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Real-Time Monitoring of Environmental Parameters in a Commercial Gestating Sow House Using a ZigBee-Based Wireless Sensor Network

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Abstract: Significant intensification in livestock farming has become prevalent to meet the increasing meat production demand, resulting in a higher density of pigs in relatively small areas in a commercial swine building. The subsequent challenges of maintaining the quality of both routine management and environmental comfort of pigs to minimize the loss of both pigs' health and welfare can be attained by implementing autonomous monitoring and intelligent management decisions based on precision livestock farming (PLF). A three-layer wireless sensor network (WSN) based on ZigBee technology has been devised to monitor four environmental parameters in real-time, namely: temperature, relative humidity, concentrations of carbon dioxide and ammonia in a commercial gestating sow house. The overall packet loss rate of the WSN system which reported 16,371 records from its 41 indoor slave nodes in a 10-min interval for three consecutive days was 4%. The carbon dioxide sensors had an average outlier rate of 6.5% after a series of preprocessing procedures. The spatial and temporal characteristics showed that the carbon dioxide level exceeded the limit of 2700 mg/m^3 twice during both 07:00–08:00 and 14:00–15:00. Besides, the overall NH_3 concentration in the swine building was maintained in a relatively low-level range with a maximum of less than 8 mg/m^3. In sum, the real-time monitoring and timely intervention of microclimate in this commercial gestating sow house can be achieved by deploying this WSN system, thereby making it possible to provide an intelligent decision on precise management of livestock automatically.

Keywords: environmental monitoring; pig house; wireless sensor network; ZigBee

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1. Introduction

Over 50% of the global agricultural gross domestic product comprises the livestock sector [1], the food demand is expected to increase by 70%, and corresponding meat production will increase by 50% by the year 2050, thus making the agri-food and livestock key industries for future [2]. This demand will be met through intensification in livestock farming by increasing densities and production units, using concentrated feed, and improving infrastructure and feed efficiencies [3]. For instance, the commercial swine confinement building, which usually rears a high density of pigs in relatively small areas, is the most common and widespread means of pig production. The Food and Agriculture Organization (FAO) reported that about 1.5 billion pigs were reared to produce meat in 2016 and its total weight of meat production exceeded 120 million tons in 2018 [4]. Nevertheless, such challenges can be attained [5] by implementing autonomous monitoring and intelligent management decisions based on precision livestock farming (PLF). According to Berckmans [6,7] the application of PLF could be a good approach to optimize the care and attention that farmed animals receive by monitoring animals at the smallest unit that can be managed in real-time since it allows to have control on animal health and welfare and the microclimate of the barn.

Precision livestock management can be achieved through PLF systems that typically consist of three separate functions [8]: sensing and monitoring, analysis and decision making, and intervention, which will allow producers to manage extensive animals, while still providing the level of care similar to what can only be done with fewer animals [9]. The application of wireless sensor networks (WSN) in improving the traditional methods of farming has received long-term focus from researchers in precision agriculture [10–12] due to its salient features including but not limited to dynamic topology configuration [13], node heterogeneity [14], scalability and tolerance against communication failures in harsh environmental conditions [15]. Among numerous wireless communication technologies, ZigBee [16,17] which defines the network and application layer protocols based on the IEEE 802.15.4 standard [18] is preferred over other technologies like Bluetooth, Wi-Fi [11] for the development of WSN, due to its reliability, low cost, and low power consumption property. ZigBee based network architecture for animal health monitoring has been proposed [19]. The real-time monitoring of physiological health parameters of animals has been attained by a ZigBee based system [20].

For optimal health and production, the air surrounding the pig should fulfill certain requirements which are often not met partly because of the influences of outdoor climate condition and because of the effects of the pigs on the housing environment. The main factors constituting the microclimate inside a swine building include air temperature, relative humidity and airspeed, as well as the concentration of harmful gases and other pollutants [21]. Temperature and humidity are the main environmental factors that are influenced by pigs in facilities, although CO_2 and even NH_3 concentrations also are strongly affected by the pigs' activity [22]. For example, pigs are especially susceptible to exposure to heat stress which can trigger behavioral and physiological responses and thus negatively affect productivity during the summer. Carbon dioxide has been widely used as a tracer gas [23] to quantify ventilation in livestock buildings and exposure to high concentrations of this gas has also been associated with impaired health of both humans and animals [24]. Ammonia is one of the most critical pollutants for pig production because of its direct threat to animal and workers' welfare and health [25,26]. Therefore, it is critical to monitor and intervene in the microclimate in time so that alternative management practices can be developed and implemented to improve overall animal health and well-being.

Few papers focus on the entire fulfillment of the indoor environmental monitoring system that consists of three layers, namely: livestock environment sensing, wireless transmission service, and multiclient application, especially in a commercial confinement building of gestating sows. In this study, the transmission performance of data packets gathered by sensor nodes which are oriented to collect surrounding temperature, relative humidity, concentrations of carbon dioxide (CO_2) and ammonia (NH_3) through the proposed WSN system was assessed, then the reported null records and abnormal observations were preprocessed before discussing their spatial and temporal characteristics of the environmental parameters in detail.

2. Materials and Methods

2.1. The Gestating Sow House Facility

Intensively ventilated pig housing is prevalent in the construction of large-scale pig farms in Europe, and is currently utilized in Yunnan and Guizhou provinces of China. The ventilation system is operated in a negative-pressure extraction mode. The fresh air from outside is cooled by a wet curtain on the side of the gestation house and then enters the cavity above the ceiling through the air inlet of the roller curtain under the eaves and is blown to the sow's head through the polyvinyl chloride (PVC) ventilation plate (air vents). The airflow is forced out of the barn after heat and mass transfer via the flock area. The overall dimensions of the wet curtain are 9.6 m in length, 0.5 m in width, and 1.8 m in height, with a total of 16 wet curtains. Figure 1 shows the gestating sow house in this study, which is located in Yunnan province, southwest of China.

Figure 1. The gestation sow housing of this study in Yunnan Province.

The overall dimensions of the pig housing in question are 164.5 m in length, 30.1 m in width, and 4 m in height. During the test, the sows were gestating sows from early pregnancy to 112 days of gestation, with a total of 2054 sows (556 sows in Units 1–7, 560 sows in Units 8–14, 394 sows in Units 15–21, 544 sows in Units 22–28, and partial confined pens are empty in Unit 19). The schematic diagram, the three-dimensional and the side view of the gestation house are shown in Figure 2a–c.

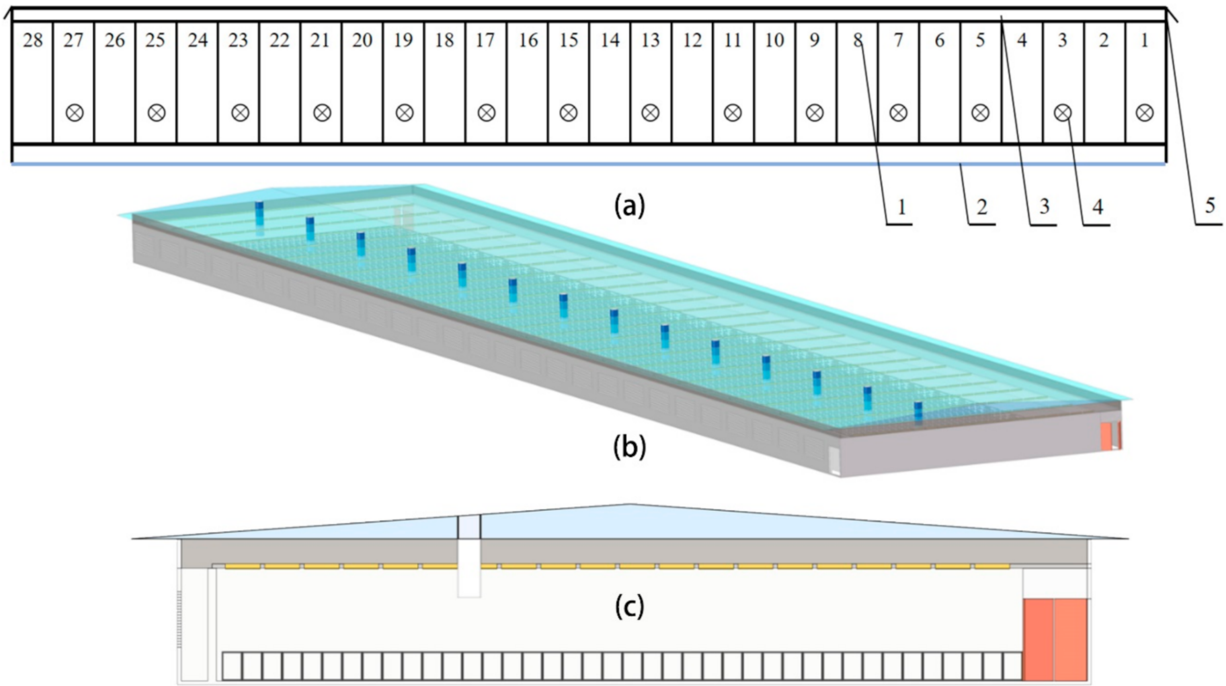

Figure 2. Pig housing in the study: (**a**) schematic model; (**b**) the three-dimensional model; (**c**) side view. [1] Number of the gestation house unit, [2] wet curtain, [3] walkway, [4] frequency conversion fan, [5] door.

As shown in Figure 2, the gestation shed has 28 units with two columns per unit, making a total of 56 columns. An inverter fan is installed in every other unit, resulting in a total of 14 inverter fans. During the experiment, the target temperature in the gestation house is set to 21 °C the adjustable range of fan ventilation rate is 50~90% of the maximum ventilation capacity, and the 100% of the ventilation capacity is 24,300 m^3/h. When the temperature in the house is less than 21 °C, the ventilation rate is set to 50% of the maximum ventilation capacity. When the temperature in the house is greater than 27 °C, the ventilation rate is set to 90% of the maximum ventilation capacity. Ventilation for the control of temperature gradient is artificially set, will be adjusted accordingly depending on the house site conditions and experience. Besides, when the temperature outside the house is greater than or equal to 23 °C, the wet curtain begins to work.

The pit beneath the slat floor of the gestation house is 1.2 m in depth and a scraper is installed at the bottom, scraping regularly twice a day for 2 h. At 8:00 a.m. every day, the scraper starts scraping in Units 1 and 2, which takes about 10 min, then it switches to Units 3 and 4, and so on until it is finished in Units 27 and 28 at around 10:00 a.m. In the afternoon, the scraping takes place from 3:00 to 5:00, with the same workflow as in the morning. At this point, the clean-up of pig manure is completed for the day to ensure a relatively favorable air environment in the barn. In addition, the barn adopts an intelligent feed supply system, with feeding time at 7:30 a.m. and 14:30 p.m.

2.2. The ZigBee-Based WSN System for Environmental Monitoring in the Pig House

2.2.1. The WSN System

WSNs are a network of sensors powered by batteries interconnected wirelessly and are frequently used to serve a specific target-oriented application [27,28]. These powerful sensors empower a sensor node in order to precisely collect the neighboring data. Based on this information collection, these nodes then network among themselves to perform the application requirements. The wireless sensor network used in this study has a stationary heterogeneous multitier architecture [29], meaning the sensor nodes are deployed at a nonchanging position, typically allowing for multiple types of sensor nodes and devices, and comprising several levels in the overall application hierarchy.

The application of wired communication technology generally has problems such as difficult wiring, complex maintenance, and high cost. The wireless sensor is convenient to move, transport, and place. In addition to that, the network setting of the wireless sensor network is flexible, and the device location can be changed at any time. Such a system can be used and reimplemented in other pig houses or farms in different scenarios with the lowest cost possible.

2.2.2. The Zigbee Wireless Communication Technology

The ZigBee technology defines both the application and network layer protocols using low power radio-enabled devices. ZigBee supports short-distance (10–20 m) data communication over mesh, decentralized, ad-hoc, and multitier sensor nodes. The ZigBee mesh topology is used for wireless distributed networking, and the node devices realize multipoint monitoring in the form of "one master nodes and multiple slave nodes". The slave nodes are based on STM32 embedded control chip and equipped with various sensors such as temperature, relative humidity, concentration of ammonia and carbon dioxide. Each slave node collects real-time data and uploads it to the server through the master node, finally the remote graphical user interface (GUI) of the system displays the real-time data on the web.

2.2.3. The Systematic Composition and Working Principle of the WSN System

The front end of the system uses ZigBee wireless communication technology in the house to achieve multiple monitoring points of distributed networking. With the technical features, all node devices can be flexibly arranged at any height and location in the barn, the ZigBee network topology will be adjusted to an optimal state upon power-on. Each node device in the system can be equipped with a variety of sensors used to collect various types of data sources, enabling a real-time reflection of the complex temperature, humidity and gas environment in the pig house. The system ends with a data transfer unit (DTU) that packages and uploads real-time environmental information to the server, and the cross-platform Web application finally displays all kinds of data in various sections. The monitoring system is meanwhile a complete set of Internet of Things application system, and its three-layer architecture consists of the pig house environment perception layer, wireless transmission service layer, multiclient application layer.

The underlying hardware is divided into two device types: ZigBee slave sensor nodes and ZigBee master node. There is only one master node, which is used to collect and summarize all the slave nodes data and upload the information to the service layer. The wireless transmission service layer receives data packets from the master node, relying on General Packet Radio Service (GPRS) technology, establishes a connection with the server according to the agreed IP address and port number, and realizes transparent point-to-point transmission of data using DTU. The server will analyze the received message data one by one and store the historical data in the software database at the same time. The multiclient application layer adopts the browser/server (B/S) model, which connects the database to the browser and realizes the remote monitoring function of the system through web pages. The browser-based application can meet the cross-platform requirements of the computer side or mobile network devices. Figure 3 summarizes the WSN system in the pig housing and its layers.

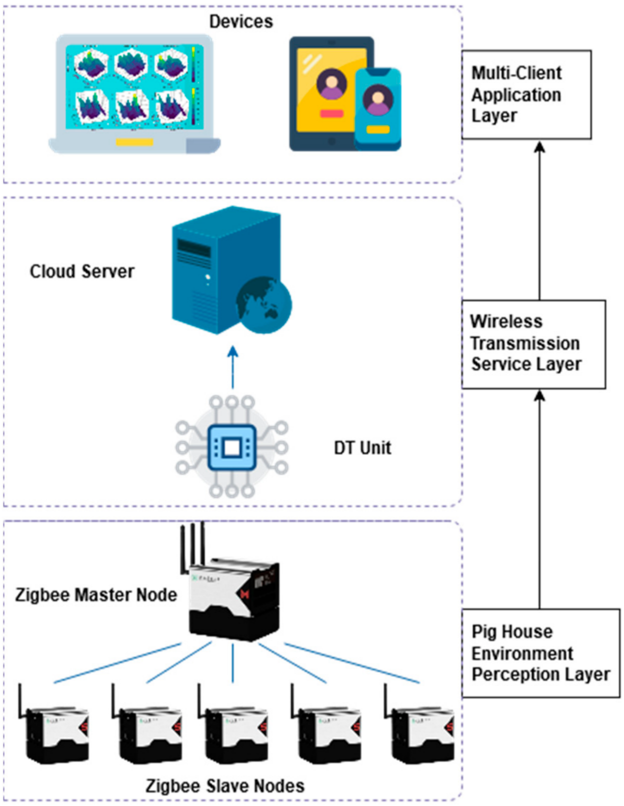

Figure 3. Flowchart of the pig housing wireless sensor network (WSN) system.

The master and slave nodes work closely together to complete the task of collecting and uploading data. Figures 4 and 5 show the positioning of the nodes in the pig housing.

2.2.4. The Design of Slave Sensor Nodes Used in the WSN System

The wireless sensor slave node introduced in this section includes a multisensor module (temperature, relative humidity, ammonia, and carbon dioxide sensors), a data processing unit, a communication debugging interface, a ZigBee transmitter terminal, a battery, and a power supply module, as shown in Figure 6.

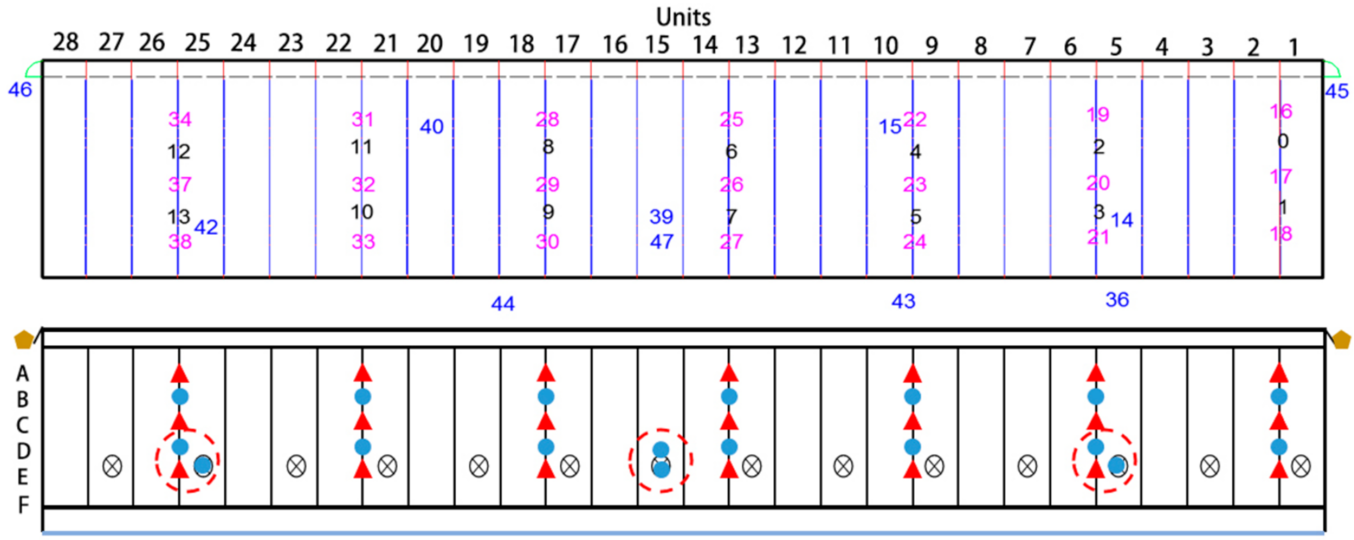

Figure 4. Views of the node distribution of the pig house. Note: 0 to 47 are the nodes IDs; a triangle represents a node arranged at a height of 60 cm, a circle represents a node arranged at a height of 150 cm, a pentagon represents a node arranged at a height of 190 cm outside the building, and the red dotted circle indicates that it is located under the fan; A–F are the rows.

Figure 5. Positioning of the slave nodes in different heights (green arrows indicates nodes at a height of 150 cm, red arrows a height of 60 cm).

The multisensor module can simultaneously detect four types of environmental parameters, including temperature, relative humidity, ammonia concentration (NH_3), and carbon dioxide concentration (CO_2). The temperature and relative humidity are integrated sensors, while carbon dioxide concentration uses infrared sensors with built-in temperature compensation, and the concentration of respirable particulate matter uses the laser detection principle. Temperature and relative humidity sensors are digitally integrated, carbon dioxide sensors use a built-in temperature-compensated infrared sensor, and ammonia sensors are electrochemical gas sensors. Most of the sensors integrate the probe with the signal processing circuitry to provide a serial output and hence can be directly connected to the data processing unit. The data processing unit is the core component of the sensor node and utilizes a 32-bit Cortex core with 100 pins. The STM32F103VET6 is the main chip that integrates the sensor information and transmits it to the ZigBee transmitter.

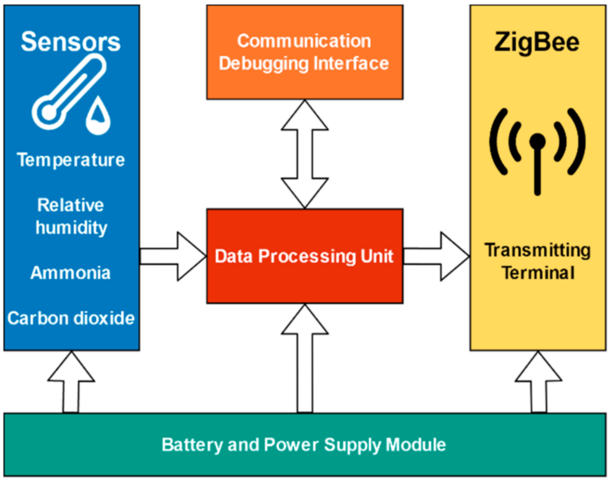

Figure 6. Slave node structure.

In the wireless network topology of "one master and many slaves", one master node can be equipped with 254 slave nodes at most, and the coverage area of single point can reach 100 m^2. The node equipment can be debugged and configured by machine. The battery and power supply module is a 12 V rechargeable lithium battery with capacity of 10,000 mAh, which can work continuously for node equipment for 170 h on a single charge, and the voltage transformer chip on the main board can meet the normal power supply of various 5 V sensors, processing units, and ZigBee transmitting terminal. The selected sensor type, model, range, resolution, and accuracy range of the wireless slave node in this study are shown in Table 1 and the network communication process is shown in Figure 7.

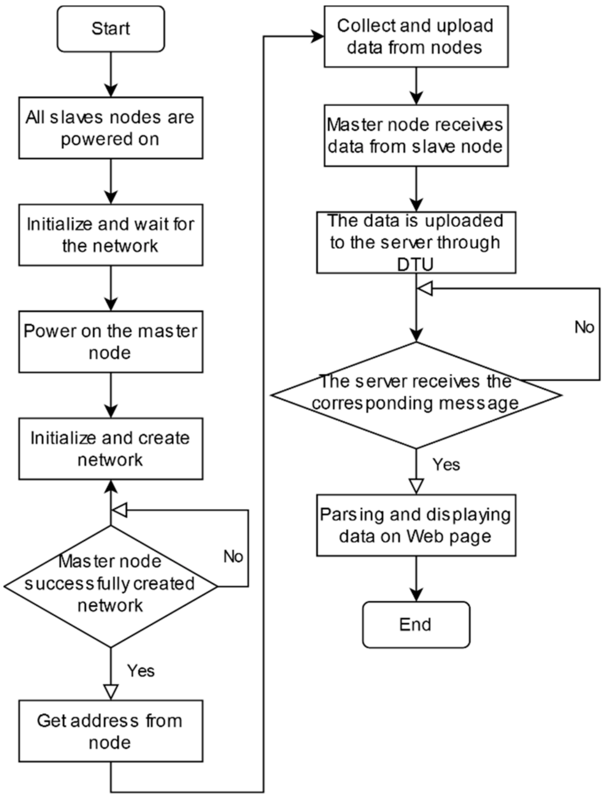

Figure 7. Network communication process.

Table 1. Parameters of the wireless sensor slave node components.

Parameter	Temperature (°C)	Relative Humidity %	NH_3 Concentration (mg/m^3)	CO_2 Concentration (mg/m^3)
Model	DHT21	DHT21	ZE03	MH-Z19B
Range	−40.0 to 80.0	0 to 100.0	0 to 5×10^{-5}	0 to 1×10^{-2}
Resolution	0.1	0.1	1×10^{-8}	1×10^{-6}
Precision	±0.5 °C	±3%	±5% to 8%	$\pm(5 \times 10^{-5}$ + 5%)

3. Results and Discussions

3.1. The Statistics of Data Packets Sent from Slave Nodes in the WSN System during the Three-Day Observation

This experiment began on 18:34 11 August 2018 and ended on 16:54 14 August 2018. Considering the sampling period of 10 min, an entire record should consist of 423 entries. Table 2 exhibits the general overview of measurement condition about all the 41 indoor slave nodes which recorded the environmental parameters in a commercial mechanically ventilated negative-pressure piggery.

Table 2. The overall statistics about the number of data packets recorded by all the 41 indoor slave nodes in the WSN system.

Item	Col.A [1]	Col.B	Col.C	Col.D	Col.E	Col.F	Rec. [2]	Exp. [3]
Valid	2810	2828	2765	2672	2850	2446	16,371	17,343
Malfunction	123	105	168	261	83	68	808	0
Defect	28	28	28	28	28	24	164	0

[1] Column (represents the mounting position of the slave node), [2] recorded, [3] expected.

The valid total number of records that were measured by all 41 indoor slave nodes is 16,371 which is 972 less than the expected or ideal 17,343. The cause of the missing part is two-fold: one is from the malfunction of slave node which consists of five modules, for example, 22 slave nodes once experienced the abnormal extremely high temperature (99.9 °C) and also two of them encountered battery failures, thus all corresponding records had been removed; the other is associated with the defect of its transmitter module, specifically, the cloud server could only receive 419 entries which was four less than the desirable 423 from each slave node, this was probably due to the accumulative lag on the communication process during the entire experimental period. Additionally, another four slave nodes were mounted nearby the wall (water curtain) and entrance (outdoor). In sum, the actual number of packets received by the cloud server was 18,263 in total while it should totally receive 19,035 packets, thus the overall packet loss rate of the WSN system was 4%.

In terms of the individual indoor slave nodes, the actual performances are shown in Figure 8. It can be obviously found from this figure that virtually all the nodes achieved a relatively stable performance with the number of valid measurements (labeled as 'Occupied') fluctuating around 400 and the missing number of records (labeled as 'Vacant') less than 20. Noticing that both node 3 and node 13 reported relatively substantial null records (94 and 85, respectively), it turned out that these malfunctions were due to the corresponding battery failures at halfway. Specifically, node 3 stopped working on 19:38 August 12 because of its battery quality issue, and the operation of battery replacement on 09:06 August 13 restored its normal working condition; node 13 ceased to upload the measurement data to the cloud server on 06:07 August 14 on account of its drained battery. The above reasons explained why the slave nodes installed on Column D held the highest malfunction rate (approaching 9%).

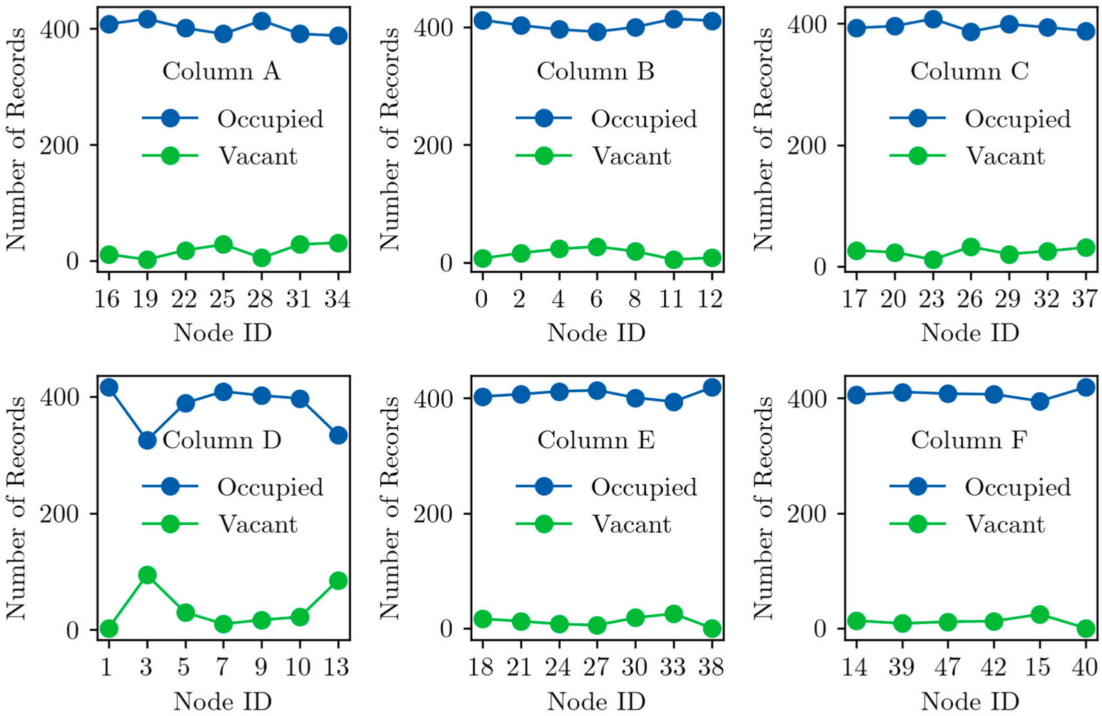

Figure 8. The individual transmission performance of data packets from slave nodes mounted on six columns in the WSN system.

3.2. The Preprocessing of Null Records and Identification of Abnormal Observations Reported in the WSN System

The original record solely consisted of 419 entries for each node despite of the fact that it should include 423 entries with a 10-min delta, therefore, it was compulsory to augment another four null entries. Meanwhile, there were also a small portion of null entries that were formed by removing the corresponding abnormal records. In this study, a combination of methods that are capable of handling null entries was adopted to determine and update the numeric values of those null entries. A second order polynomial interpolation was initially applied to cover 1/3 of the total filling of null entries. Then a forward filling approach was employed to address the remaining 66% null entries, because it is a common practice to deal with the gap-filling problem by using the previous observations in the time series. Finally, means in the relevant columns had been applied to fill the remaining null entries that were less than 1% (42 elements). Up to this point, all the records were complete and ready for further preprocessing steps.

After the completeness of gap-filling procedure, it is both necessary and meaningful to examine and evaluate the quality of data reported by four correlated sensors that were installed in six columns. Figure 9 depicted the distribution overview of each slave node in every column by its corresponding boxplot of ammonia concentration. It is obvious that the vast majority of boxplots were comparatively short which suggested that ammonia concentration of relevant nodes had a high level of agreement with each other apart from those nodes mounted on Column B and Column C. Besides, the overall number of outliers (in diamond) for nodes mounted on Column C was also the least among all the six columns, which indicated that most of nodes exhibited a stable performance except for node 32.

Outlier detection is among the most vital aspects to judge the performances of multi-sensor modules integrated in the slave nodes. The Turkey's fences [30] which use the lower and upper quartiles to define the corresponding limits were applied to indicate outliers in each node during the entire time span. In this study, four types of environmental sensors which had been integrated into the multisensor module of slave nodes were considered, namely: sensors of temperature, humidity, carbon dioxide, and ammonia. Utilizing this robust measure of scale, the outlier statistics that were distributed across six columns were compared in terms of four sensors on Figure 10.

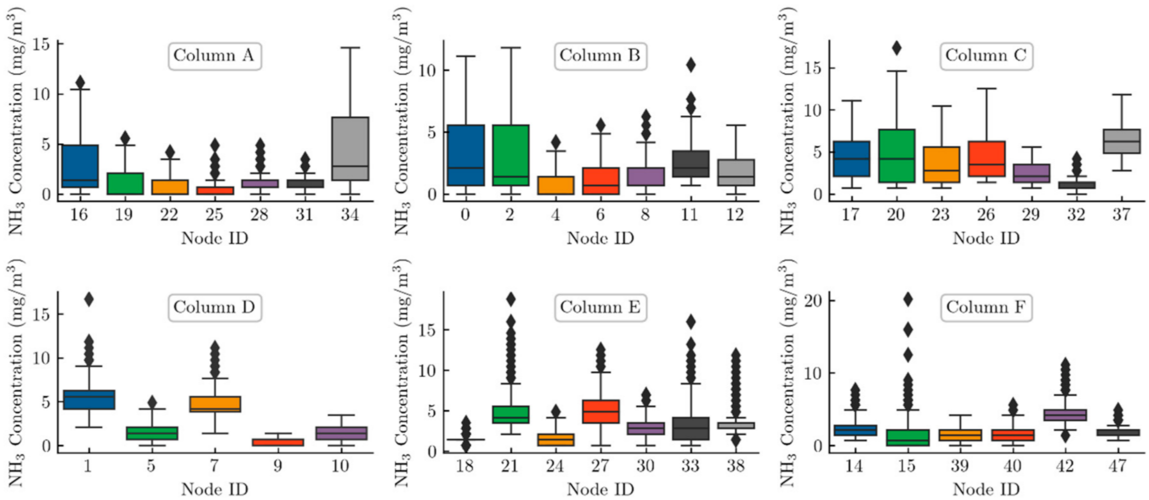

Figure 9. The boxplots of ammonia concentration recorded by the slave nodes that are distributed on six columns in the gestating sow house.

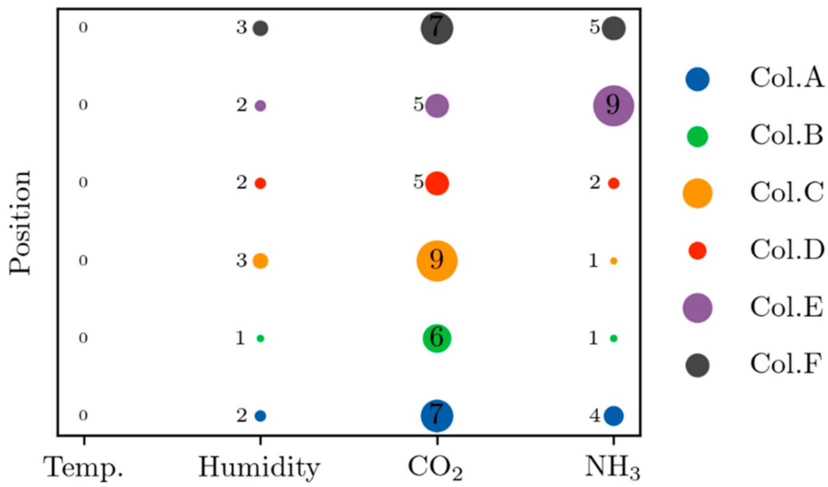

Figure 10. Percentage outlier rate comparisons on four environmental parameters recognized by the Turkey's fences in six comparative mounting positions.

From Figure 10 it is clear that the temperature subpart of the multisensor module for all the indoor slave nodes exhibited extremely stable performance with no outlier detected. Additionally, the humidity measurement submodule achieved relatively high performance with its outlier rate fluctuating around 2%. The rationale behind that is the integrated AM2301 module consists of both a capacitive humidity sensor and a temperature sensor which are connected to a high-performance 8-bit microcontroller to ensure both excellent reliability and strong anti-interference ability. On the contrary, the readings of carbon dioxide sensors showed significant drifts and its outlier rate occupied an average 6.5% of all observations for each column. Considering the fact that pig respiration is one main source of CO_2 emission, it is reasonable for nodes mounted on Column A, Column C, and Column E that represent the respiration zones of 60 cm height above ground (close to pig heads) to preserve considerable records of high concentration of CO_2. Additionally, this also makes sense for nodes mounted on Column F which are beneath the ceiling fans and 160 cm height above ground, because gases such as CO_2 and NH_3 tend to accumulate nearby the air outlet. As for monitoring of ammonia concentration, in terms of its outlier rate, the nodes mounted on Column A, Column E, and Column F displayed considerable unstable readings which are also quite noticeable in Figure 9. More specifically, nodes in Column A are nearest to the passage, and that means their associated readings can be more frequent and prone to being disturbed by the working staff of swine buildings compared to those nodes mounted on the middle part. Meanwhile, the overwhelming nodes from Column E and Column F experienced more severe disturbance of measurements as a consequence of locating underneath the ceiling fans.

3.3. The Spatial and Temporal Characteristics of Indoor Environmental Parameters in the Commercial Gestating Sow Confinement Building

It is convenient and useful to develop a rough understanding about the indoor surroundings through the means of four types of environmental sensors distributed over six columns in the swine building. Figure 11 used the 95% empirical bootstrap (sampling with replacement for 1000 times) confidence intervals to describe means of four environmental parameters observed by the multisensor module of indoor slave nodes. The mean internal air temperature as shown in Figure 11 was slightly above 23 °C which approximated to Banhazi's [31] observations measured in Australian pig buildings (average 21.3 °C for dry sow). However, the mean relative humidity reported in this study was about 78.5% which was distinctively different from theirs (61.5%). This swine building was located in Qujing Yunnan, southwest of China, which belongs to subtropical plateau monsoon climate and usually accompanies with extensive rain thereby being high relative humidity during the summer. Meanwhile, there existed a distinctive negative correlation of variation tendency between temperature and humidity in Figure 11. In fact, it well reflected that the indoor ambient conditions are comfortable for sows, because they heavily rely on evaporative heat loss which needs a relatively lower humidity to transfer more effectively with the ambient hot air during the summer. According to Donham [32] who studied the association of environmental air contaminants with finishers' disease and productivity, he suggested that concentrations up to 5.32 mg/m^3 NH_3 and 3025 mg/m^3 CO_2 were not harmful. Therefore, the CO_2 and NH_3 concentrations in this piggery were also operating in a reasonable and suitable range for gestating sow.

3.3.1. The Temporal Characteristics

Considering that there existed apparent cyclic patterns on the four environmental parameters recorded by indoor nodes in three consecutive days, for display purposes, the following Figure 12 solely plotted the latest associated 24-h data that ranged from 13 August to 14 August. During most of the whole day no apparent distinctions existed among all the indoor nodes distributed over six different sites, except for nodes of Column A and Column B that reported about 1.5 °C lower temperature than others in the night and early morning. In addition, all indoor nodes reached a consensus of approximating the highest temperatures (ranged from 25 to 26 °C) in around 15:00. Contrarily, the relative humidity displayed inverse diurnal variation patterns compared with that of temperature variation. Nodes mounted on Column A and Column B, which had the lowest temperature, instead reported the highest relative humidity during the whole-time span. According to the national standard of People's Republic of China of environmental parameters for intensive pig farms namely GB/T 17824.3-2008 [33], the ambient temperature and relative humidity of commercial barns for gestating sows should be maintained between 15 and 20 °C, and from 60% to 70%, respectively. Meanwhile, the recommended lower critical temperature (LCT) and upper critical temperature (UCT) are 13 and 27 °C. Although there exhibited a daytime high temperature (above 24 °C) starting from 10:00 to 16:00, however, it is yet acceptable in the thermoneutral zone and thereby beneficial to the welfare of gestating sows in this mechanically ventilated commercial pig house during the summer. As for the relative humidity limits, it is recommended to operate them in the barns of gestating sows from 50% up to 85%. Figure 13 nevertheless indicated that nodes from Column A and Column B reported substantial records of rather high relative humidity (over 85%) that occupied 13% and 63% of the two consecutive days' entire observations. Generally speaking, the higher the humidity level in the air, the less effective is the process of evaporative heat loss to help the sow cool off [31]. Thus, the sow would feel the effects of heat stress regardless of the relatively moderate temperature, which might cause high body temperature, affect the sow's metabolism, reduce feed conversion rate and daily weight gain, etc. Considering that nodes mounted on Column B that reported high relative humidity for most of the time (63%) were 150 cm above the ground located overhead of the sow, thereby, they could only reflect the ambient air humid condition. In terms of nodes from Column A which were 60 cm above the ground located in the respiration zone of the sow, they were capable of approaching to the realistic relative humidity that the sow could feel. They spotted high relative humidity around 08:00, 14:00, and 16:00 on the first day, and the period from 08:00 to 11:00 on the other day. Despite of the fact that monitoring the relative humidity for a much longer period of time is indispensable to uncover the underlying variation pattern of relative humidity in this swine confinement building, those periods above can still somehow provide practical guidance values to maintain the relative humidity level in a comfortable zone for the gestating sows, for instance, by appropriately increasing the ventilation rate.

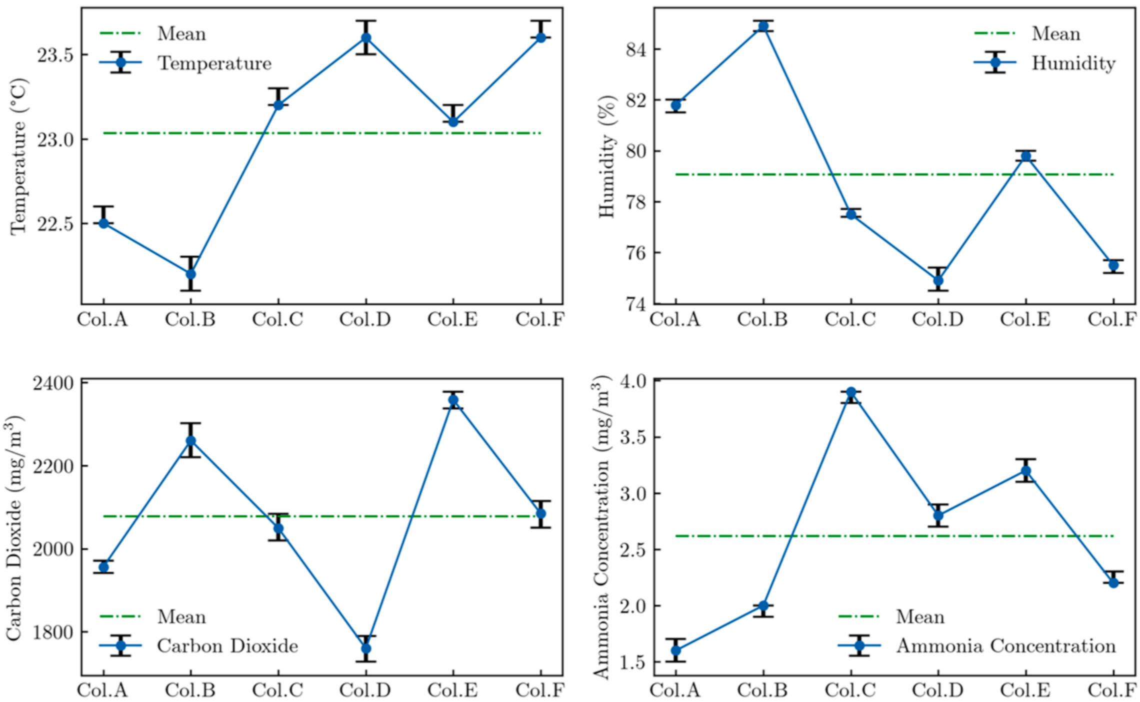

Figure 11. The 95% empirical bootstrap confidence intervals of means of four environmental parameters observed by the multisensor module of indoor slave nodes.

The GB/T 17824.3-2008 standard required that the indoor CO_2 concentration should not exceed 1500 mg/m^3, while Pointon [34] recommended that a good target for the CO_2 levels in a pig house was less than 2700 mg/m^3. Although the CO_2 concentration inside this commercial pig house had been above 1500 mg/m^3 for the whole time, there merely existed two time periods when the CO_2 levels exceeded the 2700 mg/m^3, namely: ranging from 07:00 to 08:00 and from 14:00 to 15:00. Reduced growth rate and increased prevalence of respiratory disease in pigs had been associated with levels of CO_2 above 2700 mg/m^3 [35]. Therefore, appropriate measures are required to take on those periods in order to improve pig welfare, for instance, increasing ventilation rates and reducing the number of pigs per cubic meter of airspace.

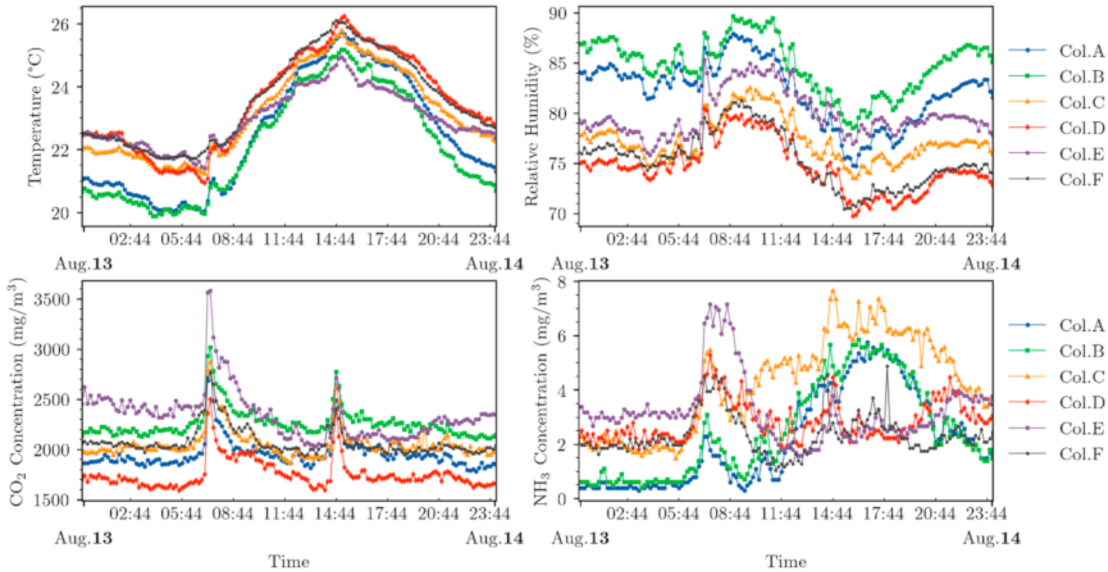

Figure 12. Four environmental parameters recorded by indoor nodes varied from August 13 to August 14.

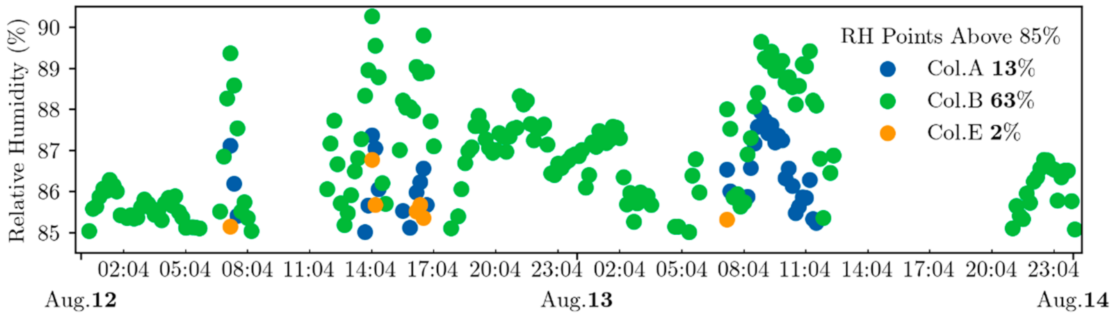

Figure 13. Substantial records of rather high relative humidity (over 85%) of the two consecutive days' entire observations recorded by nodes from Column A and Column B.

Benefiting from the demand of extensive ventilation in the summer, the overall NH_3 concentration at the piggery was maintained in a relatively low-level range with the maximal value less than 8 mg/m^3, which is far less than the recommended upper limit 20 mg/m^3 according to the GB/T 17824.3-2008 standard. In terms of time patterns about when both CO_2 and NH_3 showed peaks simultaneously, there existed two similar moments around 07:30 and 14:30. The rationale for this is that metabolic process of degrading urea through enzyme urease, which is the main source of ammonia emissions, emits both CO_2 and NH_3. Therefore, it is reasonable to find that the NH_3 concentration started to increase during the early morning and then decreased from 08:00, because manure excreted by sows at night could not be swept up promptly until the morning when the manure scraper beneath the slatted floor began to work, thus those volatile gases such as NH_3 tended to accumulate in the swine confinement buildings. In addition, due to both the pig activities and the activation of the manure scraper in the afternoon from 14:00 to 18:00, the NH_3 overall concentrations reached another peak duration in a day. Specifically, the majority of nodes mounted on Columns A, B, C demonstrated longer durations and higher levels of NH_3 peak values than that of those nodes mounted on Columns D, E, F.

3.3.2. The Spatial Characteristics

Beside the above summarized variations of environmental parameters over time, to further explore their patterns of distribution across the swine confinement building, the three-dimensional surface plots and corresponding contour plots of sow's respiratory zone (60 cm height) and upper region above sow's head (150 cm height) on 15:04 August 13 are shown in Figure 14. The overall temperature in this commercial pig house at 15:04 exceeded the comfortable limit 20 °C but maintained under the UCT 27 °C, and there were four regions that displayed higher temperatures than their nearby surroundings. They were located on both the front (Units 2–14) and rear (Units 21–28) parts of pig house, and were primarily spotted by nodes from Column A, Column C, and Column D which represented the sow's respiration zone (60 cm height) and upper area of the sow's head (160 cm height), respectively. This spatial distribution feature implied that further cooling measures should be taken to prevent sows there from reducing welfare due to the heat stress. The spatial characteristic of relative humidity sustained its negative correlation relationship with temperature, which was pointed out previously in the process of temporal characteristic analysis. Benefitting from this distribution characteristic, it is favorable for sow's health to avoid staying in a both hot and humid barn that will cause severe uncomfortableness and thereby reduce animal welfare. Regions that exhibited higher relative humidity than the recommended value 86% primarily appeared in the front parts of Units 1–3 and 13–15. Therefore, timely and accurate suggestions to improve the management efficiency of temperature and relative humidity in the commercial swine confinement building could be provided by this WSN system.

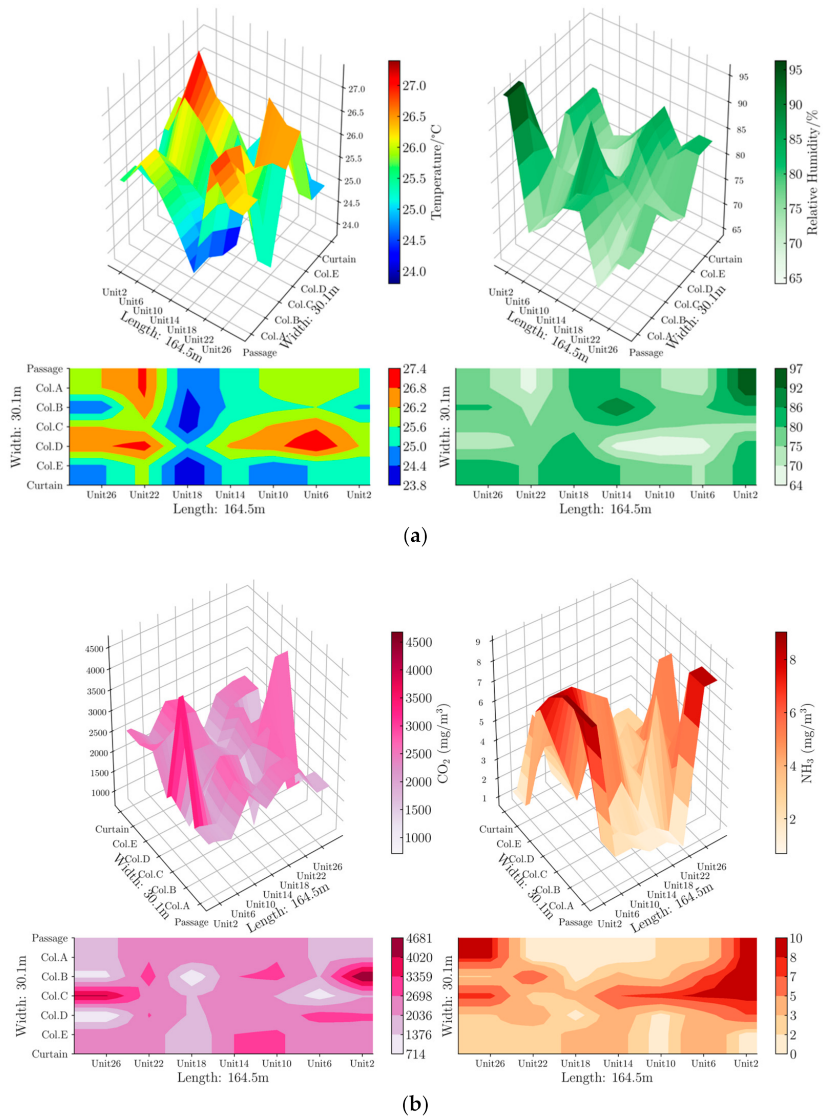

Figure 14. (**a**,**b**) The three-dimensional surface plots and corresponding contour plots of sow's respiratory zone and upper region above sow's head recorded on 15:04 13 August.

CO_2 concentrations of two small regions which were located near the side wall, referring to Units 1–4 and Units 24–28 in the middle, showed extremely high levels that far more exceeded the recommended 2700 mg/m^3. This phenomenon was probably due to the poor air exchange rate, and thereby CO_2 was prone to accumulating in those areas. Moreover, nodes mounted on Units 24–28 were 60 cm high, thus could well represent sow's respiration area, given that respiration of sows is one main source of CO_2 release and is proportional to the total heat production and the maximum accepted CO_2 concentration inside the pig building [36]. Therefore, it is of vital importance to timely exhaust this greenhouse gas from the pig barns especially in the hot summer, and the WSN system is capable of accurately identifying those abnormal regions in real-time. Although the overall NH_3 concentration in this swine building was much less than the recommendation 20 mg/m^3, high levels of ammonia accumulated in many Units in Columns A, B, and C near the side wall, which might imply that the air exchange rates in those regions were quite slow.

4. Conclusions

In this study, a ZigBee-based WSN system which consists of three layers was proposed, and it proved to be accurate and effective in assisting with microclimate management in a commercial gestating sow confinement building by monitoring four environmental parameters in real-time.

The proposed WSN system underwent three-day consecutive observations in a 10 min interval, reported 16,371 records from its 41 indoor slave nodes, thus achieving an overall data packet loss rate of 4%. A series of preprocessing steps was applied to cope with the null records and interpolation before analyzing the distribution condition of abnormal observations among four types of sensors. The corresponding analysis results showed that all the sensors were working well except for the CO_2 which performed an average outlier rate of 6.5%. Apart from the above systematic performance, it is straightforward and useful to evaluate its practical contribution to monitoring the microclimate from both spatial and temporal perspectives. A daytime high temperature (above 24 °C) starting from 10:00 to 16:00 in this commercial gestating sow house was found, however, it is yet acceptable in the thermoneutral zone. However, the relative humidity showed inverse diurnal variation patterns compared with that of temperature variation both spatially and temporally. Although the CO_2 concentration inside this pig house was above 1500 mg/m^3 for the whole time, there merely existed two periods when the CO_2 levels exceeded the 2700 mg/m^3, namely: ranging from 07:00 to 08:00 and from 14:00 to 15:00. Additionally, the overall NH_3 concentration in the swine building was maintained in a relatively low-level range with a maximal value of less than 8 mg/m^3. In sum, by deploying the WSN system in this gestating sow house, real-time monitoring and timely intervention could be attained thus making it possible to provide effective suggestions about when and where the climatic adjustment and human labor should be adapted.

Methane (CH_4) and nitrous oxide (N_2O) are greenhouse gases that need to be taken into consideration. Therefore, as a further study, our team will work on the implementation of new series of sensors that are especially devised to measure the emissions of both previously mentioned gases and thus include these extremely important parameters in our WSN monitoring system in the gestating sow house.

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