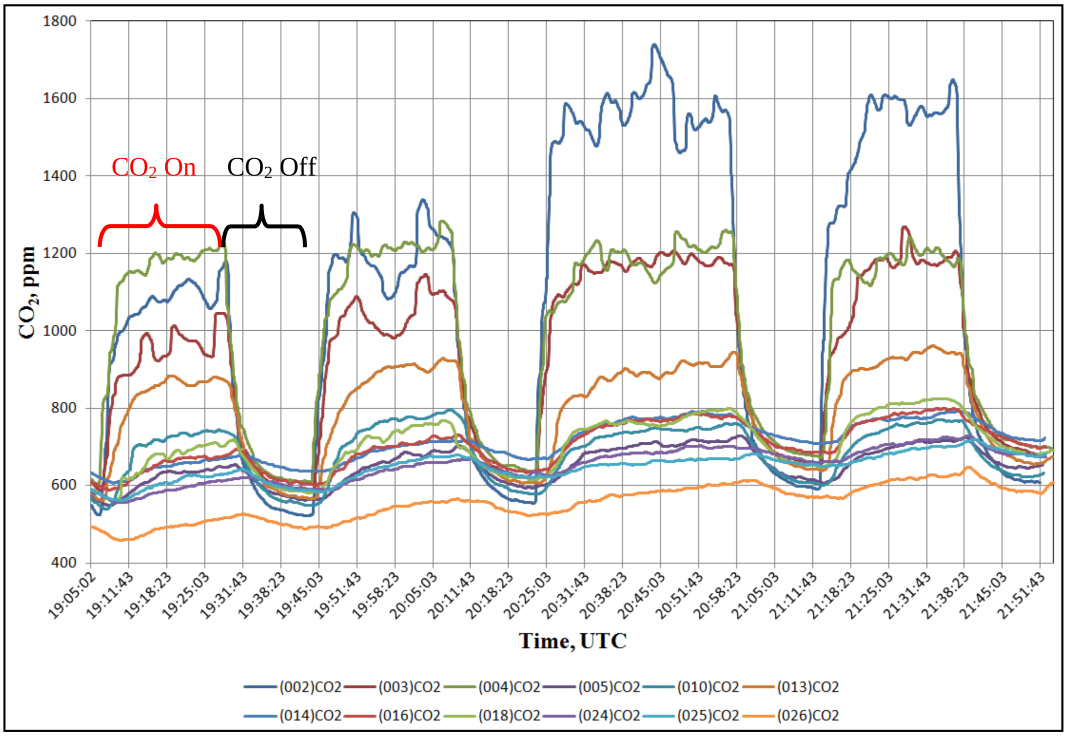

Figure 8. CO_2 Test Series 2

V. Conclusion

In previous research, baseline data has been collected in the aircraft cabin, and computer models have been developed to try to estimate the propagation of contaminants in the aircraft environment. As the environment is highly dynamic, computer models of the environment need to be validated. New tools need to be leveraged to fully characterize the way contaminates move through an aircraft cabin. Wireless sensor networks can provide the necessary coverage and cooperation to effectively monitor this system. A new high-performance wireless data acquisition system is currently under development to meet the particular needs of aircraft environmental monitoring. Many design parameters were considered during the development of the new system, which has proven effective in simulated monitoring of dynamically changing environments. A prototype of this new system has been tested in a 767 mockup cabin. A few issues related to the initial wireless network formation were discovered. However, as was illustrated by the presented data, the Fusion wireless sensor network was shown capable of monitoring multiple environmental variables, and providing real-time, correlated data. Certainly, the Fusion network provides a new tool that will improve our ability to characterize highly dynamic environmental systems.

Acknowledgments

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