Article

Bluetooth Beacon-Based Mine Production Management Application to Support Ore Haulage Operations in Underground Mines

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Abstract: In this study, a mine production management application (app) using a Bluetooth beacon and tablet PC was developed to support the efficient operation of an underground mine loading-transport system. The app receives signals from the Bluetooth beacons attached to major loading points and crushing sites through the tablet PC mounted on the truck and records the time the signals were received as well as the location of the truck. In addition, when the tablet PC receives the signal from the Bluetooth beacon, the truck driver can select and input information such as loading point, ore type, and dumping method on the tablet PC screen. Data recorded on the tablet PC during the haulage operation are automatically transmitted to the cloud server when the truck arrives in a wireless communication area. The cloud server continuously stores and manages data transmitted from multiple trucks equipped with tablet PCs. The performance test was conducted by using the system developed for a limestone underground mine located in Jeongseon, Korea. Results confirmed that the information related to ore production in the field could be effectively collected and managed, and the efficiency of production management could be improved.

1. Introduction

In the mineral resources industry, the concept of digital or smart mining began to be introduced in the form of futuristic mining in the 2010s [1]. Smart mining aims to efficiently utilize the mine's assets and maximize profits by connecting and automating each process from the perspective of the entire mining industry [2]. Smart mining technology can be realized through the convergence of information and communication technologies, such as the Internet of Things (IoT), drones, artificial intelligence (AI), big data, 3D printing, robotics, and autonomous driving, which are core technologies of the fourth industrial revolution [3]. In particular, smart and automated mines can potentially be built by gradually utilizing the IoT technology [4].

IoT refers to an environment in which people, devices, and spaces are connected through a network so that both people and objects can exchange data and communicate with each other anytime, anywhere. In the field of mining, the IoT collects necessary data from physical mines in the real world and transfers it to virtual mines. Until recently, various studies have been conducted in the application of short-range wireless communication technologies such as IoT-based radio frequency identification technology (RFID) and Bluetooth beacon technology using Bluetooth low energy (BLE) in underground mines [5–22]. Jung and Choi [16] proposed a reverse RFID system-based method that measures the transport time of a truck by using time data recorded when an RFID reader attached to the truck recognizes an RFID tag installed at a key location in an underground mine. In addition, Jung and Choi [17] installed Bluetooth beacons in the main locations of underground mines

and installed smartphones that can recognize beacon signals in dump trucks to quantitatively measure the transportation time of equipment. Baek et al. [18] developed a Bluetooth beacon-based underground navigation system that can track the exact location of dump trucks in underground mines. The mobile application recognizes the current location of the dump truck in an underground mine and visualizes the transport path to the destination using the signal transmitted by the Bluetooth beacon. Finally, Baek and Choi [19] developed a Bluetooth-based underground proximity warning system that provides drivers with progressive collision risk alerts based on the received signal strength indicator (RSSI) state. In this way, near field communication technology has been applied to underground mines. Research on navigation, proximity warning systems, and transportation-related time data collection has also been actively carried out. However, few studies have been conducted on the implementation of functions in terms of systematic production management of underground mines.

The purpose of this study is to develop an underground mine production management application (app) that can efficiently support the truck-loader haulage system and enable systematic production management of underground mines using a Bluetooth beacon and a tablet PC and a short-range wireless communication device. First, we developed an app that includes a mine production management function that can automatically create a production log and add navigation and equipment proximity warning functions. Next, the limestone underground mines were set as research areas, and Bluetooth beacons were installed at the main points of the mines. In addition, the performance of the system was tested by attaching the tablet PC with the app to the dump truck dispatched for haulage.
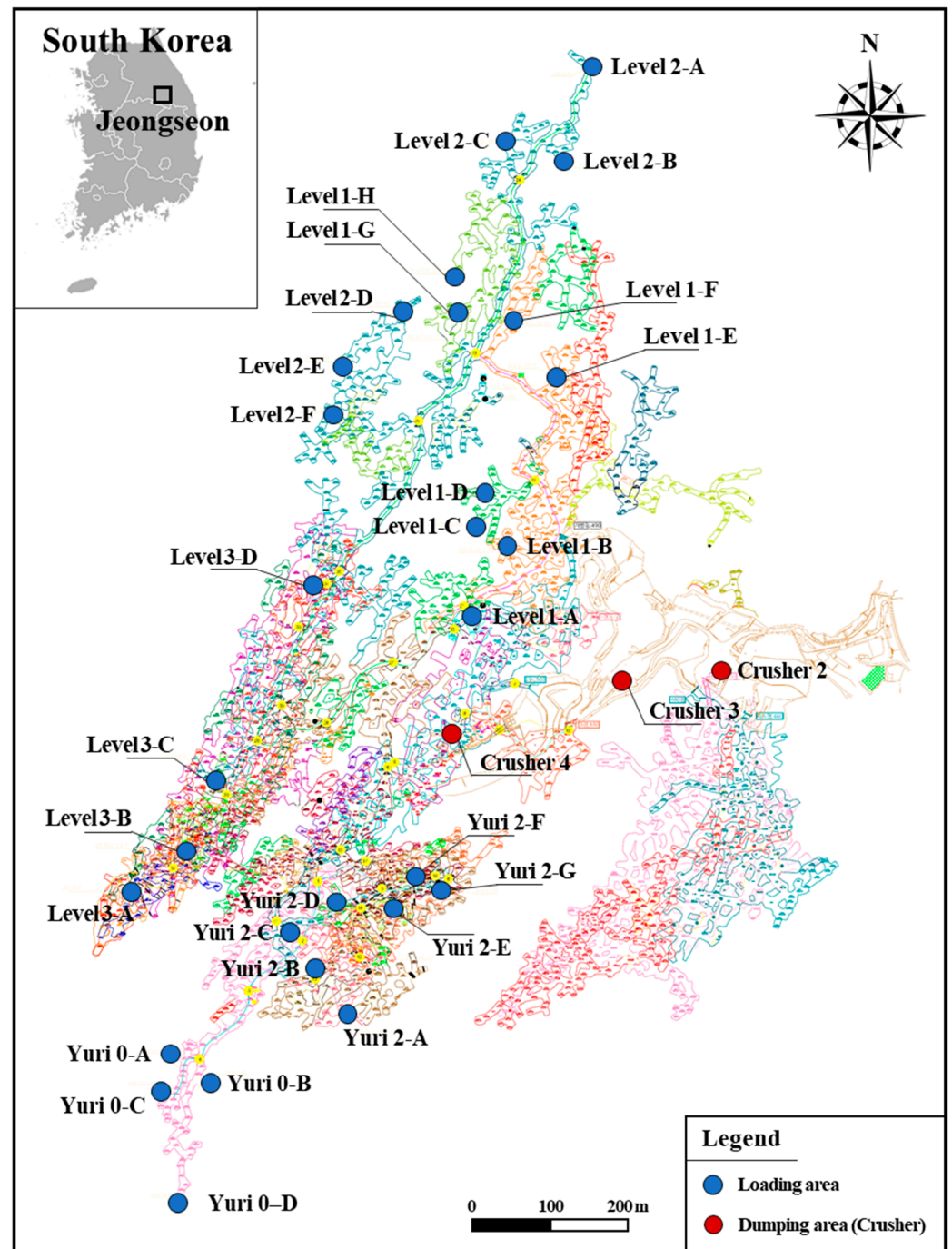
2. Study Area

In this study, for the development of an underground mine production management system and field application experiment, the Seongshin Minefield underground limestone mine ($37°17'12''$ N, $128°43'53''$ E) located in Jeongseon-gun, Gangwon-do, Korea was selected as the research area. (Figure 1). The underground mine annually produces 1 million tons of high-quality limestone by applying the room and pillar mining method. They use ammonium nitrate fuel oil (ANFO) and Emulite to blast up to six times a day, producing 3500 tons of limestone per day. The mined ore is transported to crushers located outside the mine using a dump truck (25–40 tons).

To analyze the truck-loader haulage system in the study area and to design the BLE transmitter/receiver of the Bluetooth beacon and tablet PC, environmental surveys and 3D drawing analysis were performed (Figure 2). The internal and external environmental surveys of mines were conducted by getting off at the main points on the transportation route that constitutes the truck-loader haulage system, under the guidance of field staff. Humidity was high at all points in the mine where the investigation was conducted, and there was even a point where groundwater flowed down the walls of the mine. In addition, the concentration of scattered fine dust was also high due to blasting, loading, and transporting operations in the mine.

The analysis of the path that the truck uses to transport limestone was performed by boarding the truck dispatched in the production operation and taking an orthogonal image outside the mine using a drone and a 3D model. Thus, the study area was found to have 16 loading areas and four dumping areas (Figure 3). The loading area includes major loading zones where mining and loading are performed. Three of the four dumping areas (crusher 2, crusher 3, crusher 4) are located along the mine, but one dumping area (crusher 1) is located 2.5 km away from the mine. The trucks loaded with limestone dumped the ore directly into the hopper of the crusher or deposited it in the storage yard, depending on the daily production plan or the condition of the crusher hopper in the four dumping areas.

The truck driver, responsible for the production operation, recorded items such as loading point, dumping point, time, product name, dumping method, vehicle inspection, and maintenance history when loading and dumping the limestone. The production log

is recorded every time the ore is loaded and transported, and it is used to manage the production of mines based on the workplace or product and to inspect and manage vehicles. Traditionally, the production log has been handwritten by the truck driver in the dark and harsh environment of an underground mine. Then, the production logs have been collected and stored by date and by truck or scanned and converted into digital files, and some have been computerized in the form of spreadsheet programs by office workers.

Figure 1. Map of the study area (Sungshin Minefield underground limestone mine, Jeongsun-gun, Gangwon-do, Korea) showing the loading areas and dumping areas.
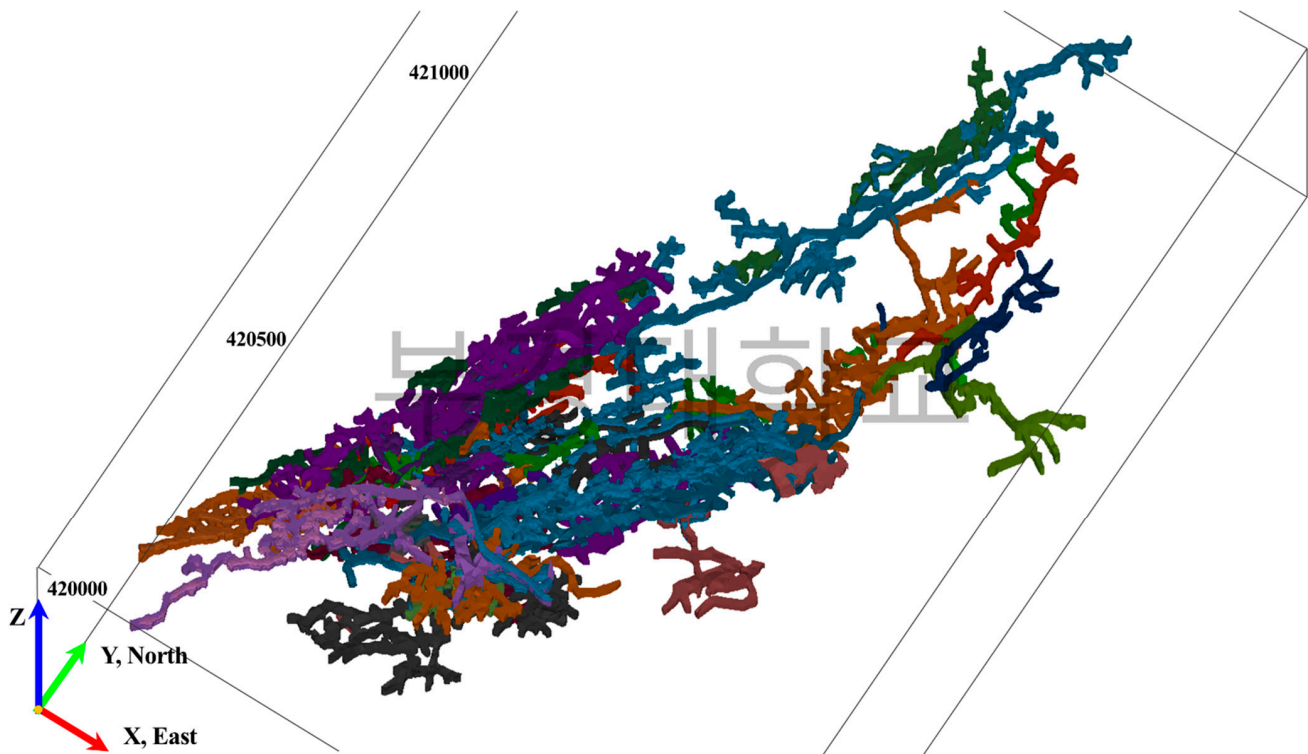
Figure 2. Analysis of truck-loader transport system in research area using 3D model (built with K-mod studio).
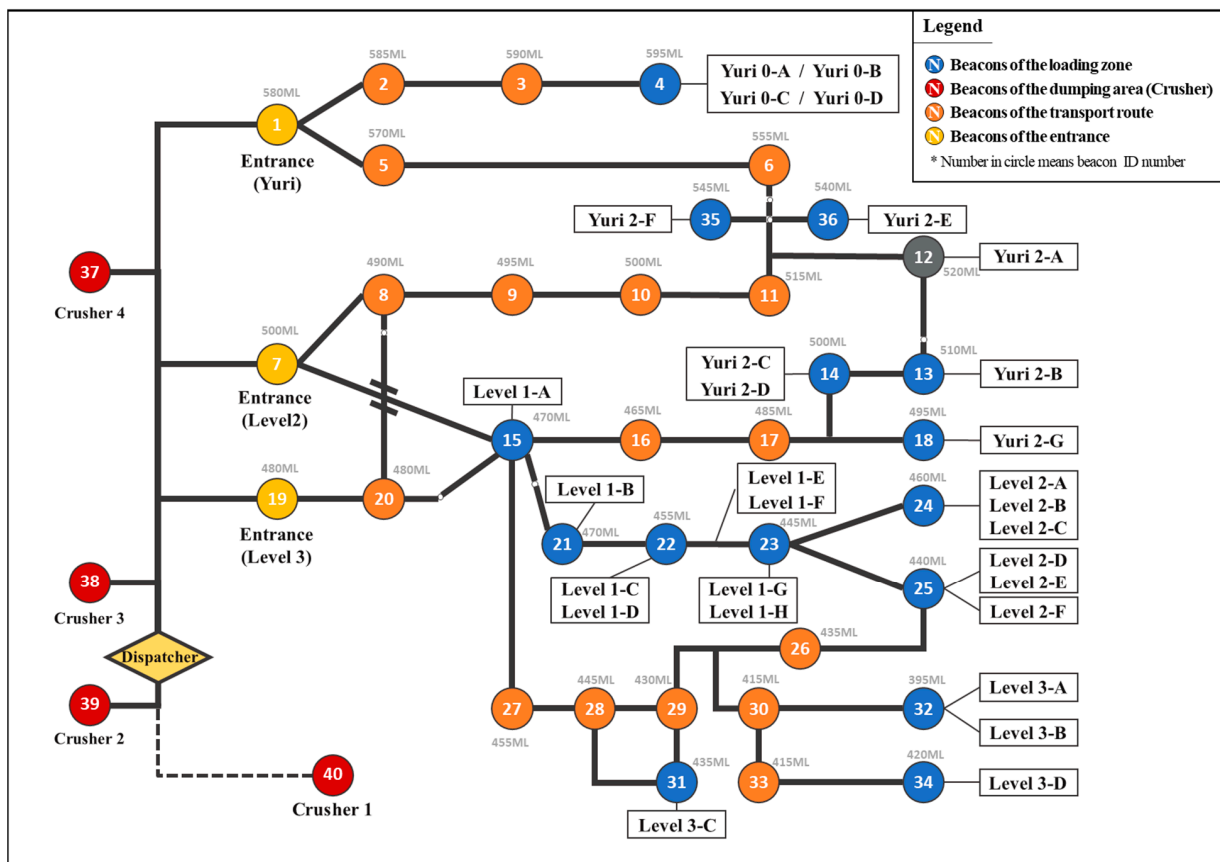

Figure 3. Schematic diagram of the transport route between major loading and dumping points in the study area and the Bluetooth beacon installation point.

3. Methods

The app developed in this study connects physical mines in the real world with virtual mines. Physical mines collect and store production-related data using short-range wireless communication devices such as Bluetooth beacon and tablet PC, and virtual mines process and analyze the collected data (Figure 4). The signals from the Bluetooth beacons installed at major points or on the loaders of the underground mine and the loading and dumping areas (crusher) are received by the tablet PC mounted in the truck. The location of the truck and the time when the signal is received through the app installed on the tablet PC is recorded. Navigation and equipment proximity warning functions are provided. Data stored in the built-in memory during the production operation are automatically uploaded to the cloud server when the truck reaches an area with wireless network. The cloud server continuously stores and manages the data transmitted from multiple trucks with tablet PCs installed. In addition, these data are automatically converted into the production log format used in the field by the production log creation automation software developed in this study.
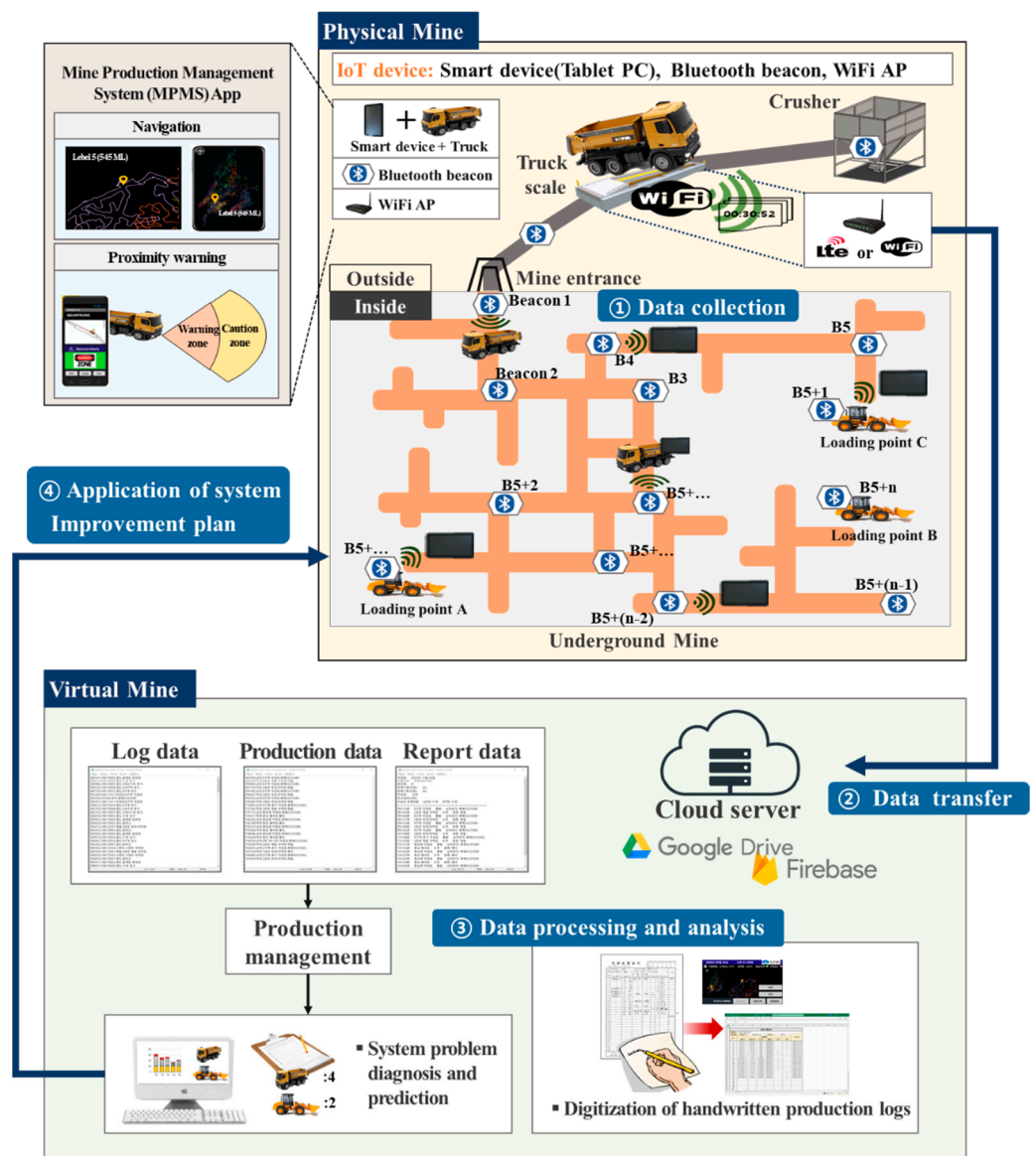
Figure 4. Conceptual diagram showing the operating principle of the mine production management system using Bluetooth beacon and tablet PC.

3.1. Design of Application

Essential functions to be included in the app were derived based on the results of environmental surveys, production log analysis, and interviews with truck drivers and management staff. As a result, it was found that the previously developed and researched navigation and equipment proximity warning functions and production management functions through automation of production log creation and data collection related to truck-loader haulage should be included.

In this study, the MIT App Inventor was used as a tool for application development. The appearance of the application is designed graphically, and the operation of the application is implemented using the drag and drop method of programming the block. Therefore, the user does not need to enter the command using the keyboard. It is characterized by the ability to design an application screen and a coding function to implement the operation using the block, all executed in one web browser [23].

The app outputs maps, information, and voice guidance on the current location when receiving signals from Bluetooth beacons installed at major points in the mine. In addition, when a signal from a beacon installed in a vehicle is received, information about a vehicle in a nearby location and a warning sound are output. The app continuously stores three types of files related to production log creation and truck-loader haulage in the internal memory of the tablet PC, while providing navigation and equipment proximity warning functions. The files include a log file, a production file, and a report file, and they have a comma-separated variable (CSV) file format that separates items based on commas and stores data. In the log file, when the tablet PC receives the Bluetooth beacon signal, the ID and information set in the beacon, receiving time, and information directly input by the user are stored. That is, all the times that the beacon signal is received. The production files only store records of limestone loading and dumping. In other words, it stores the time and place of loading and dumping, the number of loading and dumping, and information of the loader that performed the loading operation. The report file includes information about loading and dumping as well as the vehicle operation status (distance, fueling volume) input by the app user after the production operation, and vehicle maintenance details or specific matters. When a truck dispatched in a production operation passes through a wireless communication area or stops, the three types of files stored in the internal memory of the tablet PC are uploaded to the cloud server.

3.2. Design of BLE Transmitter/Receiver using Bluetooth Beacon and Tablet PC

If underground mines are continuously operated and ore is produced, the area of the loading zone will increase due to new excavations and can change from time to time. Considering the risk of opening a new loading zone, closing an existing loading zone, or changing the transport route, the Bluetooth beacon used for the app should be easy to install. In addition, maintenance and management should be easy, and the signal strength and transmission period should be adjustable. In particular, it is important to have a signal strength sufficient to cover the tunnel on the main transport route because the tunnel characteristics are not constant at all points in the mine. Therefore, in this study, the most suitable model for the app was selected by comparing models of Bluetooth beacons in the market. For the selection of Bluetooth beacons, aspects such as ease of installation and maintenance, battery life, waterproof and dustproof design, operating temperature, signal recognition distance, exclusive management application, and price were considered. After comparing various Bluetooth beacons, Beacon i3 (Hyunseung; Seoul, Korea) was selected as the beacon to be installed at major points inside and outside the mine, and at the loader. Table 1 shows the detailed specifications of the Beacon i3. Beacon i3 allows the user to adjust the signal strength (minimum −30 dBm to maximum 4 dBm), signal transmission period (minimum 0.1 seconds to maximum 10 seconds), and the maximum recognition distance at 200 m. Moreover, because it uses two AA batteries, it has a longer lifespan than the other models. Particularly, it has a waterproof and dustproof design using rubber packing for assembling beacons. The RECO Beacon (Purples Inc.; Seoul, Korea) was

selected as the beacon to be installed on vehicles entering an underground mine (trucks, ANFO chargers, drills, excavators, and management vehicles) for equipment proximity warning. RECO Beacons can be operated for up to 24 months when using a CR2450 Li-ion battery. In addition, Jung and Choi [17], Beak et al. [18], and Beak and Choi [19] testified to their performance in underground mines. For detailed specifications of RECO beacons, please refer to the above papers.

Table 1. Specifications of Beacon i3 (radio frequency identification technology (S-RFID); Seoul, Korea) installed at major points inside and outside the underground mine and loaders.

Specifications		
Appearance	Dimension (width × length, thickness)	72 mm × 45 mm, 16 mm
	Housing	Plastic
	Ingress protection	IP66 waterproof grade
	Operating temperature	−20 °C to +70 °C (Battery limit)
Hardware	Chipset	CC2541 / nRF51822
	Battery type	Alkaline battery (AA battery)
	Battery capacity	2500 mAh
	Battery life	over 5 years
Wireless signal	Wireless technology	Bluetooth®Smart 4.0
	Transmission power	Minimum –30 dBm, maximum 4 dBm
	Transmission period	Minimum 0.1 s, maximum 10 s
Certification	Europe	Conformité Européenne (CE) marking
	USA	Federal Communications Commission (FCC)
	Apple Inc. (Cupertino, CA, USA)	Made for iPod/iPhone/iPad (MFi)

The installation point of the Bluetooth beacon was determined through an analysis of the truck-loader haulage system and interviews with employees related to the production operation. As a result, it was found that installing beacons in 16 loading areas, 4 dumping points, and 20 major transport routes would be a suitable option (Figure 3). As mentioned earlier, as long as production operations are taking place in underground mines, the location of the loading zone continues to change. Therefore, the beacon was attached to the loader that performs the loading operation at the loading zone instead of attaching the beacon to the wall of the loading zone. That is, the app recognizes that the truck has arrived at the loading zone when it receives the signal from the beacon attached to the loader.

3.3. Install Bluetooth Beacon and Wi-Fi Access Point (AP)

In the case of Beacon i3 installed inside and outside the mine, the risk of corrosion and flooding was minimized by using rubber packing when assembling the Bluetooth beacon, considering the high humidity and dust in the underground mine. The assembled beacon was packaged and installed in a plastic bag along with a dehumidifying agent. In addition, beacons were installed by fixing them to the wall with screws or hanging them with strings (Figure 5a,b). At points where the reception of beacon signal is unstable due to irregular tunnel contours and irregularities on the walls of the tunnel, the beacon installation angle was adjusted using a bracket. Beacon i3 attached to the loader was installed on the dashboard of the driver's seat so that the transmission direction of the beacon signal faces the front of the loader, as shown in Figure 5c. RECO beacons on trucks and management vehicles moving at relatively high speeds were installed in front of the vehicles, at places such as the dashboard of the driver's seat or the rearview mirror, as shown in Figure 5d. In the case of the rest of the equipment (ANFO chargers, drills,

and excavators), beacons were installed in the rear of the vehicle. Because these vehicles move at a relatively slow speed, when a truck or a management vehicle approaches from the rear in the mine, it often stops for a while and yields to give way. Thus, equipment with a slow driving speed prevents rear collisions of vehicles with high driving speed.

Figure 5. Example of Bluetooth beacon (Beacon i3 and RECO beacon) installed for mine production management app: (**a**) tunnel wall on the transport route; (**b**) near the crusher at the crusher 4; (**c**) dashboard in the driver's seat of the loader; (**d**) rearview mirror in the driver's seat of the truck.

It is necessary to increase the recognition rate by setting the optimal beacon signal strength and transmission period because the tablet PC installed on a fast-moving truck must receive the signal from the Bluetooth beacon in an underground mine where the wireless communication environment is very poor. Therefore, the signal strength of Beacon i3 was set to the maximum value (transmission power: 4 dBm), and the signal transmission period was set to an average of 5 times per second (broadcasting: 200 ms). The RECO beacon installed in the equipment has the same signal strength and transmission period.

A Wi-Fi AP was installed in the study area to establish a wireless communication area for uploading data files stored in the tablet PC to the cloud server. Wi-Fi APs must be installed at the point where trucks must pass from the loading area to the dumping area, from dock to dock, or at the point where the truck is parked before or after production work begins. Therefore, in this study, based on the results of image analysis taken with drones, one Wi-Fi AP was installed in each of the operating rooms of crusher 2 and the electrical engineer's office, and it was configured as a mesh network.

3.4. Server Design for Application Maintenance and Data Storage

The server for maintaining the app and storing data is operated as shown in the conceptual diagram in Figure 6. In the cloud server, the app developer or site manager maintains and manages app installation files uploaded through a management PC or data related to app operation, and stores and manages data uploaded from a tablet PC installed in a truck. In this study, we used Google Drive, a cloud-based file storage and sharing service provided by Google and Firebase, a cloud service in the form of PaaS (Platform as a

Service). The use of two cloud servers serves as a backup in case of damage or loss of files and data stored on the server.
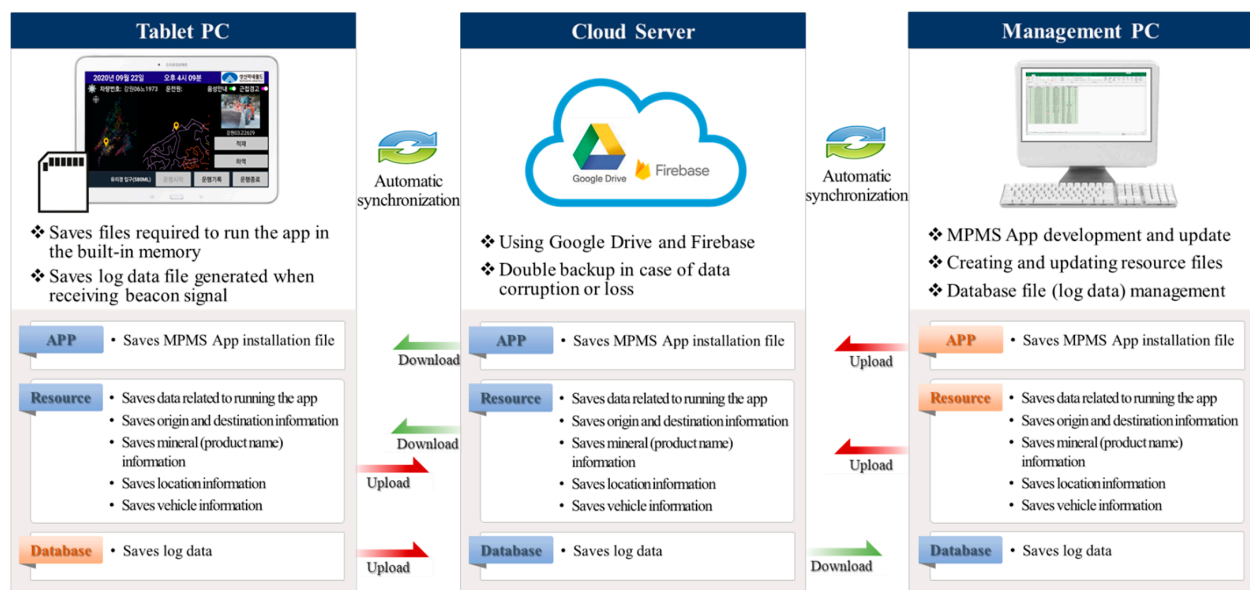
Figure 6. Conceptual diagram of a server for maintaining mine production management app and storing data.

The cloud server is largely composed of three folders: apps, resources, and databases. The app developer develops and updates the app installation file in the app folder and uploads the app installation file. The staff in charge of the app at the site downloads and installs the uploaded app installation file to the tablet PC. In the resource folder, files related to the application operation are created and updated. In the transport operation, data such as a list of the origin or destination of a truck, a list of vehicle numbers and information of the driver of equipment (vehicles), and a list of ore product names are included. In the database folder, three types of files (log, production, and report) that are continuously recorded on the tablet PC installed in the truck are uploaded and stored.

3.5. Development of Automated Production Log Creation Software

The report file created by the app is text data (CSV) that separates several fields with commas (,) and can be checked using a software such as Notepad. In the research area, the production log written by hand is directly computerized using a spreadsheet program (Microsoft Excel). Therefore, in this study, we developed a software that can automatically convert the report file in the form of a CSV generated by the app into the format used in mines. The developed software loads the report file uploaded to the cloud server, converts it into an Excel program template, and saves it.

3.6. Performance Test

In this study, the developed app was applied to the research area, and its function and performance were evaluated over four stages. First, the reception of the Bluetooth beacon signals installed in the study area and the app were tested. The test for the reception of beacon signals and tests for the functions implemented in the app were carried out while moving to 40 locations where Bluetooth beacons were installed on board the trucks dispatched in production operation and on-site management vehicles (SUVs). Then, the truck with the tablet PC installed with the app was dispatched to the actual production operation to confirm that the data was properly stored on the tablet PC and uploaded to the cloud server. Next, we checked the performance of the automated production log creation software developed using the data file uploaded to the cloud server. Finally, when the performance experiment was conducted, the production log

written by the truck driver by hand and the data produced on the tablet PC were compared and analyzed.

4. Results

4.1. Development of Application

The basic interface of the app developed in this study is shown in Figure 7a. The upper part of the app screen consists of a part that prints the date and time of production operation, another that prints the vehicle number and driver information of the vehicle on which a tablet PC is installed, and a third part that can turn on/off the voice guidance and equipment proximity warning function. On the left side of the app screen, the current location information of the truck is displayed as a map and text, and the right side consists of a part that outputs information of other equipment when the device is close, and buttons necessary to run the app. Users can use the buttons to select and enter loading or dumping, start or end the app, and enter information about the production operation.

Figure 7. User interface of mine production management app according to the location where the Bluetooth beacon is installed. (**a**) receiving a signal from a normal beacon on the transport route; (**b**) receiving a beacon signal attached to a loader located at the loading zone; (**c**) receiving signals from beacons installed at dumping area.

When the truck with the tablet PC installed arrives at the loading zone and receives the beacon signal from the loader during loading, a screen that allows the truck driver to select and input information on the loading point is displayed (Figure 7b). When receiving the signal from the beacon installed at the dumping area, a screen for selecting and inputting the product name and dumping method of the delivered ore is displayed (Figure 7c). When receiving a signal from a beacon installed on a normal transport route other than a loading point or dumping point, the location information for that point is output as a map and audio, as shown in Figure 7a. In addition, when a vehicle with a RECO beacon installed is encountered on the route, a warning voice for the proximity of the equipment and information about the approaching equipment are output.

4.2. Results of Performance Experiment

The signal reception test of the Bluetooth beacons installed in the study area and the app test were performed using trucks equipped with a tablet PC with an app and on-site management vehicles. The test for beacon signal reception was performed using a dedicated application for beacon setting, and the test results showed that the signal strength and transmission period were very good at the 40 locations where beacons were installed. The performance tests of the app were carried out for two days using trucks dispatched during the production operation. When receiving a signal from a normal beacon on the transport route, the app outputs a map and information about the point, as shown in Figure 8a. Since the map is output as a full map and an enlarged map of the mine, truck drivers can easily determine the current location of the truck through the app. When a beacon signal attached to a moving or working equipment is detected at a nearby location while the truck is moving, the information of the equipment is displayed on the right side of the app screen, and a proximity warning to help avoid collision is output (Figure 8b). In addition, voice notifications are also output to keep the truck driver alert. When recognizing the signal of the Bluetooth beacon classified as a loading area and then recognizing the beacon of the loader located at the loading zone, the app displays a screen that allows the user to select and input the loading point (Figure 8c,d). When a truck loaded with limestone arrives at the dumping area, a screen for selecting and inputting the product name and dumping method of the transported limestone is displayed (Figure 8e,f). In addition, the truck driver operates the app when the truck is completely stopped and then loading or dumping is performed. Data generated during production is automatically transmitted to the cloud server in the area where the truck passes through the wireless communication area or parked after the production operation is finished. Thus, truck drivers can safely use the app.

All the tablet PCs attached to the trucks dispatched for production operation for the performance experiment stored three types of data (log, production, and report) in the internal memory, and these data were classified by production date and truck and uploaded to the cloud server. In addition, it was confirmed that the production log creation automation software converts the report file (Figure 9a) into an Excel file (Figure 9b) with the production log template used in the field. Finally, the handwritten production logs provided at the site and the data generated on the tablet PC were compared and analyzed. As a result, it was confirmed that the place and time of the loading and dumping operations, dumping method, and product name match with each other. However, when comparing the Bluetooth beacon installation schematics shown in Figure 3 with the Bluetooth beacon signals recorded in the log file, the Bluetooth beacon signals were recorded along the route shown in the schematics, but some of the transportation operations did not detect the signals. This was confirmed to be the case where the existing transportation route was temporarily not used due to the characteristics of underground mines such as narrow tunnels, temporary tunnel closure, tunnel maintenance, and flooding by groundwater.

Figure 8. Results of performance experiments. (**a**) maps and information about the vehicle location; (**b**) equipment proximity warning; (**c**,**d**) loading point selection and input screen; (**e**,**f**) product name and dumping method selection and input screen.
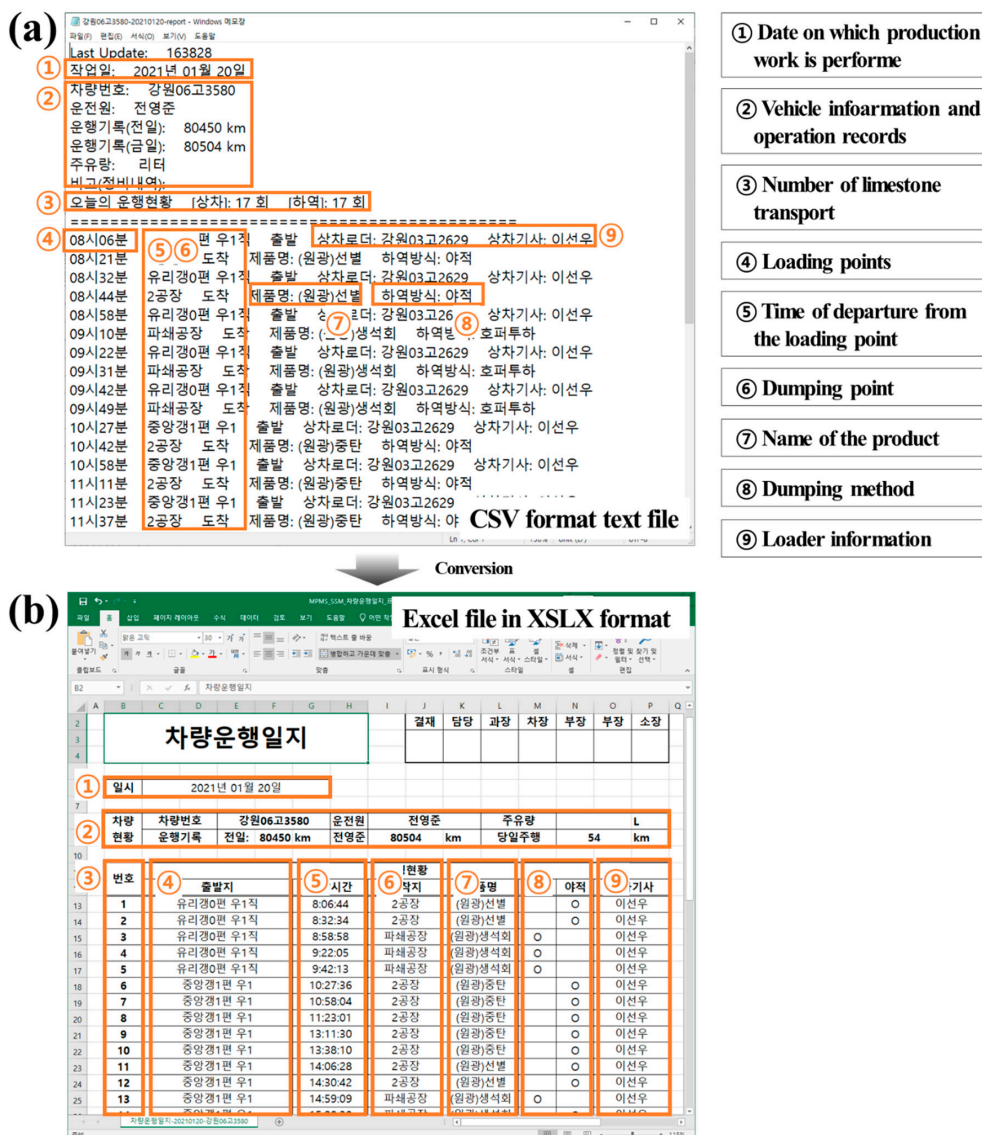

Figure 9. Report file conversion by production log creation automation software: (**a**) comma-separated variable (CSV) format text file; (**b**) Excel file in XSLX format used in the field.

5. Discussion

The mine production management app using the Bluetooth beacon and tablet PC has the following advantages and possibilities.

- Because it uses a Bluetooth beacon and a tablet PC, the system can be built at a low cost and can be easily operated with basic knowledge.
- Bluetooth beacons that transmit BLE signals do not require external power, and the system maintenance cost is low as it uses lithium-ion batteries (coin batteries) or AA batteries.
- It is possible to flexibly cope with the opening or closing of a new loading zone, and the expansion of the system is easy.
- It is possible to automatically generate a production report that was conventionally created by hand in an underground mine. Therefore, it is convenient for truck drivers and managers.

However, if the mine continues to expand and the tunnel is extended, the need to install additional Bluetooth beacons can increase the cost of building the system. In addition, when the transport route temporarily changes depending on the characteristics of the underground mine and the condition of the tunnel, there may be a case in which the signal of the Bluetooth beacon cannot be detected. Therefore, it is very important to select the optimal location of the Bluetooth beacon to be installed inside and outside the underground mine before deploying the system on the field. As a future study, it is necessary to quantitatively analyze the effect of improving production efficiency of the Bluetooth beacon-based production management app developed in this study. In addition, we will use this data to simulate truck-loader haulage systems and analyze factors that affect productivity, such as production volume and equipment utilization rate, if the app used in the study area operates stably and the data generated are adequate.

6. Conclusions

In this study, we developed an underground mine production management app that can support the efficient operation of an underground mine's truck-loader haulage system using Bluetooth beacons and tablet PCs, and presented the results of the study. The app was developed, including production management functions such as production log creation automation, navigation, and equipment proximity warning functions that were previously researched and developed. It was confirmed that the tablet PC installed on the truck properly received the beacon signal throughout the app and continuously stored the data generated during production operation and uploaded it to the cloud server. In addition, users were able to quickly create production logs that were previously handwritten, using the developed software.

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